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Proceedings of the 15th International Congress of Speleology

Errata and Omissions

The Proceedings of the 15th International Congress of Speleology contain either abstracts or full papers of the 500 contributions presented at the Congress. The three volumes of the Proceedings total 2130 pages. The pathway to this mass of material was as follows: Prospective authors submitted an initial abstract to the ICS Science Committee. These abstracts were reviewed by the Committee to ascertain that the subject matter was appropriate for the Congress. The abstracts were then returned to the authors with suggestions and an invitation to prepare a full paper limited to six printed pages. Few papers were rejected, but some were withdrawn so that of 540 initial submissions, 500 were presented at the Congress. The draft papers were sent to the Science Committee who distributed them for review after which they were returned to the authors for such adjustments as the reviewers deemed necessary. The final papers were received by the Science Committee for formal acceptance and were forwarded to the editor. The edited papers were then transmitted to Production Manager for page layout and preparation for the printer.

All of this movement of abstracts and manuscripts was done electronically. In the process of transmittals, various reviews, and editorial handling, a few errors and omissions were created. The lists that follow contain the additions and corrections that have been brought to our attention. We have limited the corrections to matters of fact; small errors in spelling, punctuation, and formatting are not addressed. We apologize to the authors whose papers were mishandled in some manner.

The Editorial Team

Errata

Volume 1, Page 541

Cave Sediments Related to Cretaceous-Tertiary Paleokarst Developed in Eogenetic Carbonate Rocks: Examples from SW Slovenia and NW Croatia by Bojan Otoničar.

The abstract was truncated in printing with only the first few lines appearing in the Proceedings. The full abstract follows.

In the SW Slovenia and NW Croatia a regional paleokarstic surface separates the passive margin shallow-marine carbonate successions of different Cretaceous formations from the Upper Cretaceous to Eocene palustrine and shallow marine limestones of the synorogenic carbonate platform. Thus, the paleokarst corresponds to an uplifted peripheral foreland bulge, when diagenetically immature eugenetic carbonates were subaerially exposed and karstified.

Among the subsurface paleokarstic features vadose and phreatic forms are recognized. For the epikarst, pedogenic features and enlarged root related channels are characteristic. Vadose channels, shafts and pits penetrate up to a few tens of meters bellow the paleokarstic surface, where they may merge with originally horizontally oriented phreatic cavities. The latter comprise characteristics of caves forming in fresh/brackish water lenses. The phreatic cavities were found in different positions regarding to the paleokarstic surface, the lowest one being some 75 meters below it. Usually only one distinct paleocave level occurs per location, although indistinct levels of spongy porosity and/or irregularly dispersed cavities of different sizes have been noticed locally. The cavities had been subsequently partly reshaped and entirely filled with detrital sediments and flowstones in the upper part of the phreatic, epiphreatic and vadose zones. The internal cave sediments and flowstones may also occur as clasts in deposits (mostly breccias) that fill subsurface paleokarstic cavities and cover the paleokarstic surface. In general, the variety of cave infilling deposits and the amount of surface derived material decrease with the distance from the paleokarstic surface. Below the paleokarstic surface $\delta^{13}C$ and $\delta^{18}O$ values of cavity deposits usually exhibit good correlation with trend significant for meteoric diagenesis.

Relatively small phreatic cavities of the lowermost part of the paleokarstic profiles are commonly geopetally infilled with laminated mudstone derived from incomplete dissolution of the hostrock overlain by coarse grained blocky calcite of meteoric or mixing meteoric/marine origin. Somewhat larger phreatic caves located shallower below the paleokarstic surface usually exhibit more complicated stratigraphy. Although the lower parts of the caves are still mainly infilled with reddish stained micritic carbonate sediment, different types of flowstone, especially calcite rafts, become more prominent higher in the cave profiles. Gradually in the upper parts of the caves, sediments derived from the paleokarstic surface prevail over autochthonous deposits. Especially channels of the epikarst zone are almost entirely infilled with pedogenically modified material derived directly from the paleokarstic surface. Regardless of their origin, cave deposits had been often intensively modified by pedogenic processes while they were exposed to the paleokarstic surface by denudation. Just prior to marine transgression over the paleokarstic surface some cavities or their parts had been infilled by marine derived microturbidites. It will be shown that especially deposits related to denuded phreatic caves may be of great importance for the study of speleogenetic, geomorphologic and hydrogeologic evolution of a specific karst region.

Volume 2, page 650

Medical and Governmental Considerations of CO_2 and O_2 in Volcanic Caves by William R. Halliday

The final sentence of the first paragraph on page 652 contains incorrect wording. The sentence should read:

“The issue resurfaced when U.S. Geological Survey and National Park Service personnel applied OSHA standards to volunteers in volcanic caves with non-toxic levels of O_2 and CO_2.”

Volume 2, page 662

Unusual Rheogenic Caves of the 1919 “Postal Rift” Lava Flow, Kilauea Caldera, Hawaii by William R. Halliday

The first paragraph on page 664 contains several errors and misstatements. The corrected paragraph should read:

"Noxious gas (probably HCl) was encountered only in one tiny cave on the edge of Halemaumau Crater. Presumed sulfate fumes were encountered in numerous caves but were found to be essentially non-toxic. Eye irritation rarely was encountered (Halliday, 2000b). Two types of CO_2 monitors previously untested in volcanic caves were required for the last five field trips. They were found to be useless in hyperthermal caves and no significant elevation of CO_2 was identified in normothermic examples (Halliday, 2007). In no cave was significantly elevated CO_2 identified by changes in normal breathing (Halliday, this volume)."

Volume 2, Page 785

Symposium #11, **Speleogenesis in Regional Geological Evolution and Its Role in Karst Hydrogeology and Geomorphology** was arranged by Alexander Klimchouk and Arthur N. Palmer (not by John Mylroie and Angel Ginés as listed on the title page of the symposium in the Proceedings).

Volume 2, Page 1033

Uranium Mapping in Speleothems: Occurrence of Diagenesis, Detrital Contamination and Geochemical Consequences

The correct authors for this paper are: Richard Maire, Guillaume Deves, Ann-Sophie Perroux, Bassam Ghaleb, Benjamin Lans, Thomas Bacquart, Cyril Plaisir, Yves Quinif and Richard Ortega. The names of Bassam Ghaleb and Yves Quinif were omitted in the Proceedings Volume.

Volume 3, Page 1307

Species Limits, Phylogenetics, and Conservation of *Neoleptoneta* Spiders in Texas Caves by Joel Ledford, Pierre Paquin, and Charles Griswold

James Cokendolpher, Museum of Texas, Texas Tech University, Lubbock, Texas was also a co-author for this paper.

Omissions

The Fossil Bears of Southeast Alaska by Timothy H. Heaton and Frederick Grady was inadvertently omitted in the final stages of page layout. The reviewed and edited paper follows:

THE FOSSIL BEARS OF SOUTHEAST ALASKA

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Southeast Alaska is home to brown bears (*Ursus arctos*) and black bears (*U. americanus*) with an unusual distribution. Both species inhabit the mainland, while only black bears inhabit the islands south of Frederick Sound and only brown bears inhabit the islands north of Frederick Sound. Brown bears of the northern islands belong to a distinct lineage and are genetically more similar to polar bears than their mainland counterparts. Bears are among the most common fossils found in caves in the region, and they indicate that both species made greater use of caves as dens when the climate was colder. But no bear fossils are known from the Last Glacial Maximum (LGM), even at On Your Knees Cave where foxes and marine mammals have been recovered across most of this interval. This begs the question of whether bears survived the LGM on coastal refugia or recolonized the islands after the ice retreated. No evidence has been found to settle the question for black bears. Black bears are far more common than brown bears in On Your Knees Cave for the period before the LGM, but they were slower than brown bears in expanding their range across the islands after the ice melted. The evidence for survival in a local refugium is much stronger for brown bears. While they are less common before the LGM, they had a greater distribution than black bears immediately following the LGM, including some of the outermost islands of the archipelago. The lack of brown bear fossils from mainland sites during early postglacial times may indicate that the mainland was not the source of this population. The distinct genetic character of modern island brown bears also suggests that they did not derive from the mainland. Two fossil brown bears from caves of Prince of Wales Island have had successful DNA extractions and match the distinct lineage that now lives only on the northern islands of Southeast Alaska. A refugium for brown bears may have been offshore on the continental shelf which was exposed during the LGM but was flooded by rising sea level in the early postglacial period.

1. Introduction

Our research in southeast Alaska began in 1991 after several bear skeletons were found in El Capitan Cave on Prince of Wales Island by a caving expedition (HEATON and GRADY, 1992, 1993). El Capitan Cave is Alaska's largest known cave and has passages that flood during storms, but the fossils were found in a quiet upper passage near the surface. One skeleton was complete and undisturbed, suggesting that the bears were denning in the cave, so cavers called this passage the Hibernaculum. It was apparent that the bears accessed the cave by an entrance that had become sealed with soil and logs, and we were able to reopen this entrance to conduct an excavation of the site. Soon cavers discovered skeletons in other caves of the region with similar dimensions, namely horizontal passages 1.5-2.5 meters in diameter. Several natural trap caves with bear fossils were also discovered. Although our research has expanded to include a variety of mammals, birds, and fishes (HEATON and GRADY, 2003), bears have remained a major focus, and our fossil discoveries have contributed to solving the question of whether animals survived the Ice Age in Southeast Alaska.

Most islands of Southeast Alaska are home to bears, but currently there is no more than one species per island. Black bears (*Ursus americanus*) inhabit Prince of Wales Island and most other islands south of Frederick Sound, while brown bears (*Ursus arctos*) inhabit the islands north of Frederick Sound, namely Admiralty, Baranof, and Chichagof (ABC) islands. Both species inhabit the nearby mainland (MACDONALD and COOK, 2007). Prior to the discovery of a fossil record, KLEIN (1965) proposed that this island distribution resulted from a postglacial colonization history: brown bears arriving from the north and black bears from the south. This hypothesis was based on the prevailing assumption that no land animals survived the Last Glacial Maximum (LGM, 24,000-13,000 radiocarbon years B.P.) in Southeast Alaska because of complete ice cover. Although the islands of Southeast Alaska exhibit a nested mammalian fauna suggestive of recent colonization (CONROY et al., 2000), fossil and genetic studies of bears have revealed a much more complex history in the region.

The complete skeleton from El Capitan Cave, as well as portions of several others, were of black bears, distinguished from the living bears on the island only by their large size. Their size seemed especially significant since they appeared to be females based on the lack of bacula and the gracile structure of their skulls. Even more significant was the discovery of even larger bear remains that we identified as brown bear. Finding that Prince of

Wales Island had been home to additional species in early postglacial time conflicted with the simple postglacial colonization model held by KLEIN (1965) and other biologists. In addition to brown bears, we also discovered fossil remains of Arctic fox (*Alopex lagopus*), red fox (*Vulpes vulpes*), and caribou (*Ranifer tarandus*) that no longer inhabit the island. Rather than lacking a fauna at the end of the Ice Age, Prince of Wales Island simply had a different fauna that was adapted to the colder and less forested habitat.

Following this initial discovery we set out to expand our dataset both geographically and chronologically by searching for caves with fossil deposits on different islands and the mainland, in diverse habitats, and of greater antiquity. During the 1990s fossil sites were brought to our attention by cavers exploring the region, often working with the support of Tongass National Forest and guided by forest agendas. After 2000 we began coordinating searches for caves specifically to fill in gaps in our dataset. In spite of limits imposed by limestone distribution and the difficulty of finding sites over 12,000 years old, a long history for both brown and black bears has emerged. During this same period geneticists began DNA studies on living bear populations in Southeast Alaska that complemented our work (HEATON et al., 1996), and we have worked in conjunction with ancient DNA researchers to trace bear lineages back in time. What has emerged is a greatly expanded, but not entirely complete, picture of bear history in Southeast Alaska.

2. Postglacial History

The postglacial record of bears in Southeast Alaska is spectacular. Following the discovery of black and brown bears in El Capitan Cave (130 m elevation), additional brown bear skeletons were found in two high elevation caves (over 500 m) on northern Prince of Wales Island: two juveniles in a natural trap called Blowing in the Wind Cave, and parts of 12 individuals in a horizontal tube called Bumper Cave, including skeletons of what appeared to be a mother and her two cubs (Table 1). By contrast, lower elevation caves (below 200 m) on the island, such as Kushtaka and On Your Knees caves (den sites) and Tlacatzinacantli Cave (a natural trap) contained only black bears from the postglacial interval (Table 2). This apparent partitioning of den sites by the two species must be kept in mind when considering other parts of Southeast Alaska where samples from diverse elevations are not available. This does not mean that brown bears were restricted to high elevations because their isotopic signature indicates a stronger marine diet than black bears (HEATON 1995; HEATON and GRADY, 2003).

Table 1. List of radiocarbon dated brown bear (*Ursus arctos*) fossils from caves of Southeast Alaska in order of age.

Laboratory #	**Age (years B.P.)**	**$\delta^{13}C$**	**Site**	**Island**	**Sample**
AA-15224	7,205 ± 65	-17.9	Bumper Cave	POW	Dentary
AA-56996	9,590 ± 95	-20.5	Deer Bone Cave	Coronation	Radius
AA-07794	9,760 ± 75	-18.0	El Capitan Cave	POW	Humerus
AA-10451	9,995 ± 95	-18.5	Blowing in the Wind Cave	POW	Ribs
AA-52223	10,700 ± 100	-17.1	Enigma Cave	Dall	Humerus
AA-15225	10,970 ± 85	-19.5	Bumper Cave	POW	Molar
AA-15223	11,225 ± 110	-16.8	Bumper Cave	POW	Humerus
AA-52221	11,600 ± 100	-14.6	Enigma Cave	Dall	Dentary
AA-44450	11,630 ± 120	-18.2	Colander Cave	Coronation	Humerus
AA-15222	11,640 ± 80	-17.8	Bumper Cave	POW	Rib
AA-15226	11,715 ± 120	-16.0	Enigma Cave	Dall	Humerus
AA-32122	11,910 ± 140	-18.1	El Capitan Cave	POW	Rib2
AA-52222	11,930 ± 120	-14.6	Enigma Cave	Dall	Skull
AA-10445	12,295 ± 120	-18.3	El Capitan Cave	POW	Pelvis
AA-33783	26,820 ± 700	-16.3	On Your Knees Cave	POW	Astragalus
AA-52219	29,040 ± 600	-16.3	On Your Knees Cave	POW	Rib
AA-52220	29,590 ± 980	-17.7	On Your Knees Cave	POW	M2/
AA-33792	31,700 ± 1900	-16.2	On Your Knees Cave	POW	Molar
AA-52218	31,900 ± 1,300	-19.6	On Your Knees Cave	POW	Claw
AA-52207	33,300 ± 1,500	-17.0	On Your Knees Cave	POW	Phalanx 1
AA-15227	35,365 ± 800	-15.9	On Your Knees Cave	POW	Femur
AA-52215	38,800 ± 3,000	-10.0	On Your Knees Cave	POW	Phalanx 2

AA-33791	39,400 ± 3100	-17.1	On Your Knees Cave	POW	Tooth
AA-52216	34,000 +	-17.4	On Your Knees Cave	POW	M/1
AA-52201	40,900 +	-16.8	On Your Knees Cave	POW	P4/
AA-52217	41,100 +	-15.4	On Your Knees Cave	POW	Vertebra

Table 2. List of radiocarbon dated black bear (*Ursus americanus*) fossils from caves of Southeast Alaska in order of age.

Laboratory #	**Age (years B.P.)**	**$\delta^{13}C$**	**Site**	**Island**	**Sample**
CAMS-27263	2,790 ± 60	-23.2	Kushtaka Cave	POW	Artifact
AA-57000	3,425 ± 50	-12.5	Lawyers Cave	Mainland	Humerus
CAMS-31068	3,960 ± 50	-20.7	On Your Knees Cave	POW	Dentary
AA-36637	4,847 ± 58	-21.2	Hole 52 Cave	Mainland	Skull
SR-5265	6,290 ± 50		Lawyers Cave	Mainland	Phalanx
AA-10447	6,415 ± 130	-22.1	El Capitan Cave	POW	Skull
CAMS-24967	8,630 ± 60	-21.4	Kushtaka Cave	POW	Rib
AA-18451R	9,330 ± 155	-23.9	Kushtaka Cave	POW	Femur
AA-32118	10,020 ± 110	-22.1	Tlacatzinacantli Cave	POW	Femur
AA-36641	10,080 ± 120	-21.6	Hole 52 Cave	Mainland	Phalanx
AA-33780	10,090 ± 160	-21.2	On Your Knees Cave	POW	Phalanx
CAMS-42381	10,300 ± 50	-20.7	On Your Knees Cave	POW	Artifact
AA-36636	10,350 ± 100	-18.9	Hole 52 Cave	Mainland	Skull
AA-36640	10,420 ± 110	-21.6	Hole 52 Cave	Mainland	Skull
AA-07793	10,745 ± 75	-21.1	El Capitan Cave	POW	Humerus
AA-32120	10,860 ± 120	-21.8	Tlacatzinacantli Cave	POW	Skull
AA-32117	10,870 ± 120	-21.8	Tlacatzinacantli Cave	POW	Ulna
AA-36638	10,930 ± 140	-19.8	Hole 52 Cave	Mainland	Skull
AA-32119	10,970 ± 120	-22.4	Tlacatzinacantli Cave	POW	Fragment
AA-33202	11,460 ± 130	-19.9	Hole 52 Cave	Mainland	Canine
AA-10446	11,540 ± 110	-20.0	El Capitan Cave	POW	Skull
AA-10448	11,565 ± 115	-18.7	El Capitan Cave	POW	Skull
AA-21569	28,695 ± 360	-20.7	On Your Knees Cave	POW	Calcaneum
AA-21570	29,820 ± 400	-20.8	On Your Knees Cave	POW	Vertebra
AA-33781	36,770 ± 2300	-18.6	On Your Knees Cave	POW	Femur
AA-33194	38,400 ± 3000	-18.4	On Your Knees Cave	POW	Humerus
AA-33198	39,000 ± 3100	-19.5	On Your Knees Cave	POW	Rib
AA-16831	41,600 ± 1500	-20.7	On Your Knees Cave	POW	Tibia
AA-36653	25,000 +	-22.0	On Your Knees Cave	POW	Premolar
AA-36655	27,000 +	-18.2	On Your Knees Cave	POW	Baculum
AA-33196	38,500 +	-19.4	On Your Knees Cave	POW	Scapula
AA-52206	38,500 +	-20.8	On Your Knees Cave	POW	Metapodial
AA-52204	39,100 +	-20.2	On Your Knees Cave	POW	Canine
AA-33200	39,400 +	-19.3	On Your Knees Cave	POW	Canine
AA-33195	40,100 +	-18.4	On Your Knees Cave	POW	Humerus
AA-33199	40,200 +	-19.9	On Your Knees Cave	POW	Canine
AA-44448	41,000 +	-21.7	On Your Knees Cave	POW	Molar
SR-5110	43,050 +		On Your Knees Cave	POW	Vertebra
SR-5111	44,940 +		On Your Knees Cave	POW	Skull

Several postglacial deposits have also been found on the mainland near the town of Wrangell and on two of the outermost islands of the Archipelago: Coronation and Dall Islands (HEATON and GRADY, 2003). Today only black bears inhabit Dall Island while no bears inhabit Coronation Island (MACDONALD and COOK, 2007). Three early postglacial cave deposits have turned up six individuals, all of which match brown bear (Table 1). Deer Bone Cave is a den cave while Colander Cave is a natural trap, and Enigma Cave is larger and more complex with bear skeletons both in horizontal den passages and at the bottom of pits. All these caves are at 200 m elevation or lower. By contrast, two postglacial cave deposits on the mainland, a den site called Lawyers Cave and a complex cave with horizontal passages and pits called Hole 52, contain only black bear remains (Table 2). Brown bears may have denned at higher elevation, but no such sites are known. The remarkable conclusion from these sites is that the two bear species had nearly the opposite distribution in the early postglacial period than they do today. Currently both species inhabit the mainland while only black bears inhabit the southern islands of Southeast Alaska. Shortly after the Ice Age only brown bears inhabited the outer islands, both species occupied the large Prince of Wales Island, and only black bears are documented from the mainland.

Discovering the postglacial history of bears in the northern islands of Southeast Alaska, where only brown bears live today, has been hampered by a paucity of limestone and a lack of any fossil discovery. Since brown bears thrived in the southern islands in early postglacial times, there is no reason to doubt their presence farther north. Whether black bears ever colonized the northern islands remains a mystery. To the south of Alaska a pattern similar to Prince of Wales Island has been documented by Canadian investigators. Haida Gwaii (Queen Charlotte Islands) and Vancouver Island are currently home only to black bears. Fossil black bears have been found dating back to 10,000 years B.P. on Haida Gwaii (RAMSEY et al., 2004; FEDJE et al., 2004) and from about 9,800 to 12,000 years B.P. on Vancouver Island (NAGORSEN et al., 1995; NAGORSEN and KEDDIE, 2000). Brown bears from Haida Gwaii have been found dating from 10,000 to 14,500 years B.P., showing that they once were widespread on coastal islands.

Another remarkable pattern visible in Tables 1 and 2 is the sheer number of early postglacial bears. With the exception of the sealed hibernaculum of El Capitan Cave, all of these sites remain open for potential denning today. Yet far more specimens of both black and brown bears date between 9,000 and 12,000 years B.P. than date to the 9,000 years since then. Most of these remains were exposed on the cave floors (not fully buried) so were not selected for dating based on their potential antiquity. Either bears were more numerous in early postglacial times or they were denning in caves much more regularly. The fact that natural trap caves (at least a third of the sites) show this same pattern suggests a high bear population. None of the other species we have studied show this distinct chronological pattern. Perhaps the early successional stages of forest development following the melting of the glaciers provided a high density of berries and other edible foods preferred by bears for the herbivorous part of their diet. Since climax forests are lacking in such foods, modern bears are attracted to forest clear-cuts, shorelines, and other disturbed areas where such plants grow.

3. Ice Age History

The single site in Southeast Alaska that has produced an extensive Ice Age record (prior to 13,000 radiocarbon years B.P.) is On Your Knees Cave. It is a small cave on the northern tip of Prince of Wales Island discovered during a logging survey and had only a few bones initially exposed. The significance of the site was only recognized when a partial brown bear femur was radiocarbon dated to 35,365 years B.P. (Table 1). Excavation began in 1996 and continued until 2004. An extensive record of mammals, birds, and fish was discovered covering at least the last 45,000 years (HEATON and GRADY, 2003) plus an extensive archaeological record including the oldest human remains from Alaska or Canada (DIXON et al., 1997). Devil’s Canopy Cave on Prince of Wales Island is the only other site where we obtained an Ice Age radiocarbon date (on marmot), but extensive excavation produced only a few rodent and insectivore remains. Our extensive efforts to find an Ice Age site on the outer islands of Southeast Alaska have so far been unsuccessful.

For a single site, On Your Knees Cave provides a superb record of animals during the LGM and the preceding interstadial. As can be seen in Tables 1 and 2 many bone dates are beyond the radiocarbon limit, but uranium dates on speleothem fragments date back to 185,800 ± 2,800 years B.P. (DORALE et al., 2003). Both black and brown bears were present and probably used the cave as a den from at least 41,000 years B.P. until the approach of the LGM (Tables 1 and 2). We have not dated enough samples to be certain exactly when their use of the cave ceased, but no bear remains have been dated to the glacial maximum itself. A sample of 25 ringed seal (*Phoca hispida*) specimens were radiocarbon dated from 24,150 ± 490 to 13,690 ± 240 years B.P., which is the very interval that the bears (and caribou) are missing. Arctic and red foxes, other marine mammals, and sea birds also date to the LGM, so the cave was available and used as a den (by foxes) during that interval. One ringed seal humerus has bite marks that match bear canines, but it could be a polar bear (*Ursus maritimus*) kill that was scavenged by foxes.

Black bear fossils outnumber brown bear fossils in On Your Knees Cave by a ratio of about 10:1. This is not evident in Tables 1 and 2 because we selected specimens of both species for dating. This difference could represent a greater abundance of black bears or a partitioning of den sites by elevation like we see during the postglacial period. Other elements of the fauna suggest that conditions during the interstadial were similar to the early postglacial interval before a climax forest was established.

4. Genetics

TALBOT and SHIELDS (1996) found that brown bears of Admiralty, Baranof, and Chichagof (ABC) islands (Southeast Alaskan islands north of Frederick Sound) are distinct from all other populations based on mitochondrial DNA and are more closely related to polar bears than to their mainland counterparts. Using nuclear microsatellite variations PAETKAU et al. (1998) confirmed this result for females but detected some exchange of males with the local mainland population. LEONARD et al. (2000) discovered a fossil from Yukon Territory matching the ABC bears and dating to 36,500 ± 1,150 years B.P., so this clade had a wider distribution before the LGM. Nevertheless, the current restricted range of this clade suggests that the islands of Southeast Alaska acted as a refugium for this population during the glacial maximum (HEATON et al., 1996). Further support for this hypothesis comes from early postglacial fossils of Prince of Wales Island and Haida Gwaii. After several failed attempts at extracting ancient DNA, BARNES et al. (2002) reported that a brown bear fossil from Blowing in the Wind Cave (AA-10451 on Table 1) belongs to the ABC clade. Further work by Sarah Bray (personal communication) also linked a bear from Bumper Cave (AA-16553 on Table 1) and ones from Haida Gwaii to the ABC clade.

STONE and COOK (2000) found that black bears from the southern islands of Southeast Alaska belong to a mitochondrial lineage that is also found on the islands and coastal mainland of British Columbia and down the coast to northern California. Several other mammal species have distinct coastal lineages with a similar range, but it remains unclear whether the source of these lineages was south of Cordilleran glaciers or on coastal refugia, possibly in Southeast Alaska (COOK et al., 2001, 2006).

5. Conclusions

The absence of a fossil record of bears from the LGM leaves open the question of whether they survived the glacial expansion in Southeast Alaska on coastal refugia or recolonized afterward. Cave faunas document that both brown and black bears were present during the preceding interstadial and reappeared in great numbers soon after the ice melted. Genetic evidence for a distinct coastal lineage, where refugial isolation is the simplest explanation, is strong for brown bears but more equivocal for black bears. Both bears are refugial species in the sense that they were adversely affected by glaciation and struggled to survive under unfavorable climatic conditions. By contrast, other carnivores such as ringed seals, Arctic foxes, and likely polar bears flourished and expanded their ranges during the LGM. The extent to which the Arctic and refugium faunas competed with one another is unknown, but their interactions could have been a factor in the temporary loss of black and brown bears from On Your Knees Cave.

What we learn from postglacial bears is that the species were able to move about freely and colonize territory that was favorable for them, rather than being restricted by barriers and competition. Solving the full puzzle of bear history in Southeast Alaska will require finding additional faunas of similar antiquity to On Your Knees Cave, as a single site cannot document the movements of species. During the LGM the expanding glaciers pushed mammal populations westward, while falling sea level opened up new habitat to the west and changed the configuration of the coastal corridor. The possibility that populations of bears and other mammals found suitable refugia to survive the LGM in Southeast Alaska is very possible.

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CONTRIBUTED PAPERS IN THE BIOLOGICAL SCIENCES

HOT CAVE RECORD IN MEXICO

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Abstract

The ecology of bat shelters has been widely reviewed. Many bats require shelter to protect themselves from predators. For others, the shelter requirements are determined by physiological demands of the adults and the young, by social considerations, or by morphological aspects.

Selection of habitat is one of the main factors in bat survival. The body temperature and the metabolic rate of the bats are dependent on the ambient temperature except when it is modified by gregarious social behavior. There are some species that have developed a microclimatic selection very close to their shelter and show physiological adaptations and behavior unique to them.

The most important microclimatic factors that intervene in the selection of a bat shelter are temperature and relative humidity. Some authors have found that the selection of a fresh shelter during active periods help facilitate bat digestion, pregnancy, growth, and development of the young. Nevertheless, there are studies recording shelters with very high temperatures and humidity (heat caves) that are selected by the bats. Previous studies have speculated that Mexico has this kind of shelters, but none have been identified.

This kind of hyperthermal caves are know as "hot caves," "hot grottos," or "hot caverns." Their most distinctive feature is that biological conditions modify the interior climate, enhanced by the speleomorphologic accident of a single entrance access. Animal populations are established, radically changing the physical conditions of the cave and, thus, modifying the exanten ecology. This activity makes for a unique population composition, density, and dynamics. No other faunal community is known to support a similar biomass with these characteristics in a confined space. The populations of bats vary depending on the type of cave and the zone where they are located.

RÉCORDS DE CUEVAS CALIENTES EN MÉXICO

Resumen

La ecología de los refugios de los murciélagos ha sido ampliamente revisada por algunos autores. Muchos murciélagos requieren de un refugio para protegerse de los depredadores y para algunos otros los requerimientos del refugio están determinados por demandas fisiológicas de los adultos o jóvenes, por consideraciones sociales, o por cuestiones morfológicas.

La selección del hábitat es uno de los factores fundamentales en la sobrevivencia de los murciélagos. La temperatura corporal y la tasa metabólica de los quirópteros son dependientes de la temperatura de su entorno excepto cuando son modificadas por el comportamiento social gregario. Existen algunas especies que han desarrollado una selección microclimática muy estrecha hacia sus refugios y presentan adaptaciones fisiológicas y conductuales muy particulares hacia los mismos.

Los factores microclimáticos más importantes que intervienen en la selección del refugio para los murciélagos son la temperatura y la humedad relativa. Algunos autores han encontrado que la selección de un refugio fresco, durante periodos activos permite realizar mejor la digestión, gestación, crecimiento y desarrollo de las crías. Sin embargo, existen estudios en donde se registran refugios con temperaturas y

humedades muy altas (cuevas de calor) y que de la misma forma son escogidos por los murciélagos. En los países en donde se han realizado estos estudios, se cree que México posee refugios de este tipo, pero no se tiene conocimiento de alguno de ellos. Por lo que es de gran importancia el detectar este tipo de refugios y determinar las características que impera en estos nichos.

A este tipo de cuevas térmicamente anómalas se les conoce como “cuevas de calor,” “grutas de calor,” o “cavernas de calor”; lo más distintivo de estas cuevas o grutas es que el clima interno es modificado por condiciones biológicas, ya que al aprovechar un accidente espeleomorfológico de un sólo acceso, se establecen poblaciones de animales que cambian radicalmente las condiciones físicas de la cueva, modificando así, la ecología existente, tornándola exclusiva por su composición, densidad y dinámica poblacional. No se conoce ninguna otra comunidad faunística que mantenga, en un sitio cerrado, una biomasa semejante y con características tan propias. Esas poblaciones de animales varían de acuerdo al tipo de cueva y a la zona.

EPIKARST MICROBIAL ASSEMBLAGES IN PADUREA CRAIULUI MOUNTAINS (NW ROMANIA)

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Abstract

Due to absence of light below ground, and thus the consequent lack of photosynthesizing organisms, microorganisms, and dead organic materials transported from the surface, provide the basis of any groundwater food web. We aim to relate the abundance of microbial assemblages to the presence and density of groundwater fauna in the epikarst of Padurea Craiului Mountains (NW Romania). For that purpose, we have determined the density of aerobic heterotrophic bacteria, coliform microorganisms, and various physiological microbial groups (i.e. Fe-reducing bacteria, ammonifying bacteria, denitrifying bacteria) in samples of water dripping in three caves.

Our analyses have revealed that the sampled groundwater is not contaminated by surface microflora, i.e., it is free of coliform microorganisms (*Enterobacteriaceae*). Although the estimation of the abundance of aerobic heterotrophic bacteria showed low numbers of viable cells (0.4–7.9 CFU/mL), other physiological tests revealed relatively larger numbers of Fe-reducers (10^1–3×10^2 cells/mL), ammonifying bacteria (4×10^2–10^5 cells/mL) and denitrifying bacteria (3×10^4–10^5 cells/mL).

The relatively large number of microorganisms involved in the nitrogen cycle can be related to ammonification and denitrification processes occurring in the aboveground soils through which percolating water passes. In general, the abundance of microorganisms was larger in locations where there was a larger population density of groundwater fauna and conversely at locations with lower density of groundwater fauna, fewer microorganisms were detected.

GUANOPHILE ECOSYSTEM OF AN URBAN CAVE POLLUTED WITH RAW SEWAGE

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Abstract

Schieks Cave is a natural maze cave in the St Peter Sandstone. The cave is located 23 m below the streets of downtown Minneapolis, Minnesota, USA, and extends under one city block. When first discovered in 1904 the cave was barren. Sewer connections from the buildings above were constructed down through the cave and for many years sewage has been leaking into the cave, creating a large pool of stagnant sewage known as the "Black Sea." In the 1970s and 1980s enormous numbers of cockroaches inhabited the cave, blackening the walls. By the 1990s there was a switch to an oligochaete/dipteran assemblage. Fungi grow upon the human feces and fungus gnats in turn live upon the fungi. The gnats are preyed upon by web-building spiders. Earthworms, entering the cave by stormwater overflows, are found in large numbers along the edges of sewage pools. No bats or rats have ever been reported in the cave. Schieks Cave seems to fit the model of a "hothouse" fauna as described from other polluted caves.

DESCRIPTION OF THE BIOTA ON A REPRESENTATIVE SAMPLE OF THE SYSTEMS OF KARST (GUANENTINA REGION AND VÉLEZ PROVINCE) SANTANDER, COLOMBIA

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Abstract

In the oriental mountain of the Colombian Andes is found the department of Santander, it is even an karstic area with diversity of formations rocky and great quantity of cavernous systems without exploring; cavities that were formed make millions of years for given way for the action of currents of underground rivers on these. The parental lithology is calcareous rocks. The speleothems in these caves are abundant in their great majority and of a lot of variety. Between 2007 and 2008 were conducted surveys and biological inventories in 32 of these caves in Santander, by identifying specimens collected manually and with some type Pitfall traps. We found approximately 70 families of arthropods, with the crickets, beetles, cockroaches, spiders and Opiliones more common to the naked eye. In addition to that reported 14 species of mammals, of which 13 are Bats, mainly of the genus *Carollia, Sturnira* and *Artibeus*. There is evidence of the presence of other groups Cordata, however, were rare. With the collected specimens were calculate the species richness for each cave, and relative abundances in those sampling methods allowed it, according to its topography and ease of sampling. Combine greater wealth and abundance of specimens to the caves with high humidity and greater quantity of guano. In addition to this, it was found that species diversity decreases with the presence of high flow of tourism to the interior of the system. In analyzing the physical conditions and environmental visited the caves and their relation to the composition and richness of the taxa found, it was shown that many of the caves have a similar composition and assembly of fauna, with abundance of troglophile species, few of type and trogloxenous and very rare type troglobies, which implies that the processes of colonization and adaptation of fauna species in tropical cave environments, is given more by processes of colonization of new niches available in the area, which the colonization of these environments, driven by large changes in climate that force species to carry out "vertical migration" towards more favorable and stable environments in order to prevent its demise (as in the non-tropical caves). This is explained by the large number of groups within the caves that are equal or similar to those present on the exterior of the caves, as evidenced by the abundance of this troglophiles groups and the few troglobite groups.

DESCRIPCIÓN DE LA BIOTA DE UNA MUESTRA REPRESENTATIVA DE LOS SISTEMAS CÁRSTICOS DE (REGIÓN GUANENTINA Y PROVINCIA DE VÉLEZ) SANTANDER, COLOMBIA

Resumen

En la cordillera oriental de los andes Colombianos se encuentra el departamento de Santander, se trata de una zona cárstica con diversidad de formaciones rocosas y gran cantidad de sistemas cavernosos aun sin explorar; cavidades que se formaron hace millones de años por oradación dada la acción de corrientes de ríos subterráneos sobre estas. El material parental rocoso principal que las compone esta conformado por

areniscas y rocas calizas masivas. Los espeleotemas presentes en estas son abundantes en su gran mayoría y de mucha variedad. Entre el 2007 y 2008 se realizaron reconocimientos e inventarios biológicos en 32 cuevas de estas en Santander, mediante la identificación de especimenes colectados manualmente y en algunas con trampas tipo Pitfall. Se encontraron aproximadamente 70 familias de artrópodos, siendo los grillos, escarabajos, cucarachas, arañas y opiliones los más comunes a simple vista. Además de esto se reportan 14 especies de Mamíferos, de los cuales 13 son Murciélagos, principalmente de los géneros *Carollia*, *Sturnira* y *Artibeus*. Se evidencia la presencia de otros grupos de cordados, sin embargo fueron poco frecuentes. Con los especimenes colectados se calculo la riqueza específica para cada cueva, y las abundancias relativas en aquellas que los métodos de muestreo lo permitieron, de acuerdo a su topografía y facilidad de muestreo. Se asocian las mayores riquezas y abundancias de especimenes a las cavernas con alta húmedas y con mayor cantidad de guano. Además de esto, se halló que la diversidad de especies disminuye con la presencia de alto flujo de turismo al interior del sistema. Al analizar las condiciones físicas y ambientales de las cuevas visitadas y relacionarlas con la composición y riqueza de los taxones encontrados, se evidencio que muchas de las cuevas poseen una composición y ensamblaje similar de fauna, con abundancia de especies trogofilo, pocas de tipo trogloxeno y muy escasas las de tipo troglobio; lo que hace suponer que los procesos de colonización y de adaptación de las especies de fauna en los trópicos a los ambientes cavernosos, está dada mas por procesos de colonización de nuevos nichos disponibles en el medio, que por la colonización de estos ambientes, impulsado por grandes cambios en el clima que fuerzan a las especies a realizar “emigraciones verticales” hacia ambientes más favorables y estables, a fin de evitar su desaparición (como en las cuevas no tropicales). Esto es explicado por la gran cantidad de grupos dentro de las cavernas que son iguales o similares a los presentes en el exterior de las cavernas, evidenciado esto por la abundancia de grupos troglofilos y los pocos grupos troglobios.

PRELIMINARY REPORT ON THE CAVE DIPLURA OF COLORADO (HEXAPODA: DIPLURA: CAMPODEIDAE)

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Two-pronged bristletails, or campodeid diplurans, have been collected from thirteen caves and a gold mine in the state of Colorado. All but two of the caves are inhabited by a different species of campodeid. The species found in the mine may be represented by one of the cave inhabiting forms, or it could be a unique species as well. The taxa represented are: *Eumesocampa lutzi*, *Tricampa rileyi*, two new undescribed species of *Metriocampa*, and eight or nine new undescribed species of *Haplocampa*. *Eumesocampa lutzi* was originally described from an epigean habitat in Colorado. *Tricampa rileyi* is a wide ranging endogean species which is also known from Colorado. One of the species of *Metriocampa* is unique to Colorado, but the other species has also been found in caves in Missouri and Illinois. The potentially nine species of *Haplocampa* from Colorado represent 35 percent of all *Haplocampa* species known from caves (total number of identified species from caves: 26). The other cavernicolous *Haplocampa* species are known from the northwestern United States and Vancouver Island, British Colombia, Canada.

1. Introduction

When I reported on the cave diplura of the United States (FERGUSON, 1981) at the Eighth International Congress of Speleology held in Bowling Green, Kentucky, to my knowledge no cavernicolous campodeid diplurans had been collected from the state of Colorado. However, DAVIS (1971) had reported the possible sightings in 1970 of a campodeid dipluran in Knox's Nasty Pit and Fixin'-To-Die Cave. Both of these caves are near Groaning Cave in Garfield County. HUBBARD (1998; SHEAR & HUBBARD, 1998) reported on his faunal discoveries in seven Colorado caves in 1996, which included four collections of campodeid diplurans. The remaining cavernicolous dipluran collections have been made by David Steinmann and Cyndi Mosch between 1999 and 2007.

2. Materials and Methods

Samples examined are from the Denver Museum of Nature & Science collection and the David A. Hubbard, Jr. collection. Whole specimens were mounted ventral side up on glass microscope slides in Hoyer's or André II media along with any loose cerci and antennae, and often with two removed hind legs. The slide-mounted specimens were examined using an Olympus compound microscope

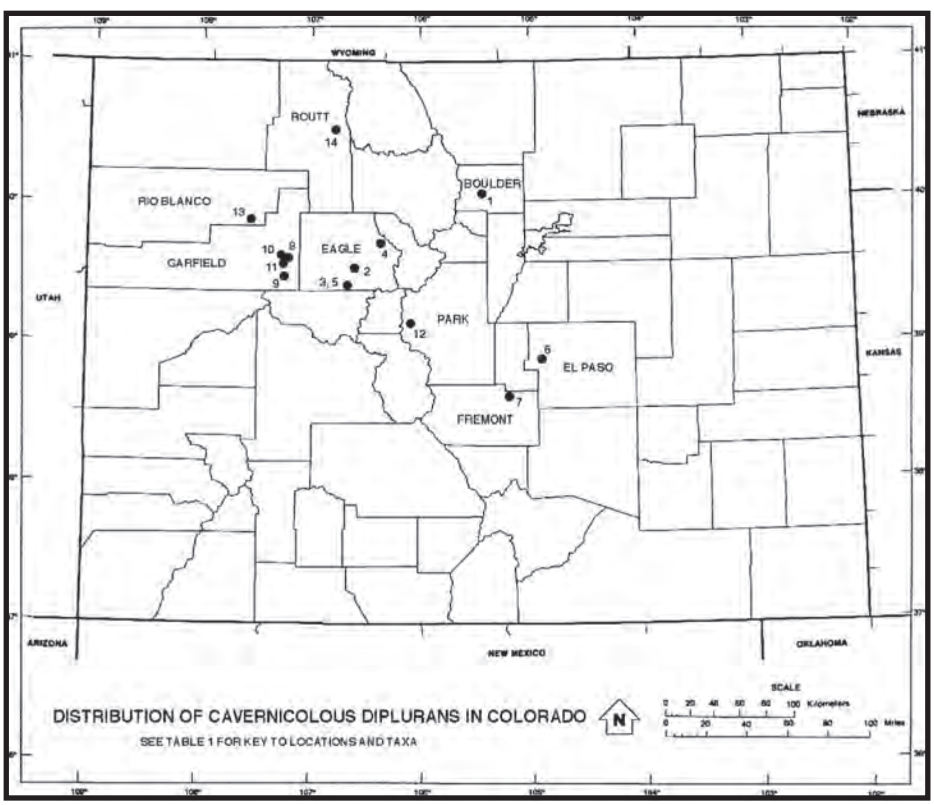

Figure 1: Distribution of cavernicolous diplurans in Colorado.

Map Number	County	Site	Taxa	Catalog Nos.	Collector
1	Boulder Co.	Gold Mine	*Haplocampa* sp. 1	LMF 1029	D. Steinmann
2	Eagle Co.	Devil's Den Cave	*Haplocampa* sp. 2	LMF 812	D. Steinmann
3		Herbie's Deli Cave	*Haplocampa* sp. 3	LMF1025, 1026	D. Steinmann
4		Hourglass Cave	*Metriocampa* sp. 1	LMF 891	C. Mosch
5		Lime Creek Cave	*Haplocampa* sp. 4	LMF 865	D. Steinmann
6	El Paso Co.	Manitou Cave	*Metriocampa* sp. 2	LMF 755	D. Hubbard
7	Fremont Co.	Marble Cave	*Eumesocampa lutzi*	LMF 756	D. Hubbard
8	Garfield Co.	Groaning Cave	*Haplocampa* sp. 5	LMF 757	D. Hubbard
9		Hubbards Cave	*Haplocampa* sp. 6	LMF 813	D. Steinmann
10		La Sunder Cave	*Haplocampa* sp. 7	LMF 811	D. Steinmann
11		Squeak Cave No. 1	*Tricampa rileyi*	LMF 864, 1030	D. Steinmann
12	Park Co.	Cave Creek Cavems	*Haplocampa* sp. 8	LMF 1028	D. Steinmann
13	Rio Blanco Co.	Spring Cave	*Haplocampa* sp. 9	LMF 758	D. Hubbard
14	Routt Co.	Sulphur Cave	*Tricampa rileyi*	LMF 1027	D. Steinmann

Table 1: Locations and taxa of cavernicolous diplurans in Colorado.

equipped with Normarski interference diffraction contrast, an ocular micrometer, a drawing tube, an Ikegami analog camera, and a Sony videographic printer. Cave location data was from PARRIS (1973), RHINEHART (2001), and D.B. Steinmann (pers. comm.).

3. Results and Discussion

My examination of the 16 collections from 13 caves and one gold mine has revealed 13 distinct taxa (Fig. 1 and Table 1). All but two of the caves are inhabited by a different species of campodeid. The species found in the mine may be represented by one of the cave inhabiting forms, or it could be a unique species as well, and is treated as such in this report.

The taxa include *Eumesocampa lutzi* SILVESTRI 1933, an endogean species which is known from north central Colorado in Larimer, Boulder, and Gilpin counties at altitudes around 3000 meters (CONDÉ & GEERAERT, 1962). It has now been discovered in Marble Cave in Fremont County.

*Tricampa riley*i (SILVESTRI, 1933) has been found in Squeak Cave No. 1 in Garfield County and in Sulphur Cave in Routt County. It is a wide ranging endogean species which has been collected at Cottonwood Pass, Colorado. At an altitude of 3615 meters, this is one of the highest locations known for campodeid diplurans.

Two species of *Metriocampa* are represented in the examined collections. The species from Hourglass Cave in Eagle County is unique to Colorado, but the other species from Manitou Cave in El Paso County has also been found in caves in Missouri and Illinois.

The remaining species belong to the genus *Haplocampa* SILVESTRI 1933 (Fig. 1 and Table 1). The potentially nine new species of *Haplocampa* from Colorado represent 35 percent of all *Haplocampa* species known from caves (total number of identified species from caves - 26). The other cavernicolous *Haplocampa* species are known from lava tubes and a few limestone caves primarily in the northwestern United States (FERGUSON, 1992) and Vancouver Island, British Colombia, Canada.

4. Acknowledgments

I thank the collectors, David A. Hubbard Jr, David B. Steinmann, Cyndi Mosch, and Dr. Frank T. Krell, Curator of Entomology, Denver Museum of Nature & Science, for the loan of the material under his care (Loan # OL-2008-20). I acknowledge the U.S. Department of Agriculture Forest Service for issuing a Special Use Permit to David Steinmann and Cyndi Mosch for the purpose of collecting and preserving cave faunas from the White River National Forest (SUP# BLA1, expiration date 12/31/2003). I also thank Longwood University for the continuing use of equipment and support for my research following my retirement from teaching.

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DEVELOPMENT AND APPLICATION OF A DATABASE FOR THE SUBTERRANEAN AMPHIPOD CRUSTACEAN GENERA *STYGOBROMUS* AND *BACTRURUS*

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A species/locality database for all species of the subterranean amphipod crustacean genera *Stygobromus* and *Bactrurus* has been developed in MS Access. Both of these genera are exclusively stygomorphic and recorded from a variety of subterranean groundwater habitats. Currently there are 3,055 entries in the database: 2,817 for *Stygobromus*; 238 for *Bactrurus*. Species of *Stygobromus* are numerous and widespread in North America, and a few occur in the Palearctic region, whereas species of *Bactrurus* occur only in North America east of the Great Plains. At present the database contains information on approximately 273 species of *Stygobromus* in North America: 129 described, 22 in manuscript and 122 provisionally recognized. Five other species in the genus are recorded from the Palearctic region. The much smaller genus *Bactrurus* contains only eight described species. The basic collection data for each species include: species name, specific locality, specific collection number; collection date; brief description of habitat (e.g., cave stream, pool; spring; seep); collection date, number of specimens (broken down into sex and level of maturity where possible); name of collector; deposition of type(s) where applicable; identifier; final remarks. Each different collection of a given species is treated as a separate entry. Locality and habitat data are as specific as possible, but vary depending on information supplied by the collector.

The second part of the project is development of a Geographic Information System (GIS) for the databases utilizing ESRI ArcGIS 9 software. This process involves creating location features and linking these data points to the existing MS database, which in turn is used to generate a GIS database. The first step of the GIS creation and data conversion process is to develop spatial data for each cave, spring, seep, well or other habitat/location in which specimens were found. The preferred source of location data are coordinates (latitude/longitude) that accompany the entries stored in the database. Other sources will be used where coordinates are not available. In addition to generation of distribution maps for publications and presentations, the GIS database will be used to plot species distributions against various backgrounds, including karst terrains, drainage basins, physiographic regions, and to distinguish hot spots of taxonomic diversity for further study, analysis and conservation. We also hope to utilize the capabilities of GIS for further map analyses that will include identification and/or determination of dispersal corridors, potential locations for taxa previously overlooked, and localities threatened by land use change. It may also be useful in some instances for assistance in explaining taxonomic relationships between species and species groups.

1. Introduction

The need for a workable database for species in large genera of subterranean organisms is obvious. Access to pertinent electronic data on these species is necessary for facilitation of both biogeographic research and conservation efforts. To meet these important needs, we have developed a species/locality database in MS Access for all species of the exclusively subterranean crustacean amphipod genera *Stygobromus* and *Bactrurus* (family Crangonyctidae). To maximize the utility of these data, we have linked the basic species data to GIS, which allows the rapid construction of species distribution maps on varying backgrounds, such as karst terrains, drainage basins, etc.

2. Discussion

The amphipod crustacean genera *Stygobromus* and *Bactrurus* are exclusively stygomorphic (i.e., lacking eyes and integumentary pigment) and to date all but a few species of *Stygobromus* have been found in subterranean groundwater habitats in North America. Species of *Stygobromus* are numerous and widespread in North America, and a few occur in the Palearctic region (see HOLSINGER, 1967, 1978, in press; WANG and HOLSINGER, 2001; SIDOROV et al., 2008), whereas species of *Bactrurus* as presently known occur only in North America east of the Great Plains (see KOENEMANN and HOLSINGER, 2001). Currently there are approximately 3,060 entries in the database: 2,820 for *Stygobromus* and 240 for *Bactrurus*. At present the database contains information on approximately 205 species of *Stygobromus* in North America: 129 described, 22 in manuscript and at least 54 provisionally recognized. Five other species in the genus are recorded from the Palearctic region. The much smaller genus *Bactrurus* contains only eight described species. The basic collection data for each species include: species name, specific locality, specific collection number; collection date; brief description of habitat (e.g., cave stream, pool; spring; seep; well); collection date, number of specimens (broken down into sex and level of maturity where possible); name of collector; deposition of type(s) where applicable; identifier; final remarks. Each different collection of a given species is treated as a separate entry. Locality and habitat data are as specific as possible, but vary depending on information supplied by the collector.

The second part of this project is the development of a Geographic Information System (GIS) database utilizing ESRI ArcGIS 9 software. This process involves creating location features in the GIS and linking these data points to the existing MS database. The first step of the GIS creation and data conversion process is to develop spatial data for each cave, spring, seep, well or other habitat/location in which specimens were found. The preferred source of location data are coordinates (latitude/longitude) that accompany the entries stored in the database. Other sources will be used where coordinates are not available, with lesser accuracies noted in the locality database. The use of unique locality codes will allow the expansion of the GIS to include any number of related species databases, increasing its usefulness.

We also plan to utilize the capabilities of GIS for further map analyses. In addition to generating a variety of maps for relaying specific information from the database (Figs. 1, 2), the GIS database will be used to plot species distributions against various backgrounds, including karst terrains, drainage basins, physiographic regions (Fig. 3). Such data allows a variety of analyses to be conducted, including the identification of hot spots of taxonomic diversity for further study, analysis and conservation, determination of species dispersal corridors, potential locations for taxa previously overlooked, and localities threatened by land use change (VENI, 2003). By comparing species locations

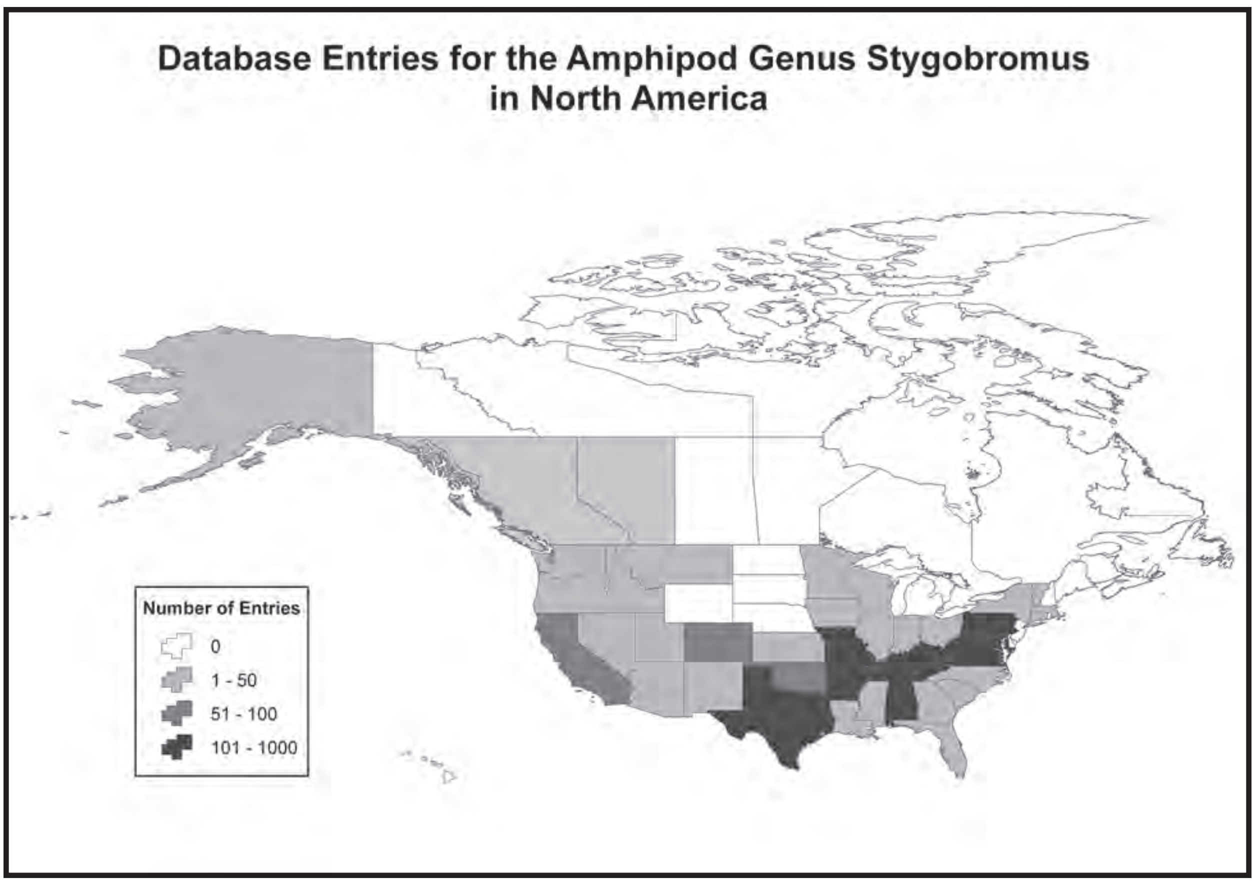

Figure 1: Number of entries to the Stygobromus database per state or province, providing a relative indication of the number of localities and/or amount of data gathered in each.

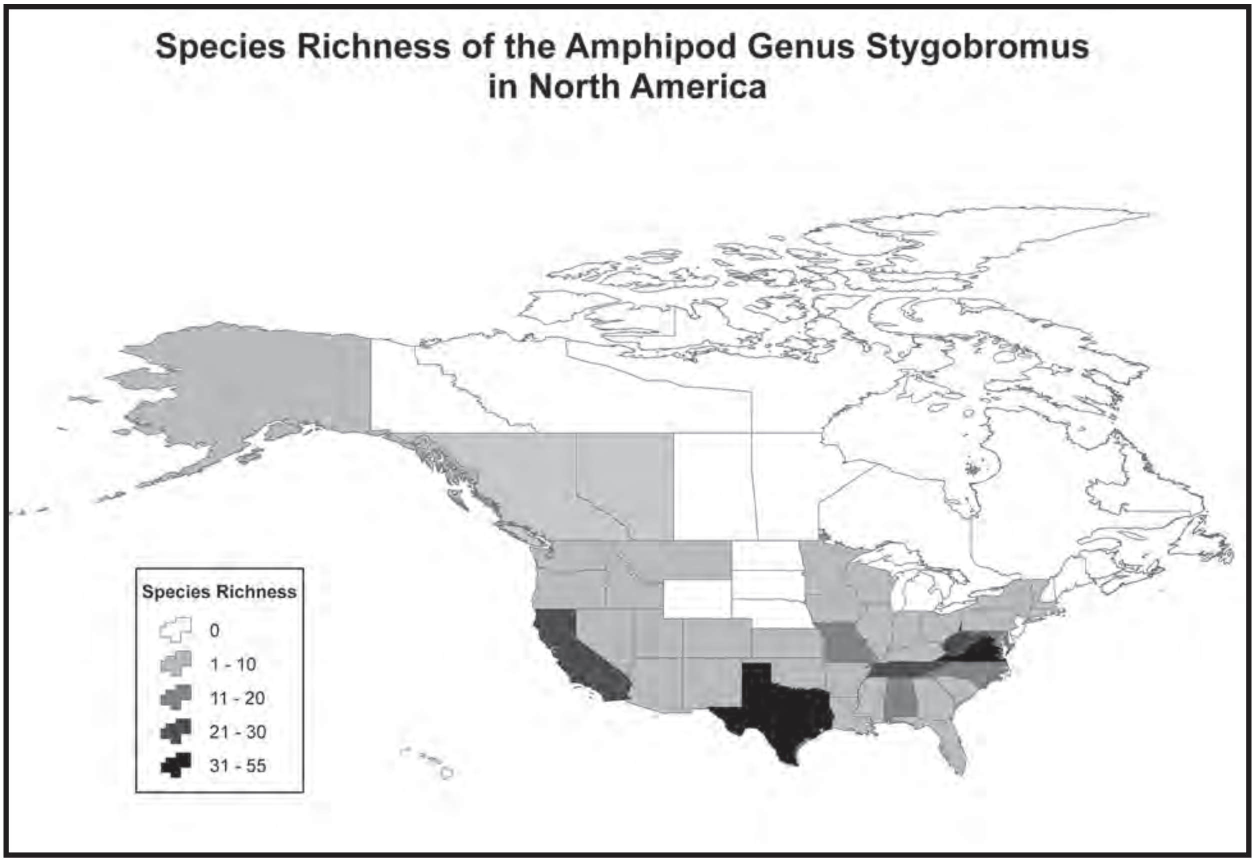

Figure 2: Number of species of Stygobromus per state or province.

to data layers such as karst geology, other surrounding geology, and hydrology, both surface and belowground, predictions of new localities for a given species may be generated. The same data, along with historical geology, might provide insight into the dispersal and speciation within the genus throughout its range. The hydrology and karst layers provide specific information on possible routes through which organisms of this genus may disperse, while data on surrounding geology can indicate boundaries to this expansion. The GIS may also be useful in some instances for assistance in explaining taxonomic relationships between species and species groups. Locations of members of species groups will be compared to surrounding, non-grouped species. Combined with cladistic information this may allow the inclusion of these ungrouped species into existing species groups based on geography and similar characters. Lastly, we hope to promote the use of this database as a tool for the conservation of the genera *Stygobromus* and *Bactrurus*, along with associated habitats and species in other genera. Locality data might be analyzed against land-use, parcel ownership and development data provided by local and regional organizations to determine which species and locations are most threatened. With these data, long-range plans can be developed to protect these habitats.

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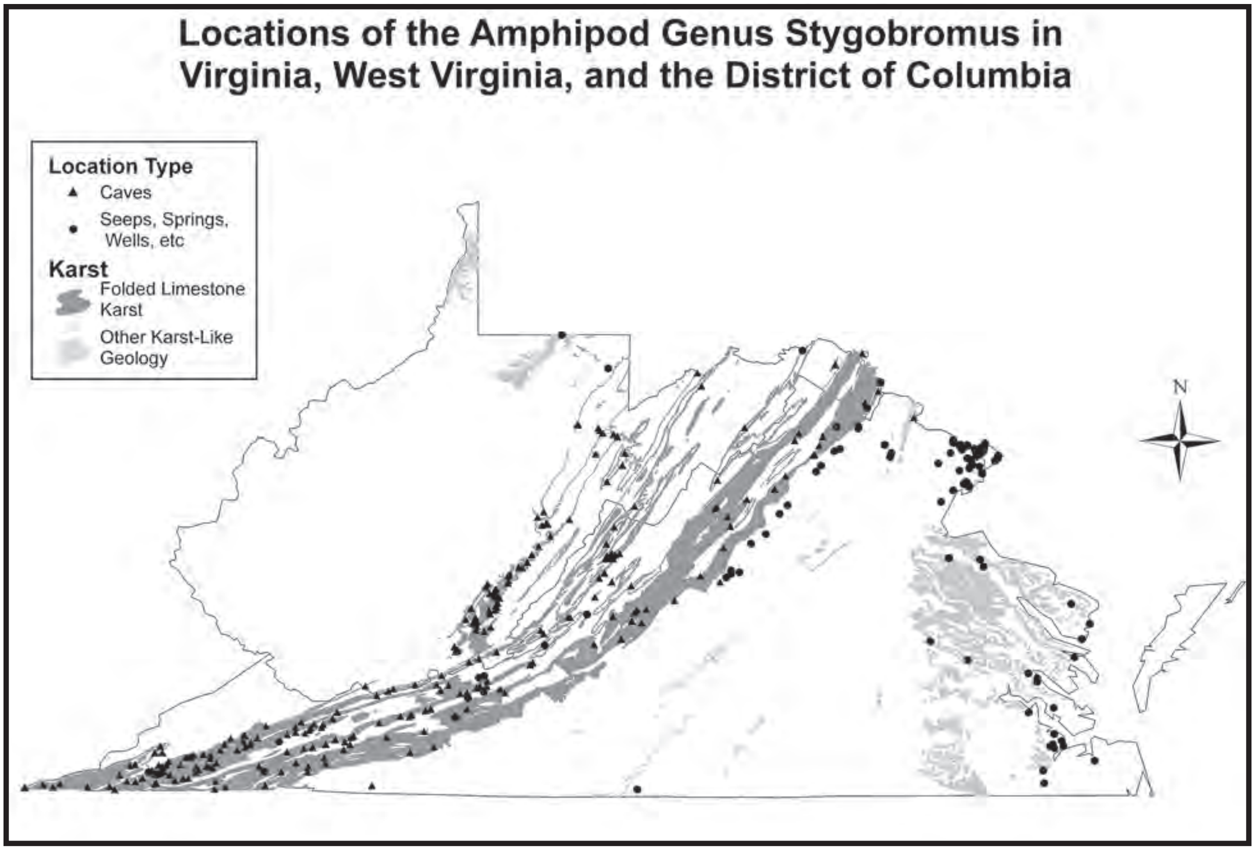

Figure 3: Locations of the amphipod genus Stygobromus in Virginia, West Virginia and the District of Columbia. Locations include caves, seeps, springs, wells and other groundwater habitats. Darkly shaded areas represent karst terrains in western Virginia and eastern West Virginia. Lightly shaded areas represent scattered "karst-like" terrains. (Geological data source: USGS).

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THE CAVE FAUNA OF TEXAS

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Abstract

Cave biology studies in Texas started in 1895 with the emergence of a remarkable blind salamander and crustaceans from an artesian well in San Marcos. The range of topics studied in Texas caves is varied, and the review of these topics gives insight into one of the most diverse regions in the world for cave biology; as well as how the changing modern landscape affects those species. Topics include taxonomy, ecology, conservation research and biogeography.

Regarding taxonomy, the distribution of collecting efforts demonstrates the activity of biospeleologists and cavers, and recent discoveries in well-collected areas (e.g. a blind weevil from Austin, new beetle localities in San Antonio) demonstrate the high potential for new species yet to be found. The number of troglobitic species described per year began to accelerate in the 1960s and is at an all time high in the 1990s and 2000s, with a record of 78 cave species described in one year. A new era of cave related research is in progress, driven by an active community of cave biologists and the rapid urbanization of karst that triggered the federal listing of 16 terrestrial troglobites and 6 aquatic species.

Ecology studies include whole ecosystem inventories initiated at caves with endangered species; these show declines in keystone species associated with urbanization. Nutrient flow research indicates differences in isotopic composition at urban and rural caves. In order to determine and defend the constituent elements affecting species with conservation needs, researchers have called upon biological topics, such as the foraging of cave crickets outside of a cave, and hydrogeological topics, such as the delineation of drainage basins of vadose zone caves. Behavioral studies include spring dwelling salamanders and troglobitic beetles. Regional inventories, species specific inventories, and population studies of rare, threatened and listed species are focused on the Balcones Fault Zone region.

Texas is divided into karst regions based on geomorphology, hydrogeology, stratigraphy, structure, and cave density and types. The attributes of each of these karst regions affects the available subterranean habitats for karst species, therefore is a framework we use for examining the distribution of Texas cavernicoles. The distribution patterns for selected species demonstrate both collecting effort and geologic controls. Recently, researchers have tested biogeographic hypotheses using molecular phylogenetic techniques for aquatic and terrestrial cave species.

WHITE-NOSE SYNDROME IN HIBERNATING BATS: ARE THESE AFFECTED BATS THE NEXT "CANARY IN THE MINE"?

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Abstract

White-Nose Syndrome (WNS) is one the most devastating conditions ever reported for bats in North America—with losses exceeding 90% in some hibernacula in New York State during the winter of 2007–2008. WNS was first recorded photographically in Howes Cave, New York, on February 16, 2006. By January 2007, WNS had been documented in nearby Schoharie Caverns, and later that winter in four other hibernacula in New York State, all located within a 15-km radius of a point in Schoharie County, Albany, New York. By March 2008, bats with symptoms of WNS had been observed in hibernacula from at least four states (New York, Vermont, Massachusetts, and Connecticut). Current evidence indicates that several hundred thousand bats have died from conditions associated with WNS in this relatively small area. To date, fatalities associated with WNS have been reported for six of the nine species of bats in the northeastern United States. Field observations have shown that bats affected by WNS are characterized by some or all of the following: (1) a white fungus that grows on the nose, ears, and wing membranes; (2) severely depleted white and brown fat reserves by mid-winter; (3) reduced capacity to arouse from deep torpor; (4) an apparent lack of immune response during hibernation; (5) ulcerated, necrotic and scarred wing membranes; and (6) atypical behavior of bats emerging prematurely from hibernacula in mid-winter. Laboratory studies of bats affected with WNS have isolated a previously undescribed psychrophilic fungus, closely related to *Geomyces* spp. that grows optimally at temperatures characteristic of hibernacula. Histological evidence has shown that this fungus sometimes penetrates the dermis, especially in areas associated with sebaceous glands and hair follicles. Genetically identical isolates of this fungus have been collected from affected bats located in widely dispersed hibernacula in the northeastern United States. Preliminary data suggest that concentrations of chlorinated hydrocarbons, pyrethroids, and heavy metals are not markedly elevated in bats thus far examined, nor have known bacterial or viral pathogens been identified. Narrowing the field of potential causative agents will require an understanding of whether the fungus associated with WNS is pathogenic. Both field and laboratory investigations are underway to determine the geographic distribution of this fungus, and to assess how it might be directly or indirectly contributing to the demise of hibernating bats in the northeastern United States.

EFFECTS OF INCUBATION CONDITIONS ON QUANTIFICATION OF CHEMOHETEROTROPHIC BACTERIA FROM CAVES

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Isolation of microorganisms by culture techniques grows less than 1% of the microorganisms in an environmental sample using standard cultivation techniques. Despite this inherent limitation, culture-based studies do have value as they shed light on the metabolic properties and physiology of the microorganisms. A common practice in cave microbiology studies is a period of in-cave incubation on the premise that it contributes to higher growth of more diverse microorganisms than returning samples to the surface before plating. We performed a comparative study of surface vs. in-cave incubation conditions for chemoheterotrophic bacteria from multiple soil and water samples from Great Onyx Cave in Mammoth Cave National Park (MACA), Ky, USA, and Carlsbad Cavern, Carlsbad Caverns National Park, NM, USA. Samples were diluted and plated in triplicate in the caves on R2A medium. One set of plates was left in the cave for incubation for 48 hours, and a duplicate set was brought to the surface for incubation at cave temperatures. The same samples were also diluted and plated on the surface. At MACA, one set was incubated on the surface under cave conditions, and a duplicate set brought to the caves for incubation. All samples were counted after 48 hours. MACA plates were left at room temperature on the surface and counted again after another 48 hours. There were no differences in numbers of microbes recovered under any incubation conditions, except for an increase in numbers when the MACA plates were incubated for an additional 48 hours at room temperature. Diversity from the MACA samples as evidenced by appearance of colonies was also identical, except for a few temperature sensitive, pigment-producing colonies. We conclude that cave incubation for isolation and quantification of chemoheterotrophic bacteria offers no advantages compared to removing samples to the surface for cultivation. Because these studies were carried out on samples from off-trail areas of show caves, we do continue to recommend a period of cave incubation for maximum isolation of more specialized or unique cave bacteria. Future studies will repeat the study with sampling in wild caves with areas of low visitation by humans and will explore whether this relationship holds true for chemolithotrophic cave microorganisms.

1. Introduction

Plate count studies have traditionally been used in microbial ecology until the advent of culture free techniques, particularly genetic analysis. Many studies of microbes in caves rely on plate count methods that greatly underestimate the total population and tell nothing about the activity of the microbes in that environment. Isolation of microorganisms by culture techniques grows less than 1% of the microorganisms in an environmental sample using standard cultivation techniques (Amann et al. 1995). Plate counts do show many of the same species isolated from caves compared to surface environments, albeit in lower densities from caves. Comparisons of cave silts with rich agricultural soils were made by Gounot (1967) at the CNRS in France. Cave soils tended to have fewer bacteria, yielding several million per gram, while the agricultural soils yielded several hundreds of millions per gram. Most other studies support her general conclusions. Studies of the biomass and activity of microbes in limestone caves in Kentucky were conducted by Feldhake (1986). He concentrated his studies on actual measurements of microbial metabolic rates in 12 sites in four caves, with comparisons to overlying forest soils. Except for a site rich in cricket guano, Feldhake found that organic matter content, microbial activity and biomass were much lower in the cave than in forest soil. He also found significant variations among sample sites within the cave, and methodological problems when samples were removed from the cave, transported to the lab, and assays made more than 24–48 hours after collection.

One notable exception to studies that show low numbers and activity of microbes in caves has been work done by Rusterholtz and Mallory (1994). They compared the microbial activity, density, and diversity of two aquatic sediment sites in Mammoth Cave. The study includes counts of cells in the sediment, staining to determine metabolic activity of soil microbes, plate counts using both high and low nutrient media, followed by extensive physiological testing of isolates from the plate counts. They recovered between 11–58% of the total cell count on culture medium. The recovery rate for most surface soils is typically 0.4–1.7%. They also detected active metabolism in 53–58% of the population, despite very low nutrient levels of total organic carbon per liter of water. The diversity of populations was extremely high, with 42% of the isolated species similar to surface organisms, with the remainder unidentified. There were no dominant species, and the type of growth medium used strongly influenced the types isolated.

Despite the inherent limitations, culture-based studies do have value as they shed light on the metabolic properties and physiology of the microorganisms. A common practice in cave microbiology studies is a period of in-cave incubation, as recommended by Rusterholtz and Mallory (1994), on the premise that it contributes to higher growth of more diverse microorganisms than returning samples to the surface before plating. We performed a study of the effects of surface vs. in-cave incubation conditions for cultivation of chemoheterotrophic bacteria from multiple soil and water samples from Great Onyx Cave in Mammoth Cave National Park, Kentucky, USA, and Carlsbad Cavern, Carlsbad Caverns National Park, New Mexico, USA

2. Methods and Materials

Samples. Water and Soil samples were collected aseptically from the following locations in Great Onyx Cave in Mammoth Cave National Park, Kentucky, and Carlsbad Cavern in Carlsbad National Park, New Mexico. Great Onyx is a small cave (approximately 2 km of passage in Flint Ridge) not connected to the larger Flint-Mammoth System. A small lantern light tour enters the cave and proceeds down Edwards Avenue. The tour takes place, at most 2 times a day. Carlsbad Cavern, located in the Guadalupe Mountains in southeastern New Mexico, is approximately 316 m deep and almost 50 km in length and formed through sulfuric acid driven speleogenesis. Established as a national park in 1930, Carlsbad receives approximately 300,000 visitors per year. Located beneath the Chihuahuan Desert, Carlsbad Cavern is a more oligotrophic habitat than Mammoth Cave.

Great Onyx Cave: Two soil samples and two water samples were collected aseptically from Great Onyx Cave from areas with little to no human impact. Soils collected were mud from Cox Avenue and a sandy soil sample from a small side passage off Edwards Avenue. Water samples were collected from dripping water at the base of Edwards Dome and from a small cryptic stream in Bubbly Pit.

Carlsbad Cavern: Two soil samples and two water samples were collected aseptically from Left Hand Tunnel, which branches from the Lunch Room in Carlsbad and has one visitor tour of a maximum of 12 people per day. Soils collected were sand from the Beach area of Left Hand Tunnel and dried mud from Left Hand Tunnel. Water samples were collected from two pools, one from a moonmilk area and one from Iron Pool, which has previously been reported to contain iron-oxidizing bacteria. This area receives moderate human impact.

Procedures. All soil samples were thoroughly mixed, and a 1 cc subsample mixed with 9 mL of sterile water. A 1 mL aliquot of each water sample was diluted in sterile water. A 1:10 dilution series in sterile water was made of each sample, and 1 mL spread plated in triplicate on R2A Agar (Difco).

Samples were diluted and plated in the cave, and one set of triplicate plated samples was incubated *in situ* in the cave and a duplicate set of plates were removed from the cave, transported on ice to a surface facility, and incubated under cave conditions (temperature and humidity in the dark) on the surface. The same soil and water samples were again diluted and plated on the surface, with one set of plates incubated on the surface under cave conditions, and a duplicate set of plates brought to the cave site for incubation. Plates were counted after 48 hours of incubation.

All plates from Great Onyx were then incubated at room temperature on the surface for another 48 hours and recounted. One additional experiment was done only with the Great Onyx samples. The original soil and water samples were held under refrigeration for 48 hours, and new dilutions made. One set was incubated in the cave and the second under cave conditions on the surface. The plates were counted after 48 hours.

The Carlsbad Cavern results were tested with a Kruskal-Wallis ANOVA for the combined inoculation location and incubation temperature to determine if there is a significant difference in the data. For the temperature of incubation and site of inoculation, we performed sign tests, since the data of both data sets were non-normal.

3. Results

As shown in Table 1 there were no differences in numbers of microbes recovered after 48 hours under any incubation conditions.

Sample	Cave dilution: Cave incubation	Cave dilution: Surface incubation	Surface dilution: Cave incubation	Surface dilution: Surface incubation
GOCA Mud	8.4×10^4	11.0×10^4	11.2×10^4	11.3×10^4
GOCA Sandy soil	3.0×10^4	3.0×10^4	3.1×10^4	3.0×10^4
GOCA Water Edwards Dome	No Growth*	No Growth*	No Growth*	No Growth*
GOCA Water Bubbly Pit	0-40*	0-40*	0-40*	0-40*
CC-LHT 38 Moonmilk "soil"	7.7×10^3	NA	1.3×10^3	4.0×10^3
CACC-LHT 40 Beach sandy "soil"	No Growth*	NA	2.2×10^3	3.0×10^3
CC-LHT 41 Soil, red clay-silt	1.0×10^2	NA	8.3×10^3	1.0×10^5
CC-LHT 36 Water Moonmilk area	1.3×10^2	NA	1×10^2	5.7×10^2
CC-LHT 39 Water from Iron Pool	4.0×10^2	NA	6.0×10^2	5.3×10^2

* Not statistically significant.

Table 1. Total number of CFU after 48 hours of incubation. GOCA - Great Onyx Cave; CC-LHT - Left Hand Tunnel of Carlsbad Cavern.

Sample	Cave dilution: Cave incubation	Cave dilution: Surface incubation	Surface dilution: Cave incubation	Surface dilution: Surface incubation
GOCA Mud	1.96×10^6	2.2×10^6	7.7×10^6	7.1×10^6
GOCA Sandy soil	1.69×10^6	1.7×10^6	7.4×10^6	7.7×10^6
GOCA Water Edwards Dome	5.3×10^3	4.9×10^3	6×10^2	No Growth*
GOCA Water Bubbly Pit	0-100*	0-100*	2×10^3	0-100*

* Not statistically significant.

Table 2. Total number of CFU after 48 hours of incubation in the cave or under cave conditions on the surface, followed by an additional 48 hours of incubation of all samples at room temperature on the surface. GOCA Great Onyx Cave, MACA.

The Great Onyx plates were all held at room temperature for an additional 48 hours (Table 2), with no change in the numbers of colonies, except for water samples from Edwards Dome, which grew between 0–10 CFU, but still not significantly different than zero.

4. Discussion

R2A agar was selected because is a low nutrient microbial growth medium intended for recovery of bacteria from potable water samples,\ which are low in nutrients as we would expect in the cave environment. In combination with low temperatures and longer incubation times, R2A agar will improve recovery of stressed bacteria from samples (Reasoner and Geldreich, 1985; Koch, 1997). The amount of growth is inversely proportional to the temperature, and counts are significantly higher from water samples using a nutrient rich medium such as PCA (Plate Count Agar).

Overall, Carlsbad Cavern samples were one to two orders of magnitude lower than Great Onyx Cave soil samples, but the CFU were higher for Carlsbad water samples. Numbers of CFU per cm^3 of soil were overall low. There were no differences in numbers of microbes recovered under any incubation conditions after 48 hours regardless of where the dilution series were made or where samples were subsequently incubated (P= 0.082 for the overall ANOVA, 0.2668 for the sign test of incubation temperature, and 0.6875 for the test of incubation site for the Carlsbad

Cavern data). Diversity as determined by a visual inspection of plates showed differences by site in the Great Onyx samples. The Mud sample from Cox had very low diversity, with only two colony types predominating. The sandy soil from Edwards had greater diversity in colonial appearance, and a few colonies of what was probably a temperature-sensitive variety that produced colored colonies under surface incubation conditions, but not in the cave.

Subsequent reincubation of the Great Onyx plates at Room Temperature resulted in a large increase in the number of CFU recovered from all of the samples. Culturable CFU from soil samples increased by 10-100 fold. Water samples were much higher for the Edwards Dome sample, and higher, but not statistically significant, for the Bubbly Pit sample. Contamination and overgrowth of plates by fungi became a problem after the 48 hrs at room temperature.

Storage of Great Onyx samples in the refrigerator for 48 hours and plating a new dilution series had no impact on numbers (results not shown) after 48 hours of incubation in the cave and on the surface compared to the samples plated immediately after collection.

Many microbes identified from deep caves are identical to surface forms, opportunistic and active only under favorable growth conditions (for example, Dickson and Kirk 1976, James 1994). Most are non-resident chemoheterotrophs transported into caves by water, air, sediment and animals. However, these enrichment-based and cultural studies have focused on typical heterotrophic microbes known from surface studies; and such techniques have been shown to grow less than 1% of microbes present in an environment (Amann et al. 1995). Culture-independent, molecular phylogenetic techniques have since shown that many novel organisms can be found in caves (Angert et al. 1998; Vlasceanu et al. 2000).

5. Conclusions

We conclude that a period of in-cave incubation for isolation and quantification of chemoheterotrophic bacteria offers no advantages compared to removing samples to the surface for cultivation from samples from moderate to low human impact areas of caves. Refrigeration of samples for up to 48 hours prior to dilution had no effect on numbers of CFU recovered from Great Onyx Cave. Because these studies were carried out on samples from off-trail areas of show caves using only one type of medium, we continue to recommend a period of in-cave incubation for maximum isolation of more specialized or unique cave bacteria. Future studies will repeat the study with additional types of media that have been shown to successfully grow cave bacteria; sampling in wild caves with areas of low visitation by humans; and will explore whether isolation of chemolithotrophic cave microorganisms is affected by in-cave incubation.

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INVERTEBRATE COLONIZATION AND DEPOSITION RATES OF GUANO IN A MAN-MADE BAT CAVE, THE CHIROPTORIUM, TEXAS USA

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A man-made bat cave, the Chiroptorium, was built on *Selah*: the Bamberger Ranch Preserve near Johnson City, Texas, USA, by Margaret and J. David Bamberger. The Chiroptorium was built in 1998 on the principle of "if we build it, they will come". It took a few years, but the Chiroptorium was colonized by *Tadarida brasiliensis* bats in summer 2003. We began monitoring the bat guano in the winter of 2004-2005 to see when the full community of guano invertebrates (excluding mites) would develop in what amounts to a primary succession in a virgin environment. In Year 1, average guano depths in both domes was about 5.5 cm, and the invertebrates very limited in number and diversity, with none of the characteristic beetles. A pseudoscorpion, probably *Hesperochernes mirabilis*, was common in the guano and on walls from the beginning of our study. Spiders *Spermophora senoculata* Duges and *Tidarren sisyphoides* Walckenaer, some with egg cases, were found on the walls. By the winter of 2005–06, guano depth had roughly doubled to about 10.5 cm, and a diverse community of invertebrates was described, including the dermestid beetles *Metoponium* sp. and *Dermestes* sp. In the third winter (2006–07), all structure of the guano deposits had been reduced to dust, probably by the action of a large population of beetles and aided by cattle. Several spiders, *Oecobius annulipes* Lucas, were found on the walls. The Bambergers built it, and the bats and the invertebrates did come, and very quickly.

1. Introduction

The Bambergers, J. David and Margaret, own *Selah* the Bamberger Ranch Preserve, in Johnson City, Texas, USA. Avid naturalists and conservationists, they wanted to add a bat colony to the ranch property and began planning in consultation with Bat Conservation International to build a man-made bat roost they described as the Chiroptorium: Chiropt- for bats and -torium from auditorium, a place to gather. The Chiorptorium was designed to house one million bats in two domes, a large outer dome 12.2 m D x 6.1 m H (40 ft D x 20 ft H) and a second, smaller inner dome that is 6.1 m D x 6 m H (20 ft D x 18 ft H), with a connecting tunnel, an entrance tunnel, and an observation area behind glass. Figure 1 shows the rebar stage of construction of the Chiroptorium with the entrance tunnel to the right and the small tunnel leading to the observation level at the top of the picture. The rebar was then sprayed with gunite, a liquid concrete. To maintain more bat-friendly temperatures, the structure was covered with tar and earth (BATS, 1997). The structure was completed in 1998, but did not attract significant numbers of bats until the summer of 2003. Gary McCracken confirmed a maternity colony of Mexican free-tailed bats (*Tadarida brasiliensis*) in 2003. Bat biologist Thomas Kunz estimated a population of 27,000 free-tailed

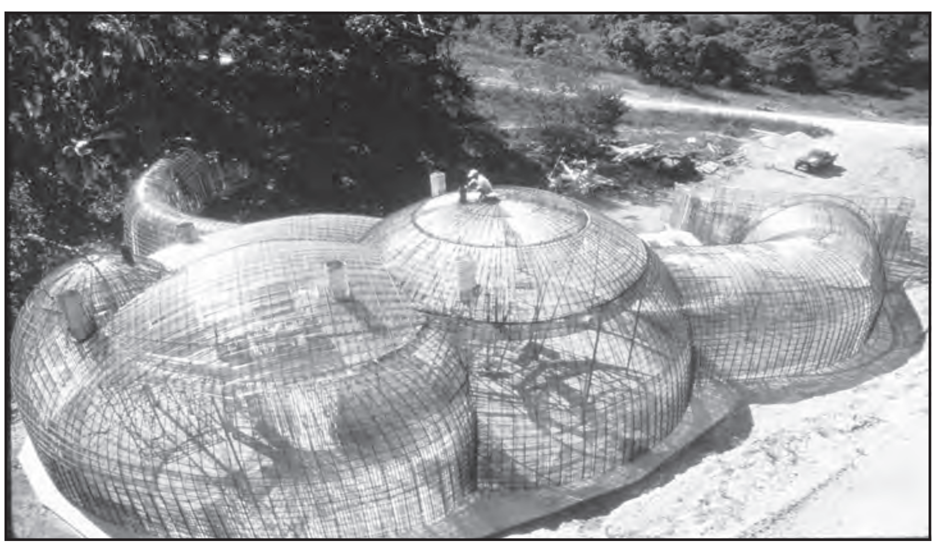

Figure 1: The Chiroptorium under construction. Note person on top of the large outer dome for scale. Photo by James Smith and Brian Keeley.

bats in summer 2006 (T. Kunz, personal communication). The plan is to ultimately use the guano as fertilizer at the Ranch. (For a panorama of the large outer dome, go to http://chriswjohnson.blogspot.com/2007/12/bamberger-ranch-chiroptorium-main.html)

Our interest in the Chiroptorium is that is a virgin environment, never before colonized by animals and invertebrates. We wanted to follow the rate of guano deposition and the process of primary succession to determine how long it would take for a full guano invertebrate community to develop, especially Dermestid beetles, and to inventory the invertebrates. We did not include mites in our study, which can represent 95% of the invertebrates in guano. Thomas Kunz from Boston University and his students are following the changes in bat populations over the same period of time.

2. Material and Methods

We began our study in January of 2005, well after the majority of bats had left for the winter. We set up an octagonal grid in the large dome, and a hexagonal grid in the second smaller dome. Both domes had wall to wall transects crossing through one central point and an inner and an outer ring 1/3 and 2/3 of the way from the center point to the walls. The points where the rings intersected the transects resulted in n=8 and n=6 sampling sites for the rings in the large and small domes, respectively. At each sampling site we measured guano depth using a meter stick. We did a visual census of invertebrates at each point for 10 cm around the intersection and below the surface. Each dome also contained a large bat box that was particularly heavily colonized by the bats. We measured the piles and made observations of invertebrates. We did a visual survey of the walls of the domes and tunnels, sampling as we encountered something of interest. Year 1 was in January of 2005, Year 2 in November 2005, and Year 3 in January of 2007.

Samples of bat guano were taken for a molecular, culture-independent analysis to detect changes in the guano from year to year (January 2005: CH050106-1 (Dome 2, big pile), 2 (Dome 1, big pile) and 3 (Dome 1, central room); November 2005: CH051112-1 (Dome 2, fresh guano), 2 (Dome 2, older guano), 3 (Dome 1, bat ring), 4 (Dome 1, big pile), 5 (Dome 1, outer ring); CH070115-3 (fresh guano), 4 (fresh guano).

DNA was extracted and purified using the MoBio PowerSoil™ DNA Isolation Kit using the manufacturer's protocol (MoBio, Carlsbad, CA). Extracted DNA was amplified with universal bacterial primers 46 forward (5'-GCYTAAYACATGCAAGTCG-3') and 1409 reverse (5'-GTGACGGGCRGTGTGTRCAA-3')(Vesbach, personal communication). Amplicons were cleaned and purified using the Qiagen PCR cleanup kit (Qiagen, Germantown, Maryland) and were cloned using the TOPO TA Cloning kit (Invitrogen, Carlsbad, CA) and sent to Washington University Genome Sequencing Facility for sequencing with primers M13F and M13R. Once received, sequences were edited and contiged with Sequencher 4.8. (Gene Codes, Ann Arbor, Michigan). To check the orientation of our sequences and to convert from antisense to sense, OrientationChecker (www.cardiff.ac.uk/biosi/research/biosoft/) was used. Sequences were classified using the Ribosomal Database Program Classifier software (http://rdp.cme.msu.edu/). Denaturing Gradient Gel Electrophoresis (DGGE) was carried out on guano samples. The 16S rRNA gene was amplified with universal primers 338 forward with GC clamp(5'CGC$_3$ GCCGCGC$_4$ GCGC$_3$GTC$_3$GCCGC$_5$GC$_3$TCCTACG$_3$ AGGCAGCAG-3'; and 907 reverse (5'-CCGTCAATTC CT$_3$ RAGT3-3'). DGGE was conducted using a DGGE-2001 System (C.B.S.*Scientific Company, Inc.). PCR products were run on 6% (w/v) acrylamide gels with a denaturing gradient of 30–60%.

3. Results

Figure 2 shows the changes in guano depths from Year 1 to Year 2 at the sampling sites in each ring. Figure 2A is from

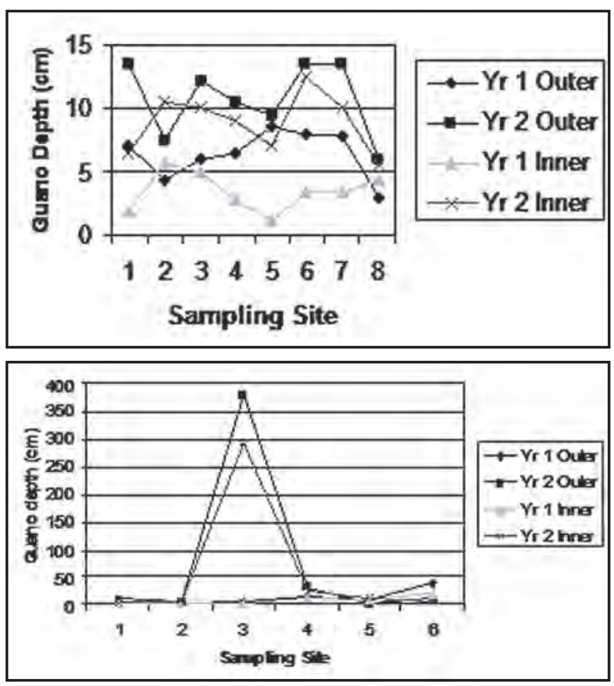

Figure 2: Changes in guano depth from Year 1 to Year 2 by sampling ring in A, the large dome, and B, the small dome.

the large dome, and Figure 2B is from the small dome. Note the difference in scale. The outer ring in the small dome included the large guano pile under the bat box at site 3.

The large guano pile under the bat boxes increased in extent from Year 1 to Year 2 by:

Large Dome. Year 1: 31 cm H x 160 cm L x 101.6 cm W to Year 2: 435 cm H x 167.6 L x 127 cm W

Small Dome. Year 1: 64 cm H x 182.9 cm L x 152.4 cm W to Year 2: 530 cm D x 323 cm L x 198.1 cm W.

Invertebrate numbers from a representative transect from wall to wall in the Large Dome are shown in Table 1 for Year 1 and Year 2.

Sample location	Year 1	Year 2
Outer 0-1	(dead lacewing)	4 dermestids
Inner 0-2	Nothing	1 flea, 1 dermestid
Center	1 ant	Nothing
Inner 5-2	Nothing	2 dermestids
Outer 5-1	Nothing	1 ant, 1 pseudoscorpion
Total	**1**	**9**

Table 1: Invertebrate numbers from a representative transect from wall to wall in the Large Dome.

A DGGE analysis of all nine guano samples (Fig. 3) reveals much similarity among samples within a given sampling time, but major differences between sampling times. Samples from January 2005 and November 2005 showed many bands, indicating the presence of many species, without dominance by any one band/species. The samples from November 2005 appear to be more diverse than those from January 2005, possibly due to sampling earlier in the winter. The samples from January 2007 are dominated by one major band/species and lack diversity.

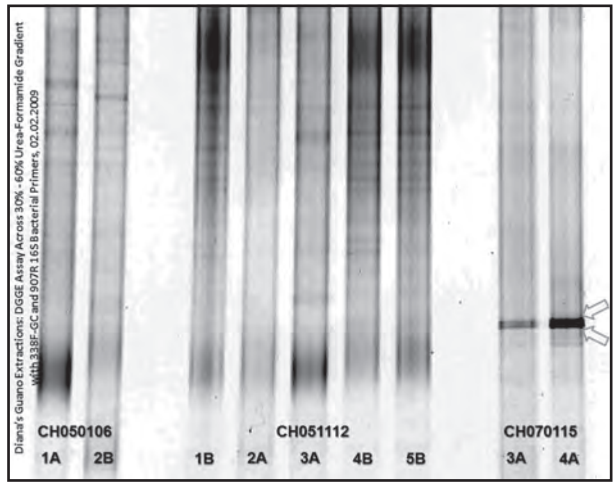

Figure 3: DGGE analysis of all nine guano samples: January 2005, November 2005 and January 2007. Each band represents a separate species.

The samples from January 2007 are dominated by one major band/species and did not have as much diversity as formerly seen. The one dominant sequence is *Lactobacillus lactis*, in the Order *Lactobacillales*.

Two samples form the November 2005 collection from Dome 1 were sequenced and closest relatives were identified. The two samples showed overlap within the *Firmicutes* phylum, in particular within the *Staphylococcus* and *Sporosarcina* genera. The bat ring in Dome 1 contained *Alphaproteobacteria* and *Gammaproteobacteria*, which were not found in the big pile sample from Dome 1.

4. Discussion

In our Year 1, the winter of 2004–05, average guano depths in both domes was about 5.5 cm, and the invertebrates

Sample	**αProteo** *Bartonella*	**γProteo** *Enterobacteriaceae*	**Firmicutes** *Enterococcus Weissella Atopostipes Lactobacillales*	**Firmicutes** *Staphylcoccus Sporosarcina Bacillaceae 1 Bacilliaceae 2 Bacillales*	**Firmicutes** Unclass Bacilli
Dome 1 Bat Ring 051112-3	1	2	3 + 1 + 0 + 1	4 + 4 + 1 + 15 + 5	1
Dome 1 Big Pile 051112-4	0	0	0 + 0 + 24 + 0	3 + 2 + 0 + 3 + 0	1

Table 2: Taxonomic groups found in clone libraries from two of the guano samples examined with DGGE. Closest relatives by genus or family are given under each phyla (in bold) and the number of clones within each of these classifications is given by sample.

very limited in number and diversity, with none of the characteristic dermestid beetles. A pseudoscorpion, probably *Hesperochernes mirabilis*, was common in the guano and on walls from the beginning of our study. Spiders *Spermophora senoculata* Duges and *Tidarren sisyphoides* Walckenaer, some with egg cases, were found on the walls. Mud dauber wasps and a phoebe nest were already well-established in the entrance tunnel by 2005.

By Year 2, guano depth had roughly doubled to about 10.5 cm, and a diverse community of invertebrates was described, including the beetles *Metoponium* sp. and *Dermestes* sp. (Fig. 4).

Figure 4: Dermestid beetle on the wall of the Chiroptorium (Photo by Kenneth Ingham).

In Year 3 (2006–07), we were surprised to find all structure of the guano deposits and of individual droppings had been reduced to dust, probably by the action of a large population of beetles (Kunz, personal communication) and aided by cattle. Several spiders, *Oecobius annulipes* Lucas, were found on the walls. Sampling was complicated by a major ice storm that made staying in the Hill Country unfeasible.

Major changes in the guano bacterial community composition occurred over the three sampling periods, with the last sampling period showing a change from a diverse community, with relatively even abundances, to a community dominated by one organism. The reworking of the guano by dermestid beetles and cows may have contributed to the major change in the bacterial makeup of the guano in 2007.

A possible complication of our study is the spreading of about 100 pounds of guano from Bracken Bat Cave prior to 2002 (J. Bamberger, personal communication). The guano was placed in the Chiroptorium in the hopes that the smell would attack bats to the structure. We doubt that this action had any significant effects on the succession, since any invertebrates transferred with the guano would have had to go through several lean years without inputs of guano, and that a guano community had not fully developed by the time we began our study, despite an abundance of raw material already in place. However, we are conducting a comparison of the Chirpotorium invertebrate community with Bracken Bat Cave, and we plan to investigate other nearby guano deposits.

5. Conclusions

A robust guano invertebrate community had developed within three years of reliable colonization of the Chiroptorium by bats. The Bambergers built it, and the bats and the invertebrates did come, and very quickly. The study is still on-going, and comparison of the invertebrate guano community in the Chiroptorium with other bat guano caves will provide additional information.

Acknowledgements

We thank the Bambergers for their interest in our project and all things natural, and for building the Chiorptorium. *Selah* Educational Programs Manager Colleen Gardner is our regular contact, and has been a gracious host. We thank James Smith and Brian Keeley for Chiroptorium construction pictures provided by the Bambergers. Tom Kunz gave us insights into both bat and Dermestid beetle behavior. Thanks to Jim Kennedy and BCI for providing guano from Bracken and Dr. Sandy Brantley for identification of the spiders. Jerry Lewis made a presumptive identification of the pseudoscorpion. Monica Moya and Amaka Nwagbologu were very helpful with sequence editing and Dr. Armand Dichosa and Jenny Hathaway helpfully provided the DGGE analysis of the guano samples. We thank Jim Lavoie and Kenneth Ingham for field assistance and photography. Funding was provided through Kenneth Ingham Consulting, L.L.C. and the Research Foundation of SUNY.

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EFFECTS OF MISSING LEGS ON DISTRIBUTION AND JUMPING BEHAVIOR IN THE CAVE CRICKET, *HADENOECUS SUBTERRANEUS*

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The cave cricket (*Hadenoecus subterraneus*) is a keystone species in maintaining biological diversity in cave communities in Mammoth Cave National Park through inputs of fixed organic material in the form of guano, eggs, and carcasses. Crickets must leave the cave to forage on nights when conditions are favorable. Leaving the refuge of the cave puts them at considerable risk for predation. Invertebrates are preyed upon by a wide range of animals and have developed defenses, including autotomy, or voluntary loss of a limb. We hypothesize that missing legs are a sign of predation pressure on the crickets, and may be different in different environments. We also hypothesize that missing legs reduce the ability of an adult cricket to escape predation. We used a visual census to record the frequency of missing legs by gender among adult cave crickets at eight different entrance locations in Mammoth Cave National Park. We expected males to be missing legs more frequently than females because they must leave the refuge of the cave to forage more frequently than females, but males and females were missing legs in equal frequency. Cave crickets were missing hind legs with greater frequency than other limbs, probably because crickets attempt to jump away from predators, making the larger hind limb closest to the predator. The frequency of crickets with missing limbs varied among cave entrances from a low of 6.6% to a high of nearly 40%: numbers are variable from year to year. In Frozen Niagara, which consistently had a high proportion of crickets missing legs, the percentage was highest in crickets roosting closer to the entrance (30.8%) than deeper (18.7%) into the cave. We collected crickets naturally missing various legs and combinations of missing legs, and measured the distances jumped. Crickets missing one hind leg jumped as far as crickets with both hind legs. Missing one or two of the front and middle legs had no impact on jumping behavior. Crickets missing both hind legs were completely unable to jump. Crickets missing hind legs had lower amounts of food in their crops than crickets with all their legs. We conclude that missing legs has limited negative effects on crickets being able to leave the cave to forage, except in the extreme case of crickets missing both hind legs.

1. Introduction

Hadenoecus subterraneus cave crickets are habitual trogloxenes, and are often abundant around cave entrances (LAVOIE et al., 2007). *H. subterraneus* is a keystone species, leaving the cave to forage on nights when conditions of temperature and humidity are favorable, returning to the cave for a daytime refuge (LAVOIE et al. 2007) The crickets maintain communities of specialized egg predators (POULSON, 2002), a diverse guano community under roosts (POULSON, 1992; POULSON *et. al*, 1995), and provide dispersed inputs of energy for troglobites.

Cave crickets are vulnerable to a wide range of predators. Inside the cave, *H. subterraneus* are preyed upon by spiders, particularly *Meta americana*, and cave salamanders, *Eurycea lucifuga*. Outside the cave crickets are frequently eaten by *Peromyscus lucopus*, white footed deer mice. VIELE AND STUDIER (1990) showed that deer mice preferentially overlap feeding ranges around a cave entrance in Mammoth Cave National Park. HELF (2003) found more than four times the number of *P. leucopus* within 50 m of a cave entrance compared to a control area without a cave entrance.

The three sets of paired legs of insects, including crickets, are attached to the three thoracic segments The attachment point at the coxa is very weak, and legs can be easily lost. In many insects, voluntary loss of legs (autotomy) is a strategy to reduce predation (BATEMAN AND FLEMING, 2005) Cave crickets primary response to a threat is to jump.

Insects walk using a characteristic pattern that is described as the alternating triangle gait. The front and rear legs on one side of the body move together with the middle leg on the other side of the body, creating a supportive triangle. The next step switches sides, maintaining the triangle. The movement is highly stereotyped, and controlled by neurons.

In some insects, the need for coordination decreases at faster speeds. Insects typically adapt rapidly to the loss of one or more legs.

Field crickets (*Gryllus bimaculatus*) with one missing hind limb had a reduced escape speed and decreased ability to jump (FLEMING AND BATEMAN, 2007) They were also slower, moved shorter distances, and used more energy than those with no hind limbs missing (FLEMING AND BATEMAN, 2007). The same pattern was found with house crickets (*Acheta domestica*), and the reduced escape abilities increased their predation risks by lizards and mice (BATEMAN AND FLEMING, 2006).

We hypothesized that male cave crickets would be missing limbs more frequently than females since males must leave the cave to forage more frequently than females (STUDIER et al., 1986). We expected the hind leg to be missing the most often since it would be in closet proximity to a threat as the cricket jumps away and it is the largest leg, making it a better target. Variability in the proportion of crickets missing legs might be higher in caves with more human impact (visitors) or in caves with sink *vs*. source populations (HELF et al., 1995). We expected to find that missing one or both hind legs would reduce a crickets ability to jump in terms of distance per jump and total distance jumped, and that crickets missing legs would not be as effective at foraging as evidenced by lower amounts of food in the crop than crickets with all legs.

2. Methods and Materials

Census for missing legs. The study was done in eight different sites (entrances and caves) within Mammoth Cave National Park, KY, USA. Cave crickets were visually censused from the entrance until population density dropped off, which ranged from 20 m up to 150 m into the cave. We did a visual census of adult crickets, noting gender and which leg or legs were missing on which side of the body. The study is limited to adult crickets with a Hind Femur Length of ≥ 20 mm (STUDIER et al., 1986). Adults have highly sclerotized (brown) legs and ovipositors and do not molt so they cannot regenerate a lost leg. Leg loss was analyzed for difference by gender and limb location (front, middle, and hind limb) by Univariate Analysis of Variance (ANOVA) and a Post-hoc Bonferroni test, respectively.

Jumping experiment. We used an area of the tourist trail in Frozen Niagara Cave 30 m in from the entrance that is wide, relatively flat, and covered in concrete, with electricity nearby. An electronic balance recording to 4 decimal places was used. Crickets were individually selected and captured by hand so that we would have a good mixture of gender, crickets with all legs, and crickets missing different combinations of legs. A total of 44 crickets were tested. Each cricket was placed into a tared plastic 35mm film container and weighted to four decimal places. We recorded their Hind Femur Length, gender, weight, and which leg(s), if any, were missing. Crickets were placed in the center of the open area and released. As crickets jumped, a coin was placed to record the starting and stopping points for each jump or distance walked. Crickets not compliant with jumping were given a gentle poke. After the cricket stopped jumping or left the path area, the distance between each jump was recorded. To make the results more comparable, only the first five jumps made by a cricket were used to determine total distance jumped and average distance per jump.

The mass of food in the crop was estimated using a regression of Hind Femur Length (HFL) vs. Crop Free Live Weight from dissected crickets (STUDIER et al., 1986). The predictive equation allows us to estimate the amount of material in the crops with a confidence of 90% without having to kill the cricket. For crickets missing both hind legs, we used an average HFL of 22 mm for the males and 23 mm for the females. A typical hind leg weighed 0.0382g and we adjusted the total weight by that amount for each missing hind leg to allow us to use the regression.

3. Results

The number of crickets at each location is shown in Table 1 by gender, with total number of adult crickets observed, the total not missing legs, and the total missing legs. Which leg was missing (Hind, Middle, Front), and the percentage of adults missing legs in the total number censused is also shown. Some individual crickets were missing more than one leg, but the proportion was very low and ranged from 1% to 2.7% in 2008. Multiples legs lost are included in the total reported in Table 1. A Post-hoc Bonferroni test for position of missing leg, using multiple comparisons showed that the Hind leg was missing significantly more than the other legs. The dependent variable was the number of crickets missing leg at each position. Figure 1 compares the proportion of the population missing legs in May 2007 compared to May 2008, for four caves and entrances in Mammoth Cave National Park.

As we censused in 2008, the students noted that there was a higher proportion of "broken crickets" closer to the entrance than deeper into the cave at the Frozen Niagara entrance. The proportion of crickets missing legs in Frozen Niagara was greater in the first 10-30 m into the cave (Males 31.9%,

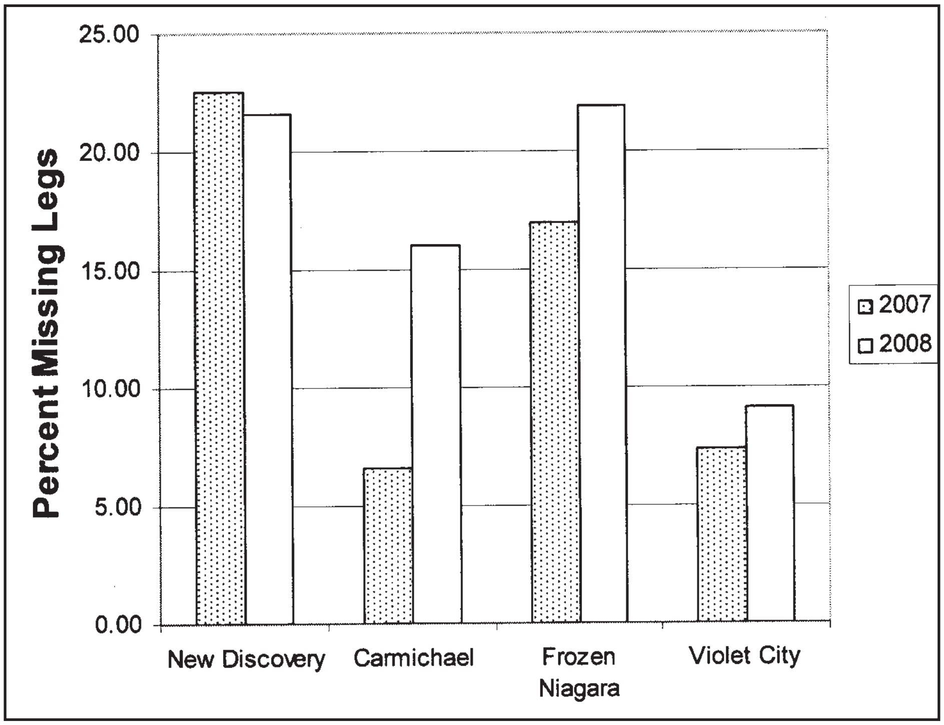

Figure 1. The percent of the censused population of adult crickets missing legs in 2007 and 2008 from four entrance and caves in Mammoth Cave National Park.

Location (cave or entrance)	Gender	Total	Total Intact	Total Missing Legs	Missing Hind Leg	Missing Middle Leg	Missing Front Leg	Percent missing legs(all)
New Discovery	M	113	91	22	17	1	4	22.6
	F	126	104	22	17	2	3	
Carmichael	M	59	54	5	5	0	0	6.6
	F	87	83	4	2	2	0	
Frozen Niagara	M	168	146	22	18	1	2	17.0
	F	218	184	34	30	1	2	
Floyd Collins Crystal Cave	M	25	19	6	6	0	0	23.6
	F	45	36	7	6	0	1	
Sophy's Avenue	M	30	25	5	1	1	3	20
	F	12	10	2	2	0	0	
Violet City	M	12	11	1	1	0	0	7.4
	F	17	16	1	1	0	0	
Great Onyx Cave	M	45	42	3	3	0	0	8.2
	F	47	43	4	4	1	1	
Little Beauty Cave	M	34	27	7	7	0	2	38.9
	F	41	27	14	14	2	3	
TOTALS		1077	918	159	159	11	21	17.3%

Table 1. Number of crickets at each location and their characteristics.

Females 30.4%) compared to crickets deeper into the cave 60-80 m (Males 14.6%, Females 20.4%).

Jumping experiments. The data for male and female crickets with all legs, missing one hind leg, and missing both hind legs is shown in Table 2 by total distance jumped in the first five jumps, for average distance jumped in the first five jumps, and in Figure 2 for the calculated crop weight. The data are graphed by individual.

4. Discussion

There is no difference in the proportion of males and females missing legs (ANOVA F=0.817). Hind legs were autotomized significantly more often than other legs (F=34.069, p>0.001). The proportion of crickets missing legs in 2007 varied from a low of 6.6% in Carmichael to a high of 38.9% in Little Beauty Cave (Table 1). The proportion of crickets missing legs from year to year showed some variation (Fig. 1). Sites vary by amount of human impact and source vs. sink populations, but we have found no consistent pattern to explain the variability.

Missing one hind leg had no effect of the total distance or the average jump length of a cricket. Crickets missing both hind femurs and were completely unable to jump. We have some indications (Fig. 2) that crickets missing one or both hind legs are less effective at foraging compared to crickets with both hind legs. Crickets missing hind legs were more likely to be found closer to an entrance, suggesting they did not want to move as far as intact crickets with all their legs, or had to leave the cave more frequently to forage. Crickets missing legs may not be as effective at foraging as suggested by a lower amount of food in the crops compared to intact crickets. A variable is that we do not know is when the cricket actually lost the leg. Future studies include repeating the census of crickets missing legs from all of the study sites. We will collect and weigh crickets will all legs and crickets with missing hind legs from near and far populations. The effect of missing legs on cricket endurance (see FLEMING AND BATES, 2007) will be evaluated. We have also noted anecdotally that crickets lose their legs more in winter when we handle them, which is another aspect to study.

Crickets by gender and number of missing hind legs	n	Average jump distance from first five jumps	Total distance jumped in five jumps
Males, None	10	21.7 cm	108.4 cm
Females, None	12	18.1 cm	83.2 cm
Males, One	6	18.0 cm	90.1 cm
Females, One	7	19.61 cm	98.1 cm
Males, Two	2	0	0
Females, Two	2	0	0

Table 2. Cave crickets by gender and number of missing hind legs: none, one, or two. The average jump length and total distance hopped is from the first five jumps.

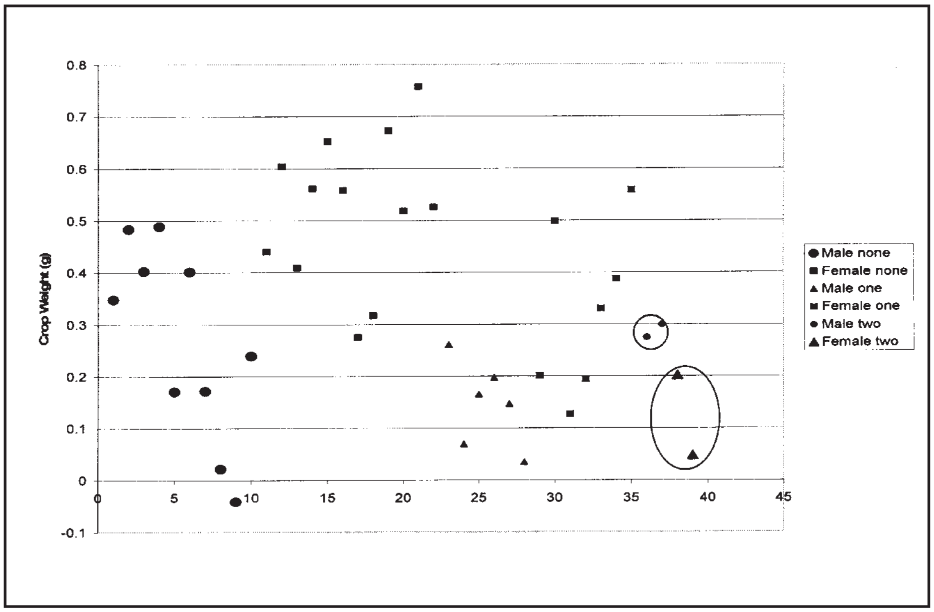

Figure 2. Calculated drop weight in adult crickets from the Frozen Niagara entrance of Mammoth Cave National Park, by gender and missing no hind legs, one hind leg, and two hind legs. Circles highlight crickets missing both hind legs.

5. Conclusions

Cave crickets (*Hadenoecus subterraneus*) show limited effects of missing one hind leg on escape behaviors as evidenced by the often high number of individual missing a leg or legs in many locations. Intact crickets and crickets missing one hind leg showed nearly identical jumping behavior in terms of average jump length and total distance jumped in the first five jumps. Crickets missing both hind legs were not able to jump at all. Losing one or both hind legs may reduce the foraging effectiveness of crickets.

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SPECIES LIMITS, PHYLOGENETICS, AND CONSERVATION OF *NEOLEPTONETA* SPIDERS IN TEXAS CAVES

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Abstract

A principal theme in biogeographic studies of troglobites is understanding the relative roles that vicariance and dispersal have played in shaping their geographic distributions. Classical studies often show troglobites as single- cave endemics, but recent work suggests that some species have wider ranges than expected and are best explained by dispersal. These findings not only have implications for understanding speciation in cave organisms, but are also central to developing accurate taxonomies upon which conservation decisions are ultimately based. Here we present a phylogeny of *Neoleptoneta* spiders in Texas based on molecular and morphological data, including specimens from published records and several new cave localities. Preliminary results show that while most species are narrowly distributed, some troglobites (including the endangered *Neoleptoneta microps* and *N. myopica*) occur more broadly than previously believed, and may not even be restricted to caves. These data suggest that both vicariance and dispersal have played important roles in shaping the distribution of *Neoleptoneta*, and this highlights the need for a comprehensive revision of the genus. A distribution map for *Neoleptoneta* is also provided, indicating areas in need of additional sampling or phylogenetic uncertainty.

UNTANGLING THE WEBS IN CALIFORNIA'S CAVES: THE BIOGEOGRAPHY AND SYSTEMATICS OF THE CAVE - SPIDER GENUS *USOFILA*

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Abstract

Despite California's diverse and endemic biota, little attention has been directed towards understanding the composition and relationships of its cave- adapted fauna. Basic taxonomic knowledge is lacking in most cases, which hampers research efforts and prevents effective conservation and management planning. This project aims to discover and describe patterns of diversity in the genus *Usofila*, a group of poorly known spiders in Western North America. The goal of the project is to develop a functional taxonomy for *Usofila* that will be used to address broader biological questions, particularly those focused on conservation, biogeography, and cave adaptation in Western North America.

ZOOGEOGRAPHY AND EVOLUTION OF THE SUBTERRANEAN ASELLID ISOPODS OF NORTH AMERICA

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Over a century elapsed between the discovery of the first subterranean asellid isopod in North America, *Caecidotea stygia* in 1871, and the realization of the true diversity of the fauna. Initially known only from caves of the large karst areas of the eastern United States, knowledge of subterranean asellids in other areas and habitats was slow to accrue. Since 1973 stygobiont asellids have been recognized in a total of 9 genera in North America: *Caecidotea, Lirceus, Lirceolus, Salmasellus, Remasellus, Calasellus, Columbasellus* and two new genera from Oregon and California currently in press. Of these only *Caecidotea* and *Lirceus* have both epigean and hypogean species, the rest possess only subterranean species. From a zoogeographic standpoint *Calasellus, Columbasellus, Salmasellus* and the two new genera are restricted to an area west of the Rocky Mountains in the U.S. and Canada. This assemblage of western North American genera is related to an Asian *Asellus* assemblage of which one epigean species extends into Alaska. From an evolutionary viewpoint, although morphological similarities exist between the Asian and North American faunas, the subterranean asellids in western North America represent at least two lineages that appear to be only remotely related to *Asellus*. No vestige of eyes nor pigmentation remain in any of the species of *Calasellus, Columbasellus, Salmasellus,* or the two new genera. This combined with the absence of epigean relatives suggests that this group of asellids invaded subterranean habitats long ago.

In contrast, the evolutionary history of some of the subterranean *Caecidotea* is clearer, with examples of species with varying degrees of morphological adaptation to groundwaters. The best example is that of the *Hobbsi* species group. Among the members of this group are species ranging from eyed and pigmented, some with vestigial eyes and traces of pigmentation, to those that are completely eyeless and unpigmented. Many of the species with intermediate degrees of morphological adapation are those that invaded shallow groundwaters, inhabiting the interstices of unconsolidated glacial sediments. There are species of *Caecidotea* on both sides of the Rocky Mountains, but none in the mountains, suggesting that these isopods have been present in North America since prior to the uplift of the range. The creation of the great plains east of the mountains apparently extirpated surface populations of asellids, with only a few subterranean species remaining. Unlike *Caecidotea*, in which the majority of species are subterranean, only two stygobiont species of *Lirceus* are known, representing localized groundwater invasion. *Remasellus parvus* in Florida is a bizarre example of an adaptive shift, in which the isopods have evolved the ability to swim in the water column, rather than crawling across the substrate as in most other asellids. Similarly, *Lirceolus smithii* possesses adaptations for its existence in the deep groundwaters of the Edwards Aquifer in Texas.

1. Introduction

When Alpheus Packard collected *Caecidotea stygia* from Richardson's Spring in Mammoth Cave, Kentucky, it was the first subterranean isopod discovered in North America (Packard 1871). Since that time dozens of species of the isopod Family Asellidae have been described among ten genera summarized by Lewis (in press 2009a). With one exception (*Asellus,* represented by the epigean species *A. alaskensis*), these genera are endemic to North America. The genus *Caecidotea* (Packard 1871) is the dominant asellid group in North America, with over 84 species, of which about 70 are obligate groundwater inhabitants, followed by *Lirceus* with 15 species (2 stygobites)(Henry et al. 1986). The other seven genera possess only obligate subterranean species. *Remasellus* (monotypic) and *Lirceolus* (7 species) occur in the eastern U.S. and are apparent derivatives of *Caecidotea* (Lewis & Bowman 1996). Five genera are restricted in distribution to the far western parts of the U.S. and Canada, of which three are currently described (Lewis 2001, Lewis et al 2003): *Salmasellus* (2 species), *Calasellus* (2 described, 1 undescribed species) and *Columbasellus* (monotypic). Two other genera that are referred to here as new genus 1 (from Malheur Cave, Oregon) and new genus 2 (formerly *Caecidotea sequoia* Bowman 1975) (Lewis, in press 2009b).

2. Zoogeography and Evolution

In analyzing the evolution of the subterranean asellids not surprisingly the fossil record is of little help. The fossil record of various kinds of isopods dates back to the Paleozoic (Wilson 1999), which affirms the antiquity of the group. Little work has proceeded with genetic analysis of the asellids in North America yet and given the extreme rarity of some of the genera and species (e.g., *Columbasellus* is known from one specimen), the prospects for additional knowledge soon is unlikely. Thus, for the moment we remain dependent on the implications from morphological, zoogeographic and paleogeographic evidence.

The holarctic distribution of the asellids (Henry & Magniez 1970) suggests that the group has been in freshwater for a long time, predating the Mesozoic separation of North American and Eurasia. The species of *Caecidotea,* and to a lesser extent *Lirceus*, are nearly continuous in distribution from the east coast through the central U.S. The asellids are absent in the Rocky Mountains except for *Salmasellus steganothrix* (known from an area encompassing Alberta to Montana), with several mostly rare and poorly known species occurring along the Pacific coastal states. Also present in far western North America, *Caecidotea* is represented by *C. tomalensis* and *C. occidentalis,* although the western taxa are not very similar to those in the east. This attests to the dispersal of this group across temperate North America at some ancient time, prior to the creation of the large swath of western North America in which the asellids are now absent.

The paleogeography of North America provides insight into this distribution. During the Cretaceous, marine transgression separated North America into eastern and western landmasses separated by the Western Interior Seaway that inundated what was later to become the Great Plains region (Fig. 1). The marine waters subsequently retreated, leaving much of present-day North America above sea level. The Laramide orogeny occurred creating the Rocky Mountains and with them, the relatively arid great plains region to the east that served to further isolate the *Caecidotea* into eastern and western components (Lewis et al. 2006).

Concerning the group of asellid genera endemic to western North America, *Calasellus*, *Columbasaellus* and new genus 1 are related to the "*Asellus* pattern" genera found in Asia (Henry & Magniez 1995, Magniez 1996). Considering that the 4 species assigned to these three genera form a geographic cluster in the U.S. Pacific coastal region, it

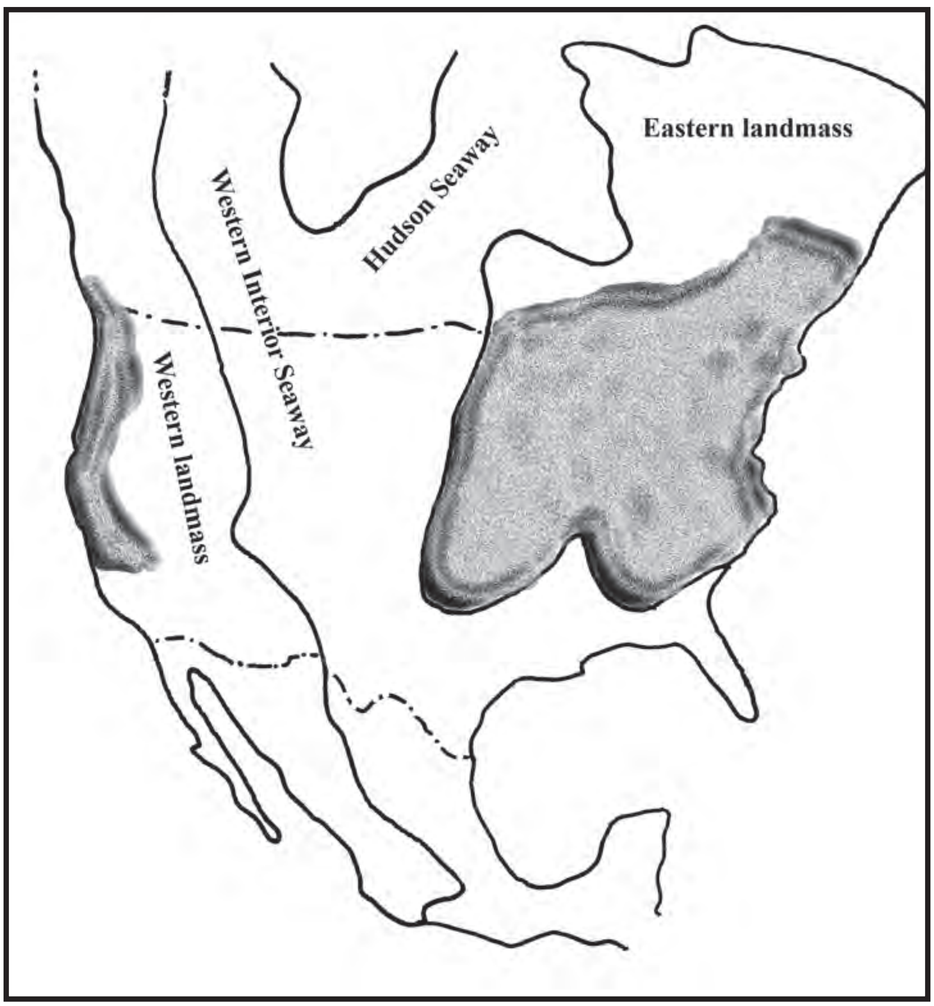

Figure 1. Map of North America as it appeared during the Cretaceous, when much of the Great Plains and southern U.S. were under seas. The Western Interior and Hudson seaways divided North American into three disjunct landmasses. Approximate present day asellid distributions are superimposed (shown as darker stippled areas) onto the Cretaceous landmasses.

seems likely that they form a sister group to the *Mesoasellus-Phreatoasellus-Uenasellus-Nipponasellus-Siberasellus* assemblage of Henry & Magniez (1995). The close similarity of the male second pleopods and geographic proximity of the species of *Calasellus*, *Columbasaellus acheron* and new genus 1 suggests a common ancestor. Since new genus 1 displays morphological characteristics on both sides of Henry & Magniez (1995) phylogeny, i.e.,mandibular palp reduced (e.g., *Nipponasellus*, *Sibirasellus*) and first maxilla inner lobe with 4 setae (e.g., *Asellus*), one or more of these characters in the new genus 1 asellid clouds the picture with apparent convergence.

Other pieces of the puzzle are the genera *Salmasellus* and new genus 2, which appear closely related as evidenced by synapomorphies listed by Lewis (in press 2009b). Although it was tempting to assign *Caecidotea sequoiae* to the genus *Salmasellus*, among other things the large setae present on the male pleopod 2 endopod in *Salmasellus* remained unique. It was preferred to erect a new genus rather than broaden the diagnosis of *Salmasellus*. The two genera certainly have zoogeographic affinities with the "*Asellus* pattern" genera, but the morphological resemblance is not as strong as in the other North American genera discussed above.

Considering the North American and Asian distribution of the "*Asellus* pattern" genera, freshwater habitats connecting the areas in which these genera now exist around the Pacific Rim must have been present across Beringia. Paleontological evidence suggests that this bridge dates to the mid-Cretaceous (Fiorillo et al 2008; Weishampel et al. 2004). The timing of groundwater invasions in western North American asellids remains obscure. All of the western asellids are either strictly epigean or completely subterranean – no morphological intermediates between eyed/pigmented and eyeless/unpigmented species have been discovered. It would seem that the subterranean species invaded groundwaters long ago and their epigean ancestors are long gone.

This is not the case in the eastern *Caecidotea*, where many examples of evolutionary intermediates are present. Although some species group lineages are completely of subterranean facies, others have species of varying degrees of morphological adaptation to groundwaters. The members of the *Cannula* Group are completely eyeless and unpigmented, with bizarre modifications of the male second pleopod that have suggested their placement in the genus *Pseudobaicalasellus* (Henry & Magniez 1970, Lewis 1980). Most of the species of the *Stygia* Group are also completely stygomorphic, with the exception of *Caecidotea beattyi*, which possesses vestiges of pigmentation (Lewis & Bowman 1981). Among the members of the *Hobbsi* Group are found species with varying degrees of adaptations to subterranean habitats (Lewis 1982; Lewis et al. 2006). The epigean species *Caecidotea kenki* and *C. brevicauda* inhabit surface streams, springs and cave streams. Both are eyed and pigmented (Fig. 2), although some populations become depigmented in caves. *Caecidotea kendeighi* and *C. spatulata* are inhabitants of saturated interstices of till plains or other unconsolidated deposits in the midwestern U.S. They have the vermiform appearance typical of such subterranean isopods, but retain vestigial eyes and light magenta pigmentation. Other phreatobites, like *C. phreatica* or *C. lesliei,* or many of the stygobites like *C. packardi* are completely eyeless and lack any pigmentation.

Some of the subterranean asellids inhabiting saturated interstices (rather than caves) have penetrated significant

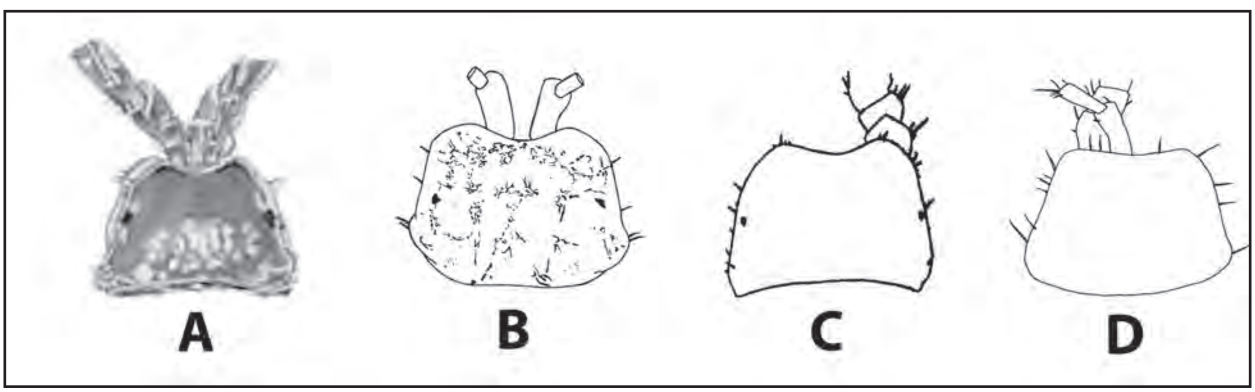

Figure 2. The possession of eyes and pigmentation varies widely in species of the Hobbsi Group in the genus Caecidotea. (A) Caecidotea kenki, epigean inhabitant of streams and springs, eyes and pigment are prominent, (B) Caecidotea kendeighi and (C) Caecidotea spatulata, phreatobites with varying degrees of pigmentation and vestigial eyes; (D) Caecidotea phreatica, eyeless and unpigmented. [Drawing of C. kenki by Carolyn Gast from Bowman 1967 with permission.]

distances into areas covered by the Pleistocene glaciers. One of the outstanding questions of subterranean asellid zoogeography is how these species arrived in the glaciated areas. Two schools of thought have been advanced. The first entails the animals remaining in subglacial refugia like the aquifers in deep unconsolidated deposits in filled stream basins (Koenemann & Holsinger 2001). The other theory is that the crustaceans followed the retreating glaciers northward. Koenemann & Holsingers' map indeed shows a correlation with deep deposits and collection sites for the phreatobitic amphipod *Bactrurus mucronatus*. However, recent *Caecidotea* collections have been made in areas where sediments are shallowest, like a collection from southeastern Bartholomew County, Indiana. Within a given surface drainage basin, *Caecidotea beattyi* is typically found in a headwater area where sediment deposits are shallowist (Lewis 2008). I am not satisfied that a good solution to the question of how phreatobitic crustaceans arrived in the glaciated regions has been found yet. As Lewis & Bowman (1981) noted, none of the theories are necessarily mutually exclusive.

The genera *Lirceolus* and *Remasellus* represent asellids in which adaptive shifts to have produced unusual morphological characteristics. Both genera are probably offshoots of *Caecidotea*. They occur in geographic areas inundated by the Cretaceous seas and represent subsequent dispersions from eastern North America into the coastal plain areas. *Remasellus* has anatomical modifications to accommodate swimming, with legs with elongate setae rows that transform the typical asellid pereopods into oar-like structures (Fig. 3) (Bowman and Sket 1985). Other North American asellids typically crawl across the substrate, but *Remasellus* is also capable of swimming weakly in the water column, an incredible behavioral adaptation.

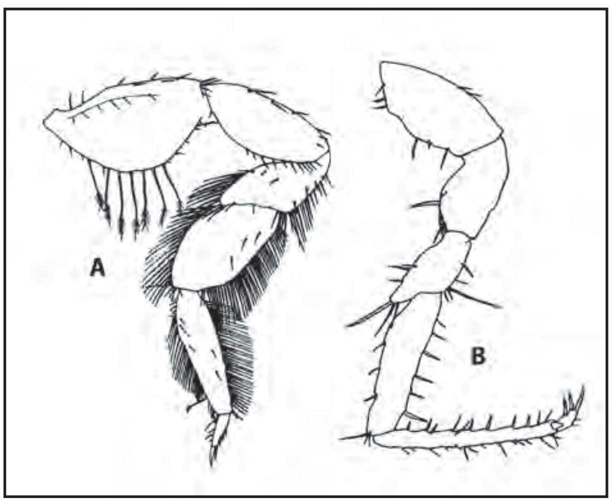

Figure 3. Comparison of pereopods of (A) Remasellus parvus, modified to accommodate swimming; and (B) Lirceolus nidulus, adapted for conventional crawling. [Remasellus drawing by late Thomas E. Bowman with permission.]

The genus *Lirceolus* is defined by a mosaic of similar morphological characteristics of males, particularly the simple first pereopod, elongate and sparsely setose first and second pleopods, and relatively simple structures of the second pleopod endopodite. All *Lirceolus* are eyeless and unpigmented, and many of the species are minute in size, with the largest species in the genus reaching a length of 8.8mm (Lewis & Bowman 1996; Lewis 2001). The zoogeography, ecology and morphology of the seven species suggest division of the genus into three subgroups:

(1) *Lirceolus serrata*, a stygobite in the Ozarks of southern Missouri and one of the smallest asellids in North America at a maximum length of 2.5mm. This species has some facets of its anatomy that are unique, including the lack of retinaculae on the male first pleopod, and male second pleopod endopod exhibiting apparent torsion as well as a prominent apical process. That not-withstanding the species appears to fit the diagnosis of *Lirceolus*. The morphology displayed by another Ozark species, *Caecidotea ancyla*, is suggestive of an intermediate between *Caecidotea* and *Lirceolus*.

(2) Stygobitic *Lirceolus* in Texas and adjacent border area of Mexico, including *L. hardeni, L. bisetus, L. pilus, L. nidulus and L. cocytus*. This group ranges from 2.2 to 8.8 mm in length and includes the smallest asellid (*L. hardeni*) in North America. All have maxilla 1 inner lobe with 5 setae except *L. hardeni*, which has only 4 setae. Some of the species exhibit varying degrees of reduction or simplification of pleopods 4 and 5.

(3) *Lirceolus smithii*, inhabiting the phreatic groundwater of the Edwards Aquifer feeding the artesian well at San Marcos, Hays County, Texas. This species has perhaps the most morphologically derived mouthparts of a North American asellid. The first maxilla has inner/outer lobes with 8/10 setae, rather than the 5/13 seen in all *Caecidotea*. Likewise, the mandible has 3-cuspate incisors and 2-cuspate lacinia mobilis, as opposed to 4/4 cuspate in most other North American asellids, including the other species of *Lirceolus* as well as all *Caecidotea*. Furthermore, pleopods 4 and 5 have the endopod and exopod fused into a single fleshy ramus (Bowman & Longley 1976).

Since Texas was inundated during the Cretaceous marine transgression, the source of the fauna was probably via post-Cretaceous dispersal from the Ozarks. *Lirceolus serratus* could be a geographic relict of a group that dispersed into Texas and northern Mexico. Further inference of the effects of the dispersal into Texas is elucidated by examination of the well-known amphipod/isopod assemblage of the artesian well at San Marcos. The seeming paucity of asellid diversity (with one species, *L. smithii)* as compared to subterranean amphipods (10 species) found in the artesian well is more understandable when the source of the faunas are considered (Holsinger & Longley 1980). Eight of the 10 amphipods were clearly derived from marine ancestors, leaving only the two species of the ancient freshwater crangonyctid genus *Stygobromus.* Thus, when compared to the part of the artesian well fauna that was derived from freshwater (rather than marine) ancestors, the asellids measure more comparably.

3. Summary

Asellids have been in North America dating back to at least the Mesozoic. Their distribution has been shaped by many factors including marine transgressions and the uplift of the Rocky Mountains. Today the majority of the species occur in the eastern United States, with most of those occurring in subterranean waters. In contrast, generic diversity is greater in western North America.

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STRUCTURE CHARACTERIZATION OF THE ARTHROPOD FAUNA COMMUNITY IN CAVE OF "THE RASCADERO," SANTANDER, COLOMBIA

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Abstract

We have characterized the communities of arthropods of Rascadero Cave in the Guanentina region of the Santander Department, Colombia. Manually collected samples were taken at intervals of 1 hour for each transect using pitfall traps without bait, and three-line transects, with 5 traps each. We identified the specimens collected at the taxonomic family level, finding a wealth of nearly 60 taxa. We assessed richness and rarefaction for the purpose of establishing diversity at the Alpha level for the cavern, and sought to identify patterns in the structure and zonation of the communities of arthropod cave fauna. We evaluated the relative abundance of species found in the pitfall traps. The estimated value of its importance within the communities was analyzed using indices of dominance and equity.

Very diffuse patterns found in community structures constitute a complex web of nonlinear dimensional trophic relationships. The boundaries of communities only allow us to distinguish three major trophic levels: the so-called guanivores (detritivores and saprophages), who depend almost entirely on guano, the omnivorous generalists, and the predators both small and large, the latter being the dominant forces in the community.

Resumen

Con el fin de caracterizar las comunidades de Artrópodos de la cueva el Rascadero pertenecientes a la región Guanentina en el departamento de Santander-Colombia, se realizaron muestreos de recolección manual en intervalos de tiempo establecidos de 1 hora por cada transecto, y se usaron trampas de caída sin cebo (Pitfall), para tres transectos lineales, con 5 trampas cada uno. Se identificaron los especimenes colectados a nivel taxonómico de Familia en su mayoría, encontrándose una riqueza de cerca de 60 taxones. Se hallaron índices de riqueza especifica y de rarefacción con el fin de establecer la diversidad Alpha para la caverna; y con el propósito de aproximarnos a identificar patrones en la estructuración y zonación de las comunidades de artropofauna cavernícolas. Se evaluó la abundancia relativa para las especies halladas en Pitfall, se calculó su valor de importancia dentro de las comunidades analizadas haciendo uso de Índices de Dominancia y de Equidad. Encontrándose patrones muy difusos en la estructura de las comunidades, que se constituyen en una compleja red tridimensional de relaciones tróficas no lineales, determinados por las adaptaciones de las especies allí presentes, en los cuales los limites de las comunidades solo son claros para distinguir tres grandes niveles tróficos: los denominados Guanivoros (Detritivoros y Saprofagos), que son los que dependen casi completamente del recurso guano, los Omnívoros o Generalistas, y los Depredadores pequeños y grandes, siendo estos últimos fuerzas dominantes en la comunidad.

SMALL-SCALE SPATIAL DISTRIBUTION OF AQUATIC FAUNA IN CAVES FROM NORTHWESTERN ROMANIA (EASTERN EUROPE)

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Abstract

Spatial patterns of groundwater biodiversity are poorly known and this type of knowledge is essential for understanding local variation in groundwater assemblages. We have investigated the local diversity patterns of aquatic fauna from percolation water in five karst caves in the Pădurea Craiului Mountains (Apuseni Mountains, northwestern Romania). The caves are located between the catchment areas of Crişul Repede and Crişul Negru rivers, in an area of approximately 3 km^2, at an average elevation of 450 m a.s.l., and drain water towards the two rivers.

Percolating water was sampled continuously between November 2007 and March 2009. Variation of physico-chemical parameters (i.e. pH, temperature, electrical conductivity, Al, Cr, Fe, NO_2^-, oxygen consumption CCO–Mn) and species distribution pattern have been evaluated. Spatial correlations were established between stations inside one cave (with a distance from one site to another that ranged from 3 to 500 m), as well as between caves (with a distance that ranged from 1 to 15 km).

The aquatic fauna of the selected caves is heterogeneously distributed and varies largely between stations. The fauna found in percolating water consists of a mixture of epigean and hypogean fauna, and includes eleven taxonomic groups: Nematoda, Oligochaeta, Gastropoda, Hydrachnidia, Amphipoda, Isopoda, Cyclopoida, Harpacticoida, Ostracoda, Collembola, and insect larvae. The biodiversity in the five caves was dominated by crustaceans with both high relative abundance and species richness, especially harpacticoid copepods. Among crustaceans, four species out of fourteen are endemic for this area, represented by harpacticoid copepods (two taxa) and niphargid amphipods (two taxa).

The percolating water was not contaminated and reveals small chemical variations throughout the year. Statistical analysis showed that the pattern of species distribution is influenced by water chemistry within caves, while between caves no significant correlation was established.

The factors responsible for the observed patterns are further discussed within local and regional context. The present study has yielded new data regarding the groundwater fauna distribution in this karst region. Long-term sampling efforts can reveal an increase in species richness that can be of high interest in developing conservation policies in the future.

ECOLOGICAL STUDIES IN INTERSTITIAL HABITATS OF ROMANIAN CARPATHIANS (EASTERN EUROPE)

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Abstract

Only the animals that live between sediment grains are considered interstitials although, according to the Latin etymology of the word "interstitial," many of the subterranean habitats can be considered as the living space of interstitials. Whether terrestrial or aquatic, and whether living in karstic or non-karstic areas, their habitats are various and encompass the crack and fracture networks of karstic massifs, the alluvia of surface rivers, the sediments of pools in a cave, etc. Environmental variations in such habitats are buffered and they represent the ecotone zone between two different habitats and faunas. Their study is important for their important biodiversity, and as a mosaic of animals with different origins.

Our present study is a parallel comparison between two interstitial habitats for groundwater fauna, (1) the water in the alluvia or surface waters, and (2) the water of the caves' unsaturated zone. Ecological studies were undertaken during a period of 14 months in two different areas of the Apuseni Mountains of Romania (Western Carpathians). Sampling on a monthly basis (alluvia) or continuously (dripping water in caves) together with measurements and analysis of the physico-chemical parameters has revealed the unknown biodiversity of hypogean animals in such habitats in relation to related epigean communities and water quality. Differences and common features of these two interstitial habitats are discussed.

The purpose of such study is to emphasize the high biodiversity of interstitial habitats, their mosaic composition of fauna of different origin, their importance in the economy of the subterranean environment and the need for complex biological studies for the conservation and protection of underground fauna.

ENERGY FLOW IN THE CAVES WITH EMPHASIS IN ITS ARTROPOFAUNA, WITH SPECIAL REFERENCE TO (SANTANDER) COLOMBIAN CAVES

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Abstract

To establish how the energy flows inside the caves, we have explored 79 Colombian caves taking into account its fauna composition, its location, the landscape around them, the ecological relation between the species and the system and its functional group. To solve it, there is a theoretical proposal about the energy flow in the neotropical underground ecosystems. Considering that there is a highest richness of species in the ecosystem, there will be the highest number of connections in the different tropical levels. This is a changeable characteristic depending on the system, its size, its fauna diversity, the aquatic component interaction and the functional groups that it has. The caverns as semi-closed systems have Trogloxenous organisms such as the bats and other bigger vertebrates that include energy in guano form. Therefore, the Trogophiles that live inside the guano are the most important energy transformers. The guano, is the main source of exogenous energy that feeds the neotropical caves and its organisms. To do it, it needs to develop assimilation process and take advantage of it, thank to some arthropod the energy could be re-included in the guano. When the organisms that live there died, or when first and second degree predator energy could be come out of the trophic net of the guano. In any case, the energy could be lost if the cavern suffers a washing seasonal, which cause could be the floods.

In Santander, Colombia at the rural zone of the town Chipatá, there has been found two caves (Cueva del Naranjo y cueva del Cenicero) with particular ecological characteristics that gives indications of special trophic conditions. In both of them, some guano tokens have been analyzed zones with different light intensities, evaluating by a bromatological study of the chemical elements in there. The "Cueva del Cenicero" has a lack of process related to the organic matter deterioration; it is known that it is not a dry cavern but here was a big quantity of dead bats mummified (*Phyllostomus discolor*), these results show a variation in some levels of the decomposition cycle. Besides, "la Cueva del Naranjo" is a system because its morphology let the oblique entrance of the sun light during the whole cavity, making a possible differentiation in the ways of starting of the energetic flow. And also, with the knowledge of the fauna composition indoor it is possible to propose some energy flow diagrams for those systems that explain the peculiarities that contribute to both caverns to have a particular trophic behavior, far away from a conventional flow system.

FLUJO DE ENERGÍA EN CAVERNAS CON ÉNFASIS EN SU ARTROPOFAUNA, CON REFERENCIA ESPECIAL UN CUEVAS DE SANTANDER - COLOMBIA

Resumen

a al interior de la cueva, se propone posibles esquemas dCon el fin de establecer cómo fluye la energía dentro de las cuevas; se exploraron 79 cuevas colombianas, teniendo en cuenta la composición de fauna, la ubicación de esta en la caverna, el paisaje que rodea la cueva, el grado de fidelidad de las especies al sistema (relación ecológica) y su grupo funcional. A partir de esto se plantea una propuesta teórica del flujo de energía de los ecosistemas subterráneos neotropicales, considerando que mientras mayor sea la riqueza de especies en un sistema, mayor va a ser el número de conexiones entre los diferentes niveles tróficos. Siendo esto variable dependiendo del sistema, el tamaño del mismo, la abundancia y diversidad de su fauna, la interacción de un componente acuático y los grupos funcionales que presente. Las cuevas como sistemas semicerrados, poseen organismos trogloxenos tales como murciélagos y otros grandes vertebrados que incorporan energía en forma de guano, en tanto que los troglófilos, que viven dentro del guano son los principales transformadores de energía. El guano, es la principal fuente de energía exógena que "nutre" la mayoría de cuevas neotropicales y sus organismos, este sufre diferentes procesos asimilación y aprovechamiento, sensacional es por parte de una diversa cantidad de artrópodos, esta energía puede ser reincorporada al guano, al morir los organismos que habitan en él, o en caso que los predadores de primer y segundo orden sea troglófilos, puede salir de la red trófica del guano. En cualquier caso esta energía se puede perder si la caverna sufre proceso de lavado estacional, a causa de inundaciones.

En Colombia, para el departamento de Santander en la zona rural del municipio de Chipatá, se encontraron dos cuevas (Cueva del Naranjo y cueva del Cenicero), con patrones ecológicos particulares, que dan indicios de condiciones tróficas especiales. En ellas se analizaron muestras de guano en zonas con diferentes intensidades de luz, evaluando mediante un estudio bromatológico los elementos químicos presentes. Se encontró que la Cueva del Cenicero, posee una carencia de procesos relacionados con la degradación de materia orgánica, Si bien no es una cueva seca, se hallaron en ella una gran cantidad de cuerpos de murciélagos momificados (*Phyllostomus discolor*), que evidencia una variación en algunas etapas del ciclo de descomposición. Por otra parte la cueva del Naranjo es un sistema que debido a su morfología permite la entrada oblicua de luz solar, a lo largo de la cavidad, generando una posible diferenciación en las vías por las que inicia el flujo energético en esta cavidad. Tomando en cuenta la composición faunístice flujo energético puntuales para estos dos sistemas, que expliquen las peculiaridades que llevan a estas cuevas a tener un comportamiento trófico particular, lejos de un sistema de flujo convencional.

COLOMBIAN BATS FROM THE CAVES

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Abstract

Since 1994 to our days, we have had some visits to Antioquia, Boyacá and Santander (Colombian departments), nearly 80 caves in which there is a report of 28 different bats species of the 178 types that live in Colombia. More than a half of them are Insectivores, followed by the fungivores, nectarivores-pollenivores, and hematophagous. Some of these species are *Lonchorhina marinkelli*, Colombian an endemic species and typical of these systems. The cave with the most species richness with 7 species, is the "Cueva Caja de Agua" located in the Huila department.

MURCIÉLAGOS COLOMBIANOS HABITANTES DE CAVERNAS

Resumen

Desde 1994 hasta la fecha se han visitado en los departamentos de Antioquia, Boyacá y Santander (Departamentos de Colombia) cerca de 80 cavernas, en las cuales se reportan 28 especies de murciélagos de las 178 que hay en Colombia. La gran mayoría de estas son insectívoras, seguidas por las frugívoras, nectarívoras – polinívoras y sanguinívoras. Algunas de estas especies como *Lonchorhina marinkelli,* especie endémica de Colombia y propias de estos sistemas. La caverna con mayor riqueza de especies es la Cueva Caja de Agua en el departamento del Huila con siete especies.

BIOSPELEOLOGICAL PROVINCES IN COLOMBIA

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Abstract

In 1998, the first map showing Colombian cavern ecosystems represented 84 reported caves and grottoes. At present, there are about 130 caves located in the following biospeleological provinces: (1) Cordillera Boyacense-Santander (Boyaca, Cundinamarca, Norte de Santander, Santander), (2) southeastern Antioquia, (3) Central Andes Mountains (Cauca, Huila, Quindio, Tolima, Valle del Cauca), (4) border (or "piedmont") of the Eastern Andes (Caqueta, Guaviare, Meta, Putumayo), (5) Guianese Shield along the mountains of La Macarena, The Lindoso, Araracuara, and the complex of mountains of Vaupés; (6) mountains of the southern Colombian Andes (Nariño and west border of Putumayo montains), (7) and the mountains of Chocó (8) Serranías Cordoba; (9) Sierra Nevada de Santa Marta (10) Serrania de Perija, (11) La Guajira mountains and (12) North of San Andres Islands, for a total of twelve biospeleological provinces, which have established partnerships with regard to their origin, biota and faunal exchange.

PROVINCIAS BIOESPELEOLÓGICAS EN COLOMBIA

Resumen

En 1998 se ubicaron por primera vez en un mapa de ecosistemas en Colombia las cavernas, cuevas y grutas, las cuales fueron cerca de 84 reportes. En la actualidad se registran alrededor de 130, localizados en las siguientes provincias bioespeleológicas: (1) Cordillera Boyacense–Santandereana (departamentos de Boyacá, Cundinamarca, Norte de Santander, Santander); (2) Suroriente Antioqueño; (3) Montañas de los Andes Centrales (departamentos del Cauca, Huila, Quindío, Tolima, Valle del Cauca); (4) Piedemonte de la Cordillera Oriental (departamentos del Caquetá, Guaviare, Meta, Putumayo); (5) Escudo Guyanés junto con las serranías de La Macarena, La Lindosa, Araracuara y el complejo de serranías del departamento del Vaupés; (6) Montañas del Sur de los Andes colombianos (departamentos de Nariño y pie de monte occidental del Putumayo); (7) Serranías y Cerros del Chocó Biogeográfico; (8) Serranías de Córdoba; (9) Sierra Nevada de Santa Marta; (10) Serranía de Perijá; (11) Cerros y Serranías de La Guajira y; (12) Región de San Andrés Islas, para un total de doce provincias bioespeleológicas, las cuales se han establecido por asociaciones en cuanto a su origen, biota e intercambio faunístico.

METHODS FOR COUNTING CAVE CRICKETS

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Abstract

Cave crickets in the genus *Ceuthophilus* are a primary source of energy for cave ecosystems that support endangered species in central Texas. Many cave preserve managers monitor cricket populations as an indicator of cave community health using various methods. Crickets are well suited as indicator species because they are more numerous and easy to detect than troglobites. They are also key to introducing nutrients into cave ecosystems by foraging on the surface at night and roosting in caves during the day. Researchers have found that in central Texas the number of individuals of *Ceuthophilus* spp. crickets counted in a cave correlate fairly well with the level of human impact at that cave, and the total numbers of individuals of other taxa in a cave strongly correlate with the total number of cave crickets counted in that cave.

Two methods, "in-cave counts" and "exit counts," are used to monitor cricket populations; however, little is known about the relative precision or accuracy of either. A study was initiated in 2005 to compare results produced by each method. In-cave counts and exit counts are performed for three days every other month at three caves on Camp Bullis Military Reservation in northern Bexar County, Texas. The in-cave counts are performed during the day and exit counts on those same evenings, allowing comparison of each method on the same day and examination of day-to-day variation.

During in-cave counts all crickets detected on the ceilings and walls are counted using timed visual searches. During exit counts crickets are counted as they emerge from cave entrances for approximately two hours following sunset. Crickets are distinguished by age class (nymph, sub-adult, adult) and species (*Cuethophilus secretus, C.* sp. B, and occasionally *C. cunicularis*).

Initial data analysis reveals that each method has strengths and weaknesses, which are important to understand when interpreting data that guide management decisions. It is also important to understand the capabilities of monitoring methods when setting monitoring goals and designing monitoring programs, for instance detecting a given degree of population decline within a certain time frame. Since monitoring cave species is difficult and funding for management is often limited, it is important that cricket monitoring programs be well designed with clear and achievable goals.

REVIEW AND ASSESSMENT OF KNOWN CAVERNICOLES AND RARE EPIGEAN BIOLOGY OF KARST AND CAVES, GREAT SMOKY MOUNTAINS NATIONAL PARK

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The Great Smoky Mountains National Park (GRSM) encompasses 2100 km^2 in the states of North Carolina and Tennessee, United States of America. The park receives over 9.5 million visitors a year, making it the most visited national park in the U.S. Karst areas in GRSM account for less than 1% of the total surface land area in the park, but most karst areas receive highly concentrated visitation.

GRSM is the most biologically diverse national park in the National Park System; only 12% of the suggested 100,000 species who live in the park have been identified. Research to date suggests that karst areas in GRSM exhibit significantly high biological diversity.

Six karst areas in GRSM contain 16 known caves with significant biological resources. Several endemic species have been identified in the caves and karst areas. In addition, park caves provide habitat for federally listed threatened and endangered species.

Under the guidance of the Federal Cave Resources Protection Act of 1988, the National Park Service is required to inventory and list significant caves on federal lands, and to provide management and dissemination of information about caves. The park does not currently have a cave management plan in place in order to effectively manage the delicate cave and karst ecosystems. Although significant advances have been made in recent years in the inventory and monitoring of the biology of the cave and karst areas in the Great Smoky Mountains National Park, resource managers still do not have a complete picture of the cavernicoles and rare epigean biology of the park. To date, there has been no compilation of the list of known cavernicoles and biota associated with the caves and karst of Great Smoky Mountains National Park.

This paper describes important cave and karst areas of concern in Great Smoky Mountains National Park, provides a review of relevant literature, both peer reviewed and National Park Service internal documentation related to cave and karst areas, and begins to identify and compile a list of the cavernicoles and rare epigean biology which have been thus far described in the literature of karst and caves in the Great Smoky Mountains National Park. This document should provide the basis for creation of a structured inventory and monitoring effort to further identify and describe species of concern for managers of the cave and karst resources of the Great Smoky Mountains National Park.

1. Introduction

Great Smoky Mountains National Park (GRSM) encompasses 2,108.76 square kilometers in the states of North Carolina and Tennesse. It receives over 9 million visitors a year, making it the most visited national park in the world. The author recognizes 16 solution caves in six main karst areas. Karst areas within the Great Smoky Mountains exist in the western portion of the Tennessee side of the park. Current management of cave resources is not based on an approved management plan for caves and karst; two draft management plans (GRSM 1979b, GRSM 1989) were developed, but their implementation has been limited due to their lack of accuracy and completion. In addition, GRSM currently recognizes and addresses management of 12 caves. Management decisions in regards to cave and karst resources currently follow general directives and the park's superintendent's compendium.

Caves and karst of the Great Smoky Mountains National Park have formed in windows of calcium carbonate in the Great Smoky Mountain thrust sheet. The older metamorphic rocks that make up the Great Smoky Mountains were thrust over much younger limestone and dolostone (dolomitic limestone) along the Great Smokies

Fault (KING, 1968; NEUMAN. 1947; SOUTHWORTH et al., 2000; WILSON, 1935). Erosion of the metamorphic rock exposed the underlying limestone and dolostone, forming the aforementioned windows, which in turn eroded into the flat, grassy valleys typical of the Valley and Ridge Provinces of the Appalachians. It is in the lower walls and floors of these valleys where karst topography and their caves have formed (BARR, 1968; GRSM, 1989).

Ecologically, karst areas of GRSM support diverse biota often completely different than areas of GRSM with non-carbonate basement rock. Although park managers are just beginning to work towards a comprehensive inventory, over 270 organisms, (including rare and endemic species), have been described in association with caves and karst. Caves in the park provide important habitat for several species of bats (including one federally listed species), and are home to at least one endemic species. In addition, species diversity of GRSM epigean (above ground) karst terrain is known to be higher than non-karst areas of comparable size. Characteristics such as these exemplify the importance of continued cave and karst research and management efforts.

2. Cave Biology (Biospeleology)

Although interest in the study of cave biota in the United States began in the mid- to late 1800s, the majority of current information has been compiled since the 1950s (BARR, 1968; ELLIOT, 2000). Cave biota exhibit unique morphology, traits associated with subterranean life such as eye and pigment loss, delicate form, and enhanced extra-optic sensory structures (CULVER et al., 1999; CULVER et al., 2000; PECK, 1998; New York University (NYU) Website, 2008). These adaptations are of great interest to scientists in the study of natural selection, gene flow, and genetic and morphologic changes in species (CULVER et al., 1999; CULVER et al., 2000; NYU Web site, 2008). In addition to morphological adaptations, obligate aquatic cave organisms have long life spans, and are therefore likely to accumulate toxins. Such organisms are highly sensitive to water contamination, and are of interest to scientists as indicators of groundwater quality (CULVER et al., 1999; CULVER et al., 2000; NYU Web site, 2008).

Cave inhabitants can be grouped into four major groups: troglobionts (and stygobionts), troglophiles (and stygophiles), trogloxenes (and stygoxenes) and accidental cave inhabitants. Troglobionts (terrestrial) and stygobionts (aquatic) are obligate cave dwellers, species that spend their entire life cycle inside caves, and have (over time) formed adaptations in order to survive life only in caves (REEVES, 2000). Species of animals including fish, salamanders, insects and spiders often have adaptations such as reduced eyes and/or no eyesight, loss of pigmentation, elongated antennae, and increased senses of smell and touch (CULVER et al., 1999; CULVER et al., 2000; PECK, 1998). There are over 1300 (425 stygobiont and 928 troglobiont) obligate cave species known (PECK, 1998), although it is thought that probably less than half of the obligate subterranean species in the United States have been described (ELLIOT, 2000). Obligate cave fauna have the highest reported level of endemism of any taxonomic or ecologic group of organisms in the United States (CULVER et al., 2003). Troglobionts (and stygobionts) are generally of greatest interest to cave biologists and managers, since they are restricted to cave habitats and are sensitive to management practices (REEVES, 2000).

Troglophiles and stygophiles are considered to breed and live in cave environments, but are not obligate cave dwellers. An example would be the Cave salamander (*Eurycea lucifuga*), which has been found to forage outside of caves. Trogloxenes (terrestrial) or stygoxenes (aquatic) are transient cave dwellers, needing to spend a portion of their life cycle in caves. For example the Indiana bat (*Myotis sodalis*) uses the constant environment of specific caves to hibernate through the winter. Accidental cave inhabitants cannot survive to reproduce in caves.

3. Cave Biology and Great Smoky Mountains National Park

The southeastern United States, including the Appalachian Mountains, exhibits significant diversity of obligate cave fauna (troglobionts and stygobionts). In addition, Tennessee, in which all of Great Smoky Mountains National Park's caves and karst areas lie, is the fourth most diverse state in regards to genus-level diversity of obligate cave fauna (PECK, 1998; CULVER et al., 1999). Great Smoky Mountains National Park is one of the most biologically diverse places in the world. Designated as a International Biosphere Reserve in 1988, the park is home to 10,000 known species, and scientists estimate there are 90,000 species yet to be identified and described (NPS Website, 2008). Although the park lies in one of the most diverse regions and states with regards to obligate cave fauna species richness, park managers are just beginning to work towards a comprehensive assessment of the distribution of obligate cave fauna and rare epigean biology of the cave and karst areas withn the park boundary.

As early as the 1930s, park managers expressed an interest in better understanding the cave and karst areas in the park. Early efforts to describe the park's caves were focused more on the geology and physical conditions inside the caves rather than the fauna (GRSM, 1936). In 1974, Great Smoky Mountains National Park began studying human impact and restricting access to park caves because of the presence of Indiana bats (*Myotis sodalis*), a federally protected species (RABINOWITZ AND NOTTINGHAM, 1979; GRSM, 1979b). Currently, the only continuous sampling of cave biota is conducted in conjunction with the United States Fish and Wildlife Service's Indiana bat hibernacula counts. It was not until the early 1980s when there was a concerted effort by Great Smoky Mountains resource managers to identify and describe species associated with caves and karst. Beginning in 1984, under the direction of Great Smoky Mountains National Park resource managers, Richard L. Wallace completed a series of biological survey reports of the Great Smoky Mountains National Park's caves. Although there existed data on bat fauna that occurred within the park's caves, Wallace noted that knowledge of other cave fauna was "incomplete or unknown." Wallace's biological surveys uncovered several new, rare, and endemic species (WALLACE, 1984, 1989, 1990). Based on these findings, park resource managers began monitoring populations of cavernicoles (e.g., *Stygobromus fecundus*) in at least one location, Gregorys Cave (JOHNSON, 1990). Management of Gregorys Cave was changed in order to provide protection for this endemic species. Without continued interest and direction through a cave management plan, over time, the monitoring efforts have fallen by the wayside with occasional spot checks by visiting scientists. Several independent researchers have surveyed a variety of cave and karst associated biota in the caves of Great Smoky Mountains National Park: amphibians (DODD AND GRIFFEY, 2001; DODD, 2003), salamanders (TAYLOR AND MAYS, 2006), spiders (NPS, 1992), annelids (REEVES AND REYNOLDS, 1999), and general invertebrate cavernicoles (REEVES, 2000). In addition, in 2007, Discover Life in America, a non-profit partner of the national park invited scientists with a specific interest in karst areas to participate in a "Karst Quest" to identify and describe both cave life and associated epigean biology related to the karst areas in the park.

Great Smoky Mountains National Park's Cave Management and Management of Threatened and Endangered Indiana Bats (GRSM, 1979a) states that "Given the unique character of the above-ground environment, there is good reason to believe that a thorough survey and analysis of the underground environment will uncover additional unique and rare biota and minerals". In addition, caves with significant vertical development, like those of the Smokies, are likely to exhibit higher species diversity than caves with extensive horizontal development (CULVER et al., 2003).

Although considerable advances have been made in identifying and monitoring the biota of cave and karst areas within Great Smoky Mountains National Park, park managers still do not have a complete picture of the cavernicoles and rare epigean biology associated with the cave and karst areas in the park. To date, biological data have not been collected, identified, or published on five of the sixteen caves within the park.

4. Known Cave and Karst Biota of Great Smoky Mountains National Park

As previously discussed, troglobionts (and stygobionts) are generally of the greatest interest to cave biologists and resource managers. Through the aforementioned inventories of cavernicoles and associated biota of the karst areas in the Great Smoky Mountains National Park, a total of ten troglobiotic organisms have been described in the caves of the park (Table 1). Of these ten organisms, five have been identified to species, and five to genus. One of the ten organisms (*Stygobromus fecundus*) is endemic to one cave (Gregorys Cave). Other organisms include amphipods, isopods, diplurans, millipedes, flatworms, and arachnids.

Approximately 270 organisms have been otherwise described in association with the caves and karst areas in Great Smoky Mountains National Park. Based on the compilation of available research to date, of these 270, over 200 organisms have been identified to generic level, and 50 to family. Over fifty of these organisms have been identified as troglophiles, and 40 as trogloxenes. Countless other more commonly occurring organisms use karst habitats non-specifically (DLIA, 2007).

Great Smoky Mountains National Park is one of the most biologically diverse ecosystems in the world. Scientists are beginning to comprehend the number of species that call the Smokies home. It is likely that many of the epigean species that inhabit the karst areas in the park are widespread in non-karst areas as well, although researchers have recently begun to inventory the species associated with the habitat surrounding the cave and karst areas (DLIA, 2007). Many species that thrive in karst habitats in the park (Table 2) are rare elsewhere within the park boundary (although they are not considered rare outside of the park). But it is interesting to note, for example, that one species of Asian liverwort's only known North American population is restricted to one of the karst areas in the park (HENTSCHEL et al., 2008). A wide variety of terrestrial snails inhabit the karst areas in the park, and based on the high level of endemism in karst

Species	Common name	Record location (cave)	Citation
Stygobromus fecundus	amphipod	GRC	Wallace 1984, 1989; Mays 2002
Stygobromus sp. (fecundus?)	amphipod	GRC	NPS 1991; NPS 1992; NPS 1993; NPS 1994; NPS 1995; NPS 1996; DLIA 2007
Stygobromus sparsus	amphipod	GRC, SGC, SPC, RMB, WOB	Wallace 1984, 1989; Reeves 2000; Mays 2002
Litocampa sp.	dipluran	BLC, CC1, RMB, SGC, SPC, WOB	Reeves 2000; DLIA 2007
Sphalloplana sp.	flatworm	GRC, RMB	Wallace 1984, 1989; NPS 1991; NPS 1992; Reeves 2000; DLIA 2007
Caecidotea incurva	isopod	GRC, MYC, RMB, WOB	Wallace 1984, 1989; NPS 1993; Reeves 2000; Mays 2002; DLIA 2007
Caecidotea sp.	isopod	MYC	Reeves 2000
Scoterpes sp.	millipede	BLC, CC1, GRC, RMB, RBC, SGC, SPC, WOB	Wallace 1984, 1989; Reeves 2000; Mays 2002; DLIA 2007
Appoleptoneta sp.	spider	RMB	Reeves 2000
Phanetta subterranea	spider	BLC, CC1, GRC, RMB, SGC	Reeves 2000; Mays 2002
Nesticus barrowsi	spider	CC1, CC2, GRC, RBC, RMB, SGC, SPC, WOB	Wallace 1984, 1989; Reeves 2000; Mays 2002; DLIA 2007
Cave location codes: BLC= Bull Cave; CC1 and CC2= Calf Cave 1 and 2; GRC= Gregorys Cave; MYC= Myhr Cave; RMB= Rich Mountain Blowhole; RBC= Rainbow Falls Cave; SGC= Scott Gap Cave; SPC= Saltpeter Cave; WOB= White Oak Blowhole			

Table 1: Identified and Described Troglobionts and Stygobionts of Great Smoky Mountains National Park.

areas and the Great Smoky Mountains National Park, it is likely once these species have been identified and described, that there will be several endemic species (CULVER et al., 2003). The karst areas in the park exhibit significant diversity of epigean species, and further research may identify additional rare and endemic epigean species.

Although several of the park's known caves have been extensively inventoried, and the cavernicoles well described, it is important to point out that not all of the park's caves'

Species	Common name	Species	Common name
Asplenium resiliens	blackstem spleenwort	*Frasera/Swertia caroliniensis*	American columbo
Asplenium ruta-muraria	wall-rue	*Hybanthus concolor*	Eastern greenviolet
Carex eburnean	bristle-leaf sedge	Hydrophyllum macrophyllum	largeleaf waterlieaf
Carex jamesii	James' sedge	*Mertensia virginica*	Virginia bluebells
Celastrus scandens	American bittersweet	*Pedinophyllum interruptum*	liverwort*
Corallorhiza wisteriana	early coral root	*Pellaea atropurpurea*	purple cliffbreak
Crataegus calpodendrin	pear-thorn	Polymnia canadensis	whiteflower leafcup
Cystopteris bulbifera	bladder fern	*Porella gracillima*	liverwort*
Decumaria barbara	woodvamp	*Quercus muhlenbergii*	Chinkapin oak
Delphinium tricorne	dwarf larkspur	*Smilax hugerii*	Huger's carrionflower
Dentaria multifida	Muhl toothwort	Solidago caesia	bluestem goldenrod
Disporum lanuginosum	yellow fairy bells	*Spigelia marilandica*	Indian pink
Dodecatheon maedia	American cowslip/shooting star	*Staphylea trifoliate*	American bladdernut
Eryngium yuccifolium	button eryngo	*Viburnum rufidulum*	rusty blackhaw
		Vitus cinerea	graybark grape

Table 2: Vascular and non-vascular plant species associated with karst areas rare to Great Smoky Mountains National Park.*

biology has been well defined. Much of the research and longer-term monitoring efforts have focused on several specific caves (e.g., Gregorys Cave, *S. fecundus* and White Oak Blowhole, *M. sodalis*) and has resulted in a more comprehensive list of species for these caves. Several known caves in the park have not been extensively surveyed, nor has the cave biota been well described. It is also interesting to note that, to date, there has been little to no research concerning the microfauna in the park's caves. In developing a comprehensive cave and karst management strategy, it is important to consider the management of both cave biota and the epigean biology associated with the karst areas.

5. Conclusions

The relatively recent progress made by the NPS and independent researchers in inventorying the cavernicoles and epigean biology of the caves and karst areas of Great Smoky Mountains National Park has highlighted need for implementing a structured inventory and monitoring program and an approved Cave and Karst Management Plan in order to manage more effectively and efficiently the cave and karst resources in the park. There is no long-term inventory and monitoring program in place for caves and karst areas, although these areas have demonstrated great diversity of species, including rare and endemic species, both troglobiotic and epigean in nature. Because several caves in the park have not been extensively inventoried, it is possible that additional species associated with caves and karst in Great Smoky Mountains National Park have yet to be discovered.

In developing and implementing a Cave Management Plan, it would be beneficial to park resource managers to incorporate a structured inventory and monitoring program to identify and describe not only the biota, but also the environmental quality and physical conditions of the caves and karst areas in the park. There is no "baseline" data for the caves in the park in most cases; establishing a record of current conditions, through a variety of indices (e.g., water quality sampling, photo documentation of current resource conditions, establishing use patterns and carrying capacity of sensitive cave and karst areas, more complete biological inventories in some cases) would provide a basis for future management decisions with regards to caves and karst in the Smokies. Developing a more complete understanding of current conditions, in combination with a long-term monitoring effort and implementation of a Cave Management Plan will allow Great Smoky Mountains National Park to protect the unique cave and karst resources in a consistent and effective manner.

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FROM CRYOPHILY TO TROGLOMORPHY: MORPHOLOGICAL AND MOLECULAR EVIDENCE FOR THE EVOLUTION TOWARDS TROGLOMORPHY IN THREE DIFFERENT LINEAGES OF THE GENUS *CICURINA* (ARANEAE: DICTYNIDAE)

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Abstract

The spider genus *Cicurina* is composed of 120 species found in North America, South East Asia and one species in Europe. The genus includes an impressive radiation of 58 troglobitic species occurring mainly in Central Texas (USA). Following the early classification of the genus proposed by Chamberlin & Ivie (1940), these troglobitic species are all placed in the subgenus *Cicurina (Cicurella).* Recent investigations of phylogenetic relationships within the genus support the monophyly of *Cicurina (Cicurella)*, and the validity of the subgenera *Cicurina (Cicurusta)* and *Cicurina (Cicurina)*. The discovery of a new troglobitic *Cicurina* from Georgia (USA), and the inclusion of an obscure Mexican species in this broader phylogenetic context, showed that evolution for cave life happened at least three times within the genus: the Texas radiation with 58 species in *Cicurina (Cicurella),* the new species from Georgia in *Cicurina (Cicurina),* and the Mexican species in *Cicurina (Cicurusta),* a scenario supported with both morphology and molecules. Affinity for cold conditions (cryophily) is proposed as the driving force towards evolution of troglomorphy in *Cicurina*, favoring the views of Barr (1967) over Howarth (1986). Examples of cryophilic affinities are given for *Cicurina*. The success of the Texas radiation *Cicurina (Cicurella)* with 58 species when compared to the other lineages where only one troglobitic species is known, may be partly due to the particular nature of the caves in Central Texas where the lineage evolved. Actual data suggests that karst of this area forms a complex network, with actual and past connections. We hypothesize that *Cicurina (Cicurella)* evolved from one karst island to another through faulting that developed with geologic age, resulting in extreme narrow endemism of numerous species found in well defined geological clusters of caves, while such connections do not exist where troglobitic *Cicurina (Cicurusta)* and *Cicurina (Cicurina)* are known.

CAVE MYOTIS (*MYOTIS VELIFER INCAUTUS*) ROOST MONITORING AND PROTECTION ON FORT HOOD ARMY INSTALLATION, TEXAS, USA.

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Suitable bat caves are rare on karst landscapes because the microclimate must meet temperature and humidity requirements for optimal metabolic regulation by roosting bats. Maternity colonies often select caves that allow nursing females to conserve stored energy and neonatal bats to develop and mature. These caves often have microroosts (recessed ceilings, domes, solutioned fractures) which trap and retain heat. Because maternity caves are rare on karst landscapes and are crucial for species persistence, they must be studied, monitored, and protected from anthropogenic roost disturbance and microclimate alteration.

Fort Hood is an 88,000 ha U.S. Army Installation located in central Texas. Over 250 caves and 620 sinks and rockshelters occur on the installation; many features contain karst-dependent biota, including 17 endemic, invertebrate species. Five caves are known roosts for cave myotis (*Myotis velifer incautus*), a Federal species of concern; one cave system is unstudied, two caves are abandoned, one cave is an alternate roost, and one cave is a warm-season maternity roost.

The primary and secondary entrances to the maternity roost were protected with marginally usable bat gates. To maximize emergence flow and bat safety, the inadequate gates were replaced with cupola-style bat gates. At the primary and secondary entrances (respectively), gate volume increased 1,200% and 920%, gate surface area increased 880% and 1,050%, and gate angle iron spacing increased to the recommended 14.6 cm. Increased gate volume, surface area, and angle iron spacing provide a safer and more efficient emergence, while ensuring roost protection from anthropogenic disturbance.

From 2005 to 2008, an estimated 10,500 bats (2006) and 23,550 bats (2008) [mean = 17,200; SD = 5,300] occupied the maternity cave during the warm-seasons. Yearly population trends exhibited typical maternity cave occupation dynamics, such as gradual warm-season population increases followed by population doublings after young bats became volant. From 2004 to 2008, cave microclimate parameters (temperature and absolute humidity) followed predictable, cyclical patterns that ranged between 10.6° C, 1.2 g/m^3 (winter) and 29° C, 29 g/m^3 (summer). Cave microclimate provided efficient maternity conditions, but inefficient hibernaculum conditions. Cave microclimate parameters fluctuated synchronously with surface parameters, suggesting surface air flow influence. However, cave conditions were dampened with respect to surface extremes and rapid changes. Despite their availability and suitability, the two abandoned roosts remained unoccupied during the warm-seasons.

It is critical to study caves exhibiting bat roost signs to determine if the roost is a maternity site. Research needs include: bat roost delineation on cave maps; population and microclimate monitoring at maternity caves; monitoring and microclimate studies at abandoned roosts; careful consideration of cave gate styles, bat emergence patterns, and cave morphology before maternity roost protection; and regular surface vegetation maintenance at gated cave entrances and abandoned roosts.

1. Introduction

Bats are the only group of vertebrates that have successfully exploited caves for permanent shelter (KUNZ 1982). Cave use by bats is determined by roost temperature range and stability, which ultimately influence bat body temperature and metabolism (HOCK 1951). In warm caves, less energy is expended maintaining an optimal body temperature (Burnett and August 1981). Metabolic conservation is especially important for pregnant and lactating bats because energy expenditure costs and burdens are greatest during neo-natal growth and care (KURTA et al. 1987, SPEAKMAN and THOMAS 2003). An important factor influencing cave microclimate parameters (temperature and humidity) is the interaction between cave morphology, and air flow exchange and entrapment (TUTTLE and STEVENSON 1978, PALMER 2007). Air flow exchange between the cave and the surface coupled with cave morphology and micro-roosts (*i.e.* domes, recessed ceilings, solutioned fractures) offer a range of temperature gradients for roosting bats (TUTTLE 2000). Spatial variation in roost temperature and humidity can be important for bats (HENSHAW 1966, RAESLY and GATES 1987, RICHTER et al. 1993, BRUNET and MEDELLÍN 2001). Prevention of air flow into or out of caves can change the temperature, thereby making a roost unsuitable to bats (RICHTER et al. 1993, CURRIE 2001). Specific roost microclimate requirements mean that suitable bat caves are severely limited on karst landscapes (TUTTLE and STEVENSON 1978, KUNZ 1982), which results in patchy distribution (HUMPHREY 1975), often restricting large bat populations to a few caves. For example, endangered gray bats (*Myotis grisescens*), an obligate cave-dwelling bat, aggregate in less than 5% of available caves (TUTTLE 1979).

Anthropogenic roost disturbance and alteration are the greatest threats and causes for decline for most cave-dwelling bats (MOHR 1976, McCRACKEN 1989). Human disturbance at cave roosts were related to an 89% decrease in gray bat populations in Kentucky (RABINOWITZ and TUTTLE 1980). LACKI (2000) suggests that human intrusion likely caused Rafineque's big-eared bats (*Corynorhinus rafinesquii*) to abandon their maternity roost. In Arizona, a maternity colony of cave myotis (*Myotis velifer*) [hereafter velifer] abandoned a roost where increased human recreational use occurred (O'SHEA and VAUGHAN 1999). Large populations concentrated in a handful of caves, and bats' low reproductive potential (BARCLAY and HARDER 2003), predispose them to rapid population decline should disturbance or destruction befall key roosts.

Bat caves can be protected from anthropogenic disturbance with gates, which allow bat emergence yet prevent human entry. However, improperly gated caves can cause bat roost abandonment and population decline (TUTTLE 1977, CURRIE 2000, 2001; PETIT et al. 2006), and likely alter emergence flight behavior, increase the potential for collisions, and increase energy consumption associated with flight (SPANJER and FENTON 2005). Even with bat-friendly gate designs, some species may reject full gates (*i.e.* gate occupies entire passage/entrance), and improper gate placement can cause roost abandonment (Currie 2000). Alternative gate designs are box-like cupolas constructed over an entrance (TUTTLE and TAYLOR 1998, KRETZMANN 2002), which allow bats to stage in the gate volume before emerging. SPANJER and FENON (2005) recommend the construction of bat-friendly gates at entrances rather than within passages and on flat ground rather than an incline. Therefore, gate type, species acceptance, cave morphology, and surface topography should receive careful consideration before a cave is gated.

Fort Hood is an 88,000 ha U.S. Army Installation located in central Texas. Over 250 caves and 620 sinks and rockshelters occur on the installation; many features contain karst-dependent biota, including 17 endemic, invertebrate species. Five caves are known roosts for velifers, a Federal species of concern; one cave system is unstudied, two caves are abandoned, one cave is an alternate roost, and one cave is a warm-season maternity roost. Herein, I present results from 4 years of protection, management, and monitoring at the maternity roost and the two abandoned roosts.

2. Study Site and Methods

Shell Mountain Bat Cave (SMBC) is a 117 m long, 11 m deep velifer maternity roost with two entrances. Both entrances are used by bats, and both are gated with box-style cupola gates. The 5 paneled gates are designed so that bats may safely emerge through horizontal spaces on 4 gate panels. The fifth panel (gate top) is covered with expanded metal grid that is impassable by bats. There are 10 known roosts (darkened ceilings with guano accumulation underneath) in the cave, mostly in recessed ceilings and micro-roosts. Observations suggest that vegetation growth around the cupola gates may restrict/prevent emergence flow and increase the potential to ground bats, thus increasing the likelihood of roost abandonment. To reduce these possibilities, I routinely cut herbaceous and woody vegetation to ≤10 cm high around the cupola gates in a 2 m perimeter (main pit entrance) and a 1 m perimeter (crawlway entrance). Tippit Cave is a 91 m long, 17 m deep abandoned velifer roost with a single, small diameter sinkhole entrance. There are 6 known roosts in the cave, mostly in recessed ceilings and micro-roosts. Egypt Cave is a 124 m long, 10 m deep abandoned velifer roost with two entrances. There are two known roosts in the cave, both in recessed ceilings and micro-roosts. Once a year, I cut woody vegetation to ground level in a 7.5 m perimeter around Tippit and Egypt cave entrances.

To count emerging bats at SMBC, I used 3 infra-red illuminators and a video camera with 0 lux capabilities (main pit cupola), and a thermal imager (crawlway cupola). Night vision equipment placed at a distance minimizes disturbance and does not alter bat emergence patterns during counts (THOMAS and LaVAL 1988, KUNZ et al. 1996). Once a month from March-October, I counted all bats emerging from the south gate face of the main cupola during a 1-minute period every 5 minutes for at least 65 minutes, which resulted in fourteen 5-minute count intervals. Then, I multiplied each 1-minute count by four (accounts for all four gate surfaces) to obtain bats-emerging-per-minute every 5 minutes. Concurrent with main cupola counts, I counted all bats emerging from the north gate face of the crawlway cupola during a 1-minute period every 10-minutes for at least 65 minutes, which resulted in eight 5-minute count intervals. For the 14 main cupola and 8 crawlway cupola intervals, I calculated parametric values and 95% confidence intervals based on the *t*-distribution equation. I used dataloggers (3 at SMBC, 1 at Tippit Cave, 1 at Egypt Cave) to record surface and cave microclimate parameters (temperature and absolute humidity) every 1.5 hours for 1 year periods.

3. Results and Discussion

SMBC entrances are gated to protect the velifer maternity colony. At the crawlway entrance, we believed there was negligible contribution to nightly emergence, so a flat, grid-style gate hinged to a receiver set in a concrete footer was constructed. Grid gates are unsuitable for emergence due to the lack of gate volume and the narrow spacing of the angle irons. This gate essentially prevented emergence and likely impacted surface-to-cave air flow exchange because the footer occupied 66% of the entrance. At the main pit entrance, an A-frame tent-style gate was constructed. This gate was marginally useable by bats because: angle iron spacing (*i.e.* horizontal gate space through which bats fly) was smaller than recommended, optimal spacing is 14.61 cm (TUTTLE and TAYLOR 1998); gate base dimensions were slightly larger than the main pit entrance dimensions, thereby limiting lateral flight space needed for cave-to-gate transition; and the tapering, A-frame design denied bats usage of the upper 1/3 and the two side faces of the gate (*i.e.* only 2/3s of two sides were useable (Table 1). Despite gate inadequacies, approximately 16,000 velifers roosted in SMBC for 9 years (Land 2001).

We replaced the inadequate gates with bat-friendly, cupola style gates that greatly increased gate volume, gate surface area, and angle iron spacing (Table 1). Increased volume allows more bats to stage inside the gate, increased gate surface area allows greater exit opportunities, and optimal angle iron spacing allows faster, safer exits. The crawlway cupola currently provides an alternate route for emerging bats that did not exist with the grid gate. Monitoring during the past 3 years suggests that 20–40% of the population exited from the crawlway (PEKINS 2008). This route likely contributes to gate overcrowding reduction at the main pit cupola and further expedites overall emergence flow. Cupola gate installation positively affected emergence behavior. The tent gate forced bats to cyclically fly between the cave and the gate (similar to popcorn popping), which increased the collision potential, severely restricted gate staging and emergence flow, and likely increased energy expenditure. The cupola gates allow bats to exit the cave entrance, then transition to circular staging flights in the gate space, and then rapidly exit from the gate. However, when compared to a cave with no gate where velifers can freely exit (see TWENTE 1955b, HAYWARD 1970, KUNZ 1974), SMBC cupola gates lengthen emergence time and slow emergence flow (Pekins 2008). Overall, SMBC gate replacements provide a safer and more efficient emergence, while ensuring adequate roost protection against anthropogenic disturbance.

From yearly population maxima during 2005-2008, an estimated 10,500 bats (2006) to 23,550 bats (2008) [mean = 17,200; SD = 5,300] occupied SMBC (Fig. 1). Others have reported velifer populations as large as 15,000-20,000 bats (TWENTE 1955a, 1955b, HAYWARD 1970, FITCH et al. 1981). Yearly population trend exhibited

		Crawlway Entrance			**Main Pit Entrance**	
Gate parameter	**Grid Style**	**Cupola Style**	**Change (%)**	**Tent Style**	**Cupola Style**	**Change (%)**
Volume (m^3)	0.38	3.88	921	0.94	12.5	1,230
Surface Area (m^2)	0.64	7.4	1,056	4.95	16.3	229
Useable Area (m^2)	0.64	7.4	1,056	1.65	16.3	887
Angle iron space (cm)	4.45	14.61	228	8.99	14.61	63

Table 1. Gate style changes and dimension improvements at two entrances of Shell Mountain Bat Cave, Fort Hood, Texas. Gates were changed to improve emergence flow and safety for cave myotis (Myotis velifer incautus). Main pit gate was changed in 2004, crawlway gate in 2006. Angle iron space is the horizontal space through which bats exit.

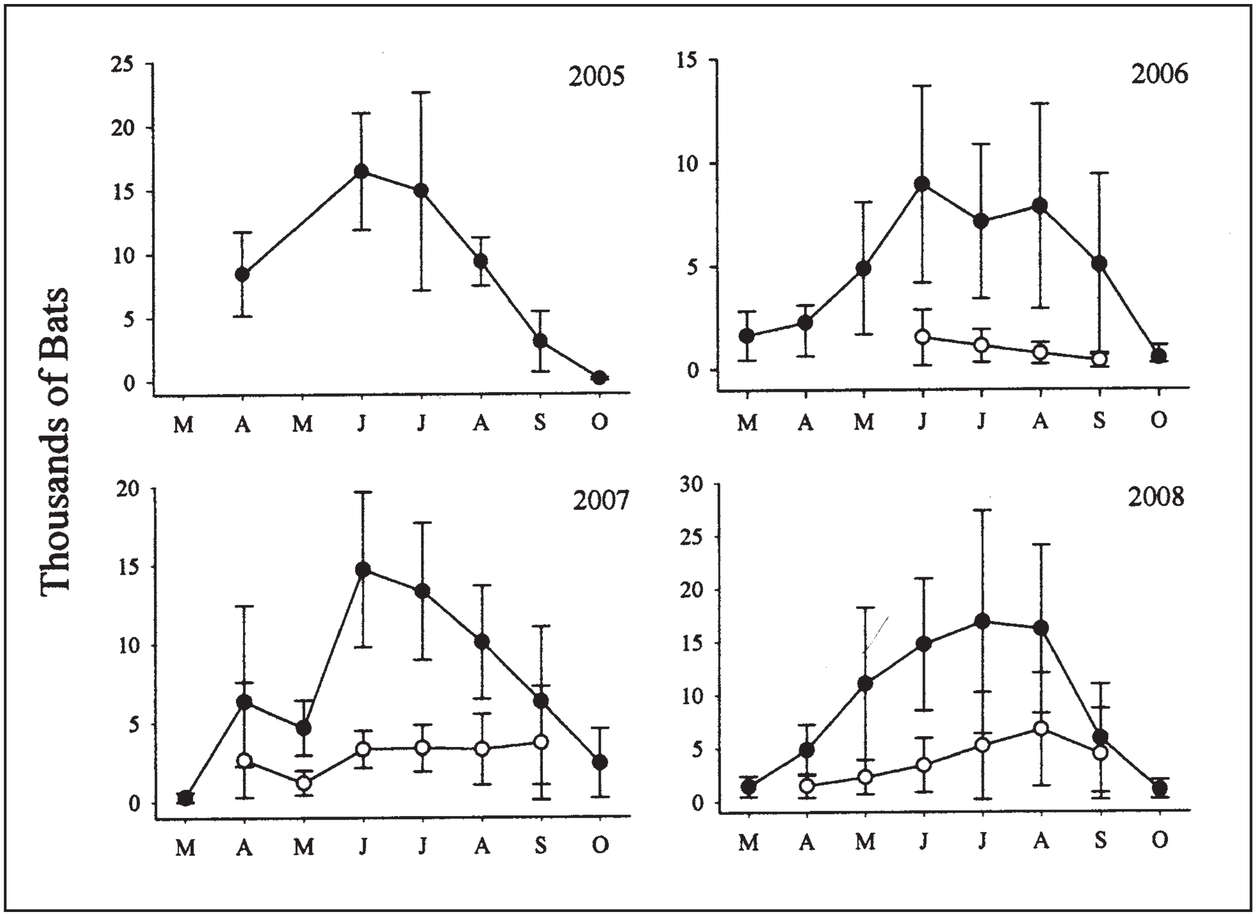

Figure 1. Monthly population estimates (mean ± 95% limits) and yearly occupation trends for cave myotis (Myotis velifer incautus) roosting in Shell Mountain Bat Cave, Fort Hood, Texas during 2005-2008. For each year, x-axis begins with March and ends with October. The cave was unoccupied by cave myotis from November to February. Closed circles = main pit cupola; open circles = crawlway cupola. Count was not conducted during May 2005. Crawlway counts began in 2006. Y-axis is variable amongst years.

typical maternal cave dynamics. The pattern followed a predictable trend of early-spring arrival of migratory bats, then late-spring occupation by parturient adults, then birth and flight of young mixed with post-lactating adults (summer peak population), then late-summer local dispersal/colony break-up, and finally autumn bat departure; the cave was unoccupied in winter. Others have observed the same generalized pattern at velifer maternal sites (DUNNIGAN and FITCH 1967, HAYWARD 1970, KUNZ 1974) and long-fingered bat (*Myotis capaccinii*) maternity sites (Papadatou et al. 2008). A caveat of my estimate is that it reflects relative abundance, which is an approximation of the true population at best. THOMAS and LaVAL (1988) suggest that emerging bats can be counted in 1- or 5-minute intervals, assuming emergence flow is constant. During all counts, SMBC emergence flow rapidly increased and peaked during the first 30 minutes, then gradually tapered during the remaining 35 minutes. Despite this pattern, flow was still constant enough to reliably estimate bats-emerging-per-minute every 5 minutes. Velifers often emerge in distinct group bursts (*i.e.* adult and juvenile) that may blur together during emergence (KUNZ 1974). This behavior may contribute to count inaccuracy and unreliability if count interval spacing is too far apart (miss the bursts) or if bursts overwhelm an observer (THOMAS and LaVAL 1988). SMBC gates pool the bats into one area (cupola gate space) for short time periods, thereby eliminating the burst effect and further reducing the possibility of count inaccuracy.

From 2004-2008, SMBC microclimate parameters followed predictable, cyclical patterns that ranged 10.6° C, 1.2 g/m^3 (winter) and 29° C, 29 g/m^3 (summer), suggesting the roost was sufficiently warm and moist for neonatal bats and nursing adults, but too warm for velifer hibernation. Others have reported velifer maternal cave temperatures ranging from 15° C to 35° C (TWENTE 1955b, KUNZ 1973, HAYWARD 1970). During the warm seasons of

2004–2008, monthly temperatures at four non-bat caves and 1 alternate velifer roost ranged 12° C to 28° C, suggesting velifers may select SMBC for additional reasons (*e.g.* cave morphology or ceiling topography). In general, cave microclimate parameters fluctuated synchronously with surface parameters, suggesting surface air flow influence. However, cave conditions were dampened with respect to surface extremes and rapid changes, and were generally warmer than surface in the winter and cooler than surface in the summer. During the warm seasons of 2004–2008, Tippit Cave and Egypt Cave temperatures ranged 19° C to 20° C, and 14.5° C to 18° C, respectively. Despite their availability and suitability, these two roosts remained unoccupied by velifers.

4. Conclusions and Research Needs

It is critical to study caves exhibiting bat roost signs to determine: if the roost is occupied or abandoned, if the roost is a maternity site, what species occupy the site, and threats to the site. Monthly and seasonal population trends, emergence patterns, and microclimate trends should be documented at maternity sites during a minimum 5 year period so patterns can be established. Abandoned bat caves and alternate roost sites should be identified, studied, monitored, and if necessary, restored. Before a maternity site or hibernaculum is gated, careful consideration should be given to cave gate styles, bat emergence patterns, microclimate alteration, and cave morphology. I recommend regular surface vegetation maintenance at gated caves to ensure a safe emergence. To better assess where bats are roosting and to what extent, I recommend that bat roost area delineation be incorporated onto cave maps.

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NEW STUDIES OF *SPEOPLATYRHINUS POULSONI* (PISCES: AMBLYOPSIDAE)

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In my comparative studies of the fish family Amblyopsidae (1961, 1963), I predicted what a more cave-adapted Amblyopsid would look like based on changes with increasing time of isolation in caves (decreasing eye size and complexity and decreasing density and complexity of pigmented melanophores). With increasing time of isolation (*Typhlichthys subterraneus* to *Amblyopsis spelaea* to *Amblyopsis rosae*) each cave species has strong convergence in troglomorphy with slight changes in relative head size (+), free lateral line exposure and numbers (+), sense organ integrative parts of the brain (+), caudal and pectoral fin length (+) and weight per unit length (-). I suggested that these trends are neotenic.

In 1967 I received two black and white photos of an apparently pigmentless and eyeless cavefish with the cryptic note "Is this what you predicted?" Initially, the fish was identified as a 10-12mm *Typhlichthys* based on its peculiar spatulate head shape, large head, relatively thin body, and unbranched fin rays. In fact, it was the 58mm holotype of what its discoverer John Cooper and his colleague Bob Kuehne described as *Speoplatyrhinus poulsoni* (1974). Quantification of the fishes brain morphology, free neuromast densities, pigmented melanophores, and gill morphology as an index of metabolic rate indicated more extreme neoteny than in any other Amblyopsid. It is found in only one cave in northwestern Alabama and is protected by the Key Cave National Wildlife Refuge. It is listed as critically endangered.

On November 5, 2008, I got to see my namesake in nature and study specimens in an aquarium for several hours while Dante Fenolio took a series of fantastic color photos. The fish were returned after three hours. I studied three fish (42, 45, and 62mm SL) in a 25 liter aquarium with water temperature 15C and depth of 15cm. There were two ~ 10 x 10 x 6cm rocks. The fish showed no change in behavior when with 1, 2, or 3 individuals or with a high density of small active amphipods and sedentary isopods. They caught no prey even when the prey touched a snout and showed no change in behavior when near or contacting another fish. They swam with short partial pectoral-caudal strokes, instead of a leisurely stroke and glide. They often repeatedly bumped gently into the side of the aquarium or nosed under the edge of a rock. They were easy to pick up by hand and returned to normal swimming rates and ventilation frequency and depth within 1–3 minutes. They often stopped swimming and floated to the surface before swimming back down. They explored all parts of the water volume and were continuously active.

1. Introduction

A comprehensive review of published, unpublished, and new data on the North American freshwater fish family Amblyopsidae is given by NIEMILLER and POULSON (2009) as a chapter in a book on cave fishes dedicated to Poulson for his many, long, and continued contributions. Here I consider *Speoplatyrhinus poulsoni* in even more detail with particular attention to my recent observations of my namesake in Key Cave and in an aquarium just outside the cave.

My predictions for the next stage in Amblyopsid troglomorphy (POULSON 1961, 1963) were based on trends seen with increasing evolutionary time in caves for the then known troglobitic species. Estimates of evolutionary time in caves were based on EIGENMAN'S classic studies of eye histology and my own studies of melanophore pigment cells. My rationale, which has better support today (POULSON 1985 and NIEMILLER and POULSON 2009), was that mutations of simplification and loss are near neutral after the early stages of isolation in caves.

In the rest of this paper, I will describe what we now know about which features of *Speoplatyrhinus poulsoni* anatomy are shared with and different from other troglobitic Amblyopsids. Then I will tie the anatomy to my recent observations of fish in an aquarium. Next, I will consider alternative hypotheses to explain the progressive restriction of geographic range of troglobitic Amblyopsids ending in the relict distribution of my namesake. Finally I will consider what size-frequency distributions and scale marks for aging suggest about life history.

2. Convergent Troglomorphic Anatomy

Based on partial data, the eyes and pigment of *Speoplatyrhinus poulsoni* (Sp) are the most reduced of the troglobitic Amblyopsid species. Here I compare it to *Amblyopsis rosae* (Ar) which has the most reduction of eyes and pigment of the other Amblyopsids. Though we have no data on my namesake's eye histology, the optic lobe volume is more reduced. For a 45 m SL fish the mm3 volume for Sp is 0.38 < 0.96 for Ar. This suggests that the eye is smaller with more parts lost and indistinguishable. It also suggests that the optic tectum visual tracts have not been co-opted by tactile tracts via negative pleiotropy. The density of pigmented melanophores of Sp is 0.6 per .175mm2 on the side of the body compared to 0.7 for Ar. The average melanophore size of .04mm2 x 10-3 is about half that for Ar. And unlike Ar the pigmented melanophores are completely lost in individuals greater than 45mm SL so the negative allometry for pigment cell number must be even lower than the *b* of -2.4 for Ar.

The most important non-visual sensory system in Amblyopsids is the lateral line which is greatly hypertrophied in all the troglobitic species. The surficial ridges (aka stitches) of neuromasts are necessary and sufficient to explain avoidance of obstacles and capture of living prey. Each ridge has 7 – 34 neuromast cups each with a gelatinous cupula. The height above the skin of neuromast cup plus cuopula is 0.8 – 1.1mm for all species. The ridges are concentrated on the head and most adjacent ridges are oriented at right angles to each other. Among the troglobitic Amblyopsids, *Speoplatyrhinus poulsoni* has about 25 percent more total neuromasts partly because many of the ridges have more neuromasts than in other species but mainly because Sp projected head area is so large relative to projected body area, i.e., 1.73 compared to 0.67 – 0.73 for the three other troglobites (NIEMILLER and POULSON 2009: Figure 5). The brain areas for primary lateral line sensory input, the cristae cerebelli and eminentia granularii, and for integration of all sensory information, the forebrain, show relatively the same degree of hypertrophy in Sp as in the other troglobites.

Despite an elaborated lateral line system none of the three *Speoplatyrhinus* observed in an aquarium for about 2 hours caught any of the approximately 40 amphipods and 15 isopods introduced to their aquarium. Surprisingly they showed no increase in swimming speed or changes in search behavior. They did not even react when they encountered a moving amphipod or when a fast swimming amphipod touched their head. Perhaps they were not hungry. They certainly seemed to have full stomachs based on the rounded belly. My past lab studies of other Amblyopsid troglobites, that showed striking changes in behavior and successful capture of living prey in the laboratory, always involved fish that had not been fed for several days. And once sated the fish returned to the behavior seen before prey were introduced.

Surprisingly, the brain areas that are responsible for input and integration of equilibrium information in *Speoplatyrhinus poulsoni* are not as hypertrophied as in the other Amblyopsid troglobites (Figure 11 in NEIMILLER and POULSON 2009). The cerebellum is smaller than for any other troglobites and not much bigger than in the troglophile *Forbesichthys agassizi*.. The semicircular canals and otoliths are larger than in *Forbesichthys* but smaller than in *Typhlichthys* and *Amblyopsis*. I saw no differences in swimming behavior which might be correlates of these differences. My only hypothesis is that the narrow and small frontal area of Sp head, relative to the blunt and broad shape of the other species, may not require as large a cerebellum and semicircular canal system (see rationale for this in POULSON 1963).

Sp's thin and spathulate head shape can displace much water as it approaches an obstacle and this may explain why all three individuals observed repeatedly nosed into rocks or corners without any obvious avoidance behavior. Unlike all other species, Speoplatyrhinus swam using short partial caudal and pectoral fin strokes and so moved very slowly. Despite having as large or larger pectoral fin and caudal fin area than other species, they did not show leisurely coordinated caudal – pectoral strong stroke and glide swimming expected of approximately one body length moved per stroke.

I observed some body positions of swimming and exploring *Speoplatyrhinus* that are correlated with its spathulate snout. The fish oriented their bodies so that the bottom of the head was parallel to and with maximum contact with the substrate. As a result the body angled upwards at about 30 degrees.

Another unusual behavior seen in all three individuals was that they often stopped swimming and floated to the water surface. Once at the surface they often rested for a few seconds with their back slightly out of the water. Then they leisurely swam back to the bottom and continued exploring the aquarium.

As with all the Amblyopsids, *Speoplatyrhinus poulsoni* has a moderately developed external olfactory intake tube and olfactory rosette and internal brain olfactory lobe and similar development of the caudal papillae system, which may be unique to the family. Sp has fewer but much larger caudal papillae than Ts (Figure 12 in NIEMILLER and POULSON 2009). We have no clue as to the function of this sensory system.

3. Phylogeny Based on Anatomy

A major difficulty is to separate convergent cave-dependent characters of troglomorphy from cave independent autapomorphies that can be used to determine phylogeny. ARMBUSTER (personal communication) is developing a phylogeny of the Amblyopsidae based on skeletal and other anatomical characters.

The following are what I judge to be clear autapomorphies of *Speoplatyrhinus poulsoni*. 1. The absence of presumed tactile sense organs seen on the head in all other Amblyopsid troglobites (NIEMILLER and POULSON 2009: Figure 8). 2. The presence of short lines of thin rod like (~ 0.5mm) presumed sense organs on the head (thinner than cupulae Figure 1 this paper). 3. The difference in relative sizes of otoliths with the sagitta smaller and utriculus larger than in any other Amblyopsid (Figure 11 in NIEMILLER and POULSON 2009). 4. The very large caudal papillae (Figure 12 in NIEMILLER and POULSON 2009). 5. Possibly the extremely thin and spathulate snout (Fig. 1). Alternative hypotheses are that it is a spandrel with no adaptive function (sensu LEWONTIN and LEVINS) related to reduction of skeletal structures around the eye orbit or it is a spandrel related to extreme neoteny.

Figure 1: Photos of 42 mm SL Speoplatyrhinus poulsoni *by Danté Fenolio.*

Part of my basis for predicting trends in troglomorphy with increasing evolutionary time was the clear neotenic trend in the three Amblyopsid troglobites (POULSON 1961, 1965, 1985, NIEMILLER and POULSON 2009). Clearly Speoplatyrhinus poulsoni is the most neotenic of all Amblyopsids as recognized in the description of the species by COOPER and KUEHNE (1974). 1. The absence of bifurcate fin rays. 2. The very large head relative to body size. 3. Absence of a supraopercular papilla opening to the enclosed head lateral line system. 4. The possibly further reduction in calcification of the skeleton suggested by poor resolution radiographs and poor alizarine staining of cleared specimens. 5. The apparently translucent appearance of even large individuals.

When histological studies of the eyes are done we may find that the parts that are lost or simplified are different than in other species of Amblyopsids. For example eye muscles, scleral cartilages, and pigmented epithelium are missing in Typhlichthys but vestiges are present in both species of Amblyopsis even though their eyes are more simplified overall (Table 2 in NIEMILLER and POULSON 2009).

4. Biogeography

Speoplatyrhinus poulsoni shows an extreme relict distribution. It shows the extreme of decreasing geographic range and number of caves occupied among the four species of troglobitic Amblyopisds (Figure 3 in NIEMILLER and POULSON 2009). Even though number of sites and caves is a much better measure of ability of the fish to move underground, total counties with any record gives an index of geographic range. Records of fish exist from 72 counties in 4 states along the eastern US coastal plain for *Chologaster cornuta*, 32 counties in eastern Missouri, southern Illinois, Kentucky, and Tennessee for *Forbesichthys agassizi*, 54 counties in seven states for *Typhlichthys subterraneus (*central Missouri and northern Arkansas and central Kenttucky and Tennessee and northern Alabama), ten counties in southern Indiana and northern Kentucky for *Amblyopsis spelaea*, nine counties in southwestern Missouri and adjacent areas of Arkansas and Oklahoma for *Amblyopsis rosae*, and one county in northwestern Alabama for *Speoplatyrhinus poulsoni*.

One hypothesis to explain current distributions of Amblyopsid cave species is that it reflects the past distributions of their surface ancestors. The Ozark vs.

Interior Lowland Province distribution of the two *Amblyopsis* species is one example. In surface teleost fish there are several species groups of darters (*Etheostoma*) with this distribution. It is also known for salamanders, with both the *Eurycea lucifuga* complex and the *Eurycea longicauda* complex found both west and east of the Misiisippi. *Plethodon dorsalis* and *Plethodon angusticlavius* salamander distributions show the same dichotomy. But I know of no surface fish or salamanders that have geographic distributions matching those of either *Forbesichthys agassizi* or *Typhlichthys subterraneus*. And there are no freshwater fish, salamanders, crayfish, or shrimp in the range of the Amblyopsidae that show the extreme relict distribution of *Speoplatyrhinus poulsoni* (there are both salamanders and fish restricted to only one or a few surface springs along the Balcones Escarpment in Texas).

A second hypothesis of competitive displacement has been proposed (e.g. WOODS and INGER in NIEMILLER and POULSON 2009) to explain why *Typhlichthys* has such a wide and central geographic distribution compared to either *Amblyopsis* species and why *Speoplatyrhinus* has such a narrow and peripheral distribution compared to *Typhlichthys* (e.g. NIEMILLER personal communication). Competition can be of two types where indirect is less effective than direct. Indirect competition involves a differential efficiency of exploiting a food resource that is not defensible. Direct competition involves direct harm during agonistic interactions at a defensible resource. Despite some evidence for density dependent population in one population of *Amblyopsis spelaea*, I now argue that neither kind of competition is likely to contribute to the differences in geographic range just described.

Indirect competition is unlikely to result in competitive exclusion among troglobitic Amblyopsids because the species show only slight differences in lateral line hypertrophy, efficiency of finding different live foods, and metabolic rates (Tables 4, 6, 8, and 9 NIEMILLER and POULSON 2009). In addition, in the few cases where putative competitor species are syntopic there is no indication that either species is doing more poorly, as judged by gut fullness, or reproduction, judged from size-frequency distributions. The cases are of *Typhlichthys* and *Amblyopsis spelaea* in Mammoth Cave and *Typhlichthys* and *Speoplatyrhinus* in Key Cave. In Mammoth the two species separate along a stream gradient from upstream high food (*Typhlichthys*) to downstream low food (*Amblyopsis*). This is the wrong direction for purported exclusion of *Amblyopsis* by *Typhlichthys*. In Key Cave one large *Typhlichthys* has been seen for 15 years (growing from ~ 50mm to a measured 82mm SL) along with as many as 10 *Speoplatyrhinus* on any one trip. Individuals of both species appear healthy with no signs of emaciation. Again these data, especially the ~ 0.5mm per year growth of the large *Typhlichthys*, are in the wrong direction to support a prediction that *Typhlichthys* is the better indirect competitor.

Direct competition is unlikely to result in competitive exclusion among troglobitic Amblyopsids because the species have little or no agonistic intraspecific interactions and there is no defensible resource in their cave habitats. In dyadic interactions with resident vs. intruder in small aquaria Bechler found much lower frequency, diversity, and intensity of agonistic acts in troglobitic *Typhlichthys* and *Amblyopsis spelaea* compared to the troglophilic *Forbesichthys agassizii* (Table 7 in NIEMILLER and POULSON 2009). *Amblyopsis rosae* showed almost no agonistic behavior. And in a small volume aquarium three *Speoplatyrhinus* (42, 45, and 62mm SL) showed no evidence that they even recognized each other as a fish when they were introduced to the aquarium sequentially and frequently contacted each other. In a large artificial stream used by Bechler the agonistic behavior was almost absent even in the species that showed occasional strong interactions in a small aquarium. And nobody has ever seen agonist behavior in a cave. In caves I can conceive of no defensible food resource and even deep, quiet water hiding places during floods are abundant and not defensible.

The only mode of possible competitive exclusion that I can hypothesize is an indirect demographic swamping. Demographic swamping could occur if one species' lifespan was shorter and its reproductive rate was much higher than for a competitor even if that competitor was a more efficient feeder with a lower metabolic rate. At present the size-frequency distributions among the Amblyopsid troglobites are similar and so no species could have a reproductive advantage. Of course, in the past there could have been exclusion by demographic swamping if a species newly isolated in caves had a shorter life span and higher reproductive rate than a species that had been isolated at an earlier time. This seems unlikely since the climatic event most likely to have resulted in isolation would be interglacial drying when the organic matter washing into or seeping into caves would be decreasing.

5. Metabolic Economies and Behavior When Disturbed

My observations of *Speoplatyrhinus* in an aquarium show almost continuous activity despite indirect evidenc for a very low metabolic rate. Among the other troglobitic

Amblyopsids there is a trend for decreasing metabolic rates but increasing percent of the day active and greater distance swum per day (Table 9 NIEMILLER and POULSON 2009). The three *Speoplatyrhinus* that I observed for ~ 2 hours were continuously active and explored all parts of the aquarium. Given the good correlation of gill surface area with metabolic rate in the other species, I infer that *Speoplatyrhinus* has about 40 percent lower metabolic rate than *Amblyopsis rosae* which has the lowest measured metabolic rate of the other three troglobites (Figure 13 in NIEMILLER and POULSON 2009). The barely visible amplitude and ~1 per two second frequency of its opercular ventilation movements are consistent with a very low metabolic rate.

As with other troglobitic Amblyopsids, *Speoplatyrhinus* was easy to pick up by hand, scarcely struggled when held, and when returned to the aquarium showed no excited swimming and returned within three minutes to imperceptible ventilation. In contrast, the 82mm SL *Typhlichthys* studied at Key Cave wiggled continuously when picked up and showed clearly faster swimming when returned to the water.

6. Life History and Inferred Growth Rates and Longevities

All the indirect data suggest an intermediate lifespan and growth rate for *Speoplatyrhinus* compared to other Amblyopsid troglobites. The putative marks of decreased growth rates on the scales look the same as in all Amblyopsids with the following growth checks and standard lengths from the type series: 33mm = 3 checks, 42mm = 4 checks, 47mm = 5 checks, and 52 mm = 6 checks. These indicate an age of the 52mm fish as 18 – 24 years based on the relation of scale checks to actual growth rates determined from mark-recapture data in the other troglobites. In the troglophile *Forbesichthys* the scale checks match the mark recapture growth rates with the known interruption of growth seasonally and a 2 and rarely 3 year lifespan. To explain the discrepancy between ages estimated by scale growth checks and actual measured growth rates, Bechler has suggested to me that cavefish may not even grow some years and so not even lay down any circuli on scales. This fits with mark recapture data that show that as many as 20 – 30 percent of recaptured fish and more of larger individuals fish show << 1mm body length growth per year or even ~ 1mm negative growth (BROWN in NIEMILLER and POULSON 2009 for *Amblyopsis rosae* and PEARSON personal communication for *Amblyopsis spelaea* and *Typhlichthys*). It does not fit with the fact that I have never found stomachs of preserved cavefish empty; >= 95 percent of the frequency and 70 – 95 percent of the volume of prey are copepods. One thought is that the marks on scales represent occasional large meals rather than times with no or few prey eaten. This is an extension of my RARE lucky large prey captured hypothesis (NIEMILLER and POULSON 2009).

The size frequency distributions of the surface and spring-cave species of Amblyopsids show clear cohorts associated with 2-3 year classes but clear size cohorts are never seen for the cave species (Figure 4 POULSON 1961 from preserved collections). In *Amblyopsis spelaea*, the only species with verified branchial incubation, there are incubating females or first year young 8–15mm SL found only in about 10 percent of many trips over 40 years to the two caves with the largest populations in streams where all the habitat is accessible for census. In caves with the largest *Amblyopsis rosae* populations there are many hiding places among rocks for small fish but the fish 20-30mm are found all the time and fish 12 – 15mm are found on perhaps a quarter of trips. I have inferred from these data that *Amblyopsis rosae* has the most frequent reproduction of any Amblyopsid troglobite. This is associated with the lowest metabolic rate, fastest growth rates, lowest cost for reproduction, and shortest inferred longevity of any cave species (Table 5 in NIEMILLER and POULSON 2009). In contrast *Typhlichthys* has only one population, Shelta Cave in Alabama, in which we routinely found small 11-21mm SL fish. And, in contrast to the case for *Chologaster cornuta* and *Forbesichthys agassizi*, we never see preserved or live individuals with bellies obviously swollen with eggs even in *Amblyopsis spelaea* with known clutch sizes of 50 – 70 in 60 – 80 mm SL females. Putting all of this together I hypothesize that, except for *Amblyopsis spelaea*, clutch sizes of troglobitic Amblyopsids are flexible and small, perhaps as few as 10. Along with iteroparity and long life this would minimize the cost of reproduction and maximize spreading of the risk of reproductive failure.

The data on *Speoplatyrhinus poulsoni* from Key Cave are consistent with a very low level but regular level of reproduction. The type series has individuals of the following mm SL; 32, 33.5, 34, 38.5, 42, 47, 49, and 58.3. The most accurately estimated and measured sizes in nature are for October and November 2008 mm SL of 15, 30, 30, 39, 41, 42, 48, 52, and 62. The 62 mm fish is the largest known and only one fish was estimated to be smaller than 15 mm in the past (12mm). The cave is difficult to census with water depths approaching 10m where the habitat is accessible in only a few isolated passage segments that are difficult to access. And only a few of these areas are large enough to snorkel.

Based on observations in the field Key Cave has a low to moderate food supply for *Speoplatyrhinus* and the two species of cave crayfish. The water is usually crystal clear and there are scattered small rocks on the bottom that could be hiding places for the one cave amphipod and one cave isopod known from the cave. The area of seasonally deposited gray bat guano next to one pool never has obviously higher numbers of fish or crayfish than other areas and no visible isopods or amphipods. On any one trip the maximum number of fish seen has been 10 with about twice that many crayfish. Baited traps yield occasional crayfish but not amphipods or isopods. If we are ever allowed to examine the stomachs and intestines of the type series I expect to find only copepods.

7. Conclusions

Speoplatyrhinus poulsoni has been isolated in caves longer than any of the other three troglobitic species but has only slightly greater elaboration of the lateral line sensory system. It shows more extreme neoteny than any other species. It has several autapomorphic anatomical features which suggest that it is very distantly related to the other troglobites But, except for its lack of stroke and glide swimming, its other behavioral and physiological traits are similar to and convergent with the other species. These include diminished reaction to disturbance, low metabolic rate, moderately long longevity, low growth rate, and very low frequency of but regular occurrence of reproduction.

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FIELD METRICS FOR CAVE STREAM BIO-INTEGRITY

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I build on the concept of Indices of Biological Integrity (IBI) successfully used for fish and macro-invertebrates in surface streams. Unlike grab samples for assay of microbes and pesticides and water chemistry, biological communities have a "memory" so one does not have to sample at the time of discharge ("smoking gun") or at the front end of a flood hydrograph to hypothesize why a stream's IBI is compromised. Also, biological censuses are much less expensive.

To develop an IBI for cave streams one needs to use all of the fauna. I suggest: 1. Counting and measuring and assessing health of all individuals of fish, salamanders, and crayfish; 2. Random timed and defined areal samples for isopods, amphipods, flatworms and stream-bank terrestrial fauna at the generic level; 3. Baited traps with rock and leaf litter refuges to assess copepods, isopods, amphipods, and flatworms that can otherwise only be reliably censused by getting frequency and abundance data picking up rocks; 4. Assess microbial biofilm by slipperiness on rocks; 5. Estimate sizes and abundances of particulate organic matter; and estimate the texture of stream bottom / bank inorganic substrate (clay, silt, sand, gravel, and rocks).

One overall metric of integrity useful across streams and regions is a graph of log abundance vs. species rank (most to least abundant). High dominance of the highest ranked species and great rarity of the lowest rank species suggests that the stream is compromised.

I hypothesize different community signatures for siltation, organic enrichment, high level acute toxicity, and low level chronic toxicity. Silt homogenizes microhabitat, organic enrichment favors trogloxenes and troglophiles, acute toxicity differentially affects the fastest growing species, and chronic toxicity harms the top predators by biomagnification and bioaccumulation.

1. Introduction

James Karr and his colleagues pioneered the concept of an Index of Biological Integrity (IBI) for streams and its application to fish in the 1980s. The US Environmental Protection Agency subsequently developed an IBI using macro-invertebrates in the 1990s because they agreed with Karr that the EPA's past reliance on chemical grab samples gave only a brief snapshot of the water chemistry and did not give an integrated picture of impacts of water chemistry, or other stressors, on biological communities. Especially important is that chemical sampling to detect a point source requires being present at the time of release from a discharge pipe ("smoking gun") or at the lead edge of a flood hydrograph to detect non-point source contamination. In addition, IBIs are cheaper and communities have a "memory" in that species identities and relative abundance reflect cumulative effects of all stressors over a time period of at least the generation time of the species present.

2. A Traditional IBI for Cave Streams May Not be Possible

Caves have very few species so a traditional IBI based on fish and/or macro-invertebrates and including indices of diversity is not practicable. So we should use all the species that can be identified at least to the generic level. Many species of isopods and amphipods cannot be separated in the field and even bait-trapped individuals would have to be sent to experts to identify making the time involved prohibitive. In addition, with only a few species, the presence or absence of the large species like fish, will have huge effects on a species diversity-based IBI due just to sampling error (WILLIAM PEARSON personal communication). So what is the solution?

I suggest that we census all the species of stream and stream bank fauna. It should be obvious that we census when the water is clear and low both for increased reliability and lowered risk of flood. Here I amplify the lower case letters in the abstract.

a. Careful measuring of a few captured individuals plus estimation of all sizes of fish, salamanders, and crayfish is important because the size-frequency distribution is a sensitive measure of reproductive frequency and success in long-lived cave animals. In cave crayfish we also can see the sizes and numbers of developing eggs through the translucent exoskeleton. Measurement of lesions, missing or broken limbs or eroded fins and fins, and visible external parasites is done only on a follow-up trip if the initial community signature suggests acute or chronic toxicity. But any signs of lethargy, unusual behavior, or lack of reaction to disturbance should be noted and lead to careful scrutiny of captured individuals for signs of emaciation or disease.

b. At one spot in each downstream to upstream quintile of the stream we census macro-invertebrates at least identified to group both in the water (flatworm, snail, isopod, amphipod, shrimp) and on the stream bank (e.g. springtail, mite, spider, pseudoscorpion, daddy-long-legs, carabid beetle, leiodid beetle, millipede, bristletail). Sketch unknown species with a scale indicated. Stream bank fauna and organic matter can become food for aquatic species during floods and can tell us different things about adverse impacts. If there are rocks we count the numbers and estimate sizes of associated animals with a sample of 10–20 rocks. If there are no rocks we do a standard time and area search. At the same locations we estimate the amounts and size distributions of sediment (silt-clay, sand, gravel, rocks, and breakdown) and the relative amounts of coarse particulate organic matter (sizes identifiable to leaf, twig, bat guano, and worm castings) and fine particulate organic matter

(not identifiable). In addition we note the color of the organic matter since black indicates old and scarcely decomposeable material. Note color of any rocks (e.g. black for manganese and orange for iron) and its feeling when rubbed (slippery means a microbial biofilm).

c. Especially if there are not rocks or mud clods to census for small fauna, I suggest using baited traps. If you are making only one trip then leave traps as you census upstream and retrieve and census them as you return. If you can return in a few days you are more likely to catch things. In either case I suggest a trap of your design that allows water circulation so that the smell of bait can be carried downstream. And I suggest small rocks plus washed leaf litter as a refuge for small species from predation by larger species or individuals. Place the contents in a white bottomed pan and census what you catch.

d. In all cases it is important and easy to distinguish among troglobitic, troglophilic, trogloxenic, and accidental species. In general troglobites are apparently white and eyeless and troglophiles are pigmented and have visible eyes on close inspection. Trogloxenes can not normally complete there life cycles in caves and in the extreme include tubificid worms and colonial sewage bacteria.

3. Potential Problems with Implementing My Community Signatures

I have had some feedback from folks at a workshop in which my ideas were discussed so here I briefly respond to a few of the perceived problems and comment on some misunderstanding. Some of my comments hold for IBIs in general. They include possible need to develop metrics for different karst regions, difficulty of identifying animals to species in the field, the misunderstanding that "health" of a stream is useful concept, and the perception that different potential implementers could not agree on the degree of expertise and training needed to use the methodology.

a. The beauty of Karr's fish IBI is that it is easy, with a little training, to identify all species quickly in the field and release them. But even Karr's fish IBI, that includes scores for generalist species and pollution intolerant species, has had to be modified for geographic regions with very different fish faunas. Different karst regions also have different cave stream faunas but my proposed signatures do not use a scoring system and deal with categories of species (troglobites, troglophiles, trogloxenes, and accidentals) that can be identified in the field. I also rely heavily on size-frequency data for these categories of animals to hypothesize the kind of impact. It could be argued that lack of a scoring system is a disadvantage but all systems have negative and positive tradeoffs.

b. Use of categories of cave animals and size-frequency distributions make the inability to separate similar copepod, isopod, and amphipod species in the field less of an impediment to identifying the category of impact. Further, in caves there are rarely more than two species of amphipods or isopods or flatworms that are difficult to distinguish in the field and they do not seem to have very different pollution tolerances. In contrast surface stream often have dozens of species of oligochaete worms and midge larvae that are impossible to tell apart in the field, very difficult to distinguish microscopically, and have striking differences in pollution tolerance.

c. I have problems with the concept of a healthy ecosystem or community because health is difficult to define. An ecosystem that is highly eutrophic, due to excess nutrients, is greatly simplified but it still has fully functional primary and secondary production, structured food chains, and nutrient recycling. And all systems change over time with natural variations in weather and climate; the effects of rare but important floods for food renewal in caves is a case in point. A better measure of impact on a community is whether it is resilient in that it returns quickly to the same state after natural or anthropogenic disturbance.

d. In my 40 years of doing biosurveys of cave streams I have found three non-scientists who spent the time needed to get the same data that I got in the same stream at the same time. The issue is interest and dedication to the task rather than initial ability or formal training. Unlike with surface streams, we do not need a huge cadre of volunteers to do the work. And there are increasing numbers of individuals who even make a living doing biosurvey work in caves.

4. Background for a Community Signature Approach to Cave Stream Bio-Integrity

I first suggested the use of community signatures in a paper on The Mammoth Cave Ecosystem (POULSON, 1992) and followed up on the idea in a proposal for Long-term Ecological Monitoring (LTEM) for which I was the lead as a Consulting Ecologist (GS-14) for summers of 1992-1994 at Mammoth Cave National Park. The proposal ranked 1 of 150 proposals, submitted by National Parks and Monuments, for scientific merit and has now been funded for over a decade. The water sampling program includes measurement of Total Organic Carbon, conductivity, temperature, and pH at major springs. And sampling is done every two years synoptically and conditionally with large rain events. Unusual results lead to more extensive sampling, e.g. for pesticides and heavy metals, and sampling in the aquifer progressively upstream to try to find the source of any unusual change in water chemistry. A biological survey is done where a cave stream is available for in any spring watershed.

A central precept of our LTEM proposal was based on a pioneering paper on The Central Kentucky Karst (WHITE et al., 1970 in POULSON, 1992). We argued that karst surface features and knowledge of the processes of cave formation would help us to identify potential threats to the cave system and that these threats should drive management. Based on horizontal diagrams of the Central Kentucky Karst and vertical profiles of different geological, mineralogical, and biological zones in the Mammoth Cave System (POULSON, 1992), we identified potential impacts on aquatic ecosystems. These exemplify worldwide problems of groundwater pollution in karst regions. In Karst, there is rapid transfer of water and contaminants from the surface to the subsurface and most contaminant transfer occurs with rainfall events. Extensive areas of recharge encompass a wide variety of land uses and threats. Here are particulars for the Central Kentucky Karst.

In the recharge areas starting with sinking streams and continuing under the sinkhole plain, agricultural activities are the most obvious threats. Productive farmlands are located among the sinkholes and sinking creeks. They are non-point sources with chronic contributions of sediment, pesticides, nutrients, and bacteria to cave streams.

Point source spills have occurred and will continue to occur along Interstate 65, the Cumberland Parkway, and the CSX railroad which traverse the watershed. Examples of spills include anhydrous ammonia, ink, diesel fuel, gasoline, heating oil, and paint. They are a constant reminder of the vulnerability of the karst aquifer.

Along the transportation corridors, urban development is expanding. Such growth will increasingly burden aquatic resources downstream. Common problems are sewage and solid waste disposal and leakage from buried storage tanks and pipelines. Emerging problems are industrial wastes.

Another class of point source pollution is associated with oil and gas production. These include spills and leaks of drilling fluids, muds, hydrocarbons, and brines. Brines encountered during drilling are high in sodium, chloride, sulfates, and some heavy metals. Illegal release of petroleum production brines has and is occurring.

Dams on the Green and Nolin Rivers have caused problems because of flooding and hydraulic damming via the major springs back into base level rivers of the Mammoth Cave System. By altering timing, of holding water back and releasing it, the normal seasonal hydrograph of level, flow, and flow direction have been altered.

Assessment of potential threats can be combined with hypothesized community signatures for each class of threat.

5. Hypothesized Community Signatures for Different Classes of Impact

Based on ecological, toxicological, and physiological principles, I have hypothesized community signatures for negative impacts of five classes of threats. These kinds of threats may be predicted *a priori* from activities and land use patterns on the surface and/or they may be hypothesized from the community signatures in cave streams. Of course interpretation may be complicated if there are multiple kinds of impacts.

a. *Organic enrichment* can have a range of effects from positive to extremely negative. Since caves are food-limited, there are always positive and negative tradeoffs. Inorganic fertilizers may have no effects on stream communities since there are no plants to respond in caves. However inorganic fertilizers will cause algal blooms in surface waters. If these blooms wash into caves that results in large amounts of decomposeable organic matter which can have negative impacts in cave streams. Of course bacterial and fecal input from septic systems, farm feed lots, manure on fields, or failed sewage treatment plants also introduce decomposeable organic matter. In either case I expect increases of secondary productivity that can be inferred from a continuum of progressive effects.

I expect the following sequence of impacts with increasing amounts of decomposeable organic matter. First the frequency and degree of biofilms will increase with lowest level organic enrichment. Next I expect increased reproduction of the shortest lived troglobitic detritivores, like flatworms and isopods that graze on biofilms and fine particulate organic matter. This effect can be inferred from size-frequency distributions and abundances. With greater organic enrichment I predict a shift to presence and then dominance of troglophiles. With still further enrichment I predict that even troglophiles are replaced by huge densities of trogloxenes, especially dense mats of red tubificid worms and stringy colonial sewage bacteria. At worst there is so much decomposeable organic matter that the biological oxygen demand of aerobic bacteria results in elimination of oxygen and death of all macroscopic organisms. And to reiterate an earlier point, even the most simplified of these communities demonstrate all aspects of ecosystems function even though our value judgment may be that they are not like what we expect or desire without disruption by human activities.

b. *Toxins* aka poisons have a continuum of effects. Chemicals that are toxic include inorganic compounds and organic compounds. In both cases they are toxic because they are rare in nature and organisms have not evolved ways to detoxify them by breaking them down or sequestering them in parts of their body where they have no effects. As a result the toxins will build up in the body as long as intake and absorption is greater than egestion, excretion, and detoxification. Inorganic toxins include heavy metals like cadmium, mercury, and lead. Organic toxins include hydrocarbons like oil and gasoline and pesticides including chlorinated hydrocarbons (e.g. DDT and chlordane), organophosphates, carbamates, and perhaps pyrethroids.

I predict that pulsed (point source) inputs of high concentrations of toxins will affect the shortest lived and fastest growing species at the beginning of the food chain. This is the reason that herbicides most affect weeds and antibiotics most affect bacteria. The species most affected in a cave stream include troglophiles, if present, and the species of troglobites at the beginning of food chains, especially isopods and copepods. I expect that their numbers will be greatly reduced if there is acute toxicity. Larger troglobites with lower growth and metabolic rates may crawl out of the water onto the stream bank. I would expect this for crayfish and some salamanders when there is a sudden pulsed input of a toxin. It is counterintuitive, but true, that long-lived large troglobites, like fish and crayfish, are not so sensitive to pulsed toxin input. The reason is that they have very low metabolic rates.

On the other hand, I predict that chronic (non-point source) inputs of toxins will most affect the longest lived and slowest growing species at the end of the food chain. There are two reasons. First, the longer an individual lives the more the toxin slowly increases over months and years by the process called bioaccumulation. Second the more steps there are in a food chain the more the toxin quickly increases by a process called biomagnification. A toxin builds up at least 10 fold at each step in a food chain and this can happen every day or week for years. The combination of biomagnification and bioaccumulation puts top predator troglobites, like fish and salamanders, at double jeopardy. Even crayfish in caves are partially predaceous, especially on isopods. As a result I predict that the largest and oldest troglobites, especially fish and salamanders, will be the first to die and so the size-frequency distribution will be shifted toward the smaller sizes. Live large individuals might show signs of weakness or might have lesions or deformities. The older individuals are normally the ones reproducing most, so the frequency of very small individuals might also be reduced. Due to a reduced number and smaller size of predators, the number of prey individuals (copepods, isopods, and amphipods) may increase.

c. *Siltation* will homogenize the stream bottom habitat and so cause a decline in diversity of species and numbers of individual in remaining species. If gravels and rocks are covered by silt then there are few hiding places for isopod and amphipod prey of large species. In addition silt may mix with fine particulate organic matter and cover biofilms; both reduce the availability of food to detritivores causing their numbers to decline. An indirect effect of less prey may fewer predators.

Troglobitic fish and crayfish are not necessarily compromised by siltation because they have food other than isopods and amphipods. Fish eat mostly copepods even when other preys are present and crayfish eat coarse particulate organic matter or even fine particulate organic matter mixed with silt. Many caves in the United States are in areas where there was massive land clearing for agriculture up until the early 1900s and these caves often have streams with mud and silt banks and much silt on the bottom.

d. *Hydropatterns* of cave streams can be changed by dams and/or reservoirs on surface streams either upstream or downstream of the cave. Reservoirs and dams upstream can reduce the amount of particulate organic matter washed into a cave and its seasonal pattern. Many cave stream species synchronize each others reproductive state and reproduce based on subtle seasonal increases in food input. Dams and reservoirs on rivers upstream or downstream from spring resurgences of cave streams may also change cave stream hydropattern by both backflooding and hydraulic damming. Hydraulic damming slows or stops the normal recession of water after a flood and so results in deposition of silt and may stop fine particulate organic matter from reaching the downstream parts of cave streams and rivers. This may also compromise shrimp and copepods, which feed only on biofilms and fine particulate organic matter. Without these prey species the food supply of cavefish is reduced. And, as with direct siltation, I predict that interruption of normal hydropatterns may compromise all troglobites and so I predict that only the large individuals of fish and crayfish can persist since they have the greatest capacity to forage over great areas and live long times with little or no food.

6. Tests of Community Signature Hypotheses; Inadvertent and Natural Experiments

In this final section I give some examples of tests of my community signature hypotheses. As a baseline I review several multidecade and continuing stream biosurveys in cave streams in the Mammoth Cave system that are local watersheds with near pristine surface watersheds. These show the kinds of variation possible within and between three streams with only natural variation including the effects of 100-year floods. Then I give snapshots of cave streams where the community structure suggests different adverse impacts due to human activities in the surface watershed.

a. Three pristine Mammoth Cave streams have maintained the same community signatures from 1965–2005. The first 25 years of study including 3–10 surveys is reported with actual data in POULSON (1992). All three streams showed a persistent change in species composition and density along an upstream to downstream decrease in substrate heterogeneity and particulate organic matter and with an increase in depth and width. And persistent great differences in particulate organic matter and occurrence of rock refuges among streams only changed overall abundances and size-frequency distributions of species (differential reproduction) rather than the relative abundance of species both for the aquatic and streambank terrestrial communities. A 100-year flood changed the distribution of riffles and pools along the stream but not the community of animals.

One of the streambank terrestrial communities was virtually lost for a year from 1966 to 1967 as a result of a pollution event but the stream community was not affected. Two sewage treatment lagoons overflowed into the headwaters leaving a line of green cyanobacteria (*Spirulina*) at the water edge along the length of the stream. This alga is known to produce toxins and I argued, as part of a successful suit to have the Job Corps and the lagoons removed from above the cave, that the short-lived terrestrial organisms ate the algae and died.

b. With catastrophic spills of toxins there is often no interpretation necessary to determine cause of complete loss of the cave stream communities. One example was a gasoline spill into Pless Cave in Indiana. It resulted in in immediate loss of a large population of cave crayfish. A second example was a breakage of a fertilizer line that released urea into the cave – spring system in Meramec Missouri. The resulting huge biological oxygen demand of bacterial decomposers causing a sudden loss of dissolved oxygen killing 100s of cave fish and 1000s of crayfish that floated out of the huge spring.

c. Hidden River Cave in Horse Cave Kentucky is perhaps the best studied case where pollution caused local loss of a cave stream community. The problem with interpretation is that both heavy metals from an electroplating operation and decomposeable organic matter from a creamery spilled into the cave over several decades. At that time the sequence of decline in the cave community was not documented but the intermittent recovery has been well-studied. The electroplating stopped and so the recovery involves decreasing amounts of decomposeable organic matter with time.as the creamery wastes could be treated by a new regional sewage plant..

As predicted the first species to reappear as dissolved oxygen started to increase were colonial sewage bacteria and mats of tubificid worms in the shallow waters along shore where maximum oxygen levels were found. The hemoglobin in the red worms binds oxygen at extremely low concentrations. As the residual creamery wastes decomposed oxygen levels increased high densities of cave isopods appeared as sewage bacteria and worms disappeared. About the same time troglophilic crayfish appeared. Finally, after several years troglobitic crayfish and amphipods and a few troglobitic cavefish appeared. All of these had recolonized the area from upstream small tributaries that had been refuges from pollution.

As of 2002 the main cave stream had still not recovered to the point that only troglobitic species occurred, as they still do in the small upstream refuges. Every time there has been a big flood the incompletely decomposed creamery wastes that had been buried by sediments were remobilized. The first time this happened the community reverted to colonial sewage bacteria and tubificid worms. After several cycles of burial and remobilization of the decomposeable organic matter the community no longer reverts to the simplest community. We do not know ho long it will be before all the buried wastes are remobilized and fully decomposed.

d. Water leached particulate organic matter, bat guano and leaves and twigs, should not change cave stream community signatures because the potential food has already lost most of the easily decomposeable organic matter. My observations over the past 50 years support this prediction. Cave streams with maternity colonies of gray bats or massive amounts of leached particulate wood and leaves have only the expected troglobites. They simply grow faster and reproduce more than in caves with very low amounts of particulate organic matter.

e. The loss of a diverse community of troglobites in Shelta Cave in the 1970s may be explained by two alternative hypotheses of human impacts. Due to a cave gate not optimum for a small colony of gray bats it was first hypothesized that disappearance of the energy from bat guano cased loss of the troglobites including three species of crayfish, one shrimp, and one fish. For the reasons summarized in the previous paragraph, I had always considered this hypothesis unlikely. Recently it has been suggested that chlordane used to control termites caused the problem as the city expanded around the cave. This hypothesis fits a community signature I predict with chronic (non-point) input of low concentrations of a toxin. Even in the 1960s, large fish were mostly absent and reproduction by the largest crayfish was very low. I expect that the last organisms that were censused in the 1970s, as the community disappeared were small individuals of fish and crayfish.

f. The historic change in community signature of base level stream communities in Mammoth Cave is consistent with the negative impact of changes in hydropattern and hydraulic damming I predicted above for effects of dams on Green River. In 1906 Lock ands Dam 6 was built just downstream of the spring resurgences from the cave and in the 1950s a large upstream dam was built. The observations of loss of the cave community have been reviewed (POULSON, 1992) so I only summarize the initial recovery here subsequent changes here. Briefly the first animals to reappear when release patterns from the upstream dam were changed to be more seasonally natural were very large cave crayfish and then large cavefish. Recently shrimp have been seen again. All of the fauna has recolonized from more upstream parts of cave streams that are not subject o hydraulic damming and still have fine particulate organic matter and refuges for isopod and amphipod prey.

Acknowledgments and a Request

Starting in the 1960s Cave Research Foundation colleagues that helped most with stream surveys over many years were Stan Sides and Richard Zopf. My work in Hidden River Cave complements studies by Jerry Lewis. John Cooper and Horton Hobbs III shared invaluable observations and data on Shelta Cave. And, since the 1990s, Bill Pearson, and his students along with Rick Olson, and Kurt Helf have continued and improved my surveys. Over the years many additional friends, colleagues, and students have helped me in the field them and have shared ideas. You know who you are and I thank you one and all. And I solicit thoughts and comments for any readers of this work in progress.

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VISUAL OBSERVATIONS OF THE MACROSCOPIC LIFE IN PUERTO RICAN CAVES FROM 2002 TO 2008

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Between 2002 and 2008 biological notes were collected during 95 visits to 43 caves in Puerto Rico. The data is non-specific, presence/absence. No census data were collected. This data set includes only the main island of Puerto Rico and does not include offshore islands such as Isla de Mona. All data were collected in total darkness with the exception of bats, the Puerto Rican boa, and depigmented crustaceans, which were noted even if found in the entrance areas of the cave. The life of the caves was photographed but no traps were set, nor were rocks systematically overturned, and no specimens were collected. Identification is not to species but to categories that can be indentified in the field. All notes were written down in the cave or shortly afterwards. Most life observed is larger than 1 cm and does not live under water or mud. The goal of this paper is to determine what forms of life are common and what are not common in Puerto Rican caves.

Large numbers of depigmented adult animals were observed on only two of the 95 trips. In Cueva de Murcielagos in Guanica hundreds of depigmented crustaceans (amphipods and isopods) were observed in a saline pool of water under a bat roost in the entrance area of the cave. In Cueva Lechuga in Camuy dozens of depigmented millipedes were observed. Both of these animals have been observed by others over a span of years. Most of the depigmented animals observed in Puerto Rican caves appear to be in a phase of their life and are not permanently without pigmentation. Depigmented cockroaches, whip spiders, and millipedes have been observed and in these cases it is a phase of their life.

A total of 36 taxonomical groups have been observed in Puerto Rican caves. Life was observed in 91% of the caves visited. In Puerto Rico, caves without life tend to flood completely or be small enough to explore in 15 minutes or less. The data were normalized so that each cave has the same weight. The most common life found in Puerto Rican caves and their frequency are bats (73% of caves visited), cockroaches (47%), whip spiders (45%), crickets (42%), plants deposited by bats (41%), crabs (39%), gnats (38%), spiders (23%), snails (22%), fungi (21%), roots (18%), rats (11%), small guano animals (8.8%), large amphibians (6.8%), fish (6.7%), small amphibians (6.0%), benthic shrimp (5.8%), water-deposited plants (4.6%), swimming shrimp (4.4%), boas (4.3%), scorpions (2.8%), earthworms (2.6%), depigmented millipedes (2.3%), pigmented millipedes (2.3%), ants (1.6%), unidentified human parasites (1.4%), depigmented crustaceans (1.2%), mosquitoes (0.5%), and earwigs (0.2%).

Three (Yuyu, Río Encantado, and Vientos) of the four caves with the highest biodiversity are in the Sistema de Río Encantado. This is the largest mapped cave in Puerto Rico. The cave has 17 km of continuously traversable passage, some of which is underwater. The land surface above the cave is rugged karst and poor farmland. The area has been abandoned and has low levels of human population. Above the Sistema de Río Encantado is one of the largest road-less tracks in Puerto Rico. Biodiversity is not the same as biomass.

1. Introduction

The animal life found in caves is often classified into four categories. Troglobites are animals that live only in the total darkness of caves and have morphological adaptations to live in caves. The most common adaptations are loss of pigmentation and eyes, extended appendages, and a slower metabolism. Troglophiles are animals that live their entire life in caves but are also found outside of caves. Frequently they are nocturnal and live in humid environments. Trogloxenes are animals that visit caves but cannot complete their entire life cycle in the cave. Bats, which must leave the cave to feed, are the best-known example of trogloxenes.

Accidentals are animals that are in the cave by accident and do not regularly visit the total darkness of caves.

In Puerto Rico, species lists have been published for Cueva Aguas Buenas (FENTON, 1968; BECK et al., 1976) in Aguas Buenas, Cueva El Convento (NICHOLAS, 1974) in Guayanilla, and the caves in the Guánica dry forest (CONDE COSTAS AND GONZÁLEZ, 1990). Invertebrate species lists for several caves have been published by PECK (1974).

There are 13 species of bats on the island of which nine regularly roost in caves (GANNON et al., 2006). Bat populations in Puerto Rico have been published for two caves. Cueva Cucaracha has 700,000 and Cueva Cuelebrones has 300,000 bats (GANNON et al., 2005). It is fair to assume that many caves in Puerto Rico have more than 10,000 bats. The largest bat populations are found in hot caves where the body temperature of the bats can raise the air temperature to more than 30 °C (GANNON et al., 2005). Hot caves are formed when tens of thousands of bats roost in a room at higher elevation than a single constricted entrance. Under these conditions bats use less energy and water but they are more vulnerable to predators that wait at the constricted entrance.

Fruit-eating bats bring seeds and leaves back to the cave roost (KUNZ AND DÍAZ, 1995). Viable seeds are dropped to the floor of the caves where they sprout and grow in the humid and dark conditions. The seeds are doomed as they will never encounter the sunlight needed for photosynthesis. The seeds grow until they have exhausted the supply of energy in the seed and then they die. These seeds are an important source of nutrients for other species that live in the cave.

Crickets in Puerto Rican caves are from the genus *Amphiacusta*. The genus *Amphiacusta* is described in DESUTTER-GRANDCOLAS AND OTTE (1997). Fungi have been studied in the Sistema de Río Camuy (NIEVES-RIVERA, 2003).

Ship rats (*Rattus rattus*) were introduced into Puerto Rico by Spanish settlers in the 16th century. Norwegian rats (*R. norvegicus*) arrived later. Both species live in the cities but the ship rat is dominant in rural areas such as the El Yunque National Forest (ENGEMAN et al., 2006).

Terrestrial coastal areas of Puerto Rico have a variety of crab species but the center of the island has only the Puerto Rican Freshwater Crab (*Epilobocera sinuatifrons*). The reason for this is that all other crabs and shrimp spend part of their time in saltwater. They may spend most of their lives on land but they must migrate to the ocean to breed. The freshwater crab reproduces in freshwater and does not migrate (COOK et al., 2008).

Puerto Rico has freshwater shrimp from the genera *Macrobrachium*, *Xiphocaris*, and *Atya* (CROWL et al., 2000). *Macrobrachium* are benthic and have pincers. In the 1960s a 50 cm long *Macrobrachium carcinus* was captured in the Tres Pueblos Sinkhole (GURNEE AND GURNEE, 1987), which is part of the Sistema de Río Camuy. *Xiphocaris* are usually less than 4 cm long and are depigmented even though they live in surface waters. They also have the tendency to jump over obstacles such as swift water. *Atya* is a swimming shrimp intermediate in size between *Macrobrachium* and *Xiphocaris*. All these shrimp need to migrate between freshwater and the estuary and all have suffered population losses as the construction of dams has broken their migratory routes. The largest undammed river in Puerto Rico is the Río Grande de Manatí in the north central part of the island.

At caves with huge bat populations the Puerto Rican Boa (*Epicrates inornatus*) waits at the constricted entrance and then captures bats as they nightly exit the cave (RODRÍGUEZ AND REAGAN, 1984). The boa is protected by both Puerto Rican and federal law. In a study in El Yunque National Forest the boas averaged 1.4 m in length (WUNDERLE, 2004). The boas in El Yunque have limited access to bats.

The cave in Puerto Rico with the best-documented sightings of depigmented animals is Cueva de Murcielagos in Guánica and all the depigmented animals are crustaceans. PECK (1974) saw the depigmented crustaceans and reported that the water was hypersaline. CONDE COSTAS AND GONZÁLEZ (1990) saw *Typhlatya monae, Stgiomysis holtuisi*, and *Metaniphargus bousfieldi* and the specific conductivity of the water was 7,600 µS/cm. which is about 15 percent of the ocean.

For centuries the residents of Puerto Rico have used caves as another resource in the struggle to survive. Water, guano, crabs, and shrimp have been extracted from caves. In the 20th century caves were lit with homemade kerosene lanterns, constructed with glass bottles and wicks. These are called *jachos* in Puerto Rican Spanish. GURNEE AND GURNEE (1974) described the air in Cueva Aguas Buenas in Aguas Buenas as "smoky".

The largest mapped cave system in Puerto Rico is the Sistema de Río Encantado (COURBON et al., 1989) in the municipios of Floriada, Ciales, and Manatí. From upstream to downstream this cave includes Cueva La Escalera, Cueva Río Encantado, Cueva Juan Nieves, and Cueva Aguas Frias. Cueva Aguas Frias is the resurgence of the Río Encantado. This system has 17 km of continuously traversable passage, short sections of which are underwater. Non-traversable but linked by dye tracing to the Sistema de Río Encantado are Cueva Yuyu, Cueva Zumbo, and Cueva Vientos (MORALES, 2007). A dry cave in the drainage basin of the Río Encantado is Cueva Balcones. The different entrances of the system are widely separated and separated by sumps. The Río Encantado is a tributary of the Río Grande de Manatí.

2. Methods

For this study 43 caves were visited 92 times between 2002 and 2008. Cueva Clara de Camuy in Camuy is the section of the Sistema de Río Camuy that is a show cave. All the other caves were not developed for commercial use. Life in the caves was observed while caving and no trip made was solely to collect biological data. The data is non-specific presence/ absence. No attempt was made to collect census data. No traps were used and no rocks were systematically overturned. Attempts were made to photograph the life but no specimens were collected. Most life observed is larger than 1 cm and does not live under water or in mud. The life was observed by the author or another member of the party. The data was normalized so that each cave has the same weight in the numbers presented. For the purpose of this study each cave entrance in the Sistema de Río Encantado is considered a separate cave.

Living organisms were classified to categories that could be identified in the field. In most cases the species cannot be identified. There are two problems with species level identification. First it would require collecting samples and sacrificing the animals and second it would require specialists that may not be readily available.

3. Results

The results are shown in Table 1. Living organisms were observed in 91% of the caves surveyed. In Puerto Rico, totally dark caves without observed life tend to be small enough that they can be explored in 15 minutes or flood completely. Bats were observed in 73 percent of the caves surveyed. I have photographed bats with orange parasites.

Cockroaches or cockroach-like animals were observed in 47 percent of the caves in this survey. This category includes anything called *cucaracha* in Spanish. This category includes beetles, native species such as the Puerto Rican Cave Cockroach (*Aspiduchus cavernicola*) and the invasive American cockroach (*Periplaneta americana*). In Cueva Mucara in Aguas Buenas cockroaches were photographed in the act of copulation. In caves with thousands of cockroaches it is common to observe depigmented animals. For several hours after shedding their exoskeletons cockroaches are depigmented.

Whip spiders were observed in 45 percent of the caves surveyed. Most whip spiders observed in Puerto Rican caves are probably *Phrynus longipes* as this is the largest and most readily observed species on the island. Whip spiders have been observed eating cockroaches and crickets. Between December and June whip spiders have been observed mating, carrying reddish-brown eggs on their stomach, or yellowish-green newly hatched offspring on their back. The reproductive season of the whip spiders coincides with the driest part of the year. In caves where whip spiders are observed it is common to observe 5 to 10 during the cave trip.

Crickets were observed in 42 percent of the caves surveyed. It is common to observe 5 to 10 crickets at a time. In Cueva Aguas Buenas in Aguas Buenas crickets were photographed in the act of copulation. Sprouting plants that were deposited by bats were observed in 41 percent of the caves surveyed.

Crabs were observed in 39 percent of the caves surveyed. Crabs can be found either under or over the water surface. A dead crab was observed in a dry cave, Cueva La Mora in Comerio. Crabs have been photographed eating bats and seeds. Gravid females have their offspring in a compartment in their abdomen and if they are near to hatching and the crab is picked up it can rain baby crabs. This has been observed in Cueva Represa in Hatillo.

Gnats were observed in 38 percent of the caves surveyed. Gnats are detected in caves solely because they are attracted to the headlamps of the cavers. Usually they are only a few millimeters in size and would pass unobserved if they were further from the lights. In some caves, with large bat populations, the gnats flying into the mouth, ears, and nose become so bothersome that cavers turn off their headlamps and use only hand lights.

Spiders or spider webs were observed in 23 percent of the caves surveyed. Observed spiders have been small and did not have hairy tarantula-like bodies. In Cueva Represa in Hatillo a spider was photographed carrying an egg sack.

Table 1. Macroscopic Life Observed in Puerto Rican Caves From 2002 to 2008

Cave	Visits	Biodiversity Score	Rank	Bats	Cockroaches	Whip Spiders	Crickets	Bat-deposited plants	Crabs	Gnats	Spiders	Snails	Fungi	Roots	Rats	Small Guano Animals	Large Amphibians	Fish	Small Amphibians	Benthic Shrimp	Water-deposited plants	Swimming Shrimp	Boa	Scorpions	Earthworms	Depigmented Millipedes	Millipedes	Ants	Biters	Depigmented Crustaceans
Percent Observed	95			73	47	45	42	42	40	39	23	22	21	18	11	8.8	6.8	6.7	6.0	5.8	4.6	4.4	4.3	2.8	2.6	2.3	2.3	1.6	1.4	1.2
Yuyu	3	10.7	1	100	100	100	100	100	100	100	100	33	67	67	0	0	0	0	0	0	67	0	33	0	0	0	0	0	0	0
Vientos	2	10.0	2	100	100	100	100	0	100	100	100	50	50	50	0	100	0	0	0	0	0	0	0	0	0	0	0	0	50	0
Convento	2	10.0	2	100	100	100	0	0	100	100	0	100	50	0	0	100	0	100	0	50	0	100	0	0	0	0	0	0	0	0
Río Encantado	4	9.5	4	100	100	100	100	75	100	100	0	0	50	0	75	0	0	0	0	100	0	0	0	0	0	0	50	0	0	0
Minga	1	9.0	5	100	100	100	100	100	100	100	0	0	0	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Represa	5	8.8	6	100	100	20	40	60	100	100	60	80	60	0	0	20	0	80	0	0	20	40	0	0	0	0	0	0	0	0
Aguas Buenas	9	8.6	7	100	891	00	78	89	100	44	22	44	33	33	44	33	33	0	0	0	0	0	0	11	11	0	0	0	0	0
Mucara	11	8.5	8	91	82	73	73	73	73	73	27	73	36	55	18	27	9	9	9	0	9	0	0	9	0	0	0	18	9	0
Cucaracha	2	8.5	8	100	100	50	0	0	50	50	50	0	0	0	100	0	100	50	50	0	0	50	50	0	0	0	0	50	0	0
Mantilla	2	8.0	10	100	100	100	100	100	100	50	0	0	50	0	50	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0
Balcones	2	8.0	10	100	100	100	100	100	0	50	0	50	100	0	50	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lechuga	1	7.0	12	100	100	0	0	0	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	0	0	0	0
Quintero	2	7.0	12	100	100	100	50	50	0	50	50	0	50	50	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0
(Hatillo C)	1	7.0	12	100	100	0	0	100	100	100	100	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Juan Nieves	2	5.5	15	0	100	50	0	50	0	50	0	100	50	0	0	50	0	50	50	0	0	0	0	0	0	0	0	0	0	0
Corozo	2	5.5	15	100	50	0	100	100	0	50	50	0	0	0	0	0	0	0	0	0	0	0	0	50	0	0	50	0	0	0
Cabros	1	5.0	17	100	100	100	0	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Murcielagos AB	1	5.0	17	100	0	0	100	100	0	0	0	100	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
La Mora	1	5.0	17	100	100	100	0	0	100	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0
(Hatillo A)	1	5.0	17	0	0	0	0	0	100	0	100	100	0	100	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0
Grillo	3	4.7	21	100	33	67	100	33	100	0	0	0	0	0	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Carmelitas	2	4.5	22	100	0	50	100	50	0	50	0	50	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Camuy Clara	2	4.5	22	100	0	100	100	50	50	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rafaela	2	4.5	22	0	0	50	100	0	0	50	50	50	100	0	0	0	0	0	50	0	0	0	0	0	0	0	0	0	0	0
La Escalera	3	4.3	25	100	100	67	33	67	67	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Murcielagos VA	1	4.0	26	100	0	0	0	0	100	100	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0
Lucero	2	4.0	26	100	0	50	100	100	0	0	0	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(Pulpo)	1	4.0	26	100	0	0	0	100	0	0	0	0	100	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0
Murcielagos G	2	3.5	29	100	0	0	0	0	0	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50
La Mora II	1	3.0	30	100	0	0	0	100	0			100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(Muchacha)	2	3.0	30	0	0	50	100	0	0	50	50	0	0	0	0	0	0	0	0	0	0	0	0	50	0	0	0	0	0	0
(Rescate)	1	3.0	30	100	0	100	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Humo	1	2.0	33	100	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Puente Natural	1	2.0	33	100	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(Jacho)	5	1.8	35	0	0	20	40	0	0	20	0	0	20	80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sorbetos	2	1.0	36	0	50	0	0	0	0	0	0	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ventana	1	1.0	36	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Zumbo	1	1.0	36	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pencho	3	0.3	39	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Grillo Stream II	1	0.0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Grillo Stream	1	0.0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(Hatillo D)	1	0.0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Monte Encantado	1	0.0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Names in parenthesis are unofficial.
There are three caves in this dataset named Murcielagos--AB stands for Aguas Buenas, G stands for Guanica, and VA stands for Vega Alta.

Live snails or snail shells were observed in 22 percent of the caves surveyed. Based on color and shell morphology there are at least three species of snails present in Puerto Rican caves. No slugs have been observed.

Fungi were observed in 21 percent of the caves surveyed. The filaments of the fungi are usually white but are sometimes black. The most common substrate of the fungi is organic material such as wood or a dead animal. Sometimes the filaments were on a soil or rock substrate that did not appear to be organic. No fruiting bodies were observed.

Roots extending into total darkness were observed in 18 percent of the caves surveyed. Trees on the surface are extending their roots into the cave to extract water and nutrients. These roots are then eaten by other residents of the cave.

Rats were observed in 11 percent of the caves surveyed. A dead rat was found in Cueva Aguas Buenas in Aguas Buenas and the tail was longer than the body which identifies it as a ship rat.

Small guano animals were observed in 8.8 percent of the caves surveyed. This non-specific category includes the myriad of small animals seen moving on guano piles.

Large amphibians have bodies larger than 10 cm and were observed in 6.8 percent of the caves surveyed. This category is probably mostly Cane Toads (*Bufo marinus*) and to a lesser extent Bullfrogs (*Rana catesbeiana*). Both of these species are invasive and not native.

Fish were observed in 6.7 percent of the caves surveyed. Most were under 5 cm in length and were described by the observer as guppies.

Small amphibians were observed in 6.0 percent of the caves surveyed. Small amphibians are less than 5 cm long. The native amphibians in this category include several species from the genus *Eleutherodactylus* as well the white-lipped frog (*Leptodactylus labialis*). This category would also include several invasive species.

Benthic shrimp from the genus *Macrobrachium* were observed in 5.8 percent of the caves surveyed. These are typically from 15 to 30 cm long. Most of these shrimp were observed in the Sistema de Río Encantado which is a tributary of the Río Grande de Manatí. Unlike crabs, shrimp have only been observed only underwater.

Plants deposited by water were observed in 4.6 percent of the caves surveyed. Water-deposited plants can be distinguished from bat-deposited plants because they tend to be in alluvial deposits and at lower elevation than bat-deposited plants.

Swimming shrimp from the genus *Atya* were observed in 4.4 percent of the caves surveyed.

The Puerto Rican Boa was observed in 4.3 percent of the caves surveyed. In this data set if a boa was observed in all cases only one was observed. Cueva Quintero in Corozal is a horizontal dry river passage with a large bat population. Typical passage diameters are 10 to 20 m with no constrictions. The arrival of the cave explorers disturbed the bats and they flew to other locations in the cave. During this process a boa on the wall about 1.8 m above the floor was observed capturing a bat in room that was about 10 m wide.

Scorpions were observed in 2.8 percent of the caves surveyed. In all cases if a scorpion was observed then only was seen.

Earthworms were seen in 2.6 percent of the caves surveyed. In Cueva Lechuga in Camuy cockroaches appeared to be feeding on an earthworm.

Depigmented millipedes were observed in 2.3 percent of the caves surveyed. The lone cave where this was observed is Cueva Lechuga in Camuy. Another cave explorer had observed the same animals in this cave in 2001 (Miller, written communication, 2008). Pigmented millipedes were observed in 2.3 percent of the caves surveyed. In Cueva Río Encantado an adult millipede was observed and then one week later an adult was observed in the same location with newly hatched millipedes. One interpretation of the observation is that the adult was guarding a nest. It is impossible to know if the adult was the same even though the location was the same.

Ants were observed in 1.6 percent of the caves surveyed.

In 1.4 percent of the caves surveyed I received bites from an unknown animal. This unidentified human parasite is the only thing in a cave that has ever bitten me.

Depigmented crustaceans were observed in 1.2 percent of the caves surveyed. The only cave where this was observed is Cueva de Murcielagos in Guánica where depigmented amphipods and isopods were seen in an entrance area in the slurry from Lago Guano. The cave has thousands of bats and is the only cave in Puerto Rico where the bat fecal material falls directly into saline water.

Visitation and resource extraction from Puerto Rican caves have declined dramatically. In the 1960s and 1970s cave explorers saw many groups of Puerto Ricans visiting Cueva Aguas Buenas in Aguas Buenas (BECK et al., 1976). The author has visited caves in Aguas Buenas 31 times and has never seen another group. There is no evidence that anyone is entering caves to mine guano or collect crabs or shrimp. Most of the water-supply systems in caves have been abandoned. The author is aware of two operating water-supply systems in caves. *Jachos* have been observed were they have been left at the entrances to the cave. In most cases the kerosene has evaporated long ago. In 2006 a functional *jacho* was observed and lit in Cueva Aguas Buenas in Aguas Buenas. The *jacho* had been made from a 2003 wine bottle from Argentina.

4. Discussion

Of the 43 caves surveyed only one, Cueva Lechuga in Camuy, has freshwater and depigmented animals that live in total darkness and have been observed on two visits over seven years. It is a mystery why depigmented crustaceans are routinely observed in the entrance area of Cueva Murcielagos in Guánica. This cave has tens of thousands of bats and is the only place known to the author where bats roost over saline water. The salinity varies significantly. It has been speculated that the depigmented crustaceans evolved in total darkness and then migrated out to the entrance that has higher nutrients (CONDE COSTAS AND GONZÁLEZ, 1990). In the entrance area of the cave being white should make it easier for predators to capture them.

For many animals found in Puerto Rican caves we do not have enough knowledge to classify them. In temperate caves it is well documented that crickets leave the cave at night to feed near the entrance. NICHOLAS (1974) speculated that crickets in Puerto Rico did the same. There is no evidence that crickets must leave caves in Puerto Rico to find food.

There is the only cave where a change in the fauna can be identified. Thirty years ago the Bigclaw River Shrimp (*Macrobrachium carcinus*) and the Web-footed coqui (*Eleutherodactylus karlschmidtii*) were observed in Cueva Aguas Buenas in Aguas Buenas. In 10 visits between 2002 and 2008 neither of these animals were observed. The migration of the shrimp has been cut by the construction of the Carraizo Dam in 1953. The fact that the Bigclaw River Shrimp were still being observed in the 1970s indicates that this shrimp can live for at least 20 years in the wild. The Web-footed Coqui is extinct. In both cases the changes inside the cave were the result of changes outside of the cave.

Puerto Ricans are no longer visiting caves or using them for resource extraction. This means that the life in the caves has fewer disturbances. It also means that people have less direct knowledge of the caves of the island. It is difficult to conserve what is unknown.

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VERTEBRATE SPECIES IN UNDERGROUND FEATURES OF ARIZONA

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Underground features, including caves and abandoned mines, provide important resources for a wide variety of vertebrate species in arid and semi-arid regions. Resources used by these species include shelter, nest sites, water, foraging sites, and relief from extreme environmental conditions. Arizona has a wide variety of vegetative communities resulting from high variability in elevation, precipitation, and average temperatures. These vegetation types range from Sonoran Desert in the southwest part of the state to Alpine tundra on the San Francisco Peaks. Agency files, literature sources, internet sources, and site visits were used to compile records of species using caves and mines throughout Arizona. The majority of features with records of vertebrates were abandoned mines, but data were also obtained from many limestone caves and a few basalt and gypsum caves. At least 101 vertebrate species have been recorded in these underground features, including 63 mammal species, 15 birds, 17 reptiles, and 6 amphibians. Records of vertebrates were obtained for sites in the Sonoran Desert, Semi-desert Grassland, Madrean Evergreen Woodland, and seven other biotic communities. A common pattern in each of these communities is that a few species are found in many sites, and numerous species are found in relatively few sites. Similarly, many caves or mines support a few vertebrate species, and a few sites have larger numbers of species. Differences in the species composition among the biotic communities are due to differences in the pools of species present in each biome and to the differences in the availability of data for each area. The availability and structural characteristics of the caves and mines in each biome may also contribute to differences in species use of these features. These underground features provide important resources that may allow individuals or species to survive in harsh climatic conditions. With the large range in elevations, these conditions can include extremely hot and dry summers and very cold winters. Protection of these resources may be critical for the survival of some species and for the maintenance of regional biodiversity.

1. Introduction

Caves are widely known to provide habitat for a variety of vertebrate species that spend all or significant portions of their life cycles inside the totally dark areas of the caves. It is less well known that caves, and particularly cave entrance areas, can provide an important resource for an even wider variety of species. Particularly in arid regions, caves may provide temporary relief from extreme temperature or low humidity conditions. In addition, they may provide hiding places to escape predators, den sites, nest substrates, or hunting locations for predators.

While many individual observations of vertebrate species in caves in Arizona have been reported, there have been few attempts to compile this information in any systematic way. KINGSLEY et al. (2001) compiled a list of species known to use caves or abandoned mines in the Sonoran Desert. This list was based primarily on personal observations or knowledge of the four authors and on records listed in HOFFMEISTER (1986), but it did not include a thorough literature review. However, this preliminary list included 67 vertebrate species (4 amphibians, 14 reptiles, 11 birds, and 38 mammals). The primary conclusion of that paper was that caves and mines in the Sonoran Desert are significant wildlife habitat resources and worthy of protection. More recently, STRONG (2006 and 2007) has documented many more sites and species in research on the Sonoran Desert of Arizona and the Chihuahuan Desert of New Mexico.

The state of Arizona covers a wide range in elevations, from barely 30 m above sea level on the Colorado River near Yuma to about 3,850 m at the top of Mt. Humphreys near Flagstaff. This range of elevations in turn produces corresponding variations in temperatures and rainfall, which support different vegetative communities. The biotic communities present in Arizona include desertscrub, semidesert, and other grasslands, evergreen woodlands and savannas, coniferous forests, and alpine tundra.

The southern and western part of Arizona is in the Basin and Range physiographic province, with broad, low valleys separated by mountain ranges. Some of these mountain ranges may be over two thousand meters above the valleys, such that the mountain tops are in Petran Montane

Coniferous Forest and while Sonoran Desertscrub covers the valleys. Geology of this region is complex, with bedrock exposures in the fault-block mountains separated by wide valleys of alluvial deposits. Sedimentary rocks, including limestone and gypsum are present in isolated patches, and igneous and metamorphic rocks are common in the mountain ranges. The northeastern part of the state is in the Colorado Plateau physiographic province, underlain by relatively flat-lying Paleozoic and Mesozoic sediments, with some broad folds and volcanic areas producing higher mountains. This region also has desertscrub, grasslands, evergreen woodlands, and coniferous forests, and it includes the only areas of Alpine Tundra in the state. A Transition Zone lies between the Colorado Plateau and the Basin and Range provinces. This zone also has complex geology and very rugged topography.

The wide ranges in topography, climate, and vegetation lead to high levels of species diversity across the state in all classes of vertebrates. Caves or abandoned mines are present in all physiographic areas of Arizona, and many vertebrate species are available to take advantage of the special resource conditions provided by these features.

2. Methods

Data in this analysis were compiled from a variety of sources. KINGSLEY et al. (2001) provide a reliable list of species known to utilize caves and mines in the Sonoran Desert of southern Arizona, but they did not document species in any specific sites. Other sources, in particular HOFFMEISTER (1986) and COCKRUM and PETRYSZYN (1991), provided valuable information, including site records. Several internet sites have extensive information on vertebrate species and their habitat usage and requirements. In particular, the Biotic Information System of New Mexico (BISON 2008) supported by the New Mexico Department of Game and Fish, the heritage data management system supported by Arizona Game and Fish Department (AGFD 2008), and NatureServe Explorer (NATURESERVE 2008), supported by natural heritage programs. Other standard literature sources were also searched for relevant information.

In Arizona, there are no dense concentrations of caves on public lands, and therefore, no file records comparable to those at the Bureau of Land Management (BLM) or Carlsbad Caverns National Park in New Mexico. Caves are relatively rare in the Sonoran Desert, largely because of the limited exposures of limestone or gypsum in this region, but they are more common in other parts of the state. Areas of basalt are also relatively rare in the Sonoran Desert of Arizona, although there are extensive basalt flows in central and northern Arizona. In contrast, abandoned mines are relatively common throughout Arizona and provide underground resources similar to natural caves. Direct observations of vertebrate species were made in many caves and abandoned mines throughout the state.

Observational evidence of vertebrate species can take several forms. Visual observations of living animals are the most reliable evidence of species using underground resources. These animals got into the cave or mine under their own power, which suggests that they made a conscious choice to use the underground site for some purpose. The presence of nests or den sites is also positive evidence of the mammal or bird that constructed the nest, and it also provides evidence of the reason for the use of the underground feature. Similarly, the presence of feathers and egg shells indicates that birds were nesting in the cave or mine, and the condition of the egg shells can indicate successful hatching. The presence of scat in a cave or mine demonstrates that the animal was alive while in the site, and it also indicates that the animal was in the site for a significant period of time. Tracks indicate the presence of a live animal in the site, but they provide no evidence for the reason for or the duration of the visit. Skeletal material in a cave or mine is more ambiguous. While it can generally be identified to species, it does not necessarily provide confirmation that the animal entered the site by its own choice, or even whether it was alive when it entered the site. Skeletal material at the bottom of a pit generally indicates that the animal died as a result of the fall. Although it may have entered the cave by choice, it probably did not intend to fall into a pit.

Data from all of these sources were entered into spreadsheets, including species, sites, biotic communities, dates of observation (if known), and original observers (if known). Biotic communities are based on BROWN (1982). Each report of a species from a cave or mine was entered as a separate record. For common species, particularly bats, there were often multiple reports from a single site. Site information was compiled in a separate spreadsheet to avoid duplication of sites, particularly with the large number of unnamed, abandoned mines.

3. Results

The literature reports, personal communications, and personal observations provided 582 records of 101 species of vertebrates in the caves and abandoned mines of Arizona. Eighty-two of these species are documented with specific locations, and another 19 species are considered confirmed but without specific locations, based on KINGSLEY et

Biotic Community	Number of Sites	Number of Records	Number of Species	Mammals	Birds	Reptiles	Amphibians
Sonoran Desertscrub	41	184	77	48	11	15	3
Semidesert Grassland	39	67	24	18	4	2	0
Petran Montane Conifer Forest	5	14	10	8	2	0	0
Mohave Desertscrub	9	13	11	10	1	0	0
Madrean Evergreen Woodland	102	229	32	25	3	1	3
Interior Chaparral	10	23	14	14	0	0	0
Great Basin Conifer Woodland	10	17	10	8	0	1	1
Great Basin Desertscrub	15	24	10	8	2	0	0
Plains Grassland	1	1	1	0	1	0	0
Great Basin Grassland	5	10	5	2	2	1	0
Summary	**238**	**582**	**101**	**63**	**15**	**17**	**6**

Table 1. Distribution of vertebrate species by class and biotic community.

al. (2001). These records are primarily in the Sonoran Desert scrub, Semidesert Grassland, and Madrean Evergreen Woodland, which accounted for 480 records. The remaining records are distributed among seven other biotic communities, as listed in Table 1. The 238 sites with vertebrate records include 156 abandoned mines and 82 natural features, including limestone, gypsum, and basalt caves, rock shelters, and sinkholes.

3.1 Taxonomic analysis

The data collected in this research can be analyzed in a variety of way. The first approach is to sort the records by taxonomic group. The 101 species recorded include 63 mammals, 15 birds, 17 reptiles, and 6 amphibians. No fish have been documented in the caves of Arizona. The distribution of these groups among the ten biotic communities is shown in Table 1. These vertebrate classes can be broken down further into orders and families.

The 63 mammal species are distributed among six orders and 19 families. These six orders represent all of the native orders of mammals in Arizona. As expected the order Chiroptera (bats) is well represented, with 20 species in three families documented in the caves and mines, but Rodentia (rodents) is the most diverse group with 22 species and five families documented. Carnivora (carnivores) is also well represented with 13 species in five families. Artiodactyla (even-toed ungulates), Lagomorpha (rabbits and hares), and Soricimorpha (shrews and moles) complete the list with four, three, and one species, respectively. The 15 bird species are distributed among five orders and 11 families, with nine species from the order Passerifornes. The 17 reptile species include three orders and seven families. The dominant group of reptiles is in the family Viperidae, represented by six species of rattlesnakes. Three species of turtles have been reported in these underground features. The six amphibian species include two orders, Caudata and Anura, and five families.

The distribution of classes, orders, and families among the different biotic communities is generally similar to the overall distribution. The Sonoran Desertscrub, Semidesert Grassland, and Madrean Evergreen Woodland have the greatest numbers of species, but this diversity may only reflect the fact that these communities also have the greatest numbers of sites and total records. The strong correlation between species number and the numbers of sites or records suggests that additional research in the other communities would likely increase the numbers of species observed in those areas.

3.2 Species distribution

A further analytical approach with these data is to examine the distribution of species among the sites. When the data are sorted by species and sites, it immediately becomes apparent that a few common species are found in many sites across a wide range of biotic communities. Some other species are found in numerous sites but may be limited to only one or two biotic communities. However, the majority of species are sparsely distributed, and many are only reported from a single site. This pattern is illustrated in Figure 1, with bars broken down by taxonomic class. From this figure, it is again obvious that very few species are found in large numbers of sites. The species with the widest distribution is the white-throated woodrat (*Neotoma albigula*), which was recorded in 46 sites. Seven of the ten most widely distributed species are bats, which is an indication of the intensity of research and availability of data on bats.

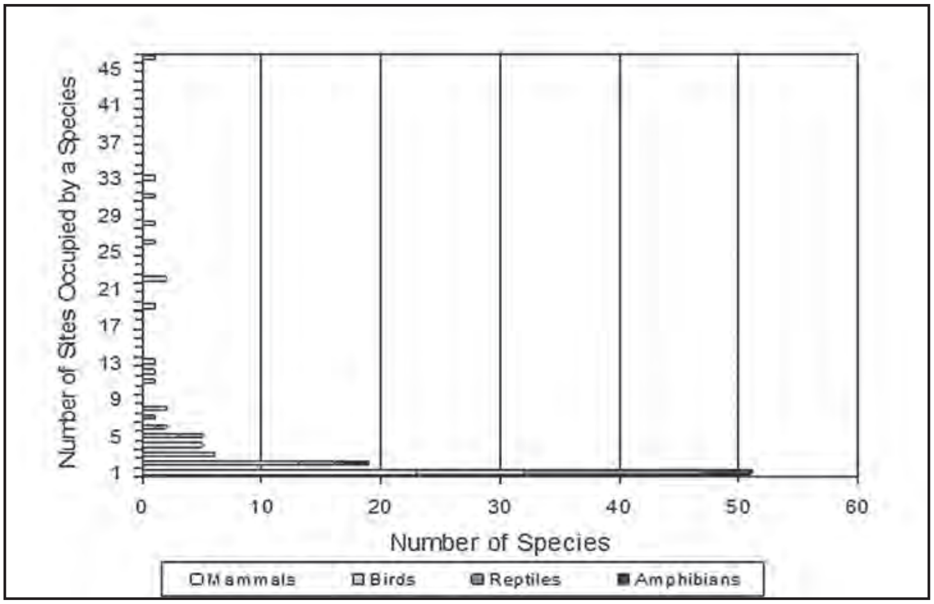

Figure 1. Species distribution among sites. The horizontal axis represents the number of vertebrate species that are found in the number of underground features shown on the vertical axis. The bars are broken down by taxonomic class.

3.3 Site diversity

An alternative way to analyze these data is to examine the number of vertebrate species using each cave or mine. These results are illustrated in Figure 2 for the summary of all biotic communities. The vast majority of sites (almost 83%) have records of only one or two species, and very few sites have more than five species. The site with the greatest diversity is a small basalt cave in Sonoran Desertscrub, where 11 species were recorded during one site visit with intensive searching. Although fewer data are available for the individual communities, the same pattern is persistent across all communities.

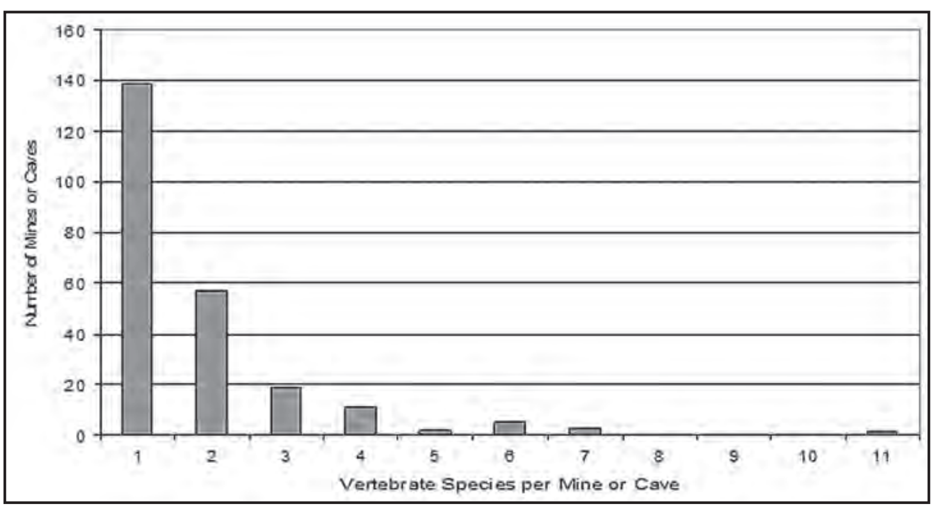

Figure 2. Species diversity within sites. The horizontal axis represents the diversity of species within a site and the vertical axis represents the number of sites with that diversity.

4. Discussion

While the diversity and distribution of vertebrates using underground features is of interest, the reasons why vertebrates seek out these resources is even more interesting from an ecological point of view. The simplest use of a cave or mine would be as a temporary roost site. Several species of birds have been observed roosting in caves, particularly owls using caves as daytime roost sites. Similarly, many species of bats use caves or mine as temporary nighttime roosts between foraging bouts.

Caves and abandoned mines provide good sites for nests or dens for a wide variety of birds and mammals. In particular, woodrat (*Neotoma* sp.) nests are found in many sites in nearly all biotic communities. Caves and mines are also important as maternity sites for many bat species, and the only reported maternity sites for the endangered lesser long-nosed bat (*Leptonycteris yerbabuenae*) are in caves and mines of the Sonoran Desert (COCKRUM and PETRYSZYN 1991). Many vertebrate species are known to use caves or abandoned mines as hibernation sites.

Underground features in arid regions are likely to provide water sources for a variety of animals. Caves and mines may provide points of access to groundwater or small perched aquifers in areas where surface water is rare. In addition, caves or mines may provide relief from extreme environmental conditions. In desert regions with very high summer temperatures and very low humidity or in mountainous areas with severe winter conditions, caves and mines could provide sites with moderate temperatures and higher relative humidity. It seems likely that many vertebrate species would deliberately select these favorable microclimates, although choice might be very difficult to demonstrate. Some species, particularly ringtails, snakes, and raptors, are apparently using caves as foraging sites. It is likely that some of the skeletal material found in caves or mines was carried there by predators. Other skeletal material may represent an animal that merely fell into a pit entrance of a cave or a mine shaft and was unable to escape.

5. Conclusions and Recommendations

The results of this study clearly demonstrate that underground features of many biotic communities of Arizona are being used regularly by a wide variety of vertebrates. In spite of the reliance on random observations and the lack of extensive, systematic surveys of vertebrates in caves, there are reliable records of over one hundred species using a large number of caves and mines. This level of usage and the documented types of usage by these species demonstrate that these underground sites provide a habitat feature that is an important resource for many species. In arid or semiarid environments with extremes of high temperatures and low relative humidity, these sites could be critical to the survival of many vertebrates, including some threatened or endangered species. .

With so many species depending on the underground features of Arizona, it is imperative that federal and local land management agencies maintain policies that provide protection for these species and their habitat requirements. Under the National Environmental Policy Act (NEPA), federal agencies are required to analyze potential environmental impacts prior to taking any action. Based on the evidence of vertebrate use of these caves and mines, potential impacts on these wildlife species and their habitat requirements must be considered in any action. In addition, when federal or state agencies are giving permits for recreational caving or for scientific research, they should provide the permitees with information about wildlife species using the caves and any precautions they should take when visiting the caves. When mines are to be closed for public safety, surveys should determine the use or potential for use by vertebrates, primarily bats, and specially-designed gates could provide access for bats and other vertebrates while restricting human access.

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CAVE COMMUNITIES IN MISSOURI – A COMPARISON OF NUTRIENT RICH AND NUTRIENT POOR SETTINGS

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Projects within Cave Research Foundation's Ozark Operation have resulted in detailed aquatic census data for two large caves in different sinkhole-plain settings: Devils Icebox Cave, Boone County; and Crevice Cave, Perry County. Baseline biological inventories over the past 15 years have meanwhile resulted in a considerable amount of data on community make-up in caves of the Missouri Ozarks, primarily within the Mark Twain National Forest and Ozark National Scenic Riverways. In stark contrast to the sinkhole plain caves, a majority of Ozark Highland caves are highly oligotrophic as a result of their setting within a covered karst, where sinkholes are usually cryptic, and coarse organic material is almost entirely excluded by a deep covering of residuum. Although there is a great deal of overlap in species composition, stream populations are more diverse, and population densities are on average at least an order of magnitude more in the sinkhole-plain caves compared with Ozark caves. Stream population densities are most readily compared by restricting faunal counts to the most favorable habitat type – shallow riffles with much loose rock, gravel and/ or bedrock – and by focusing on *Caecidotea* sp. isopods, the most widespread and common group of aquatic invertebrates. Community makeup in sinkhole-plain caves also tends to be skewed towards stygophiles and away from stygobites. Some large stygobitic invertebrates such as *Kenkia* sp. flatworms, on the other hand, appear to be confined to the nutrient-rich sinkhole-plain caves. Although *Caecidotea* population densities show wide variations, the ranges of measured population densities do not overlap, and the mean density in Ozark Highland Caves is at least an order of magnitude less than those of the sinkhole plain caves.

1. Introduction

There is a fairly large amount of data on the species make-up of Missouri caves, although this still represents only a rather scanty sampling. About 1000 caves have some sort of biological information on record – approximately 15% of the more than 6,400 caves recorded (Elliott, 2007, 2008; Missouri Speleological Survey database). However, many of those caves have had little research, and there has been very limited quantitative or semi-quantitative assessment of population densities. Several Cave Research Foundation (CRF) projects over the past two decades have serendipitously allowed some conclusions to be drawn regarding cave stream population makeup and densities in caves in two different physical settings: sinkhole plain caves within the Ozark Border province and caves within the covered karst of the Ozark Highlands province (Fig. 1).

The longest running of these projects, which continues today, began in 1990 as a response to a short-term management problem for the Mark Twain National Forest (MTNF). A mineral lease application in an environmentally sensitive, karstic area in southern Missouri required development of a detailed Environmental Impact Statement. As part of this process CRF undertook to perform mapping and baseline biological surveys for a group of 50 or so MTNF and privately owned caves within and near the proposed lease area. The project was in part an extension of earlier work by GARDNER (1986), who had published fauna lists for a large number of publically owned caves, including some within the lease area. Although Gardner made occasional comments as to species abundance and

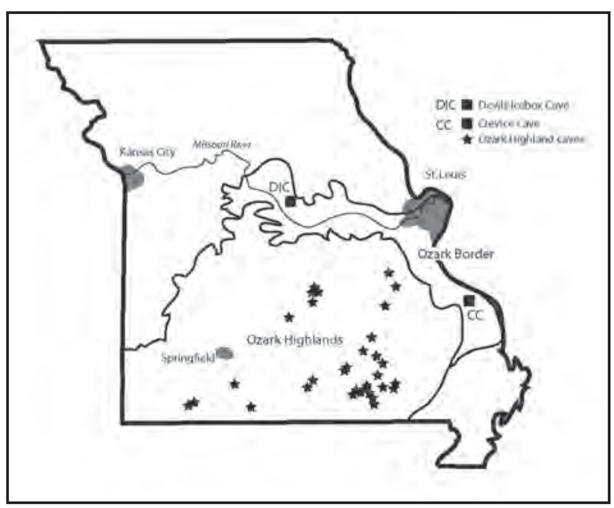

Figure 1: Location of caves contributing to the stream fauna density data. Physiographic provinces adapted from Nelson, 2005.

ecology, no systematic attempt was made to quantify populations. The CRF project was likewise focused on obtaining a quick, once-off assessment of the biological makeup of a large number of caves (SUTTON, 1993, 1998). Nevertheless, some quantification was attempted in that macrofauna – vertebrates and crayfish – were individually counted and, somewhat sporadically, counts were attempted of terrestrial and aquatic invertebrates. After the initial project ended, MTNF elected to continue funding, and to expand the project to other caves within the Forest. MTNF is the largest cave owner in Missouri, with nearly 600 caves currently recorded, and these are distributed throughout the Ozarks. As the project has evolved and matured, simple timed and/ or areal faunal counts have become routine practice (Sutton, unpublished results).

Several other Ozarks Highlands caves were assessed as a result of two short-term projects within Ozark National Scenic Riverways (ONSR), Shannon and Carter Counties. One project was closely tied to the prospecting lease application, which also threatened to compromise groundwater quality within ONSR. Several stream caves were inventoried and semi-permanent stream census plots established in gravel/ rock riffle habitat (SUTTON, 1999). Another project to assess caves subject to high levels of public use also involved some quantitative stream census, generally by timed counts of suitable habitat (SUTTON, 2006).

Caves within the Ozarks Highland province are for the most part in a covered karst setting – the soluble bedrock surface is mantled with a thick layer of residuum consisting largely of clay and insoluble (chert) rock. Open sinkholes are scarce, and cave entrances are generally gravity spring outlets or fossil spring outlets. Water infiltrates the subsurface through the insoluble mantle via cryptic, residuum-filled sinkholes and gravel-covered losing stretches of stream bed (ALEY, 1978). Coarse organic material is almost entirely filtered out, and routine nutrient input consists only of soluble and microscopic material, together with small amounts of coarser material brought into the cave via the downstream entrances by trogloxenes. Periodically, sinkhole collapse occurs by stopping upward through the insoluble cover (GILLMAN et al*.,* 2007), injecting a quantity of forest litter into the system, but although such events are relatively common in Missouri as a whole, they are rare within the watershed of any particular cave stream. The streams typically have a "clean-washed" appearance with little or no particulate organic matter, except near entrances.

In 2002, CRF undertook a project in a very different cave setting. The project was to develop census protocols for an endemic stygobite in Devils Icebox Cave, a large stream cave in Rock Bridge Memorial State Park within the Ozark Border province of central Missouri (Boone County). The cave occurs in a sinkhole plain with very open water input. The future of the "pink planarian" (*Kenkia glandulosa*) was considered questionable owing to water quality issues exacerbated by urbanization of the cave's watershed (FRUEH et al*.,* 2007). Although the focus was on the large, relatively scarce flatworm, the approach was to put *Kenkia* within a broader ecological context by counting all stream fauna. After trying various approaches, the most effective strategy turned out to be focusing census efforts on those types of stream habitat most likely to be occupied by the flatworm. The stream habitat was extremely patchy, with no flatworms and little other fauna observed in pooled sections with fine sediments - rather, flatworms together with stream fauna in general, were strongly concentrated in the relatively limited sections of shallow rocky riffles, provided that rocks in the riffles were not cemented in place by calcite deposition. Several such areas were set up as semi-permanent census plots, covering 5 linear meters of stream bed. The protocol was to count all fauna within each plot (SUTTON, 2004). In 2007–2008, CRF conducted a biological census in another Ozark Border cave in a sinkhole plain in southeastern Missouri (Perry County) (SUTTON, 2008). Crevice is the longest known cave in Missouri (> 40 km), and like Devils Icebox Cave, it is in a mixed agricultural and urban setting, leading to serious water quality issues (POBST AND TAYLOR, 2007).

A practical approach to compare population densities between the two sinkhole plain caves and the Ozark Highland caves was achieved by focusing on the group of *Caecidotea* sp. isopods. There is a suite of 15 species in the Missouri subsurface, 14 of which are stygobites or phreatobites. The exception is *C. brevicauda*, a stygophile which is predominant in the sinkhole plain caves. Being far less troglomorphic than the other species, *C. brevicauda* is easily distinguished at a glance, even in young, small specimens. The various troglomorphic species are almost ubiquitous in Missouri Highlands cave streams, and with the exception of several small species of extremely limited distribution, they are of comparable size. Only two species, *C. antricola* and *C. salemensis*, are widespread and common (ELLIOTT, 2008).

2. Methods

Methods were simple and straightforward. Semi-permanent census plots were established by labeling the downstream end of each plot, which were 3-5 m in length along a stretch of riffle with a high proportion of rock and/ or gravel. The investigator then moved slowly upstream, turning over each moveable rock, sifting through coarse gravel, and visually searching areas of open bedrock or fine sediment, while a note keeper recorded numbers of each species encountered. For the wide stream channels typically found in Devils Icebox Cave, a measuring tape was used as a central dividing line so that two counters could work in parallel. The characteristics of the plots were recorded in terms of percentage of each broadly defined substrate, average width, and average depth of water. For the Ozark Border caves, most semi-permanent census plots were counted multiple times over the period of the respective studies. Counts and the resulting population densities were averaged for each plot, and those means were then averaged to obtain an overall mean population density for rocky riffle habitat in the cave. Ozark Highland cave census plots were counted only once.

Timed counts, usually of 5 or 10 minutes, were also used – these were especially useful in situations where available time was limited, or a suitably extensive continuous stretch of rocky riffle habitat was not available. In the Devils Icebox study, and for some of the Crevice Cave counts, the areal counts were also timed, so that data from timed counts could be directly compared with the counts by area. The timed counts in Crevice Cave were at quasi-random locations outside the fixed census plots; for the Ozark Highland caves the timed counts were also at quasi-random locations. In two caves multiple random counts were conducted; these counts were averaged for each cave, and the resulting means used to calculate the overall mean. Several caves with large gray bat colonies were excluded from the analysis in order to avoid the potential complicating factor of guano input to the system.

3. Results

See Table 1, Table 2, Table 3, and Table 4

Devils Icebox Cave	**Crevice Cave**	**Ozarks Highlands caves**	
	Cottus cf *carolinae* SB?	*Typhlichthys subterraneus* SB	fish
Eurycea longicauda TP	*Eurycea longicauda* TP	*Eurycea longicauda* TP	salamander
Eurycea lucifuga TP	*Eurycea lucifuga* TP	*Eurycea lucifuga* TP	salamander
		Eurycea spelaea TB	salamander
Kenkia glandulosa SB	*Sphalloplana evaginata* SB	(*Sphalloplana hubrichti* SB)	flatworm
Caecidotea brevicauda SP	*Caecidotea brevicauda* SP		isopod
(*Caecidotea* new sp.) SB	*Caecidotea antricola* SB	*Caecidotea* sp. SB	isopod
Bactrurus brachycaudus PB	*Bactrurus brachycaudus* PB	*Bactrurus* sp. PB	amphipod
		(*Allocrangonyx hubrichti* SB)	amphipod
Crangonyx forbesi SP	*Crangonyx forbesi* SP	*Crangonyx forbesi* SP	amphipod
	Gammarus troglophilus SP	*Gammarus* sp. SP	amphipod
		Stygobromus sp. SB	amphipod
Orconectes virilis SP?		*Cambarus* sp. SB	crayfish
Physa sp. SP	*Physa* sp. SP		snail
	Fontigens aldrichi SP	*Fontigens aldrichi* SP	snail
Agabus sp. SP?	(*Agabus* sp. SP?)	(*Agabus* sp. SP?)	diving beetle

Table 1. Cave adapted stream fauna lists for the two sinkhole plain caves and a generalized list for the total of Ozark highlands caves. PB – phreatobite. SB – stygobite, SP – stygophile, TP – troglobite, TP – troglophile. Taxa in parentheses are scarce, and single site endemics for Ozark Highlands caves are omitted.

Plot	**area (m^2)**	**no. of counts**	***Caecidotea* population densities** (animals/ m^2)	**s**	(animals/person-minute)	**s**
1	21	5	65.4	27.5	15.8	6.6
2	15	2	63.5	--	22.4	--
3	12	6	52.4	19.2	8.5	5.0
4	9.5	2	48.2	--	9.7	--
5	9.5	1	54.7	--	8.7	--

Overall population density = **56.8 *Caecidotea*/ m^2**, s = 7.4, cv = 13%;
Overall population density = **13.0 *Caecidotea*/ person-minute**, range = 4.2-37.8, s = 5.9, cv = 45%

Table 2. summary of Caecidotea sp. counts for Devils Icebox Cave. s = standard deviation, cv = coefficient of variation.

Plot	area (m^2)	no. of counts	*Caecidotea* population densities (animals/ m^2)	s
1	1.1	5	45.8	23.8
2	1.75	2	16.2	--
3	2.4	3	23.1	12.5
4	3	3	22.2	15.3
5	3	3	30.1	13.5

Overall population density = **27.5 *Caecidotea*/ m²**, s = 11.6, cv = 42%
Random timed counts: n = 28, mean = **7.9 *Caecidotea*/ person-minute**, range = 0.2-30.4, s = 9.2, cv = 116%

Table 3. summary of Caecidotea sp. counts for Crevice Cave.

County	Cave	County	Cave
Barry	Chimney Rock Cave (BRY018)	Oregon	Pipe Spring Cave (ORE036)
Barry	Mushroom Rock Cave (BRY048)	Oregon	Posy Spring Cave (ORE112)
Barry	Twin Cave (BRY053)	Oregon	River Level Cave (ORE055)
Carter	Blue Spring Cave (CTR022)	Oregon	Statue Cave (ORE092)
Carter	Camp Yarn Cave (CTR003)	Oregon	Walters Cave (ORE020)
Carter	Panther Spring Cave (CTR037)	Phelps	White Pine Cave (PLP094)
Christian	Rattlesnake Cave (CHR013)	Pulaski	Onyx Cave (PUL027)
Douglas	Still Spring Cave (DGL036)	Pulaski	Peninsula (PUL190)
Howell	Crocker Cave (HWL037)	Shannon	Bay Branch Arch Cave (SHN150)
Laclede	Pittman Cave (LAC041)	Shannon	Bounds Branch Cave (SHN222)
Oregon	Bliss Camp Cave (ORE040)	Shannon	Bunker Hill Cave (SHN014)
Oregon	Blowing Spring Cave (ORE111)	Shannon	Jam Up Cave (SHN020)
Oregon	Boze Mill Cave (ORE038)	Shannon	Powder Mill Creek Cave (SHN021)
Oregon	Chaney Cave (ORE082)	Taney	Gilbert Cave (TNY120)
Oregon	Kelly Hollow Cave (ORE007)	Washington	Chimney Cave (WSH015)
Oregon	Falling Spring Cave (ORE022)	Washington	Little Scott Cave (WSH004)
		Washington	Susan Cave (WSH002)

Overall population density: n = 23 caves, mean = **2.6 *Caecidotea*/ m²**, range = 0-11.4, s = 3.8, cv = 146%
Timed counts: n = 12 caves, mean = **0.6 *Caecidotea*/ person-minute**, range = 0-2.3, s = 0.8, cv = 133%

Table 4. Ozark Highlands caves included in population density analysis. Figures in parentheses are accession numbers correlating caves to location and other data in the Missouri Speleological Survey database.

3. Discussion

Table 1 compares community makeup in the two sinkhole plain caves and the Ozark Highland Caves. Note that in the latter case, all fauna is not represented in all caves – the community structure is generally a good deal simpler than the list of potential inhabitants would imply (SUTTON, 1993, 1998; ELLIOTT, 2008). Stream community structure is skewed towards stygobites and phreatobites in the sinkhole plain caves compared with the Ozark Highlands caves. A possibly stygobitic fish, the grotto sculpin (*Cottus* cf *carolinae*), occurs in Crevice Cave but not in Devils Icebox. The fish is slightly troglomorphic, but not nearly as much as the widespread southern cavefish (*Typhlichthys subterraneus*) of the Ozark Highlands (BURR et al., 2001). Troglophilic salamanders of two closely related species, *Eurycea lucifuga* and *E. longicauda*, occur commonly in both Ozark Border and Ozark Highland caves, but a troglobitic salamander, *E. spelaea*, is confined to the Ozark Highlands. Stygobitic isopods (*Caecidotea* sp.), common throughout the Ozark Highlands, are partly replaced by the stygophile *C. brevicauda* in Crevice Cave (32% of > 2000 observations), and almost entirely in Devils Icebox (>99.9%). A new species of stygobitic isopod was discovered in Devils Icebox in the course of the study, but is represented by only a single specimen and a total of two observed individuals. An interesting pattern emerged in Crevice Cave, in that the stygobite strongly predominates in the most upstream reaches of the various streams examined, but is gradually replaced by the stygophile downstream (SUTTON, 2008). The main exceptions to stygobitic paucity in the sinkhole plain caves are the large (up to 3.5 cm) triclad flatworms. These two species together with a third, *Kenkia lewisi*, occur only in Devils Icebox and the Perry County sinkhole plain caves; in the Ozark Highlands, a much smaller species of *Sphalloplana* occurs very sparsely in widely scattered locations. Phreatobitic amphipods -

various species of *Bactrurus* - are relatively common in both settings.

By focusing the population density analysis on *Caecidotea* sp. isopods, the problem of comparing species of widely different size is obviated. For example, the tiny troglophilic snail *Fontigens aldrichi* is numerically the dominant stream animal in Crevice Cave, but is absent from Devils Icebox, and occurs only sporadically throughout the Ozarks. Since *Fontigens* is a good deal smaller than *Caecidotea*, including the snail in the analysis would require a problematic correction for biomass, for which data is lacking. Large animals (fish, crayfish, salamanders) rarely turn up in census plots or random counts, but if there is significant predation pressure on isopod populations from these animals, it could significantly reduce isopod densities, and may be one reason for the high variability discussed next. Ideally, one would like to compare biomass densities, but this would be a difficult undertaking – data on the masses of Ozark cave stream animals is lacking, and it is not obvious how one would adequately assess densities for large, rare animals.

Comparing population densities has a number of obvious pitfalls. The habitat is extremely patchy, and even by excluding all habitats except superficially similar rock/ gravel riffles, species densities vary greatly. There is also considerable temporal variation, as shown by repeated counts of the same plots in the sinkhole plain caves, where the coefficients of variation for isopod density (cv = s/mean x 100%) for multiple counts of the same plot are typically in the range of 50% (36%-69%). Overall coefficients of variation for areal counts in the sinkhole plain caves are 13% for Devils Icebox Cave and 42% for Crevice Cave. By comparison, Ozark Highland caves are much more variable, with counts of zero animals being fairly common, and a cv for the entire set of areal observations of 146%. (Zero density does not imply an absence of isopods from the cave, just from a particular plot). The wide variation potentially makes it difficult to draw conclusions regarding the relative abundance of isopods in the different types of cave. However, the means population density in Ozark Highland caves differs by more than an order of magnitude from those of the sinkhole plain caves, and even with such a wide variability, the ranges of areal isopod densities in the three cases do not overlap:

Ozarks Highlands caves:	0-11.4 isopods/m^2
Crevice Cave:	16.2-45.8 isopods/m^2
Devils Icebox Cave:	48.2-65.4 isopods/m^2

The Devils Icebox study showed that the relative abundance of *Caecidotea* between plots was similar whether plotted by area or by effort. However, Tables 2 and 3 show that the coefficient of variation is considerably higher in the sinkhole plain caves for timed versus areal counts. The differences between the two settings are therefore less clear when population densities by unit search effort are compared, but the range for the Ozark Highland caves still differ greatly (Tables 2-4). It is therefore very likely that isopod abundance is genuinely less in Ozark Highland caves. It is also at least somewhat probable that Devils Icebox Cave densities are significantly higher than those of Crevice Cave.

The relative scarcity of cave stream fauna in the Ozark Highlands is not an unexpected result, given the hydrological differences between the two settings – open sinkhole input in the one case and a combination of diffuse and highly filtered discrete input in the other. In both sinkhole plain caves, and in strong contrast to the clean-washed streams of typical Ozark Highland caves, coarse and fine particulate organic matter are conspicuous components of the stream bed material. Moreover, all of the Ozark Highland caves examined are in relatively undeveloped oak/hickory forest in areas with low human population density. The sinkhole plain caves are both in urban-edge situations with intensive agricultural activity within the caves' watersheds. Although the Ozark Highland have been subject to considerable post-settlement alteration, including a period of widespread deforestation, it is safe to assume that the sinkhole plain cave streams are more severely affected by post-settlement activity. Unfortunately, there are few or no sinkhole plain caves in the Ozark Border province which have not been subject to the effects of agriculture and/ or urbanization. It is therefore impossible to deduce how much of the difference in population densities is due to human alteration of the environment and how much to the geo-hydrological differences between the caves.

Within the Ozark Highlands, stream caves with major gray bat (*Myotis grisescens*) colonies form a special case, in that the resulting guano might render the streams a good deal less oligotrophic. However, the small amount of data on the isopod densities in bat caves collected during these projects falls well within the range of non-bat cave streams (SUTTON, 1993, 1998). In one case where a large colony roosts almost entirely over the water (Bat Cave, Ozark County), the population of twilight zone crustaceans does seem subjectively high, but the effect does not extend into the dark zone, which is upstream from the bat roost (unpublished data). In Turner Spring Cave (Oregon County), and again rather subjectively, the population density of isopods is comparable upstream and downstream from the main bat roost. Possibly, bat guano falling into a cave stream is leached of nutrients rather rapidly, but a good deal more data on bat cave stream communities is required.

In conclusion, the analysis here presented attempts to make a start at putting hard numbers on Missouri cave stream population densities, an aspect of Missouri cave stream ecology which has been largely lacking, and demonstrates numerical differences in the densities of two very different cave settings.

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SPATIAL AND TEMPORAL DISTRIBUTION OF TERRESTRIAL MACROINVERTEBRATES IN LEHMAN CAVES, A TOURIST CAVE IN GREAT BASIN NATIONAL PARK, NEVADA, USA

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Abstract

Monthly macroinvertebrate counts and measures of physical and environmental parameters were used to study the biology and distribution of cave species in Lehman Caves (White Pine County, Nevada), which averages more than 30,000 visitors per year. Counts at paired bait stations (near-trail and far-from-trail) demonstrated that diversity and abundance drop off with increasing distance into the cave. This pattern is correlated with changes in environmental parameters (2 cm soil temperature, air temperature, humidity, lower available nutrients), but also with human visitation levels which decrease with increasing distance into the cave. Analysis of near-trail vs. far-from-trail bait stations showed no consistent differences in abundance and diversity. Measures of physical and environmental parameters in 30 study plots showed an expected distribution of troglophiles nearer to the entrance and troglobites far from the entrance. We were not able to demonstrate that tourist trails in Lehman Caves are affecting the diversity or abundance of the fauna, although two Park-endemic troglobites were more abundant at low impact sites and far from trails. *Microcreagris grandis* (Pseudoscorpionida: Chelonethida: Neobisiidae), presently classified as a troglobite, was found much more commonly proximal to the entrance than in more remote areas of the cave, suggesting possible reclassification as a troglophile. Our results point to the importance of maintaining healthy, low impact areas near entrances of commercial caves.

CONTRIBUTED PAPERS IN CONSERVATION AND MANAGEMENT

DOCUMENTATION OF CAVES AND KARST IN WESTERN AUSTRALIA

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Abstract

In Western Australia, speleologists work in partnership with land managers in relation to the conservation, management and protection of karst systems. This paper will discuss two projects that have involved collaboration and partnerships – between land managers and speleologists. In 2006, the WA Speleological Group (WASG) received funding to undertake research on Christmas Island, off the WA northern coast. Then, in 2007, the WASG participated in a project with the State Government, undertaking local research in karst north of Perth. Both of these projects involved improving land manager awareness of karst systems and important biological values – subterranean fauna and habitats.

The Christmas Island Expedition, involved a team of about 10 speleologists undertaking research on the subterranean fauna of Christmas Island. Christmas Island is located off the north coast of WA, and although considered the legal responsibility of WA, it is managed by Parks Australia North. The team were on the island for a month, visiting a number of caves on a regular basis, documenting fauna and collecting specimens that were then examined by the WA Museum. The team visited and relocated all known karst features and also discovered and described several new karst features.

The *Hidden Treasures* Project studied the biodiversity of the Northern Agricultural Region (NAR). Caves and their associated biodiversity were one type of natural asset being considered. The 2007 Subterranean Biodiversity Inventory was a key component of the *Hidden Treasures* Project. The project aimed to collect information to allow the highest priority conservation areas in the NAR to be identified and to assist in the development of a Biodiversity Conservation Plan. The study was funded by the Northern Agricultural Catchment Council (NACC) and delivered by the Department of Environment & Conservation in association with the Australian Speleological Federation (ASF). Fauna sampling within caves focussed on invertebrate populations and revealed a diverse assemblage of organisms. Several teams of speleologists assisted in field trips over the year.

PRELIMINARY STUDIES ON SOIL EROSION INTENSITY GRADING IN SOUTHWEST KARST AREA, CHINA

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The concentration of insoluble matter in carbonate rocks is very low in southwest China. Consequently, soil formation is slow and soil layers are usually thin on karst slope. The results from remote sensing and monitoring sites show that soil loss intensity is mostly weak and light. In fact, the area of rock desertification in karst regions, is continuously increasing, with the soil eroding and the ecological situation becoming worse. The traditional standard for soil erosion gradation is confronted with challenge. Risk valuation and intensity classification of soil erosion in karst region should be redefined. Depending on the factors of limestone formation and carbonate rock dissolution, related data and images have been collected. With the help of ArcView3.2, the rate of limestone soil formation can be produced. By also considering a soil loss tolerance, a new standard for soil erosion gradation suitable to karst region can be put forward. The duration of feeble, light, middle, strong, very strong, and acute soil loss gradation, is <30, 30~100, 100~200, 200~500, 500~1000, and >1000t/(km^2·a), respectively. On the basis of features of soil loss processes and the karst environment, four suggestions for soil protection in karst region are brought forward: (1) depending on the karst hydrological structure, the key part to prevent the soil loss from surface to ground, is the sinkholes and dolines, and effective measurement for soil protection should be taken; (2) on karst hill, in top part, the carbonate rock is largely exposed with little soil cover, the way to close hillside to facilitate afforestation can be selected; the middle slope part, the rock desertification is middle gradation, to build the wall and prevent the soil loss, and planting the economic plants to increase the land productivity, should be suitable measurement; in the foothill part, thick soil layer and little rock, the farmer land construction, modern agriculture activity and food production are taken; (3) in the karst region with thin soil layer, biogenic fence technology is advocated, shrub species are recommended, particularly shrubs belonging to the C4 plant with high photosynthesis capacity and bean family with nitrogen fixation. Moreover, they have flourishing roots to bear drought and poor habitat; (4) limestone soil is characterized by high calcium content and alkaline. The high calcium level activates many nutritional functions. The effective soil improvement can enhance agricultural productivity.

1. Introduction

In the factors that affect ecosystem formation and evolution, the climatic and hydrological elements are long-term and slow driving forces shaping the ecosystem, while geological and geomorphological factors are the carrier and material foundation of ecosystem existence and development (LIU Yanhua et al., 2001). Most of the parent rock of soil formation are hard and thick carbonate rock in the southwest of China, and the concentration of acid insolvable matter in carbonate rock is very low, so the speed of soil formation is very slow (YUAN Daoxian et al., 1988). The depth of soil layer is usually only 10 to a few dozens centimeters, and the soil drains away to become rock desertification after a few heavy rains without covering vegetation. After evaluating the harm of soil erosion, the new standard for soil erosion gradation that is suitable to karst regions should be put forward. According to the scientific data collected during scientific surveys on soil erosion and ecological safety conducted by the Ministry of Water Resources, the Chinese Academy of Sciences, and the Academy of Chinese Technology in 2006–2007, and mechanism studies on karst dynamic systems, the preliminary standard for soil erosion gradation suitable to the southwest karst region has been put forward.

2. Process and Impacting-Factor of Soil Formation

WANG et al.'s (1999) research data on five limestone soil profiles in Guizhou and Hunan provinces, showed the geochemistry process of carbonate rock being eroded to form limestone soil following two stages: carbonate rock dissolution and acid insolvable matter transform to soil.

2.1 Content of acid insolvable matter in carbonate rocks

There are much data showing that carbonate rock dissolution is impacted by rock and mineral types and structure and chemical component. For example, in the Guilin karst area, the carbonate rocks are the pure and thick layer limestone rock in the Devonian through Carboniferous Periods. The results of carbonate rock dissolution experiment on samples from 103 different strata indicate that in the pure carbonate rocks, dissolution rate has positive correlation with the CaO content in the rocks and negative with MgO content; in the impure carbonate rocks, the physical destruction increased due to the addition of acid insolvable matter, but the rate of chemical dissolution reduced (Weng et al., 1987).

Nie (1994) collected 124 carbonate rock samples from Cambrian, Ordovician, Devonian, Permian, and Triassic beds and the results of carbonate rock dissolution experiments show that in the pure carbonate rock, the relative dissolutional rate decreased as Mg content increasing, from 0.96 for pure limestone to 0.50 for pure dolomite; in the impure carbonate rock, the relative dissolutional rate decreased as acid insolvable matter content increasing, from 0.96 to 0.52 for limestone with different acid insolvable matter content, and from 0.50 to 0.26 for that of dolomite.

2.2 Condition of hydrodynamic and hydrochemistry

Carbonate rock dissolution is a typical interaction between water and rock. There is a diffused- boundary level (DBL) (Liu et al., 2000a) between solid carbonate rock and water interface. As the rate of the flow increasing, the DBL becomes thin, and the carbonate rock dissolution rate increases.

Liu et al. (2000b) conducted a test to quantify the allogenic water erosion capability at Yaoshan, Guilin. The dissolutional rate of pure limestone of Rongxian group in Devonian was 1,000–1,500 mm/ka, 10-15 times higher than that of limestone water. Meanwhile, it was proven that the dissolution rate of pure limestone in flow-water at the speed of 20 cm/s and 60 cm/s was two and six times that of non-flow water, respectively.

2.3 Temperature and precipitation

Temperature and rainfall are the most important factors on the carbonate rock dissolution because the amount of rainfall influences the hydrological and runoff conditions and the temperature influences bioactivities and exchange rate between water and CO_2. Most of the prevailing mathematic models were made in the past. Liu (2000b) established linear correlation between carbonate dissolution rate and runoff:

$$D_R=0.0544(P-E)-0.0215 \quad r=0.98$$

where P is rainfall(mm), E is evaporation(mm).

Pulina(1974)established the relationship between dissolution rates, temperature, and rainfall utilizing a large set of data. The relationship is that the influence of the rainfall change on dissolution rate will be weak at lower temperatures, but the dissolution rate would increase rapidly with the increase of rainfall at higher temperatures (16-20^{o}C).

2.4 Biological activities

In the earth surface system, the biosphere links up the entire system by exchanging and transferring matter and energy with adjacent spheres (Golubic et al., 1978; Zhang, 1992). Organisms are one of the most active geological agent in the Earth Surface System (Yin, et al., 1994). Organisms could stimulate carbonate rock dissolution, mainly through the metabolic activities of vegetation and microorganisms to produce high concentration of CO_2 and erosive secretion. The results of the simulated test by Cao et al. (2004) show that different vegetation covers lead to carbonate rock dissolution difference. The dissolution rate under the system of tree-soil-rock with flourishing root is 3.84 times higher than that of soil-rock and 2.36 times higher than that of herb-soil-rock. Jennings (1985) found that soil-vegetation cover enhanced the carbonate rock dissolution when he collected data and established the relationship between the dissolution rate and the average annual runoff from different countries.

3. Estimation of Soil Formation Rate

3.1 Methods

Carbonate rock soil formation closely correlates with carbonate rock dissolution and its content of acid insolvable matter. Therefore, a mathematical regression equation could be established depending on the limestone dissolution rate of typical sites. The collection impact-factors on limestone soil formation including lithology, temperature, precipitation, net primary productivity of vegetation, and soil respiration. We calculated the spatial distribution of carbonate rock dissolution rate with the regression equation by comprehensive influence from the difference of carbonate rock lithology and the hydrological conditions. And then, we estimated the soil formation rate of the carbonate rock by adding content of acid insolvable matter and dissolution rate together.

3.2 Data collection and processing

The data were collected from the region of southwest China karst, including east of Yunnan, Guizhou Province, and Guangxi Province. The soil area is 553 thousand km^2, the limestone area is 2555 thousand km^2.

Lithological type, combination and distribution: Carbonate rock types and distribution are shown on the geological map along with detailed stratum descriptions (Fig.1). The figure shows that continuous limestone and limestone-dolomite are mainly distributed in the east and southeast of Yunnan, the southwest of Guizhou and Guangxi; dolomite are mainly in the northeast of Guizhou, meanwhile, the dolomite usually interbedded with limestone and clastic rocks; impure limestone in the northeast of Yunnan.

Content of acid insolvable matter: The most data on the composition of acid insolvable matter in carbonate rocks are from Institute of Geology, the Chinese Academy of Sciences(Karst Research Group from the Chinese Academy of Sciences, 1979). The carbonate rock in the east of Yunnan are Permian and Triassic limestones Their composition data for acid insolvable matter came from Wang et al. (2003). The carbonate rock in the south of Guizhou Province and Guangxi Province karst region are pure, blocky, thick limestone from the Carboniferous and the Devonian Periods. Data on their acid insolvable matter composition came from Weng et al. (1987).

Temperature and precipitation and hydrological condition: Temperature and precipitation data are from the average temperature and precipitation grid image of 1993-2000, provided by the Chinese Academy of Sciences.

In the research region, there are 3 different hydrological zones from west to east: Yunnan-Guizhou Plateau, Guangxi Basin and the slopes transition zone between them.

(1) Yunnan-Guizhou Plateau: Gradient ratio of surface and underground rivers is small, with slow water flow, thick DBL. Therefore, the intensity of carbonate rock dissolution decreases.

(2) The slopes transition zone: Gradient ratio of surface and underground rivers is large, the altitude has a big difference, water cycle is fast in both vertical and horizontal directions, and with thin DBL. Karst processes are enhanced.

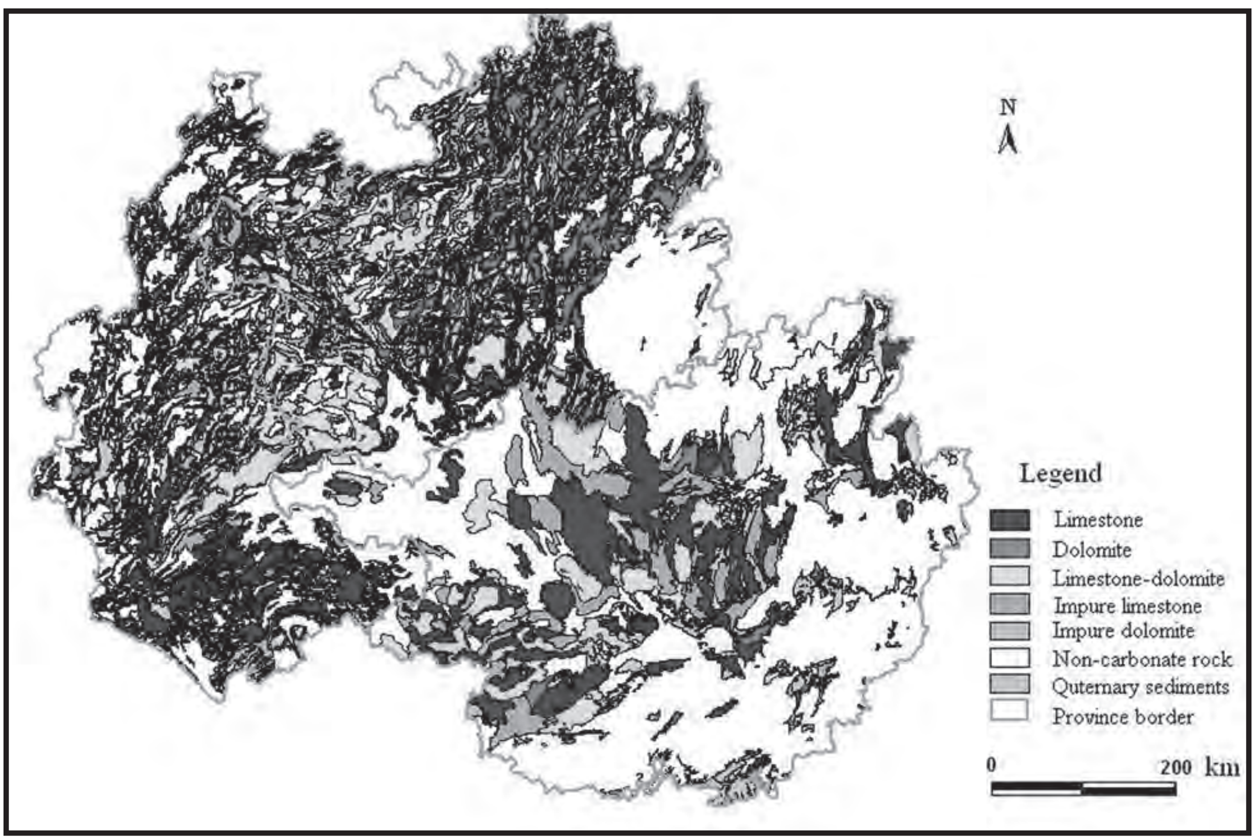

Figure 1: Geologic map of research area showing carbonate rock outcrop.

(3) Guangxi Basin: the basic condition for karst processes is characterized with low elevation, gentle water flow gradient, and long time of water-rock interaction. As with high precipitation, the water flow is fast with thin DBL. The karst process is also accelerated.

In the research region, limestone, dolomite, and clastic rocks are interbedded in the middle and the northeast of Guizhou Province; impure limestone and clastic rocks are interbedded in northwest Guizhou Province and in northeast Yunnan Province. Allogenic water from clastic regions with low-pH strongly accelerates carbonate rock dissolution.

Biological activities: The biological activities on carbonate

Region	Site	P/mm	T/°C	N_{pp}/gC·m^{-2}·a^{-1}	S_r/gC·m^{-2}·a^{-1}	Ldr /mm·ka^{-1}
East of Yunnan	Mengzi	1058	18.1	316.5	1179.2	41.1
	Mile	884	16.5	244.8	1365.8	30.0
	Qujing	1030	14.6	190.0	1352.4	45.0
	Luoping	1492	15.1	202.8	1498.1	65.0
	Huyuan	1332	15.0	190.4	1446.2	50.0
	Lunan	932	15.3	219.6	1344.1	32.0
	Tonghai	880	15.9	196.3	1339.6	30.0
Guizhou	Libo	1194	17.9	1116.2	309.4	65.5
	Qinglong	1407	14.5	268.3	1445.8	55.0
	Anlong	1260	16.1	203.7	1502.5	60.0
	Ziyun	1203	16.0	194.5	1487.5	50.0
	Guanling	1342	15.7	208.4	1496.6	50.0
	Zhengfeng	1290	16.6	229.6	1527.4	70.0
	Luodian	1182	18.9	222.6	1605.7	55.0
	Guiyang	1112	14.9	248.2	1398.1	44.5
	Wuchuan	1094	16.0	245.0	1438.1	36.1
Guangxi	Huanjiang	1338	19.1	313.3	911.5	59.1
	Yongfu	1702	19.0	498.1	1759.9	60.0
	Yizhou	1321	20. 2	304.4	1733.9	55.0
	Liucheng	1372	20.0	421.5	1733.5	55.0
	Liuzhou	1362	20.6	398.8	1745.5	56.0
	Tian'e	1377	19.9	226.9	1721.4	50.0
	Duan	1496	20.9	264.7	1814.5	80.0
	Longlin	1158	18.6	297.1	1577.6	70.0
	Mashan	1542	21.4	344.5	1842.1	80.0
	Shanglin	1559	21.0	365.7	1845.8	65.0
	Luzhai	1481	19.7	474.7	1747.8	54.0
	Xincheng	1379	20.8	283.9	1778.9	60.0
	Gongcheng	1452	19.4	470.5	1718.6	60.0
	Rong'an	1622	19.2	455.6	1755.3	70.0
	Rongshui	1438	18.8	422.5	1671.9	70.0
	Nandan	1355	19.4	211.9	1708.9	50.0
	Guilin	1703	18.9	383.0	1753.3	89.7

Note: the data of the table is from Jiang et al. (2000); Zhu et al. (2008); Fang et al. (1993

Table 1: Limestone dissolution rate and relative temperature, precipitation, net primary production of vegetation and soil respiration rate of typical sites in southwest karst region, China.

rock dissolution are mainly through production of high CO_2 concentration in soils and secretion of erosive organic matters, such as organic acid, enzyme and chelate compound (Cao et al., 2000a; 2000b; Liu, et al., 2001). The influence also can work via biophysical and biochemical processes (Cao et al., 1999). Soil respiration (S_r) is a good index for ecosystem metabolic activity including plant roots respiration, soil microorganism respiration and oxidation, and decomposition of soil organic matter (Pan, 2001). The net primary production of vegetation (N_{pp}) is the amount of organic matter through photosynthesis by producers, minus organic matter consumed by plant metabolism. What remains can be used for plant growth and reproduction, and by other animals and microorganisms. The N_{pp} of vegetation is the important index maintaining and promoting the progress and evolution of ecosystem (Sun et al., 1993). The images of soil respiration and the N_{pp} of vegetation were provided by Institution of Geography Science and Resource, the Chinese Academy of Sciences (Company of Zhongkeyongsheng, Beijing).

Data collection from typical sites: The data of limestone dissolution rate (Ldr) were collected from the research area and the relative data including the precipitation(P), temperature(T), net primary productivity(N_{pp}) of vegetation, and soil respiration(S_r) were obtained (Table 1).

4. Soil Tolerant Loss and Erosion Intensity Gradation

The soil tolerant loss was calculated by the process as follows.

4.1 Producing the image of limestone dissolution

According to the data from Table 1, the regression equation was calculated to a confidence level of 95%, with the help of EXCEL2003.

$$D_R=0.038P+0.071N_{pp}-2.758T-0.029S_r-48.002 \ (r=0.66)$$

Where D_R is dissolution rate (mm/ka); P is annual average precipitation (mm); T is annual average temperature(°C); S_r is soil respiration (gC/m^2·a), N_{pp} is net primary production of vegetation(gC/m^2.a).

With the help of ArcView3.2, the image of limestone dissolution rate can be produced.

4.2 Image of soil formation rate

The soil formation rate was influenced by carbonate rock type and the content of acid insolvable matter. The dissolution rate of limestone is about two times higher than that of dolomite. But, the dolomite readily weathers

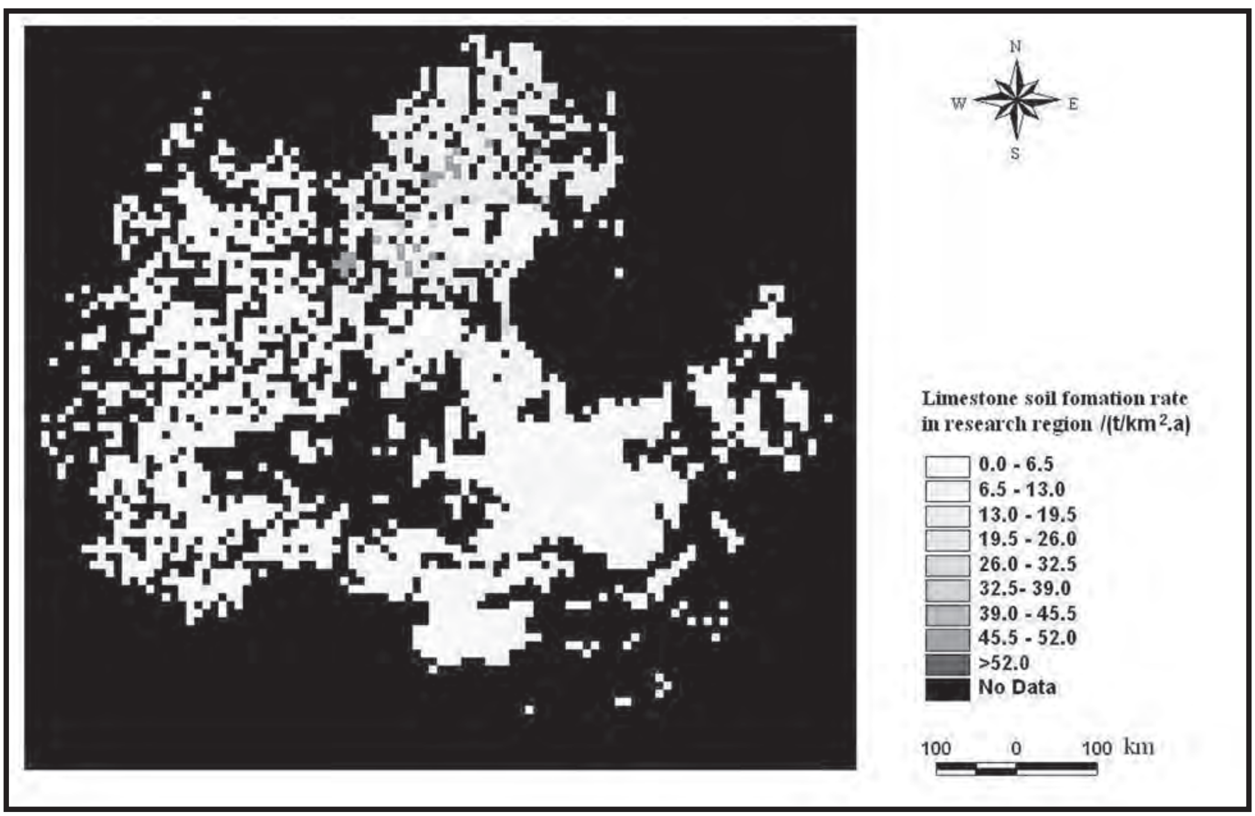

Figure 2: Limestone soil formation rate in research area.

physically to produce dolomite sands, which can become the mechanical component of soil. The rate of dolomite physical weathering is 4-5 times higher than that of limestone. Therefore, under the same condition of acid insolvable matter and others, the rate of soil formation in dolomite terrain is 2-2.5 times higher than that in limestone areas.

Comprehensively considering the influence of stratification of dolomite and limestone and allogenic water from clastic rock area, the rate of soil formation in the middle-northeast Guizhou, 2.5 coefficient was added. And then with the help of ArcView3.2, the image of the soil formation rate was produced with the grid image of acid insolvable matter folded to the grid image of limestone dissolution (Fig.2).

Figure 2 shows in northeast Guizhou, where the conditions of soil formation are relatively superior, the maximum soil formation rate is 40~120t/(km^2·a), while it is just 4~20 t/(km^2·a) in more than 70% of the other study areas. The average rate of 30~40 t/(km^2·a) is defined as the soil tolerant loss. Li et al. (2006) estimated the soil tolerant loss in karst region of Guizhou as 6.84~103.46 t/(km^2·a).

4.3 Soil erosion intensity gradation

According to SL 190-1996 "Standard of Soil Ersion Gradation" (SSEG), the soil tolerant loss of different types of erosional areas are 200 (northeast blackland region and north soil-rock region) to 1000(northwest plateau) t/(km^2·a). Based on this standard, the lower limits of "light" degree are difference for various soil erosional regions, but the upper limit all are 2500 t/(km^2·a). This standard could not be adopted in southwest karst area. Thus, a new standard suitable to a karst region is needed. Depending the above results, the duration of feeble, light, middle, strong, very strong and acute soil loss gradation is <30, 30~100, 100~200, 200~500, 500~1000, and >1000t/(km^2·a), respectively. The gradation is compared with past standards (Table 2).

5. Evaluation on Soil Erosion and Suggestion

The rain water goes to underground directly through the sinkholes and dolines, on account of the hydrogeologic structure with upper-under ground double layers. The typical soil erosional process starts with soil falling to underground rivers then emerges back in a surface river. While in the non-karst region, the surface river system developed. The typical soil erosion is that the soil is eroded down the hillside surface with water flow, then goes into the surface river directly.

5.1 New requirement of soil erosion hazard evaluation

Beyond soil fertility declined, soil layer thinning, and river channel blockage, soil erosion in the southwest karst region of China causes rocky desertification formation. Consequently, evaluation of soil erosion hazards in karst region should be worked out in two stages: 1) on the premise of soil-covered karst, evaluated with the soil erosion coefficient; 2) when gave soil loss has occurred and rock is exposed (shi-ga-la land), evaluated with the ratio of the rock desertification area.

5.2 Suggestion

On the basis of the particulars of soil erosion processes and mechanisms in karst regions, we put forward countermeasures for soil conservation. Four suggestions for soil protection in karst region are brought forward:

(1) Depending on the karst hydrological structure, the key part to prevent the soil loss from surface to ground is at sinkholes and dolines, and effective measurement for soil protection should be taken.

(2) On karst hill tops, where the carbonate rock is largely exposed with little soil cover, closing hillsides to facilitate afforestation can be helpful; the middle slope part, the rock desertification is middle gradation, to build the wall and prevent soil loss, and planting economic plants to increase the land productivity, should be suitable measurement; in the foothill part, thick soil layer and little rock, farm land construction, modern agriculture activities, and food production are conducted.

Gradation	feeble	light	middle	strong	very strong	acute
SSEG	<200,500,1000	200,500,1000~2500	2500~5000	5000~8000	8000~15000	>15000
Cai(1989)	<68	68~100	100~200	200~500	≥500	
Wei(1996)	<50	50~100	100~200	200~500	500~1000	≥1000
Wan, et al(2003)	<46	46~230	230~460	460~700	700~1300	≥1300
authors	<30	30~100	100~200	200~500	500~1000	≥1000

Table 2: Preliminary standard of soil erosion intensity in southwest karst region, PR China, t/(km2•a).

(3) In the karst region with thin soil layer, biogenic fence technology is advocated, shrub species are recommended, particularly some shrubs belonging to the C4 plant with high photosynthesis capacity and bean family with nitrogen fixation. Moreover, they have flourishing roots to bear the drought and poor habitat.

(4) Limestone soil is characterized by high calcium content and alkaline. The high calcium level activates nutritional productivity. The effective soil improvement can enhance agricultural yield.

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RESEARCH PRIORITIES FOR UNDERGROUND ECOSYSTEMS IN COLOMBIA

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Abstract

Cave research in Colombia has been developed mostly as an occasional activity since the beginnings of the XX century, and throughout the Andean cordillera. Just during the last three decades there has been some development of systematic efforts about the subject, and recently they have received the benefit from the Convention on Biological Diversity (CBD) principles of conservation and sustainable use, applied to underground ecosystems. The road has not been easy, although plenty of pleasant moments. What have we accomplished? First at all, 130 reported cave systems, with just 6% of them with topography, 10% with some geology, and less than a third with some fauna and flora information. Despite the available data, they have not been used for conservation or sustainable use purposes, which should be the goals for the next decades. We suggest a regional planning approach, but beforehand, a specific policy development for underground ecosystems, something missing in the Colombian environmental law. There are unsolved questions about the property of cave systems (public or private), and rules for its management, that must be adopted by the Ministry of Environment, Housing and Territorial Development, as well as the regional environmental authorities in Colombia and other stakeholders. We are proposing to complete a "National Strategy for the Conservation of Colombian Caves and other Underground Ecosystems" within the frame of the National Biodiversity Policy initiative that is being developed at the ministerial level, together with a Biodiversity National Action Plan 2009–2019 in perspective.

A CAVE SURVEY FOR RESEARCH AND TOURIST CAVE MANAGEMENT

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The Jenolan Caves Survey Project Group is preparing a 'State of the Art' survey of the Jenolan Cave System, New South Wales (NSW), Australia. The survey has a number of potential uses but this paper only discusses those pertinent to speleological research and tourist cave management.

The survey is a total station traverse through the main tourist routes. Less accurate survey instruments were used elsewhere. All entrances were linked using a surface theodolite network that was tied in to the Australian Map grid using differential GPS. The surface network is critical to tying the entrances of the cave system together, proving the accuracy of main tourist loops and fixing underground data to the map grid allowing GPS use on the surface. Radio location equipment was used to check selected less accurate traverses. The Walls cave-surveying program developed by the Texas Speleological Society was used for reduction of the cave survey data. Walls was chosen because of its features: simple text file input and Scalable Vector Graphics (SVG) output that can be imported directly into Adobe Illustrator. Other useful features are XYZ coordinates output, SVG round tripping and SMAPS Exchange File. Computer drafting was performed using Adobe Illustrator as it uses brush and symbol libraries to provide a consistent style. Details such as geology, mineralogy, infrastructure, lighting and text are placed on separate layers. These layers are maintained when exported to Adobe Portable Document Format (PDF). Throughout the system, permanent-survey stations have been placed as aids for passage sketching, research and management use. A private contractor has carried out an aerial survey with a resolution of five meters of the general area. From this a 3D map of the area has been produced with the caves below the surface terrain. The cave coordinates have been used to find the points on the surface above underground features using a GPS.

Uses of the survey are illustrated. The 3D map has been used to show the relationship between the cupolas in an area of the cave that has been formed by rising thermal waters. The surface location of these features and their depth below the surface has been obtained from the survey plan and GPS studies. GPS studies also allow the depth to be calculated for drip sites that have been sampled and analyzed for their water chemistry. The survey plan, GPS and radio location were used to establish the route that the fossil jaw bone of a Diprotodon, a species of Australian mega fauna extinct for some 30,000 years, entered the cave. For general management of the caves the survey plan is the most useful. The Adobe Illustrator files have additional layers that may be devoted to any particular task such as speleothem cleaning or infrastructure changes such as re-lighting a cave. The plan and the contour map of the surface have been used to assess the impact of a car park on the cave that it partially covers. However, for showing what tourists will encounter on a traditional cave tour or cave adventure tour, a developed long section of data and sketches is best.

1. Introduction

In 1986 the Jenolan Scientific Advisory Committee established that a complete high-grade survey of the Jenolan Tourist Cave System (New South Wales, Australia) was required. The survey was needed to allow scientific studies, notably of the geology and hydrology, to be adequately interpreted (James et al., 1988). The Jenolan Caves Survey Project Group undertook to prepare a 'State of the Art' survey of the Jenolan Cave System. In addition, the committee felt that the survey would be a useful aid to cave management and development decisions. The proposal to survey the tourist caves and connected wild caves was endorsed and supported (without financial commitment) by the Jenolan Caves Reserve Trust. The surveying project commenced in 1987. The Jenolan Tourist Cave System has historically been considered to comprise a number of almost separate 'caves' although they are the sections of one cave system. The names of these 'caves' are used here when discussing the survey as they divide the cave system into manageable sections for surveying, management and publication. This paper focuses on the detailed survey of the tourist cave section which comprises approximately one third of the 20+ km system.

The tourist sections within the Jenolan Cave System are complex: parts are a 3D maze, in other areas boulder collapse dominates and there are many entrances. The field work for the initial surveying exercise was undertaken between 1987 and 1990. Although the early traverse data was of the highest standard, the cave map when drafted was little more than a record of the work reflecting a wide range of sketcher's abilities and hence could only be used to answer minor management questions. The traverse data was never published in an accessible format for use by research workers. The project was re-initiated in 2005. As survey data reduction and computer drafting software had advanced considerably the project was recast to take advantage of a mixture of free and commercially available software in order to produce a 'state of the art' cave survey that could be used for research and tourist cave management.

2. Instruments and Methods

2.1 Underground field measurements

The 1987/90 survey through the tourist routes is a total station traverse. A non-magnetic technique was necessary because of interference from cave furniture and power supplies. A Sokkisha total station with an SDR2 electronic field book, data logger/computer was used. This instrument has infra-red electronic distance measurement (EDM) and a resolution of 1 mm for distance and one second for angles. In terms of accuracy, the standard deviation is +/- (5 mm + 3 ppm) for distance measurement and +/- 4 seconds for angles. The Sokkisha computer calculates rectangular station coordinates as each leg is surveyed. These were recorded in the data logger's memory (subsequently down loaded to a PC) and on booking sheets by a recorder. In some areas less accurate survey instruments were used. These are listed in Bonwick et al. 1988 with their method of use and calibration. The Sokkisha was also used to take the large number of measurements required for the 1:200 contour maps of the large chambers.

2. 2 Surface field measurements

All entrances to the system were located using a surface theodolite network. This allowed the accuracy of main tourist cave loops to be proven and once converted to map grid coordinates allowing GPS use on the surface. An important difference of the surface survey from the underground survey was the use of triangulation (and trilateration - measuring distances). In contrast the underground survey was almost entirely traversing, i.e. progression from station to station one leg at a time. Because of the relatively long survey legs involved in the surface survey (up to 850 m), it was desirable to establish a network of stations where the connecting legs form a series of braced figures. To illustrate: a rectangular figure where the diagonals have also been measured is a mathematically stronger figure, than one where only the sides have been measured. Surface survey stations are typically marked with a drill hole and wing; a surveyor's peg or a New South Wales state survey disk.

2.3 Survey station recording

In 2005, the initial five digit system for station numbering designed to prevent duplication of survey station numbers was replaced with a six digit system that contained two letters that allowed the data to be identified to a specific 'cave'. The survey stations also needed to be recovered. At times, this required considerable effort as the original markers had disappeared. Passage junction stations were marked with 30 mm stainless steel disks stamped with the six digit survey station numbers and fixed with stainless steel screws and epoxy. All survey stations have been photographed and a digital photograph library compiled to assist in relocating stations for passage sketching, research and management. Station locations have also been recorded by sketches giving the distance from the nearest infrastructure such as handrail posts and stairs.

2.4 Reduction of field data

The early data had been reduced and traverses plotted using both mainframe computers and PCs involving a complex series of steps and programming (Bonwick et al. 1988). By 2005, survey reduction programs had advanced and become more numerous and many were freely available. For this project several such programs were considered, resulting in the choice of Walls, a cave-surveying program developed by the Texas Speleological Society

(www.utexas.edu/tmm/sponsored_sites/tss/Walls/). It features simple text-file input and Scalable Vector Graphics (SVG) output that can be imported directly into Adobe Illustrator. Other useful features are XYZ coordinates output and SVG round tripping. Walls allowed traverses to be produced both as profiles and plans. The program also closes traverse loops. However, particular care has had to be taken where a loop contains both high and lower accuracy data. The loop is closed on the basis that any adjustment is restricted to the lower accuracy legs. This is justified as closure errors in loops surveyed entirely with the Sokkisha total station are typically less than 50 mm. The high grade total station survey effectively constrains the coordinates of many junctions in the complex network resulting in the closure problem being reduced to fairly small partial loops. The survey was originally based on an arbitrary coordinate system with magnetic alignment. In 1998 Australian Map coordinates were established for two points in the Jenolan area using differential GPS (part of a topographical mapping exercise commissioned by the Jenolan Caves Reserve Trust). The surface network was extended to pick up these two points thus allowing the surface and underground surveys to be tied to map grid coordinates, currently the Australian Geodetic Datum 1966 (AGD66) coordinates. However, today the datum for mapping is the Geodetic Datum of Australia 1994 (GDA94). The project has plans to convert to GDA94.

2.5 Sketching

In the 1987/90 survey the sketchers accompanied the surveying teams. The Sokkisha total station provided instant XYZ coordinates which allowed the sketcher to plot to scale. Despite this when the archived sketches were examined most were found to be lacking. In 2005, the decision was made to re-sketch the entire tourist cave routes in a separate exercise. The sketchers worked from a 1:200 scale traverse line. The widest section of the passage or chambers was used as the limits of the cave walls with the conventional methods of representing overhangs and ledges. Ideally a sketcher would have had one or more assistants and a laser distance measurer. They drew their rendering of a plan in the cave and at each marked station drew a cross section of the passage. This sketch was drafted, then printed to scale and taken back into the cave for checking and the addition of further detail.

When re- sketching commenced the following was observed:

- The total station survey had too many long survey legs to adequately sketch from (survey legs had initially been maximized). Infill survey legs were required. These were a lower survey grade but in the view of the sketchers, "the shorter the better".
- The tourist cave paths, stairs and viewing platforms if surveyed in were of immense value to the sketcher.
- Infill stations, platform and stair locations were located using triangulation methods. Hand held laser EDM units, steel tapes and handyman laser levels facilitated this work.
- During the period of re-sketching many of the hand rails in the caves were replaced by stainless steel and provided they were used with caution, magnetic bearings could be taken and plotted to assist the sketchers
- Not all cavers have the ability to produce a suitable sketch: that is one that can be first interpreted by a draftsman, checked, and used by others.

To produce developed long sections, the profiles of the caves were sketched along the traverse lines.

2.6 Computer drafting

The initial plan was hand drawn on Mylar film in black ink at a scale of 1:200. It was limited by the quality of the sketches available to the draftsman. Adobe Illustrator allowed the current survey to be drafted in color. First drafts of the sketches could be prepared by a number of draftsmen using Illustrator brush, swatch and symbol libraries to provide a consistent style. These libraries were based on the UIS survey symbols as published by the UIS surveying commission (www.carto.net/neumann/caving/cave-symbols/). A number of modifications were made to the set with special symbols added when required. The master plan of the tourist caves is kept by one person to ensure that the drafting of the entire map is consistent. The Illustrator layer and sub-layer construction has been used extensively to separate the component caves on the master plan and their associated details such as geology, mineralogy, infrastructure, lighting and text. One level of these layers is maintained when exported to Adobe Portable Document Format (PDF). When additional work is carried out in the cave the most recent version of the master plan is used to produce maps for us in the cave and then the information obtained is up dated on the master plan.

2.7 Preparation of 3D Models

The surface and caves require different treatment. The 3D cave models were constructed using custom software to generate VRML files based on the cave survey and left right up and down data. DEM data (altitude points on a regular grid) was used to produce a surface to put into the VRML file along with the cave 3D data. VRML allows a map, air photo, Google earth photo or other graphic file to be pasted onto surface. Although aligning the photo to the surface can be problematic. This VRML file is then processed into Acrobat Professional Extended which gives a product that can be viewed on any computer with Acrobat Reader.

2.8 Preparation of "high resolution" 3D cave models

A 3D cave model generated from left right up and down data gives a general idea of cave passages, but it over-simplifies the cave. To get a better result more cross section data is required. The number used for this project was 12 points. These were taken using a pole that could be leveled with a board at its top marked with 12 white lines radiating at 30 degree increments from its centre. The length of the pole was adjustable to allow the marked card to be as near as possible to the center of the passage, but still reachable. The white lines were used as guides to angle the laser distance measurer attached the centre of the board. The survey legs need to be short and depending on the situation. Where the total station survey leg was along a flat surface for example on the tourist paths a tape was stretched between existing stations and the 12 point data taken at regular intervals or where there was a significant change in passage shape or size. The distance along the traverse line was noted and the data given the same bearings as the traverse line. The alternative is to run a completely new survey line with short legs down the centre of the passage tying its ends into the total station survey stations. The 12 point survey data is input into an Excel file that outputs data in a simple 3D format that can be imported into AC3D. Once in AC3D the results can be edited to tidy up poorly defined corners and a smoothing process run to round off sharp edges. Finally the AC3D model is output as VRML and integrated with the rest of the 3D model prepared as described above.

2.9 Data organization and archiving

All original data, line drawings and photographs are digitized and filed either with respect to cave and/or station number. The computer reduced material and map drafts are backed up on two external hard disks which are kept in separate locations. All maps will be presented to the Jenolan Caves Reserve Trust in soft copy so that they can be used for management purposes. It is proposed to publish the cave and surface maps as a special addition of Helictite, the Australasian Journal of Cave Research. All maps and data will be available to researchers.

3. Results and Discussion

3.1 The plan

The plan of the tourist Caves fits on a sheet 5 m x 1.5 m at a scale of 1.200. Individual cave plans and cross sections have been printed at 1:200 and have been already used for

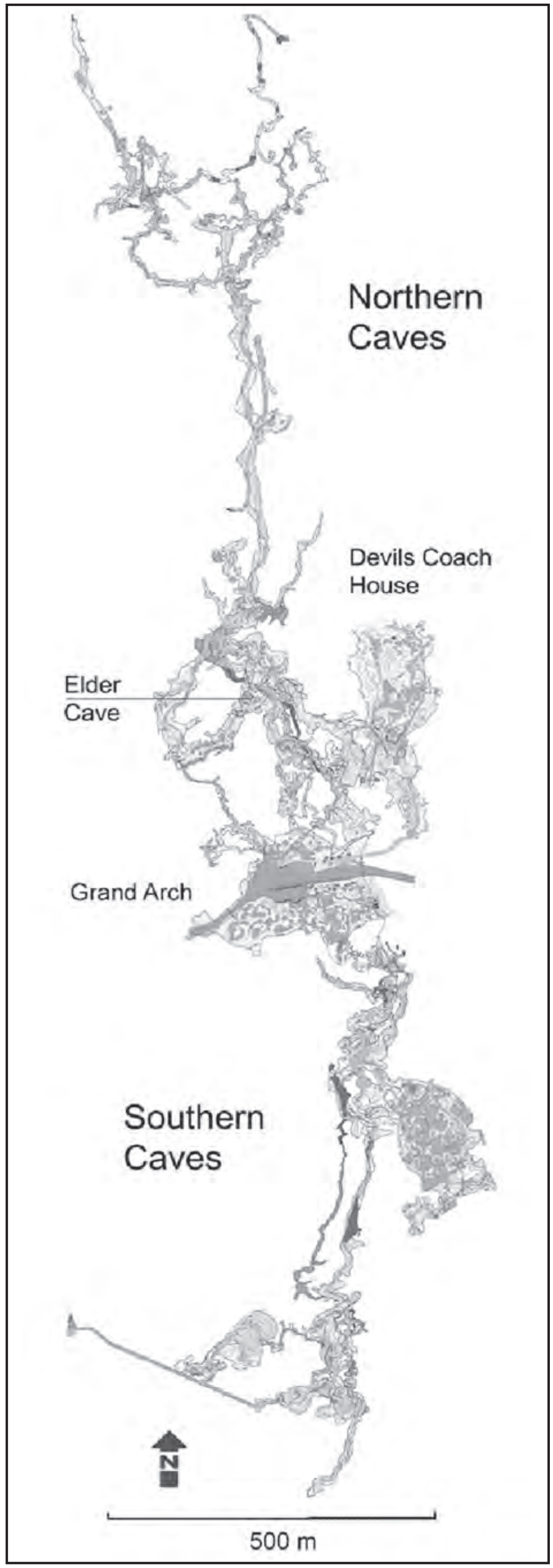

Figure 1: The Plan of the Jenolan Tourist Caves.

a number projects, for example, a Spelean History (Whitby et al. 2009) and a Spelean education project (Kennedy et al., 2009) (Fig. 1).

The detailed survey master plan is the most useful tool for management of the caves and recording research. The Adobe Illustrator files have layers that may be devoted to any task such as speleothem cleaning, infrastructure changes, or re-lighting a cave.

3.2 Plan beneath the contoured surface

A management problem often encountered at Jenolan is whether infrastructure that has been placed in the area in the past is likely to impact on the caves. Figure 2 shows how the plan and the contour map were used to assess the relationship between a car park and the tourist cave below.

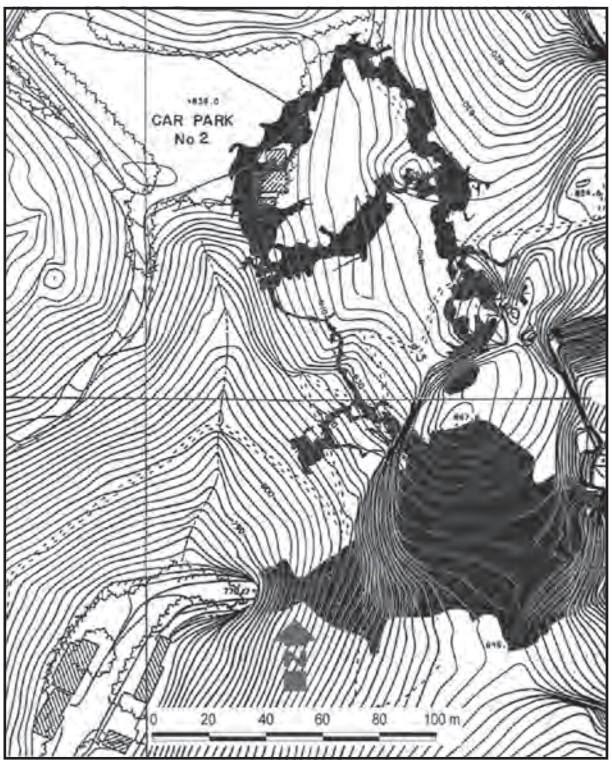

Figure 2: Cave plan in silhouette beneath contoured surface.

3.3 XYZ coordinates and GPS

For the first time, questions such as how deep sites within the caves are below the precipitous Jenolan terrain can be rapidly answered. The xyz coordinates converted to GPS coordinates have given depth data for drip sites that have been sampled and analyzed for their water chemistry. The same method was used when the jaw bone of the rhinoceros-sized *diprotondon optatum* was found in the caves. The species became extinct some 30,000 years ago (Long et al., 2002). The jaw bone was in a boulder collapse in a section of the tourist caves inaccessible to such a large animal through known passages. On the surface above the jaw bone site is a pit trap cave containing an extensive boulder collapse the bottom of which is a few metres above the jaw bone.

To illustrate for tourists what they will encounter on a traditional cave or adventure tour, a developed long section is best. Figure 3 shows the developed long section of the adventure cave tour that is marketed as the Plug Hole Adventure Cave. Examination of the plan shown in Figure 1 will show that even to those used to interpreting such complex plans (the cave has several levels above each other) it is difficult, but for the inexperienced it is impossible.

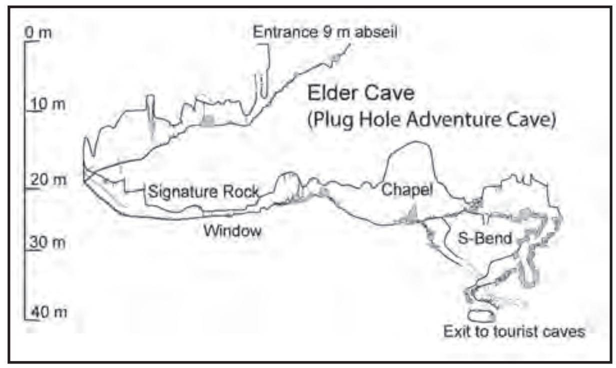

Figure 3: A developed long section through Elder Cave.

3.4 3D-Models

The 1987/90 survey data was sufficiently complete for it to be used for three dimensional computer graphics model (Fig. 4) generated using left, right up and down data taken at the time of surveying. It has been used on a number of scientific posters to show the location of sampling sites within the cave and is on display in the interpretation centre at Jenolan Caves. The model illustrates geological features of the system such as the down cutting of the Jenolan River to form the northern caves. Initially it oversimplified the shape of the Devils Coach House and the Grand Arch so it was improved by the use of 12 point cross section data taken at 10 m intervals along their center lines. The representation of the two chambers is shown without smoothing so that the 12 point net can be observed.

The area (Fig. 5A) in the southern part of the southern caves (Fig. 1) was attributed to the solution of the limestone by rising aggressive water resulting in a series of domed chambers – known as cupolas (Armstrong, 2004). Figure 5B illustrates how poorly left, right, up and down data taken with long survey legs represents such a complex area of the cave. It is inadequate for depicting the shape of cupolas and

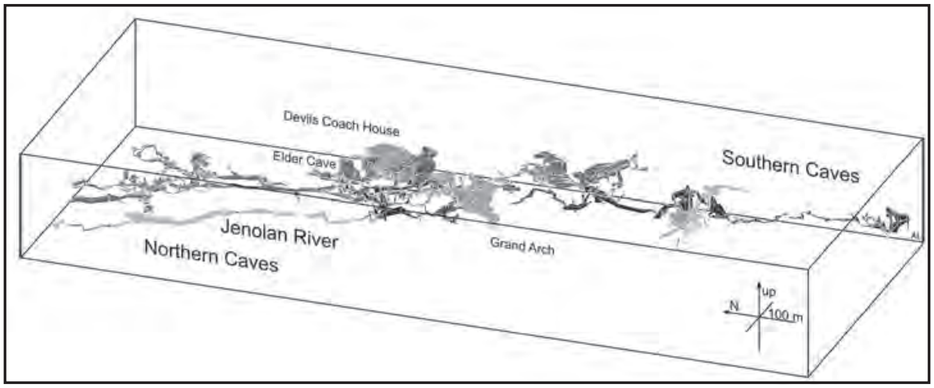

Figure 4: A modified 3D of the Jenolan Tourist caves which also shows the route of the Jenolan River.

management and research workers. Finally the cave survey which commenced as obtaining, recording and presenting field data as a cave map has turned into a continuing research project in itself.

Acknowledgments

The Jenolan Caves Reserve Trust for financial support for software and consumables and making available an office in the JCRT research facility that is dedicated to the production of the survey. The Jenolan Cave guides and numerous cavers both national and international that have worked on various aspects of the survey project. Both R.Q. Bridge and C.D. Dunne for operating theodolites and reducing data. The School of Civil and Mining Engineering, University of Sydney for supplying surveying equipment and computer facilities.

the way they are interconnected. Figure 5C shows the first attempt to represent part of this series of domes by the 3D high resolution method.

The methods have described the computing involved in placing the 3D cave map below the Jenolan Surface. A monochrome figure does not adequately demonstrate the power of this method of representing the cave system and its surface. In addition, the advantages of ability to rotate and enlarge are lost in any passive mode of presentation. It is proposed that the model will be made available on a webpage so that it can be viewed in Acrobat Reader enabling all of the above features to be used.

4. Conclusions

The accuracy of the 1987 surface survey and underground traverse allowed it to be used in the 2005 redressing of the project. A systematic approach to the organization of data and additional surveying has resulted in high quality maps of the caves being produced. The availability of freeware, shareware and commercial computer programs has enabled the end product to be produced both as hard and soft copy. The project has achieved one of its major goals to produce the survey in an accessible form so that it can be used by

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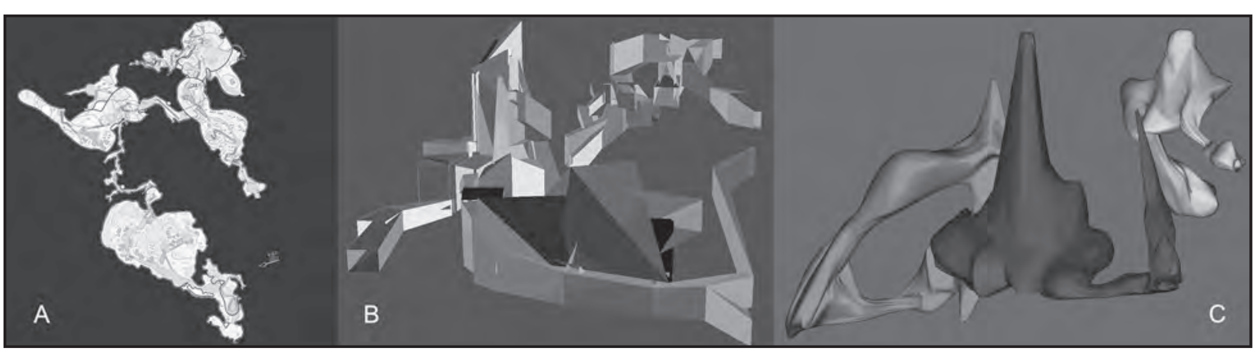

Figure 5: A, the plan of the southernmost caves in the Jenolan Tourist Caves (Fig. 1). B, the same section as A of the original 3D model using left right up and down. C, the high resolution 3D model of the same area.

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CAVE AND KARST RESOURCE INVENTORY AND MONITORING ON THE TONGASS NATIONAL FOREST, SOUTHEAST ALASKA, USA

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The Tongass National Forest is the largest forest in the National Forest System in the United States, encompassing over 6.9 million hectares covering the islands of the Alexander Archipelago and the narrow band of mainland from Dixon Entrance to Icy Bay. The Tongass contains 85% of the total karst in southeast Alaska, approximately 400,000 hectares primarily on Chicagof, Prince of Wales, and surrounding smaller islands. In this century, inventory and monitoring of our karst resources is a new priority. Most recently in 2008 an amendment to the Tongass Land Management Plan updated the karst standards and guidelines developed and put into place in 1997. Expeditions to map and inventory karst features were revived in 2008. Projects to evaluate the baseline characteristics of spring flow in karst watersheds were completed in the last 4 years. A project utilizing these baseline data is being developed for quantitatively evaluating the effectiveness of our karst standards and guidelines through karst watershed monitoring on Kosciusko Island. A massive effort to digitize and organize cave and karst inventory data is currently underway, with cave locations being recorded with high resolution GPS for integration into a comprehensive GIS database with resource inventories. These data will be used to organize and guide efforts to conduct a biological inventory of caves on the Tongass in the future. As budgets grow tighter every fiscal year, cooperation with local groups such as the Glacier Grotto of the National Speleological Society and national groups such as Geocorps America of the Geologic Society of America have helped to support our cave and karst programs.

1. Introduction

On the Tongass National Forest, the protection of cave and karst resources came about shortly after the Federal Cave Resource Protection Act of 1988. The Tongass Cave Project (TCP) began inventorying and exploring caves in southeast Alaska in the early 1980s, and basic karst resource inventories began in the late 1980s and early 1990s. The initiation of karst resource protection on the Tongass together with the mapping projects led by the TCP spurred interest in karst and cave resources in southeast Alaska. El Capitan Pit, the deepest limestone pit in the United States, was mapped at 182.4 meters, and El Capitan Cave, the longest cave in Alaska was mapped at approximately 3.2 kilometers (Lewis 1997). Initial work began on inventorying the biological resources in Tongass caves on Prince of Wales and surrounding islands in the early 1990s. Researchers found that mammal species and birds used caves as critical roosting and hibernating habitat, including five species of bats (Baichtal and Swanston 1996). Invertebrate collections from over 300 caves and resurgence sites yielded at least five troglobitic and forty troglophilic invertebrate species, three of those newly discovered (Carlson 1994 and 1996). The caves were found to be rich in paleontological and cultural resources, including the finding of the oldest bones in North America in On Your Knees Cave (Carlson 1993, Dixon et al. 1997). As a result, the Forest Service included the Karst and Cave Resource Significance Assessment of 1993 as part of the Tongass Land Management Plan (TLMP) revision process.

The 1997 TLMP incorporated a karst management strategy in accordance with Aley et al.'s recommendations in 1993, including integration of continuing research as well as inventory and monitoring priorities in southeast Alaska's karst.

This karst management strategy was implemented on two timber projects in highly developed karst areas (Lab Bay and Heceta Sawfly Salvage) with mixed results. While both areas were inventoried for karst features prior to harvest, monitoring of the harvest contractors work on the ground was thought to have not been conducted properly due to the, "limited experience of resource managers" (Baichtal 1997). In addition, no physical monitoring of the karst watershed occurred in order to determine actual effects on the water quality and quantity at karst springs due to timber harvest. Inventories of cave and karst features continued through the TCP and Forest Service expeditions. Cave resource inventories were not documented at the time of cave survey, but short reports were filled out on each cave including observations, if any, on cave resources such as biological, archaeological, and paleontological. Since Carlson's studies in 1993, however, no further professional work inventorying the potentially diverse populations of cave fauna in southeast Alaska occurred.

In the 21st Century, the Tongass again began to revise the forest management plan, and resource managers proposed changes to the karst management strategy. In 2002, a panel was contracted by the Forest Service to assess the implementation of the karst standards and guidelines established in the 1997 TLMP and to analyze proposed changes.

The Karst Review Panel found that generally the implementation of Karst Standards and Guidelines had ensured a high level of protection for karst resources; however they recommended a higher level of training for karst specialists and identified some revisions to the proposed changes (Griffiths et al. 2002).

Finally, in 2008 the Amendment to the 1997 Tongass Land Management Plan was published, including some changes recommended by the karst review panel for cave and karst resource inventory and monitoring. Today, the current inventory and monitoring objective for cave and karst resources on the Tongass is stated as, "The significant cave and karst ecosystems should be maintained and protected Forest-wide, and natural karst processes should continue while the productivity of the karst landscape should be maintained" (TLMP 2008). The current inventory and monitoring question for cave and karst resources on the Tongass is, "Are the biological, mineralogical, cultural, paleontological components, and recreational values of the karst and caves maintained?" (TLMP 08). The budget decline across the Forest Service reached the Tongass in approximately 2004. Since that year, budgets for inventory and monitoring have all but dried up, and finding funding for projects such as these has required creative thinking and partnerships.

2. Setting

The Tongass National Forest is the largest forest in the National Forest System in the United States, encompassing over 6.9 million hectares covering the islands of the Alexander Archipelago and the narrow band of mainland from Dixon Entrance to Icy Bay (Fig. 1). The Tongass contains 85% of the total karst in southeast Alaska, approximately 400,000 hectares primarily on Chicagof, Prince of Wales, and surrounding smaller islands (Fig. 2). The largest area of karst development exists on Prince of Wales and surrounding islands, which contain approximately 1,813 km^2 of karst (Baichtal 2006). These karst areas are concentrated on the north end of the island and surrounding smaller islands, where over 600 caves have been mapped. Karst formed to some extent on Prince of Wales prior to the Wisconsin glacial advance 21,000 to 14,000 years ago. This period of glaciation caused scouring, passage collapse, and sediment fill in karst systems, as well as leaving thick glacial till deposits and razing epikarst development at lower elevations. The intense development of karst on the Tongass National Forest is controlled by several factors including the high percentage of calcium carbonate ($CaCO_3$) in the limestone of southeast Alaska – averaged at 97.65 percent (Maas et al. 1992). In addition, faults and fractures resulting from the northward movements of the Alexander Terrane are dominated by northwesterly trending strike-slip faults and second order intersecting north-trending strike-slip faults, which define karst conduit formation (Gehrels and Berg 1992, Aley et al. 1993, Baichtal and Swanston 1996).

Figure 1:The Tongass National Forest is located in southeast Alaska, USA (USDA Forest Service).

3. Methods

3.1 Inventory

In order to maintain and protect cave and karst resources forest wide, they first must be inventoried. Inventory methods for cave and karst features on the Tongass National Forest are quite progressive, with the exception of biological surveys. Areas with karst development are now assessed using a whole ecosystem approach – an area of carbonate

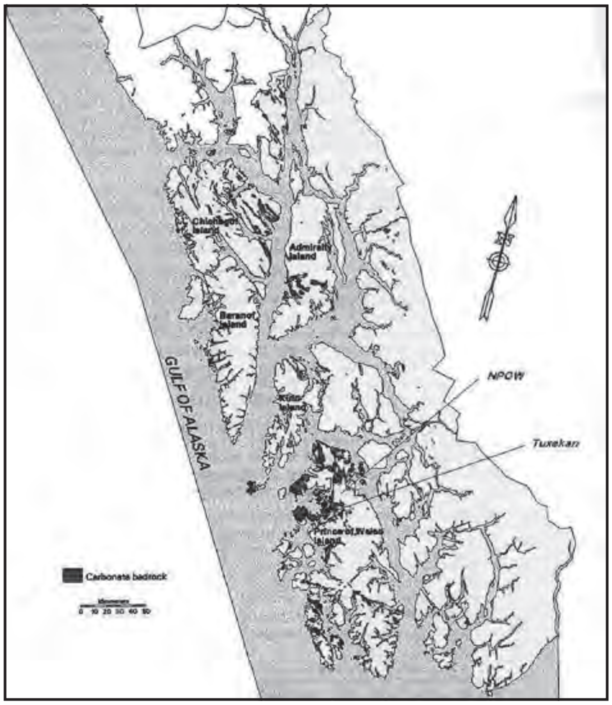

Figure 2: Areas of carbonate bedrock on the Tongass National Forest (USDA Forest Service).

bedrock is assessed as a complete karst system, as opposed to individual karst features. Aerial photograph, geologic, and topographic map interpretation is utilized prior to field reconnaissance. Surface streams and where they seem to disappear are noted as well as obvious disturbances in the forest, which could suggest karst features. Geologists locate karst features and caves out on the ground, mark them with GPS points, and integrate them into the master GIS database of features. Caves are generally noted and added to a list to be explored further during a cave expedition in the summer season. Cave resource inventories are conducted with surveys. Generally karst inventory work is associated with timber sales due to budget constraints. Karst features located are often found within proposed timber harvest units, and part of the GIS database process is associating buffers with highly sensitive or vulnerable karst features and caves representing a high degree of openness, or ability to transport sediment or contaminants to the subsurface watershed. If the majority of the proposed timber harvest occurs in areas of karst development, often dye tracing will be conducted to fully understand the effects of harvest on the karst watersheds. In addition, large dye trace projects were conducted on Prince of Wales and Tuxecan Islands in conjunction with road project evaluations (Prussian and Baichtal 2007). The results of the traces help resource managers understand the scope of karst watersheds on the Tongass, and how timber harvest and road building impact these areas. No current methods exist for biological monitoring of cave fauna on any level.

3.2 Monitoring

In order to maintain the natural processes of the karst systems on the Tongass, first resource managers must understand how those natural processes work. Monitoring methods on the Tongass lag significantly behind inventory efforts. Currently, the only karst and cave resource monitoring accomplished is qualitative in nature and in conjunction with the actual timber harvest itself. Geologists go out on the ground in current harvest units and assess the harvest contractor's compliance with the karst standard and guidelines for that particular sale. This involves evaluating whether or not buffers placed around karst features were successfully applied in practice and analyzing new temporary roads built and culvert placement.

In addition, the Tongass boasts the only show cave in the state of Alaska, El Capitan Cave. El Capitan Cave also happens to the longest mapped cave in Alaska at approximately 3.2 kilometers. This cave is open to visitors from May through August each year, and averages around 500 visitors during that time. The cave is gated to prohibit access unless on a guided tour. Other than the 372 wooden stairs to the entrance and the bat gate, the cave is undeveloped. Photographic visitor use impact monitoring was attempted in the early 1990s, however no follow up work on this project has occurred. Other caves on the Tongass also see recreational visits from guided adventure groups and locals. One cave displays a basic register in the entrance, however none of the other caves are monitored for visitor use and impacts. One of the difficulties with monitoring visitor and land use impacts on Tongass caves is the lack of base level data to compare changes.

4. Results and Discussion

While inventory methods on the Tongass are producing a comprehensive catalog of cave and karst features, monitoring methods are in the very beginning stages of development. In addition, the management of cave and karst inventory data needs to be reorganized and updated for the 21st century into a useable tool for resource managers. While the new inventory and monitoring objective and question begin to address the issues, a more efficient statement would be useful. Resource geologists and karst resource specialists were not consulted in the development of the current monitoring question. A new question is proposed which would allow for the monitoring of key indicators of karst system health. In a Forest wide inventory and monitoring workshop in 2008, geologists proposed the monitoring question, "Are we maintaining the functionality of the karst ecosystem in order to not diminish the hydrological, biological, minerological, cultural, paleontological, and recreational resources?" (Kovarik 2008). Water quality in a karst system affects all the resources within it. Through monitoring certain gauges within the systems such as changes in water quality, impacts to all resources can be assessed.

To date, no quantitative monitoring of changes in water quality, quantity, sediment, or turbidity below harvested units in karst areas has occurred during or post harvest. A forest service hydrologist monitored water quality in 2004 and 2005 at four karst springs in an attempt to understand general water quality trends of the karst systems. In 2006 a Master's thesis analyzed storm response at two karst springs in order to look at hydrologic function and storage in unharvested karst watersheds on the Tongass (Kovarik 2007). These projects are the first step at establishing base line conditions on the Tongass. A project is in development for Koscisuko Island, where a large timber sale is proposed. Both old growth and young growth (areas harvested in the 1940s and 50s) units are being assessed for harvest. Watershed analyzation is in progress right now in order to place instruments at karst springs below units that will be harvested in the future. Data gathered from these sites will address the efficacy of the current karst standards and guidelines and the feasibility of thinning in young growth units as a restoration method for harvest impacted karst watersheds.

Biological inventories are the next logical step for the cave and karst inventory program on the Tongass. However, before a comprehensive biological survey can begin, the current cave inventory data needs reorganized and updated. The current cave and karst resource inventory is in a master GIS database, however the majority of cave locations are lacking data such as the name of the cave. While hard copies of all cave maps are filed, survey data has either been lost or only exists as the original survey sheets taken into the cave. The TCP wrote short reports on each cave found, surveyed or unsurveyed. These reports contain vital resource inventory data. Currently the only copies of these are in paper format. All cave data needs scanned to .pdf and saved, and all cave surveys need entered into a cave data management program. Cave locations lacking names need to be relocated in the field, and field checked for the metal tags labeling each cave with its inventory number. This project will require many hours of field time attempting to relocate caves based on fairly vague location data. During the summer of 2008, the Tongass received funding through working with the Geological Society of America Geocorps Interns for two cave technician positions to begin the relocation and digitizing. In addition, through contracting with the Glacier Grotto of the National Speleological Society, two TCP project members will be assisting with the relocation of caves found in the early days of the project. During cave relocation, additional information is gathered utilizing cave and karst feature inventory sheets developed by the Hong Megui Cave Exploration Society. Data gathered on this sheet includes photos of the cave entrance and general location of the cave, sketches of the entrance location, and precise location details.

Once the locations are linked with the cave names, and survey data has been entered electronically, the master GIS database will include line plots for each cave. These line plots will be a sort of "underground watershed map" to which resource managers can link all pertinent resource information, including entrance photos, archived reports, inventories linked to cave survey stations. This database will be a tool that will greatly diminish the chances of loss of corporate data from the Tongass cave and karst program, and will provide a strong foundation for future resource inventory information such as comprehensive biological surveys.

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KARST CAVE SYSTEM TYPES AND THEIR PROTECTION IN CHINA

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In China, there is widely developed karst cave systems, (1) particularly the carbonate rocks have formed a lot of special and wonderful cave systems as the important resources. On the other hand, the karst cave systems can harm local people's living and constructions. In ancient Chinese saying for the carbonate rocks' regions are "no mountain without cave and no cave without wonderful." Some problems related to the karst cave systems are discussed in following**:**

1. Basic Features of Karst Cave Systems

Based on different principles, karst cave systems will be separated. For examples, by the lithological features, the cave systems developed in the carbonate rock, sulfate rock, and halide (Lu and Zhang, 2007) are classified, but in the carbonate rocks, usually the two main sub-types must be distinguish, (Lu et al., 2006).

1.1. Sub-surface karst river stream:

The surface river water sinks into underground cave and passage way through a certain distance, and then the sub-stream is flowing out to the surface to form the surface river again. The related formula is expressed in the following:

$$Q_{oi} = Q_{I,i-t} \pm \sum_{p=1}^{n} q_{p,i-tp} \pm \sum_{f=1}^{m} q_{f,i-tf} + \sum Q_d \quad (1)$$

where Qoi = exit flow quantity of the sub-surface karst river stream in i time, m^3/s; QI, i-t = entrance flow quantity of the sub-surface karst river stream in i-t time, m^3/s; qp, i-tp = the flow quantity of p branch of the sub-surface karst river stream in i-tp time, m^3/s; qf, i-tf = the flow quantity through corroded fissure into the sub-surface stream in i-tf time, m^3/s; ΣQd = the condensation water between i-t to i time into the sub-surface stream, m^3/s.

1.2. Karst underground river systems:

The karst subterranean river systems are mainly collecting the percolating raining water through sinkholes; corroded fissures to subsurface. The related formula is expressed in the following.

$$Q_{oi} = \sum_{s=1}^{n} q_{s.i-ts} \pm \sum_{p=1}^{n} q_{p.i-tp} \pm \sum_{f=1}^{m} q_{f.i-tf} + Q_O \sum Q_d \quad (2)$$

qs.i-ts—when prior i-ts time, the flow quantity directly sinking into ground by depression (m3/s), other marks are ditto formula (Lu, 1986).

Referenced to the formations of cave systems and related environments, the cave systems in China will be classified into twelve models (Lu, 1999) (Fig. 1).

All the developments of cave models are controlled and influenced by local structures (Fig. 2).

2. Protection and Exploitation of Cave Systems

Considering both karst cave system resource conditions and hazard factors for economic constructions and mankind's living, the main purposes for studying cave systems are reasonably exploitation the different resources related to cave systems while providing protections, and avoiding or reducing the hazards to harm the constructions and people' lives. Some important problems are discussed in following.

2.1 Exploitation of resources related to cave systems

Many kinds of liquid, gaseous, and solid mineral resources have been formed in cave systems, but karst water resources are the most important ones. In Southwest China, about 3358 cave systems have been investigated for their water resources (Table. 1).

The comparison related to karst water systems between Southern China and Northern China will be listed in Table 2.

The karst water recourse in cave systems will be exploiting through many ways, such as pumping karst water from vertical passages, guiding water by artificial tunnel to connect the underground river, or constructing a dam in a cave system to form an underground reservoir (Lu, 2003; Milanovic, 1981). But, the important problem is that the karst collapses and other hazards have often been promoted. Therefore, to protecting cave systems is the first duty before exploiting water and other resources in cave systems.

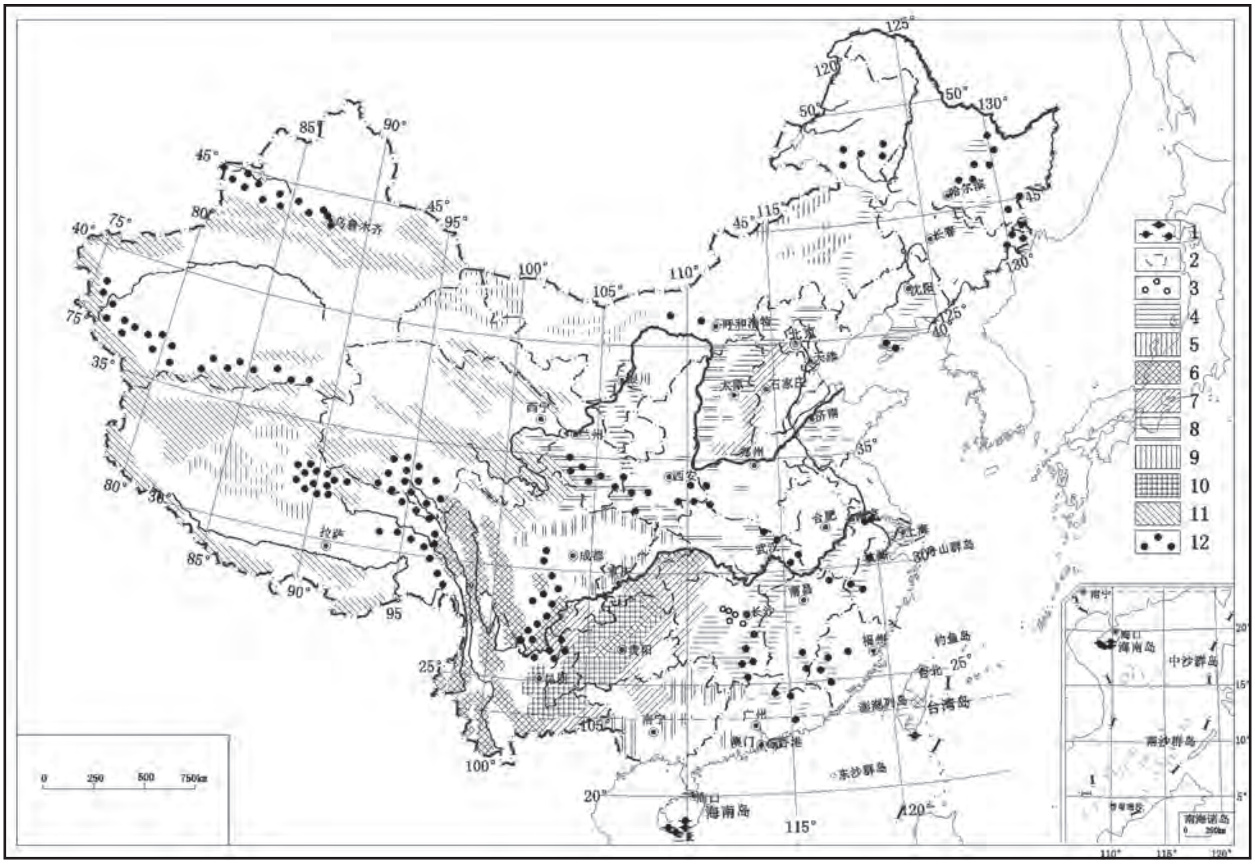

Figure 1: Main models related to formation environments of karst cave systems: 1.- sea eroded coastal cave model; 2—reef cave model; 3—hill and shallow valley cave model; 4—lacustrine cave model; 5--tower peak–valley cave model; 6--high mountain –deep gorge cave model; 7—slope mountain land cave model; 8—ridge mountain cave model; 9—high-cold plateau cave model; 10—moist-hot plateau cave system;11—glacial cave model; 12—thermal cave model.

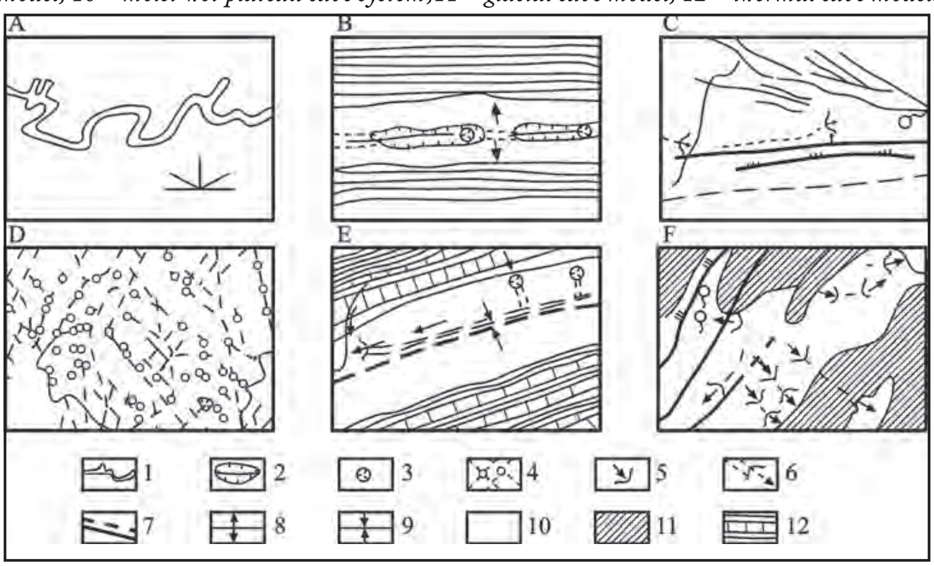

Figure 2: Analyses of cave systems controlled by structures: 1—cave passages; 2—large valley; 3--depression and sinkhole; 4—fissures and vertical cave passage and sinkhole; 5—entrance of surface river into ground; 6—exit of karst subterranean stream; 7—fault; 8—anticline axis; 9—syncline axis; 10—carbonate rock; 11—sandstone and shale; 12—sandstone and shale with less carbonate rock; A—the cave development controlled by structural fissures; B—underground river controlled by elongated anticline; C—the karst subterranean river and spring controlled by fault; D—vertical karst cave and passages controlled by fissures; E— subterranean river controlled by syncline; F—cross tension fissures controlled the development of subterranean river.

Table 1. Some conditions of water resources in cave systems in Southwest China (5)

Content / Regions	Ground river Number	Flowing quantity in dry season108m3/a
Yunnan	148	39.02
Guizhou	1130	71.35
Sichuan	895	63.96
Chongqing	201	28.68
Guangxi	435	191
Hunan	338	17.65
Hubei	211	14.85
Total	3358	426.69

Table 2 Comparison of Karst water systems' features between Southern China and Northern China

Contents / Region	Southern China	Northern China
System feature	main karst ground river systems	Karst spring systems
Passage feature	main karst cave and larger corroded passages' net	main corroded fissures' net
Catchment area Km^2	50—>3000	500—>4000
Ground water flowing speed m/d	100—>11400	1—>50
Ground run-off modulus $L/Km^2.s$	8—>35	2—>10
Karst water age a	main 1—>10	main 3—>20

2.2. Prevention and reduction of harms resulted by the compound flows from cave system.

In karst cave systems, there are usually existing compound flows, which are mixed with liquid (water). Gas (air, vapor, CO_2 and other gas masses) and solid (e.g., clay, sand and gravel) (Milanovic, 2000).

For the uncompressed liquid and solid materials:

$$\frac{\partial v_x}{\partial x}+\frac{\partial v_y}{\partial y}+\frac{\partial v_z}{\partial z}=0 \quad (3)$$

v_x, v_y, v_z——express the component of flowing speed in x, y, z axis.

ρ(intensity)as constant then : $\frac{d\rho}{dt}=0$ (4)

So that: $\text{div}v=0$ (5)

But for the compressed gas mass:

$$\frac{d\rho}{dt}=\frac{\partial\rho}{\partial t}+\frac{\partial\rho}{\partial x}v_x+\frac{\partial\rho}{\partial y}v_y+\frac{\partial\rho}{\partial z}v_z \quad (6)$$

$$\text{div}v=\frac{1}{\rho}\frac{d\rho}{dt} \quad (7)$$

$$\Delta\varphi=\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial^2\varphi}{\partial y^2}+\frac{\partial^2\varphi}{\partial z^2}=\text{div}v \quad (8)$$

$$v_{ac}=\frac{\partial\varphi}{\partial s} \quad (9)$$

In a subterranean cave system, gas mass compressed together with liquid and solid materials in the closed passages under high pressures results in the speed potential $\Delta\phi$. When subsurface engineering destroys their balance, the compressed three phrases' mass will suddenly explode up to form the three phrases' flows with very high starting speed Uac to harm the underground engineering.. In China, some tunnels with their lengths of 12-17 km had been utilized as warming systems and undergone a series of treatments for the hazards. On the other hand, the mechanical stability of the big cave systems also are the important problem either for the subsurface constructions or for the surface buildings.

The Karst cave systems commonly have speleothems (Fig.3),

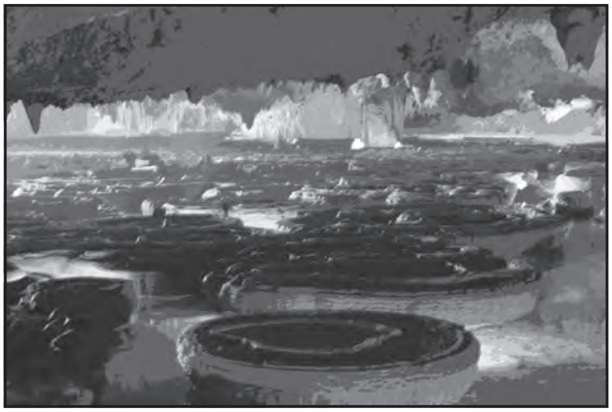

Figure 3: A lot of special speleothems in Lianhua Dong Cave, Guilin.

Figure 4: A big cave to be treated by ferroconcrete columns.

but big underground halls are also developed. A big cave near the railway tunnel is enhanced by a lot of ferroconcrete columns (Fig. 4).

3. Development of Tourism Resources Related to Cave Systems

In China, about four hundred cave systems are already opening for tourism and some are designated as a National Geopark or World Geopark. At present, only the Furong Dong Cave System is designated as a World Heritage Site. Multiple purposes for geopark include: 1. protecting natural resources; 2. decreasing hazards; 3. studying geosciences; 4. improving environmental quality; 5. promoting local development; 6. gaining financial benefits. The sustainable development of geoparks must include the six qualifying characteristics, which are potential benefits to the fields of science, evolution, culture, ecology, architecture, and economics.

Harmonious relationships for geopark are also very important, which include: 1. resources and hazards; 2.development and protection; 3. water supply and environment; 4. arbor forest and shrub cover; 5. energy and impacts; 6. communication and reception; 7. building style and landscape; 8. artificial actions and natural processes. Otherwise, the speleothems and fractural depositions in cave systems may provide a series of messages for studying the environment's evolution.

4. Evaluation of Cave Systems

The about mentioned factors related to sustainable development of cave systems are expressed in Fig. 5.

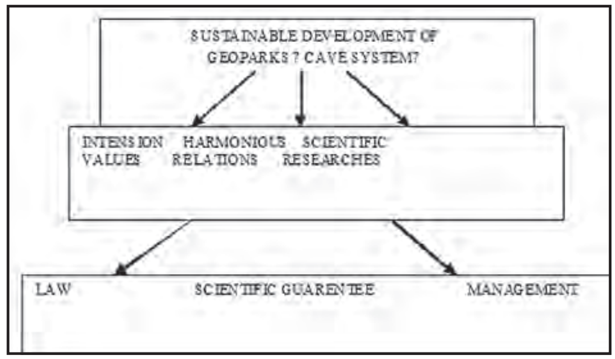

Figure 5: The evaluation of environmental quality related to geopark and/or cave systems must consider the chemical, physical, mechanical, and biological compound processes.

QTT = f(G, E, W, A, B, Hg, HC. HB) (10)

QTT—Total quality of geo-environment; G—factors of trip resources; E—Eco-hydrology; W—factor of water environment; A—air quality; B—biological resources; HG—factor of geo-hazards; HC—factor of climatic hazards; HB—factor of biological hazards.

By a comprehensive evaluation related to karst water activity, eco-hydrology, speleothems depositions, karst collapse and destruction of cave passages, fractural depositions in cave, and vegetation in surface, it is possible to separate cave systems into best ecological, good ecological, deteriorated ecological, and bad ecological conditions --- the four types of cave systems.

5. Conclusions

There are numerous cave systems of a wide variety in China, which are closely related to people's life and economic construction. However, at present, very few careful surveys and studies have been done to reveal the karst development rules. A large number of cave systems have developed into tourism resources, while more are effectively exploited into karst water resources. Karst cave systems are precious resources, and we must insist on the principle to exploit while protecting and protect while exploiting. Special attention must be paid to the hazards provoked by cave systems during construction activities. Therefore, we must avoid geo-hazards provoked by cave systems during engineering constructions as well as prevent and control disasters caused by caves.

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CONTRIBUTED PAPERS IN THE EARTH SCIENCES

KARST CAVE FEATURES OF MONGOLIA

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Abstract

In the research paper are reflected cave geneses, morphology and cave evolution features of Mongolia. The karstic caves are distributed in Mongolia accordingly to the distribution of carbonate rocks. The sharp climate, plateau height and precipitation changes have had an influence on the origin and evolution of the karst caves. There are three large regions where karst caves are widespread. In these regions the biggest multi-phase caves are formed. Caves in Mongolia have developed through the following 5 stages: 1. Split stage or first stage. The surface water penetrates down a fissure, erodes rocks and causes the initiation of caves; 2. Canal stage. Given further penetration of water from the surface, the cave is enlarged and the volume of water flowing through it increases, causing karst processes to be more active; 3. The stage to originate underground water flow. Underground canals get wider and the erosion activities increase; 4. Water stage to originate the karst. Underground canals get wider permanently, the canal water corrodes the bottom part and penetrates downwards, developing new passages below and leaving dry upper-level passages ; 5. Failure and dry stage. In this stage, the cave roof fails and some parts of the cave become open.

Karst caves of Mongolia are famous for their rich archeology. In 1995, the scientists of Mongolia, Russia, and America made excavation in the TSagaan agui and proved that ancient people lived there before 750,000 years ago. Many hundreds of archeological finds were made, including stone tools. In 1997, excavations were made in the Chehen agui and 317 ancient stone tools were found.

THERMAL SEDIMENTATION IN CAVES: A NOTE

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Abstract

The concept of "temperature" is meaningful only for a system in the condition of thermodynamical equilibrium. Its application to a system quite far from it, like the external air, is usually purely conventional. For instance, the "local temperature" is defined as the temperature of a thermometer exposed to air but shielded from radiation, at an height of 2 m above ground covered by grass, on a flat surface, far from buildings and so on.

The idea of "cave temperature" is usually considered more meaningful, because underground fluids and radiation are essentially at the equilibrium condition. Nevertheless, if measures are pushed strongly ahead, significant gaps from equilibrium appear. The main unbalance is surely the thermal sedimentation, i.e. the trapping of relatively warm air above relatively cold one.

This can introduce significant biases in the definition of "local cave temperature," which then depends on the height above the "floor." This can affect the estimations of underground lapse rates, it introduces biases in the estimation of human impact on very sensitive show caves, it can result in condensation processes in case of forced mixing of air sheets, it can explain probably Martel's "degree rule" and can finally affect local thermal insulation, then explaining something about the location of bats and crystals. It is important to emphasize that thermal sedimentation cannot be a stable structure in an insulated system (it would violate the Second Principle), and it has to be fed by some "external" forcing.

The paper shows that the local vertical temperature gradient in conduits is usually around 30–50 mK/m in alpine caves, but it can increase to 100–200 mK/m in special cases and to 0.4 K/m in very dry caves.

In the Rio Martino laboratory we have shown a seasonal disappearance of thermal sedimentation, which corresponds to expectations. Thermal sedimentation measurements are nevertheless quite complex to be taken. As regards this matter, the new generation of thermocameras is going to allow a significant step ahead.

THE SOUND OF NATURAL CAVES

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Complex karstic underground systems, i.e. deep and long caves with more than one entrance, are known to be characterized by intense underground airflows. During the last decade, the physics of underground winds has started to be unravelled and this natural phenomenon has been shown to depend upon the interaction between the external and the internal atmospheres. We have used sonic anemometry to measure and record wind speed at various entrances of Italian caves with different known depths and lengths. Signals were sampled at 1 Hz and analyzed using classical method from signal processing theory. Spectral analysis of the overall signals showed a $1/f^{\alpha}$ decay with an exponent ranging between 0.7 and 2.5 for different caves and within different frequency ranges, the exponent being very close to unity for the air flowing in the greatest underground systems analyzed.

Spectrograms were obtained using the method of the sliding windows and the results subjected to rigorous statistical analysis. Significant peaks were isolated from spectrograms at various frequencies for all caves, demonstrating that each cave can play sounds if properly excited by the external atmosphere.

1. Introduction

Most cavers know from experience that big underground systems are characterized by intense air circulation. Indeed, this natural phenomenon is empirically exploited by cavers to guide their explorations of new caves or of yet unexplored branches of known karstic systems. During the last decade, however, the physics of underground winds have started to be unraveled and experimental data and theoretical models in this field are rapidly accumulating.

The air circulation in caves is basically driven by two independent forces: one is proportional to the density difference between the internal and external atmospheres and the other to fluctuations in the pressure of external atmosphere (Lewis, 1990). Both components fluctuate in time and this means that a large cave system never attains equilibrium. Indeed, the underground atmosphere is unstable and receives energy from the outside (Badino, 1995). It is therefore expected that underground winds measured at caves' entrances should contain information on atmosphere dynamics, both of the external and the internal ones, as well as on the geometry of the underground system itself (Plummer, 1969;, Lismonde, 2002).

Sonic anemometers equipped with data loggers are now available and measure wind speeds and directions with great precision. We therefore exploited sonic anemometry to measure wind velocity in different underground systems and provide first analyses of recorded signals using conventional methods borrowed from signal processing theory.

Here we present some result of our first data acquisition campaign (2006–2007), with 2.5 million wind velocity measurements in five different caves.

2. Recording of Signals

Measurement was accomplished with one or two sonic anemometers Gill Windsonic (accuracy 2% at 12 m/s, resolution 0.01 m/s), usually in the middle point of smallest conduit section, in order to increase accuracy and reduce noise. Acquisition frequency rate was set to 1 Hz. Signals were sampled for a total time interval of two days and nine hours. Measurements required continuous human control in order to avoid interferences (or thefts) because the anemometers were almost always in the middle of well-visited cave entrances. For this reason the acquisition could not last more than two or three days.

4. Wind Speed Sampled at the Entrances of Various Caves

The importance of choosing very large caves and with strong air flows became apparent quickly; the large inertia of air movements and the high wind velocities might in fact reduce noise created by local fluctuations and increase the relative accuracy in the spectral analysis. The first test was made in the Corchia underground system (near Lucca), the largest in Italy, which is characterized by very strong winds in its many entrances. The Corchia cave system is a conduit net extended inside the mountain over 1.2 km of vertical extent and 3 square kilometers of surface area; 53 km of conduits are surveyed, but the cave probably has a development 2 or 3 times larger. Our first choice was the Eolo entrance, because it is the most classical and has the strongest air discharge. At this entrance, the airflow, apparently quite continuous, is in fact highly modulated and shows a complex structure which is very likely to depend upon the dynamics of internal oscillators.

The Piaggia Bella complex (near Cuneo) has 42 km of known conduits over 1 km of vertical relief and 10 square kilometres of surface area (so, it is much "flatter" than Corchia). It has several entrances, and we chose to record wind speed at the Mastrelle entrance. The Grotta Gigante, near Trieste, is a vast cave essentially characterized by a huge internal room (approximately 600,000 m^3) connected to the external karstic plateau by three entrances; regular oscillations of its internal wind have already been observed and discussed (Cigna, 1968).

5. Signal Analysis

The signals shown in Figs. 1-3 were analyzed using standard methods borrowed from signal processing theory. Preprocessing of non-stationary signals is usually recommended and the most common way to do it is to subtract the trend from raw data. Fig.4 shows the periodogram of the detrended signals. The periodgrams show a region where the power spectral density decreases with increasing frequencies. This trend follows the power law $S(f) \propto 1/f^{\alpha}$ and this equation has been nonlinearly fitted to data within the frequency intervals to provide estimates of the exponent α.

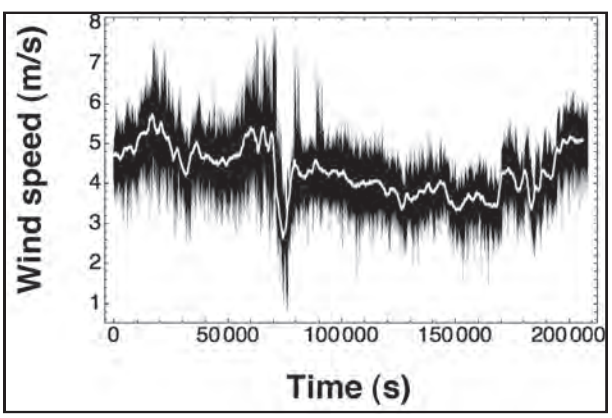

Figure 1: Data for Corchia System.

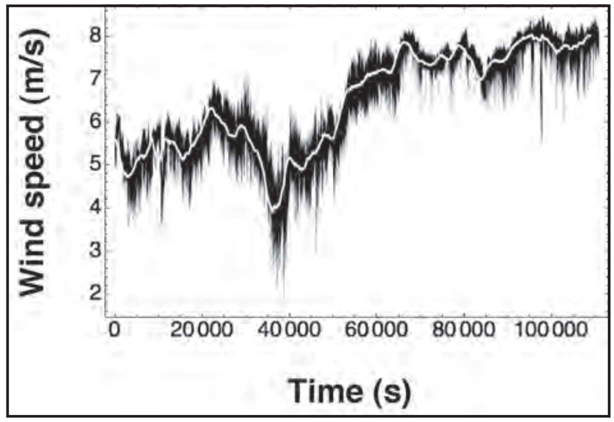

Figure 2: Data for Piaggia Bella Complex.

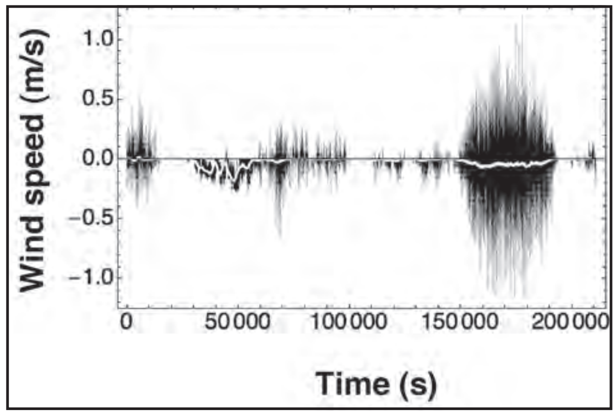

Figure 3: Data for Grotta Giganta.

6. Statistical Analysis of Spectrograms and Peaks Identification

We used the local Gaussian white noise assumption as the null hypothesis. In essence, we assumed that within a narrow time interval the noise associated to the signal is Gaussian white noise. White noise provides flat power spectra and its amplitude fluctuations are exponentially distributed. The probability density distribution of the amplitudes in the spectrum of Gaussian white noise is given by:

$$p(S_k) = \frac{1}{\langle S_k \rangle} e^{-\frac{S_k}{\langle S_k \rangle}} \qquad (1)$$

where $\langle S_k \rangle$ is the mean power spectral density. Thus, it is straightforward to calculate the probability P_{S_k} of each peak in power spectra for the null hypothesis:

$$P_{S_k} = \int_{S_k}^{\infty} p(S_k) \cdot dS_k \qquad (2)$$

A peak was labeled as significant if its probability turned out to be below the threshold value P_{Sk}=0.005 (in other words, we have <0.5% probability that the peak is due to a random fluctuation). The rationale for considering this value stems from the observed relative fluctuation (i.e. the CV) of estimated power spectra that, on average, was 15 %. If this

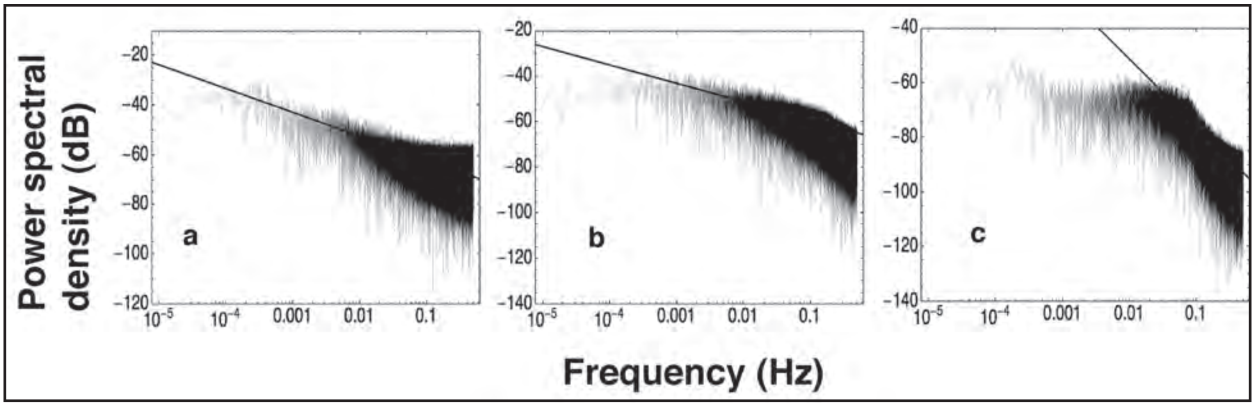

Figure 4: The trends have been estimated by the moving average method on the number of samples. The trends were then subtracted from the signals.

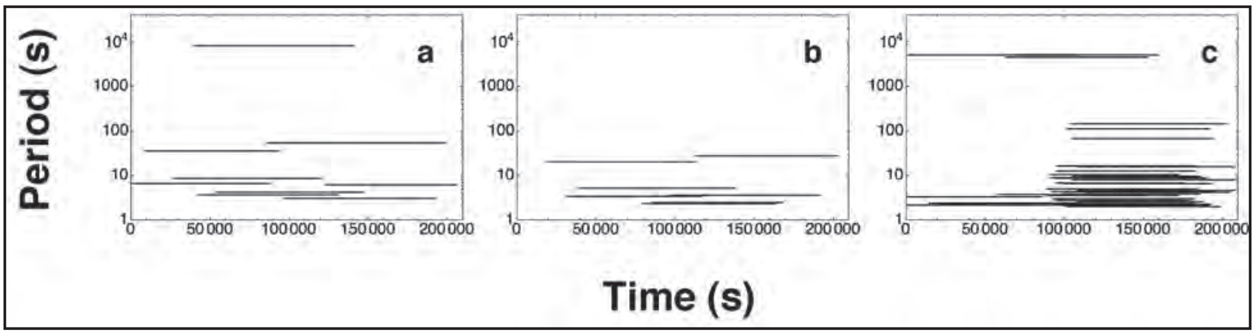

Figure 5: Exponent of the power law decay of spectral amplitude with increasing frequencies as estimated by nonlinear fitting of the spectra within the indicated frequency ranges (see also Fig.1-3).

fluctuation is associated to a given peak with P_{Sk}=0.005, then its probability, at worse, would still be <0.01 and the peak would nonetheless be considered as highly significant.

Figure 5 shows the period of the significant peaks isolated from all signals and plotted as a function of time. Periodic winds can be observed for all caves and in some instances - such as for Grotta Gigante - a great number of low period waves appear to concentrate within a given time interval. Thus, the caves play sounds and each entrance seems to be characterized by a different sound print which likely depends on the local shape of internal paths.

7. Conclusions

We have started to investigate the sound of natural caves with the hope of highlighting possible correlations between the acoustic properties and the structure of underground systems. In principle, one might think to carry out a sort of remote acoustic survey of a cave. However, internal winds, that at first sight appear to flow very regularly, show unexpected complex dynamics that pose important problems of physical interpretation. Overall power spectra of sampled signals decay with increasing frequencies following a power law.

Depending on the exponent of the power law different scenarios can be drawn: in the 1/f regimen (pink or flicker noise) the energy decreases linearly with frequency, then each octave contains the same energy. Pink noise is intermediate between the $1/f^0$ noise (white noise), in which the system has no memory of previous states and energy is equally distributed among frequencies, and the $1/f^2$ noise (brownian noise), in which the system has no memory of previous increments. We show that the overall power spectra of large underground systems tend to behave as pink noise, with the exception of the Grotta Gigante cave.

Pink noise is rather ubiquitous and shows up in very different natural systems such as: the variation of time intervals between human heart contractions, the postural sway of a person standing on a platform, the electrical noise originated by ions dynamics in brain neurons, and many others.

Pink noise has been interpreted by means of the superposition of dynamic processes that relax exponentially with different characteristic times (Milotti, 2002). This is very interesting because from the infra-acoustic point of view, complex caves can be considered as systems of many different damped and coupled oscillators, and this is probably the origin of the pink noise. Indeed, the Grotta Gigante is not a complex cave since it is essentially formed by a huge chamber connected to the karstic plateau by three entrances and thus it cannot be considered as a system of many coupled oscillators. This might explain why noise in this cave appears to be different (i.e. brown vs. pink) with respect to that measured in the vaster and more complex caves. Modulation of wind speed appears to vary in time and this is surely correlated to the dynamics of the external atmosphere (e.g. windy days), which is able to trigger oscillations. Our first approach (measurements carried out at a single entrance, sampling at 1 Hz) was probably not appropriate. In fact, the data show a lot of noise in the high frequency range and important daily variations. This suggests an appropriate modification of the experimental approach. In future data acquisition campaigns sampling will be switched to 0.1 Hz and carried out on much longer acquisition times. Also, the use of two anemometers in the same cave, in tandem located at different entrances with simultaneous acquisition of outside meteorological data, is highly warranted.

Acknowledgement

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THE CUEVA DE LOS CRISTALES MICROMETEOROLOGY

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Cueva de los Cristales, Naica, is one of the most interesting caves ever explored. During the Proyecto Naica, led by SpeleoResearch & Film, we undertook a complex series of measurements with the goal of understanding its current physical state. This was mostly carried out by the Department of General Physics of the University of Turin. Its natural state is at a depth of 170 m immersed in 54°C mineralized water. Now it is filled with air, partially surrounded by ventilated galleries at 35–38° C.

All kinds of micrometeorological processes are happening and unfortunately we are rather unprepared to follow the details because it is what in physics is called a "transitional state." It is, in other words, experiencing a "fall" towards a new state of equilibrium that we still have not determined, but that we hope to be able to influence in some way in the future. In the meantime, all the environmental parameters vary far more than expected and in an irreversible way, so the techniques usually used to study caves aren't applicable here.

The climate of a normal cave is in fact substantially static, with minimal oscillations, whether daily or seasonal, around a point of equilibrium. They are oscillations related to the shape of the cave, but which also partly determine it, because they are able to start air currents and condensation processes which, over millennia, can significantly alter the rock. But we are still speaking about systems near equilibrium and which are therefore relatively easy to study. The climate of Cristales is evolving in an irreversible way, as well as quickly.

Our measurements have shown various phenomena. The cave continues cooling by approximately half a degree per year, because it loses heat by conduction towards the nearby mine galleries to the North-West, as well as by irradiation along the access corridor. We have also noticed that in the upper areas the air is stably warmer and more humid than the lower zones and those close to the exit. An unexpected find has been that, while the temperature is very stable, even if in slow decline, the humidity shows strong variations, on both the short and seasonal time scales. This is probably due to meteoric water infiltrations along the fractures created by the mining activity. Finally, there is an air current of about 50 L/s which starts when the access door is opened.

1. Introduction

The Cueva de los Cristales Gigantes, or simply Cueva de los Cristales, is located in Mexico, near the Naica village in the state of Chihuahua, at an altitude of 1100 m asl, is one of the most interesting caves until now explored. It was discovered during the excavation of a tunnel in 2000. Since then it is closed with a steel door (not airtight) and more recently by a transparent veranda which protect the visitors from the exposure to the hostile atmosphere. In fact, at the moment, around 2–3000 people per year are permitted to visit the cave during weekends, but without opening the last, transparent door.

During the Proyecto Naica, led by SpeleoResearch&Film, we undertook a complex series of measurements with the goal of understanding its current physical state. This was mostly carried out by the Department of General Physics of the University of Turin.

2. General

The climate of a usual cave is in fact substantially static, with minimal oscillations, whether daily or seasonal, around a point of equilibrium. They are oscillations related to the shape of the cave and its contact with the external environment, but which also partly determine it, because these fluctuations around the equilibrium are able to create "micro-meteora" (transient processes like air currents and condensation) which, over millennia, can significantly alter the rock. But we are still speaking about systems near the equilibrium and which are therefore relatively easy to study.

The main characteristic of the Cristales micro-climate is that it is not stationary or quasi-stationary; it is evolving in an irreversible way, as well as quickly. The Cristales natural state is at a depth of 170 m immersed in 54° C highly mineralized water. Now it is filled with air, partially surrounded by ventilated galleries at 35–38° C. All kinds of micrometeorological processes are happening and unfortunately we are rather unprepared to follow the details because it is what in physics is called a "transitional state." It is then experiencing a "fall" towards a new state of equilibrium that we still have not determined, but that we hope to be able to influence in some way in the future. In the meantime, all the environmental parameters vary far more than expected and in an irreversible way, so the techniques usually used to study caves aren't applicable here.

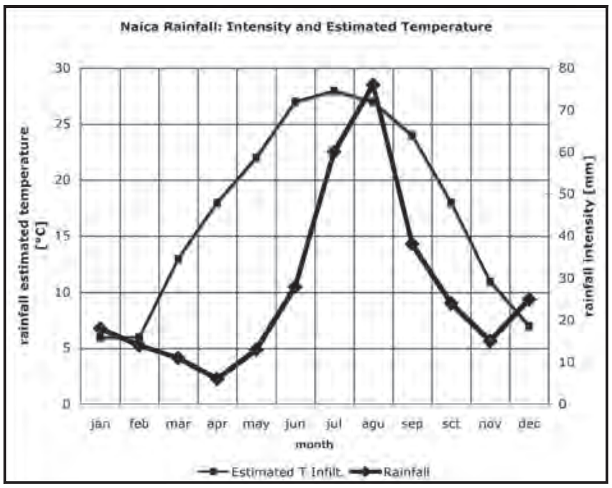

Figure 1: Rainfall intensity and temperature at Naica.

3. Cristales Environmental Conditions

The equilibrium temperature of cave in the Sierra Naica is given by the average temperature of infiltrating waters (Badino, 2005). In Europe the yearly average temperatures of infitrating waters and air are quite similar, but here they are not because precipitations are concentrated during summer. Corrections due to the Latitude (-4°) and Altitude (+300 m) effects give a Sierra Naica average temperature 1° C higher than El Paso (data from worldclimate.com).

Rainfall average temperature is generally 0.5–1° C less than the air, then we can assume that in Naica infiltration is roughly at the same temperature of El Paso. We obtain then an average yearly temperature of 17.5° C, but an average rain temperature of 21° C if weighted with precipitation intensities. Figure 1 shows precipitations and average monthly temperatures.

In the fall to the aquifer surface altitude (Cueva de las Espadas) the water temperature increases by about 0.75 °C. We can then assume that the equilibrium temperature of a cave at 1250 m asl is 22±1° C. This has to be considered the asymptotic temperature of "external heat source" which drives thermal exchange processes in contact with the Naica caves. Some temperature measurements inside Cristales were first taken in October 2002 (Testo 910, 0.01 °C resolution), giving 47.1° C at the floor and 47.4° C at 2 metres with a Testo 910. We repeated the same measurements with the same instrument in January 2006, obtaining 45.5° C.

The humidity, taken in June 2006 with an Assman psicrometre, was between 92 amd 94 %, then monitoring of relative humidity was possible. We have done this from May 2006 until now with a set of six Testo 175-H. Humidex is an index of the "perceived temperature," which depends on temperature and humidity (Masterton et al., 1979). It is in "degree Humidex;" 35–39: uncomfortable; 40–45: strong and general discomfort, danger; 46-53: highly dangerous; >54: imminent heat shock, death (Fig. 2). Cristales Humidex is around 90-95, twice the lethal, which gives an idea of the technical problems faced during exploration.

Our measurements inside Cristales have shown various phenomena, due to its non-equilibrium state and its

HUMIDEX

temperature [°C] \ relative humidity [%]	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
21	17	18	18	19	20	20	21	22	22	23	24	24	25	26	26	27	28	29	29
23	19	20	21	21	22	23	24	24	25	26	27	28	28	29	30	31	31	32	33
25	21	22	23	24	25	26	26	27	28	29	30	31	32	33	33	34	35	36	37
27	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
29	26	27	28	29	30	31	32	33	35	36	37	38	39	40	41	42	43	45	46
31	28	29	30	32	33	34	35	37	38	39	40	42	43	44	45	47	48	49	50
33	30	32	33	34	36	37	39	40	41	43	44	46	47	48	50	51	53	54	55
35	33	34	36	37	39	40	42	43	45	47	48	50	51	53	54	56	57	59	61
37	35	37	38	40	42	44	45	47	49	51	52	54	56	58	59	61	63	64	66
39	37	39	41	43	45	47	49	51	53	55	57	59	61	62	64	66	68	70	72
41	40	42	44	46	48	51	53	55	57	59	61	63	66	68	70	72	74	76	79
43	42	45	47	49	52	54	57	59	61	64	66	69	71	73	76	78	81	83	85
45	45	47	50	53	55	58	61	63	66	69	71	74	77	79	82	85	87	90	93
47	47	50	53	56	59	62	65	68	71	74	77	80	83	86	88	91	94	97	100
49	50	53	56	60	63	66	69	73	76	79	82	86	89	92	95	99	102	105	108
51	53	56	60	63	67	71	74	78	81	85	88	92	96	99	103	106	110	114	117
53	55	59	63	67	71	75	79	83	87	91	95	99	103	107	111	115	119	123	127
55	58	63	67	71	76	80	84	89	93	97	102	106	110	115	119	124	128	132	137
57	61	66	71	75	80	85	90	95	99	104	109	114	119	123	128	133	138	142	147
59	64	69	74	80	85	90	96	101	106	111	117	122	127	132	138	143	148	153	159

Figure 2: Perceived temperature.

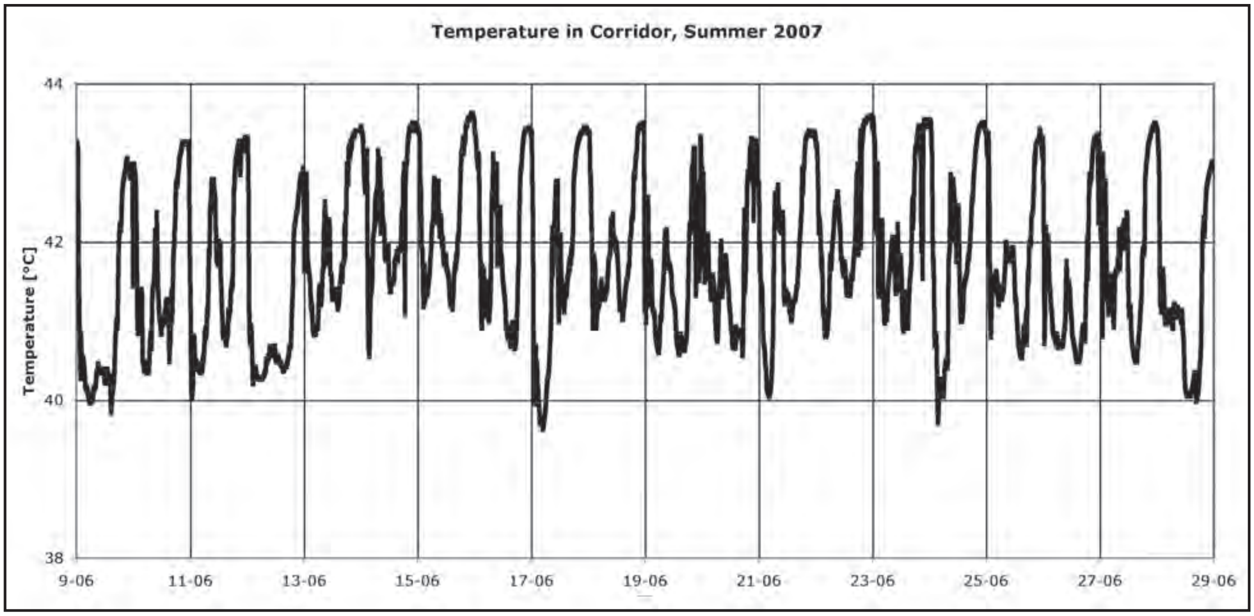

Figure 3: Diurnal temperature variations near the Cristales entrance.

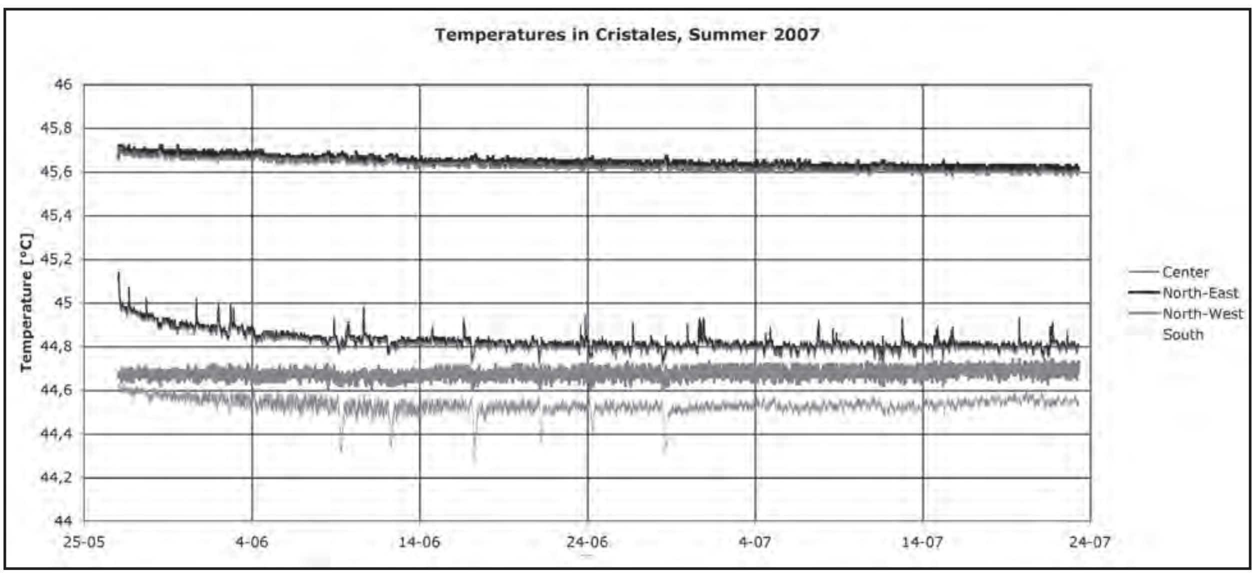

Figure 4: Temperature variations and values in different stations.

probable thermal connection with larger structures in the north-eastern branch.

Main phenomena are:

- Strong thermal sedimentation;
- General temperature decrease;
- Important air draught with open doors;
- Strong relative humidity variations.
- Thermal Sedimentation

In April 2006 we have begun a set of measures with an acquisition system Sigma 3000 (20 PT100, in four groups of four sensors inside the cave) of Lombard&Marozzini, which has given non-continuous data until August 2007 with a relative accuracy <4mK.

The thermal sedimentation in Cristales is extremely strong and shows diurnal variation. In fact, the highest part of the cave is quite stable, at a temperature around 45.5 °C, highly humid; also the "cold trap" at the bottom of the cave is quite stable at 44.6 °C (Fig. 4). The intermediate region shows important variations. It looks like a hot bubble that fills the highest part of the cave (and surrounding regions) has a diurnal variation and fills or empties the cave, leaving the highest and lowest parts undisturbed, but filling the intermediate area with hot air, including the access corridor (Fig. 3).

It shows a strong, regular daily effect, not depending on direct intervention on the doors. The maximum is at 00.00 UTC (16.00 LT), with often a sudden, very short drop. After that, the temperature falls down in few hours.

There is a secondary, less regular maximum around 09-10 UTC (01-02 LT). It seems due to temperature daily variations, maybe with some trapping effects, or pressure variations inside the mine due to regular actions on the ventilation.

There is a vertical sedimentation with an average gradient of 1.4/10° C/m at the end of 2006, reduced to 0.9/10° C/m at the end of 2007; there was also a N-S gradient of 0.6/25° C/m (Fig. 4). The downward hot bubble drift causes condensation on crystals surface in the highest part of cave.

5. Temperature variations

In the period 2002-2008 the cave has cooled by approximately half a degree per year, because it was losing heat by conduction towards the nearby mine galleries to the North-West, as well as by irradiation along the access corridor (Fig. 5). The estimated heat losses (the two of around 100 W each), as compared with the temperature decrease allow to calculate in 6×10^9 J/K the total thermal capacity of the "Cristales thermal system", roughly 30-50 times larger than the thermal capacity of known crystals.

At the end of 2007 the mine conduits surrounding the cave have been closed to airflow and their temperature quickly increased to approximately 40° C. This fact, accompanied

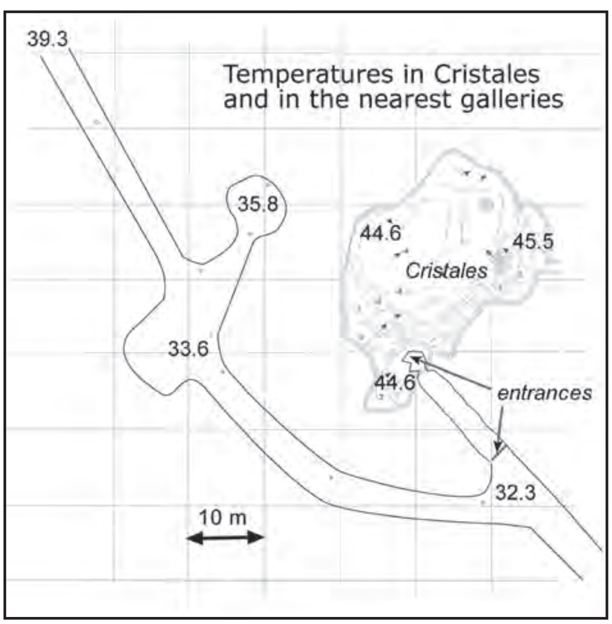

Figure 5: T-field in Cristales and surroundings.

probably with a careful management of internal door, which is now always kept closed, has almost stopped the temperature decrease of Cristales. The temperature at the top (North-East) has become stable around 45.5° C, whereas the temperature near the door, where there was a strong heat loss, has increased by 0.7° C to 45.2° C in January 2009 (Fig. 6). Condensation onto crystals in the upper parts of the cave is now virtually stopped.

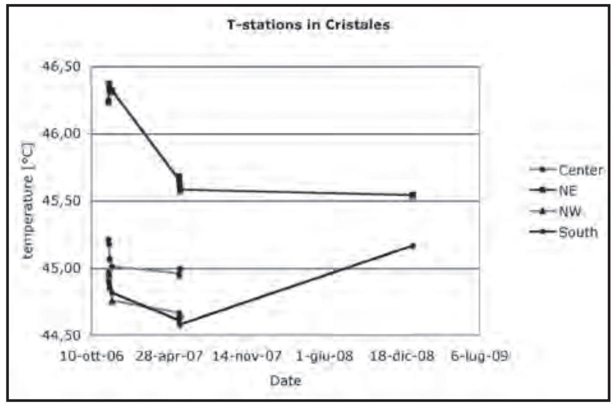

Figure 6: Temperatures in Cristales stations.

Fig. 5 shows the general temperature trend since the beginning of operations, in the region South, near the entrance. Geochemical data suggest that the Cristales temperature when drained by waters was around 56° C.

An unexpected finding has been that, while the temperature is very stable, even if in slow decline, the humidity shows strong variations, on both the short and seasonal time scales. This is probably due to meteoric water infiltrations along the Naica Fault and to movements of the hot-humid air bubble, which is in contact with Cristales (Figs. 7, 8, 9)

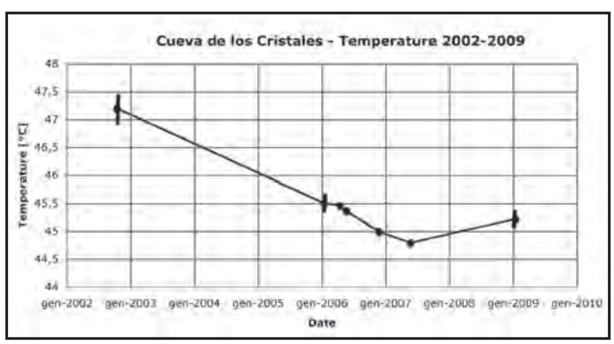

Figure 7: Temperature vs Time in Cristales Center-South.

6. Air draught

With the door nearly closed it is possible to perceive an air current coming from the cave. In May 2007 we have measured the air flow (50–100 l/s) and the moving pressure with a Testo instrument for differential pressure

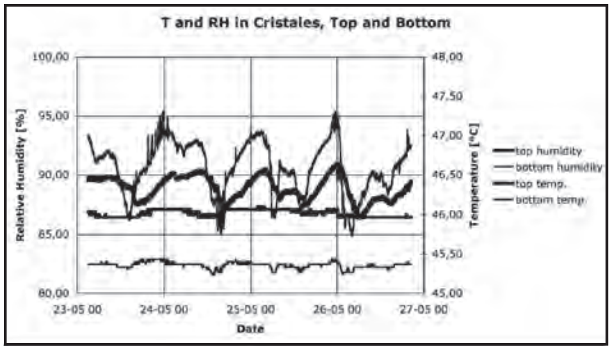

Figure 8: Temperature and Relative Humidity variations in Cristales.

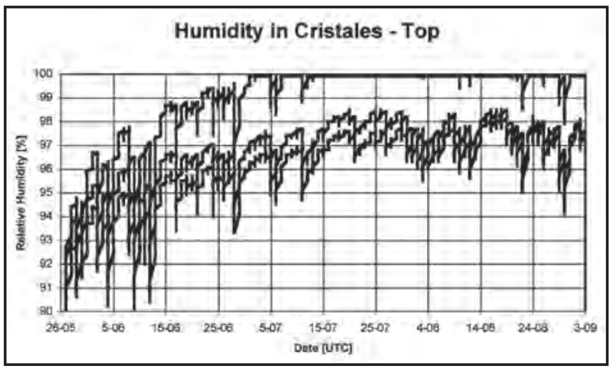

Figure 9: Relative Humidity in the Top Station, 3 sensors.

measurements. The Testo 6349 was outside the main door, connected with the cave by a tube (Fig. 10).

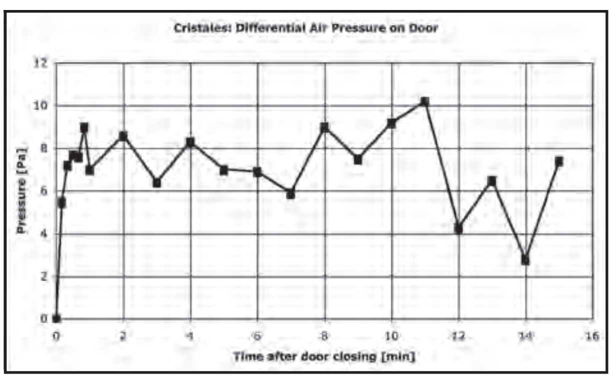

Figure 10: Differential Pressure on the main door after a sudden closure.

As expected, the pressure changes a lot due to infra-acoustic effects inside the mine, nevertheless it has an average value around 10 Pa, which corresponds to an air column 10-15 m high with a temperature difference around 10° C.

Also mines explosions have large effects on the cave. We have seen two types of behaviour: the overpressure flows out from cave after 6–8 s from the explosions, the overpressure coming to the cave from the mine galleries and bounces on the door. In the two cases, the overpressure or its bouncing is able to open the ajar door. The cave general structure as deduced by micro-meteorological data is shown in Figure 11.

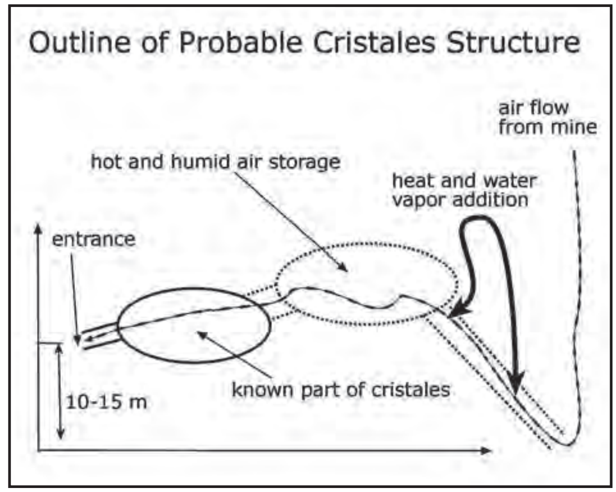

Figure 11: Probable shape of Cristales and connected structures.

7. Conclusions

These measurements have therefore shown us that the part of the cave which we know is only a fragment of a much vaster structure, which, depending on environmental conditions, introduces or extracts air from the environment we call "Cristales", including the surrounding cave like Ojo de la Reina. Moreover, the air currents show that the cave is connected to the mine through another passageway, probably fractures. Basically, these measurements show that the cave continues.

The heat loss, which was able to damage the crystal surfaces with vapor condensation,is probably finished, but a systematic monitoring of environmental parameters inside the cave is necessary to preserve it and, if necessary, to drive the internal atmosphere to a new state compatible with cave maintenance and study.

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DECLINE OF CAVE ICE – A CASE STUDY FROM THE AUSTRIAN ALPS (EUROPE) BASED ON 416 YEARS OF OBSERVATION

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Due to their geographic position and high elevation, the Austrian Alps in Europe host a large number of ice caves. About 14,000 caves are currently known in this region, and some 900 of them feature permanent ice fillings. Our study object is the "Geldloch" cave in Eastern Austria, which is a part of a 27 km long and 662 m deep cave system. The main entrance of Geldloch opens at 1446 m a.s.l. The cave shows dynamic air flow due to openings at different elevations. Ice is mainly found in a chamber (ice dome, 50 x 20 m) about 100 m behind the entrance and in the passage leading into it.

The cave was visited first in 1592, and a report including detailed drawings was published. The visitors were impressed by the ice formations, including a large frozen lake. Expeditions in 1747, 1808, 1855, 1897, and 1900 also observed the ice formations and the ice lake which often set an end to their exploration. First photographs of the ice were taken in 1902. In the second half of the 20th century, regular cave exploring trips allowed to make accurate notes on the ice decrease. The comparison reveals that in general the ice is declining. The most recent visit in October 2008 showed that the cave is completely free of ice after summer nowadays. We present the different data sources (drawings, photographs, and descriptions) and quantitatively estimate the ice loss based on the height changes of the ice lake.

1 Cave Characteristics and Regional Settings

The *Geldloch* (Fig. 1) is part of the 27 km long and 662 m deep *Ötscher Cave System* that is located in Lower Austria (Europe). Mount Ötscher reaches 1893 m and is a rather isolated high alpine mountain in a pre alpine environment. The *Ötscher Cave System* (Hartmann & Hartmann, 1985; 1990; 2000) comprises two major caves: *Geldloch* and *Taubenloch*, which both open on the southern hillside at 1446 and 1505 m a.s.l. respectively. A connection between those two caves was found as recently as 1994 (Hartmann & Hartmann, 2000).

The Ötscher is part of the Northern Calcareous Alps and consists of Upper Triassic, well karstified lime- and dolostones of the Dachstein Formation. The alpine climate is chilly with heavy snow falls in winter. The average temperature at the meteorological station of the nearby village of Lackenhof at 805 m asl is 6.0° C (Land Niederösterreich, 2009). Assuming a gradient of 0.35°/100 m, the temperature at the altitude of 1500 m extrapolates to 3.5° C. Average annual precipitation at Lackenhof is 1814 mm.

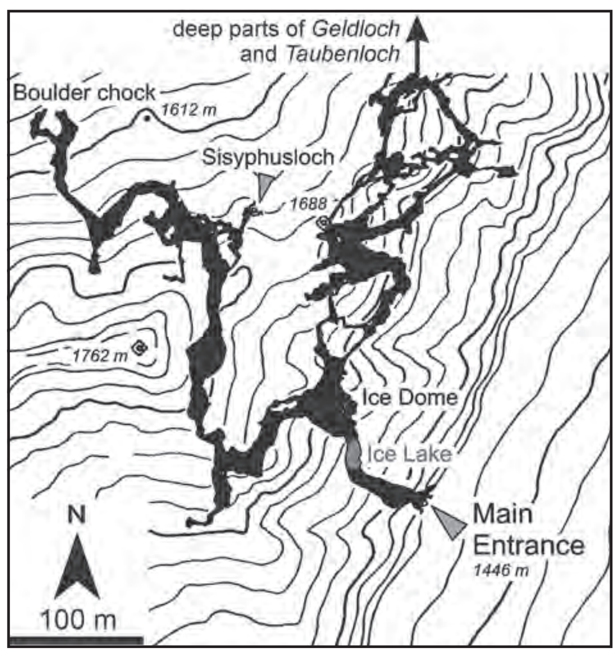

Figure 1: Overview map of the Geldloch as part of the Ötscher Cave System. Map by E. Herrmann, Survey: Speleological Society of Vienna and Lower Austria.

2. Description of the Ice Formations

The *Geldloch* has two entrances: the main entrance, a large portal 10 m wide and 5 m high at 1450 m asl and a very small upper opening at 1663 m a.s.l. called *Sisyphusloch*. The latter was discovered and artificially enlarged in 1988 (Hartmann & Hartmann, 1990). Within the cave, six sections can be distinguished, of which especially the 700 m long main gallery and its connection to the *Sisyphusloch* are of interest for our study. Ice formations are restricted to the beginning of this section. Their growth and decline is controlled by the air current between the main entrance and upper opening: the known *Sisyphusloch* and many others that are not passable by humans.

The main entrance leads to a 10 m wide gallery which is partly covered with snow in winter and spring. Approximately 100 m behind and 30 m below the entrance the *Ice Lake* is situated (Fig. 1). The *Ice Lake* is historically described as an accumulation of water in summer, mostly frozen in winter (e.g. Levenstein & Riedl, 1879). The biggest reported extent is 25 to 35 m while it can cover the whole width of the gallery which is about 10 m.

Behind the *Ice Lake*, early visitors reached the *Ice Wall*, a frozen waterfall that was gone by 1992 (Greilinger, 1992). It was ca. 12 m wide and reached an impressive height of up to 10 m over two cascades. On top two ice stalagmites grew having several meters in diameter. The *Ice Dome*, a chamber measuring 50 m x 20 m, was reached by climbing the *Ice Wall*. Early descriptions mentioned the *Ice Dome* to be covered with massive ice formations.

Behind the Ice Dome, the cave divides into two major parts. To the North, a series of vertical drops leads down to a sump 444 m below the entrance. To the West a large horizontal gallery terminates after some 600 meters in a boulder chock. In the second half of this section, a series of chimneys leads to the upper entrance Sisyphusloch 217 m above the main entrance. Several other chimneys with air draft have not been explored yet.

3. History of Exploration and Remarks on Ice Formation

In the past *Geldloch* was considered to host "one of the most magnificent subterranean ice formations" (Haselbach, 1876, p. 204) which is one of the reasons why its first exploration dates back as early as 06-09-1592. This fact also explains the importance of the *Geldloch* in the history of the scientific exploration of European caves (Shaw 1992, p 255f). A review of the exploration history is given in Hartmann & Hartmann (1992).

During all expeditions, notes on the ice formations were taken, but not in a systematic way. The ice often was a major obstacle. The reports were sometimes sparse and some were lost. Nevertheless, it is known that, at the time of the first expedition (1592), the *Ice Lake* was frozen and the Ice Pyramids had a circumference of five meters (Fugger, 1891; Soukup, 1887; Haselbach, 1876; Hartmann & Hartmann, 1985).

In 1747 an expedition was ordered by Emperor Franz I. of Austria. It was led by A. J. Hacker and J. A. Nagel. The group failed to cross the *Ice Lake* but produced detailed sketches of the entrance part which show the ice formations in the entrance part and at the *Ice Lake* (Fig. 2).

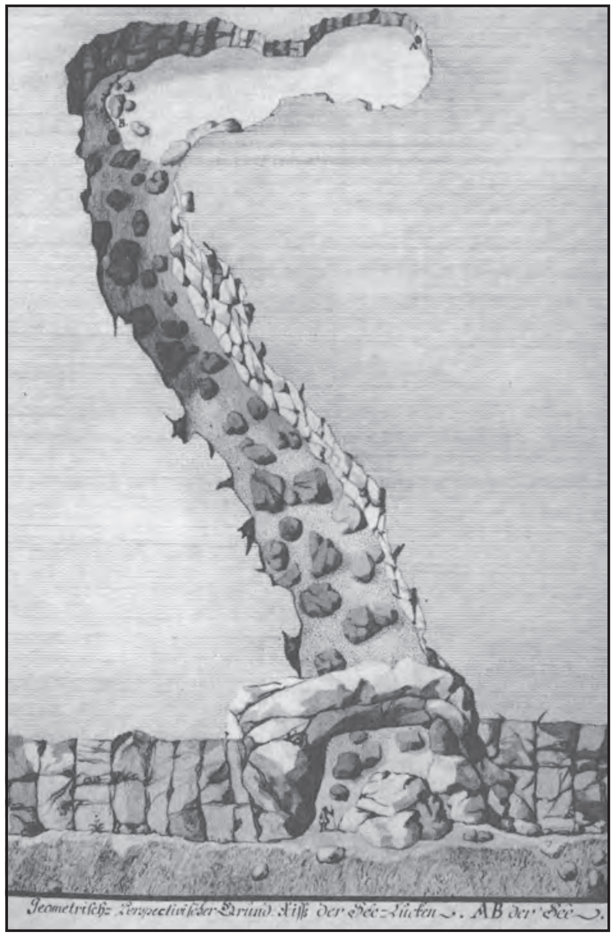

Figure 2: Basic map of Geldloch from Nagel, 1747.

The *Ice Lake* was reported to have completely vanished in 1847 (Haselbach, 1876). Refilling obviously occurred relatively quickly. The lake itself had different manifestations throughout the centuries (unfrozen, totally or partially frozen surface, different ice thicknesses).

In September 1855 another map was drawn by Becker and

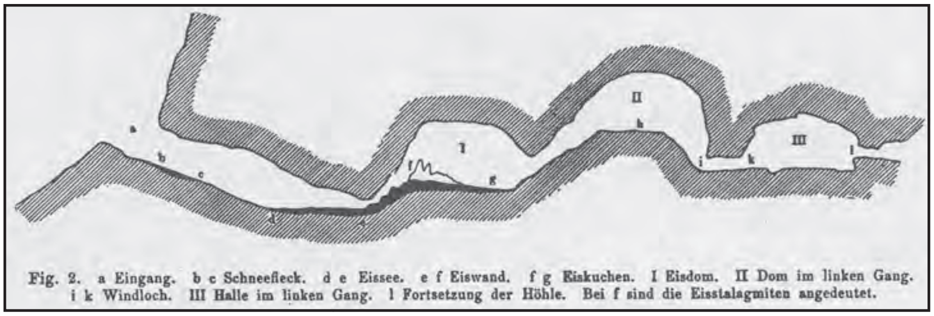

Figure 3: Section of Geldloch from Crammer & Sieger, 1899. a: Entrance, d-e: Ice Lake; e-f: Ice Wall; I: Ice Dome.

Hörtler (Becker, 1859), including the ice formations, but the map covers only the entrance parts. It is simple but gives an impression of the ice formations at that time. In 1897 the maps were extended by Crammer & Sieger (1899) who also investigated temperatures and ice appearance (Fig. 3).

The entire horizontal part of the cave was fully explored by the beginning of the 20th century and mapped from 1900 to 1902. This was also when first photographs of the cave were taken (Anonymous, 1953). The vertical section was explored and mapped in 1923. After that, research became more extensive with several expeditions (e.g. 1953, 1974). Major degeneration of the ice was reported before 1960 (Pfau, 1960). Up to then, the reports are frequent and diverse. Greilinger (1992) sums them up, revealing a massive decline at the *Ice Lake* since the beginning of the 20th century.

In 1992, 400 years after the first exploration, only little of the ice in the *Geldloch* was left. In 1988 the introduction of the battery driven drilling machine led to the discovery of the *Sisyphusloch*. In 1994, the link between *Geldloch* and *Taubenloch* was discovered. The most recent visit in October 2008 showed the *Geldloch* being completely free of ice.

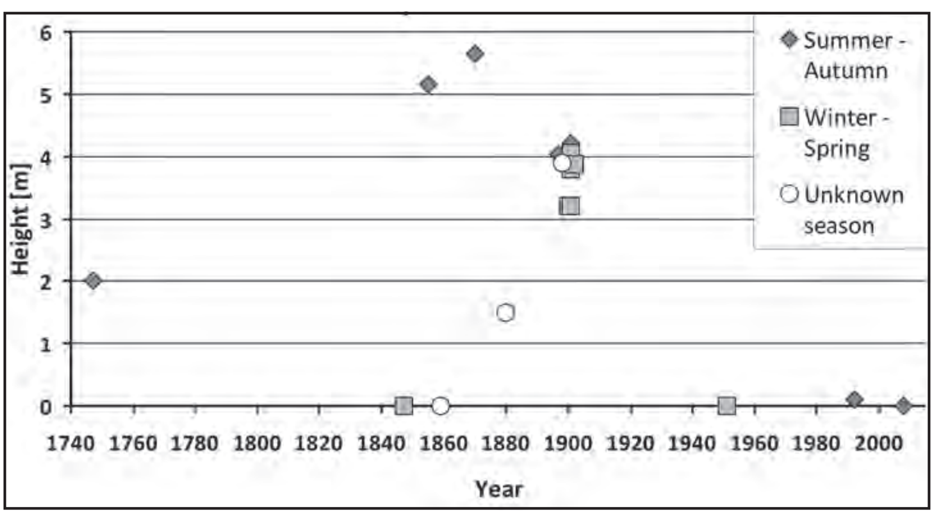

Figure 4: Level (above ground) of the Ice Lake in the years 1747 until 2008.

Figure 4 shows a summary of historic data available on the ice formation of the *Ice Lake*.

4. Historic Explanation of Periodic Ice Formation in the Geldloch

As opposed to the nearby *Taubenloch*, the *Geldloch* hosted permanent ice. Until 1747, it was believed that the ice of the *Ice Lake* existed in summer only, melting down completely in winter. Various explanations were given on this phenomenon. Most of them involved a cooling of the rocks of the Ötscher in winter which conserves the ice during the hot summer months. Water on the otherwise frozen lake was explained as melting water originally coming from the snow at the entrance. Crammer & Sieger (1899) proved these theories wrong after doing extensive meteorological research. This led to the modern theories on air circulation in caves and ice caves in particular (Crammer, 1899).

5. Discussion and Conclusions

Although there are many observations dating back to 1592, only few of them provide accurate data on the thicknesses of ice at the *Ice Lake*. Further difficulties arise from ice level changes due to seasonal variations, sometimes contradicting descriptions and the fact that the observations are based on infrequent and irregular visits. Despite these limitations, the data summarized in Figure 4 allow for the following interpretation: The *Ice Lake* had its largest extent around the mid of the 19th century and has been declining since then. This coincides with the progress of glaciation in the Alps. In general, the glaciers advanced until around 1850 and have been retreating since then. The mid of the 19th century is also the end of the little ice age in the Northern Hemisphere which followed the Medieval Warm Period. The *Ice Lake* seems to have completely disappeared in the mid of the 20th century. The constant decline of ice in the adjacent ice dome supports this interpretation. Few but reliable observations indicate that the *Ice Lake* can completely disappear and reform within a few years.

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EFFECTS OF SURFACE MORPHOLOGIES ON FLOW BEHAVIOR IN KARST CONDUITS

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The 1974 work from Blumberg and Curl on scallops in karst conduits is revisited using three-dimensional, time-dependent computational fluid dynamics simulations. The original work presented the results from theoretical analysis and experimentally observed scallop formation as an expression including Reynolds number, friction factors, and scallop size. This expression is often used to determine karst conduit flow velocities based on observed scallop sizes in caves. In the current work, flow behavior is simulated using the CFD code, STARCCM+, for vadose and phreatic cave passages containing scalloped walls in order to create comparisons with and extend the results of the original work. Results of simulations are used to demonstrate potential impacts of momentum-dominated speleogenesis.

1. Introduction

Long-term development of karst groundwater flow conduits is governed by discharge, the hydraulic gradient, rock properties (e.g., solubility and porosity), and chemical aggressiveness of the water (Palmer, 1991). Each makes a significant contribution in defining the end-product groundwater system. Porosity, i.e. percent of void volume, of the medium is what allows the karst development to occur. The pores are commonly characterized by their shapes and volumes. Their connectivity defines rock permeability (White, 2002).

Mechanically-derived groundwater systems with flow path apertures of <1 cm have been referred to as fracture systems while voids having diameters of ≥1 cm have been referred to as conduits. Conduit flow is governed by viscous drag on walls, floors, ceilings, and flow-path obstructions, including pathway bends. These are often described by hydraulic-flow and geometry based variables. They affect travel time through the groundwater system, and subsequently, influence the formation of the conduit itself. Furthermore they have a significant impact on larger-scale descriptors of groundwater systems, namely determination of tracer breakthrough curve tailing behavior, and estimation of total system discharge.

A large amount of research has been conducted to determine the effects of various hydraulic-flow and geometry factors, including Field et al. (1997), Hauns et al. (2001), Peterson et al. (2006), Geyer et al. (2007), and others. Much of this work describes the application of numerical approaches to predict the impact of conduit surface features on tracer breakthrough curves. A smaller group of researchers, e.g., Hauns et al. (2001), have generated detailed simulations of critical portions of large conduit systems, such as potholes, meanders, and pools. Work in this area is important for determining the friction factors that may be present due to conduit morphologies and conduit surface morphologies, including scallops, which are concavities eroded into conduit surfaces by flow associated with near-wall detachment and reattachment patterns (White et al. 2005).

In this regard, Blumberg and Curl (1974) developed a friction factor expression for flow in conduits with fully-developed scalloped walls, dependent only on flow Reynolds number. The current paper revisits the work of Blumberg and Curl (1974) with 3D flow simulations using STARCCM+V3 (CD-adapco, New York, NY) with the goal of determining a level of validation with the original findings and to examine fine-scale phenomena that could not be observed or measured in the original experiments.

2. Previous Work

Blumberg and Curl (1974) conducted a theoretical and experimental investigation to obtain an expression for how a mean size of scalloping depends upon conduit flow velocity, by applying dimensional analysis and the universal law of the wall for turbulent flow over rough surfaces. Such an approach was critical for proceeding past the recirculating dilemma caused by coupling dissolution with generation of turbulence inducing surface features. Their work involved the calculation, measurement, and dimensional determination of key descriptors of the fluid behavior. These included channel Reynolds number, friction velocity and friction-velocity Reynolds number, mean channel velocity, scallop (or flute) period length, a Sauter mean characteristic length, and a roughness function. Their resulting expression provides a friction factor, ff, as follows:

$$\bar{f}^{-1/2} = 1.77 ln\left(\overline{Re}_d \bar{f}^{1/2}\right) - 11.44 \quad (1)$$

where $Re_d Re_d$ is the Reynolds number based on conduit diameter, *d*, and on mean flow velocity, and where $B_L B_L$ is a roughness function for pseudo-smooth pipe flow. The above equation can be further simplified to predict paleoflow conditions based on scallop size (Curl, 1974a, 1974b). In this equation $\overline{Re}_L \overline{Re}_L$ is a Reynolds number for mean scallop size as follows:

$$\overline{Re}_L = \frac{\rho \bar{u} \overline{L_{32}}}{\mu} \quad (2)$$

where $\bar{L}_{32} \bar{L}_{32}$ is measured as the maximum length of the ith scallop determined by

$$\bar{L}_{32} = \frac{\sum L^3{}_i}{\sum L^2{}_i} \quad (3)$$

and $\rho\rho$ is density, $\bar{u}\bar{u}$ is mean flow velocity, and $\mu\mu$ is dynamic viscosity. Previous to the 1974 work, Curl (1966) had observed a unique relationship between Reynolds number and scallop formation, independent of kinematic viscosity, therefore results obtained from the experimental observations in the 1974 work can be extended to other conditions beyond those described here.

3. Theoretical Background

Details of fluid flow systems can be predicted numerically in finite-volume formulations where matrix solutions from multi-diagonal matrices are solved based on discretizations of the Navier-Stokes equations with mass, momentum, and energy being continuous and conserved. More extensive details of CFD are described by Ferziger and Peric (2002), Anderson (1995), Pope (2000), and Patankar (1980). Regarding CFD in speleology, Jeannin (2001) and Houns et al. (2001), as well as others, have presented the governing equations in terms of karst-conduit flow applications. In this work, the CFD package, STARCCM+V3 (CD-adapco, New York, NY) was used. This CFD tool was selected for its ability (1) to create closed, clean surfaces of "dirty" CAD representations, (2) to create polyhedral control volumes that promote orthogonality, (3) to study transition turbulent flows, and (4) to calculate near-wall modeling parameters needed for turbulence models.

For viscous flows, two near-wall layers are commonly described and need to be accurately measured (experiment) or calculated (simulation). They are the viscous sublayer and the turbulent boundary layer located just above. In the past it had been commonplace to populate a near-wall region with large numbers of cells in order to accurately calculate viscous shear-dominated flow in this region. However, such an approach is very costly in time and computer memory resources. To overcome these limitations, the use of a blended wall function, originally based on law-of-the-wall approaches, that requires many fewer cells in the boundary and near-wall layers is applied here. This approach is described in CD-adapco (2007) and receives detailed attention in Popovac et al. (2007).

For making useful comparisons with results from Blumberg and Curl (1974), the near-wall velocity (which also can give friction-velocity Reynolds number, etc.) and the scallop-length (peak to peak) velocity are calculated in the simulation. The latter is the result of advective flow calculation in a turbulent regime, while the former is determined from the following equation used in STARCCM+V3 (CD-adapco, 2007):

$$u^+ = \frac{1}{\kappa} ln(1+\kappa y^+) + \left(\frac{1}{\kappa} ln \frac{\left(\frac{E}{f}\right)}{\kappa}\right)\left[1 - exp\left(-\frac{y^+}{y_m^+}\right) - \frac{y^+}{y_m^+} exp(-by^+)\right] \quad (4)$$

where energy generation, $\kappa\kappa$ is initially by default 0.42, and energy dissipation E = 9.0, $y^+ y^+$ is a measure of the distance to the wall in the sublayer, $y_m^+ y_m^+$ represents the intersection of the viscous sublayer with the turbulent region just above, and *b* is a further expansion of the discretization.

4. Computational Grid

3D surfaces of the gypsum scallop fields generated in the work by Blumberg and Curl (1974) (Figure 1) were scanned by the University of Michigan 3D Lab (Ann Arbor, MI) and stored in a stereolithography file (STL). Scans were made at a resolution of 1e-3 m. The resulting STLs were imported into STARCCM+V3 where a computational region was added above the scallop field to create a fluid flow region. An inside surface wrapping procedure was applied to extract the scallop field and flow region of interest. A closed surface with surface cell size of 1e-3 m resulted. Based on surface, a volume mesh was built from polyhedral cell control volumes to promote orthogonality and was grown at a rate of 17% from the surface to the maximum cell size of 0.01 m. Figure 1 shows the result of the surface wrap of the scanned scallop field for the 1 m/s Blumberg-Curl experiments.

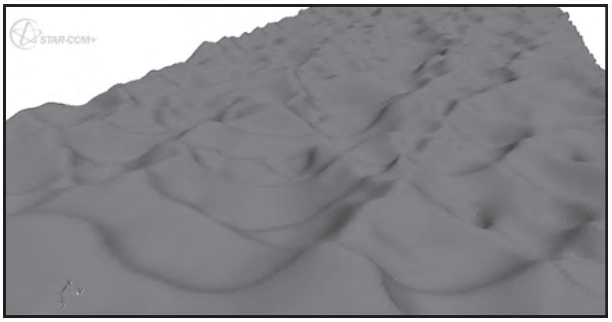

Figure 1: Looking downstream over the 3D scanned and discretized surface scallop fields from Blumberg and Curl, 1974. Upstream is at the bottom of the image and downstream at the top.

5. Results

Simulations were obtained for individual scallops, a scallop field, fully submerged potholes, and free surface potholes. Comparisons with Blumberg and Curl experiments were possible for the two former cases, while qualitative comparison with Hauns et al. (2001) is made for the two latter cases. Since Reynolds number provides a common comparison, CFD calculation results for 1 m/s Blumberg-Curl scallop fields are presented in Figure 2.

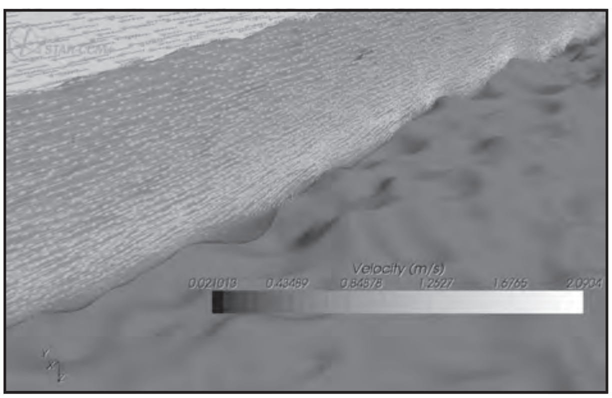

Figure 2: Velocity vectors from centerline section slice of calculated flow over scallop field. Upstream is top-right side of image. Scallop where Blumberg and Curl made experimental measurements is just to the left and below of center.

The location of measurements in the 1 m/s Blumberg and Curl (1974) scallop field were at 53.4 cm downstream from the leading edge of the gypsum block. Of note, the velocity used in Blumberg (1970) and adopted by Blumberg and Curl (1974) is $U_m U_m$, which is the maximum measurable near-wall velocity and which is not a traditional near-wall friction velocity. Using this value of velocity, Blumberg and Curl reported near-wall $Re_m Re_m$ of 2120 and 2320 for two different roughness functions, $B_L B_L$, of 8.8 and 8.9. CFD simulation in this work slightly under predicts $Re_m Re_m$ with a value of 1405 for a corresponding $B_L B_L$ = 9.0. For the location above the scallop where $Re_L Re_L$ was determined, CFD agrees well with Blumberg and Curl. Their reported values were 20500 and 21000, while CFD gives 22300. This shows a reasonable qualitative validation of the results, and allows further expansion of applications of the current CFD models.

While it is usually thought that conduit meanders, intersections, and sharp bends have the most impact on the velocity of the water flow, CFD results here show that as scallop field population increases for small numbers of scallops, the drag increases and subsequently fluid velocity decreases. Drag force coefficient for the Blumberg and Curl scallop field is 0.0182, which contains approximately 360 scallops. Drag coefficients calculated for fields containing 1, 3, 5, and 7 scallops were 0.002409, 0.002577, 0.002742, and 0.002778, respectively. Decrease in flow velocities, as drag increases with increase in scallop number, are visible in Figure 3a,b. Figure 4 shows centerline flow velocities for the 1m/s Blumberg-Curl scallop field.

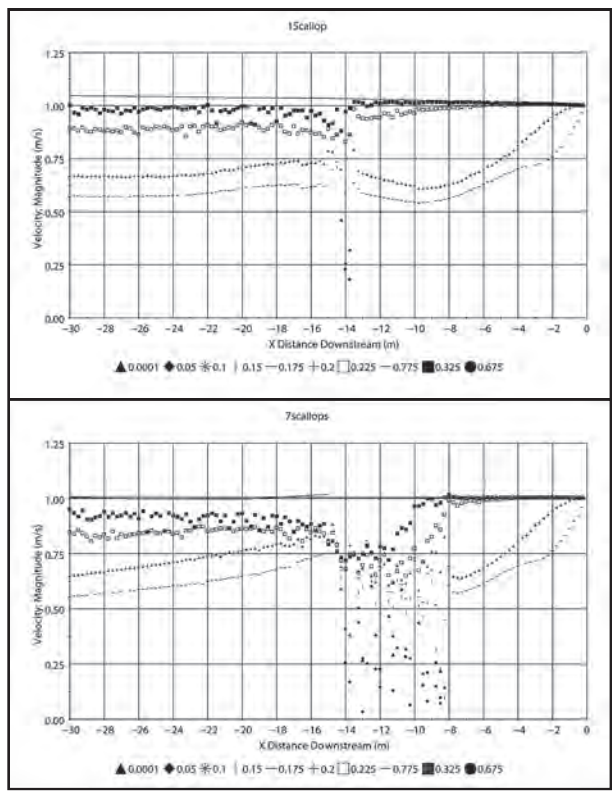

Figure 3: From left (a), for single scallop centerline flow velocities at heights above scallop basin of 0.0001, 0.05, 0.1, 0.15, 0.2, 0.225, 0.325, 0.675, and 0.775 m; and right (b) 7 scallops. Simulations with 3 and 5 scallops further demonstrate this trend.

Overall mean flow velocities are reduced when features are present on conduit walls. Simulation results for 1, 3, 5, and 7 scallops show a 3–5% mean-flow velocity reduction (Fig. 3). For a fully developed scallop field, significant flow effects are present throughout the flow field due to turbulence generated from the scallops. However direct impact of a scallop field in fully developed turbulent conditions is not as significant as are lightly populated scallops. This is due to the acceleration of the water at the leading edge of a scallop (Fig. 5) as it is "squeezed" between the inertially dominant channel flow and the slower moving eddy in the scallop.

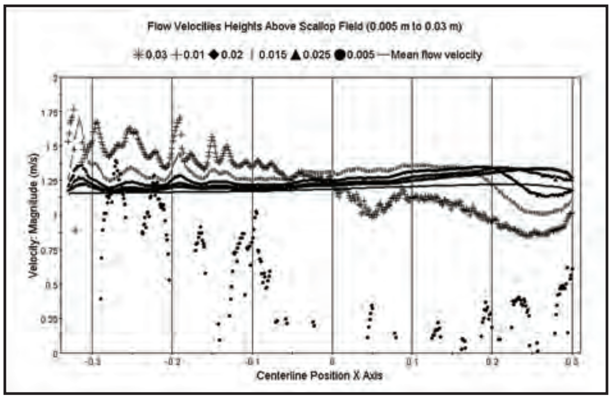

Figure 4: Simulation results from the Blumberg-Curl 1 m/s scallop field for centerline velocities at heights above scallop basin of 0.005, 0.01, 0.015, 0.02, 0.025, 0.03 m.

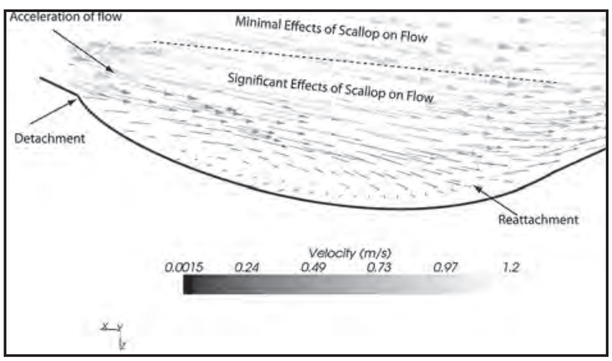

Figure 5: Vector plot of flow in and above scallop. Vector size indicates magnitude.

Detachment of the flow in the scallop occurs where the acceleration is highest, which is at the leading edge. Reattachment occurs at a location approximately 2/3 scallop length downstream from the leading (Fig. 5). Experimental observations suggest this to be the location where scallop propagation, i.e. significant dissolution, occurs in the scallop. This location corresponds with a condition of locally dominant momentum being perpendicular to the affected medium, i.e. the wall of the conduit.

Another location where locally dominant momentum

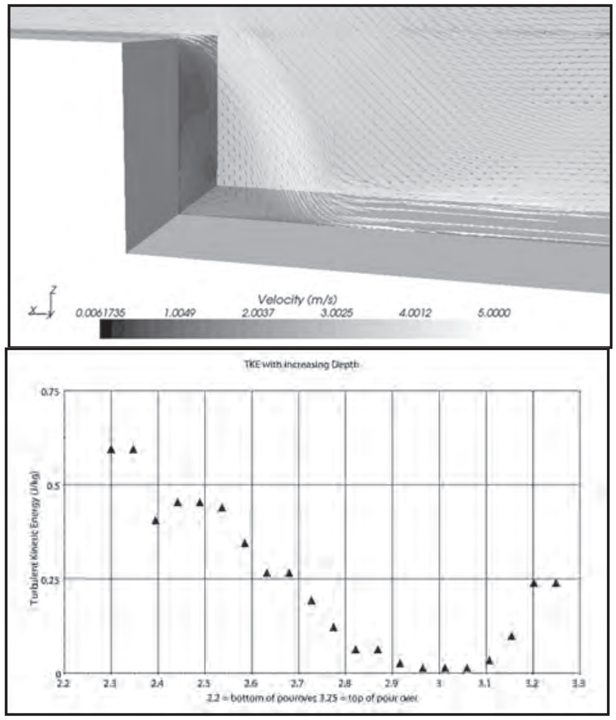

Figure 6: Vector plot of free surface flow in a pourover (a), and (b) plot of turbulent kinetic energy in the pourover.

is perpendicular to the conduit surface is the floor of a pourover or waterfall. Field investigation by Brucker et al. (1972), also suggests vertical enlargement of shafts, i.e. where momentum is perpendicular to the affected medium, is a dominant event in karst conduit evolution. Figure 6 shows simulation results and turbulent kinetic energy (TKE) plot for a 1-meter high pour over. Together with the falling mass of the water and the already high momentum, a great deal of force is available to act on the floor and walls of a conduit.

6. Conclusions

Scallops are a relatively common geometric and hydrodynamic feature of karst conduits. The work of Blumberg and Curl (1974) led to further understanding of the formation of scallops as well as an expression to relate scallop size to flow Reynolds number, which allows estimation of paleoflow discharge. The current work reported in this paper has qualitatively validated the original experimental results using CFD. This allows further extension of the CFD simulations to additional conditions, including singular scallops and their effect on flow conditions, as well as other conduit features such as pourovers. In the 1974 work it was observed that reattachment occurred at approximately 2/3 scallop-length downstream from the leading edge of the scallop. This is the location where new scallop development is most significant. The location of reattachment in the scallop is seen at the same location in the CFD results. It is of not that this is the point where locally dominant momentum is perpendicular, or at a high angle, to the affected medium, i.e. the wall of the conduit. This condition of locally dominant momentum being perpendicular to the surface is present not only at the reattachment point in scallops but also at the base of pourovers and waterfalls.

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PRELIMINARY WATER QUALITY AND BOUNDARY REDEFINITION OF THE SCOTT HOLLOW DRAINAGE BASIN, APPALACHIAN PLATEAU, USA

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Scott Hollow Cave is a major (>43 km) vadose conduit system developed within a mature karst upland in Greenbrier and Monroe Counties, West Virginia, USA. Previous mapping and dye tracing revealed that the cave drains an estimated 48.2 km^2, with a major conduit transmitting water northward to discharge at the Greenbrier River. The majority of conduits are developed in the lower units of the Greenbrier Group (Mississippian), especially the Hillsdale and Sinks Grove Limestones.

The present study sought to refine the boundaries of the overall basin, identify sub-basins within the system, and to evaluate specific water quality parameters. A series of qualitative dye-traces were undertaken to identify hydrologic connections between the surface and subsurface and to help better define the drainage basin boundary. Multiple dyes, including Sodium Fluorescein, Rhodamine WT, and Eosin, were used, along with charcoal detectors. Within and outside the cave 14 locations were identified for water quality sampling. Coliform counts, and nitrate were repeatedly measured.

The incised Second Creek must limit the eastern margin of the basin. Even so, no injections near this boundary have flowed in that direction; they have moved westward toward the cave. Extreme complexity of flow, apparently caused by structural features, is found. For example, three different dyes were placed in close injection points in a single sinkhole, the entrance sink of the main cave entrance, and were recovered in four different places. In the southern part of the area the basin appears to wrap around the nose of the plunging Sinks Grove Anticline. Time-averaged nitrate values vary from 4 to 47 mg/L at the in-cave locations fed by known surface catchments.

1. Introduction

Karst areas are recognized for their susceptibility to groundwater contamination. The current research project sought to characterize and explain the variability of water quality entering Scott Hollow Cave, an extensive dendritic cave network. The cave is developed in the Big Levels region

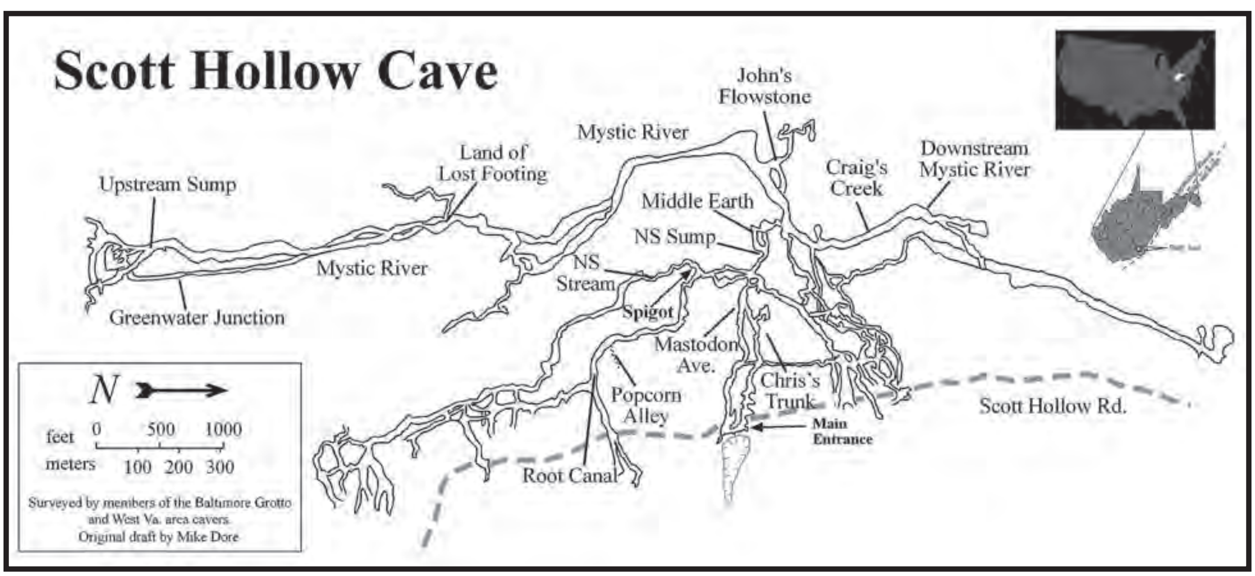

Figure 1: Partial Scott Hollow Cave map showing the in-cave sample locations.

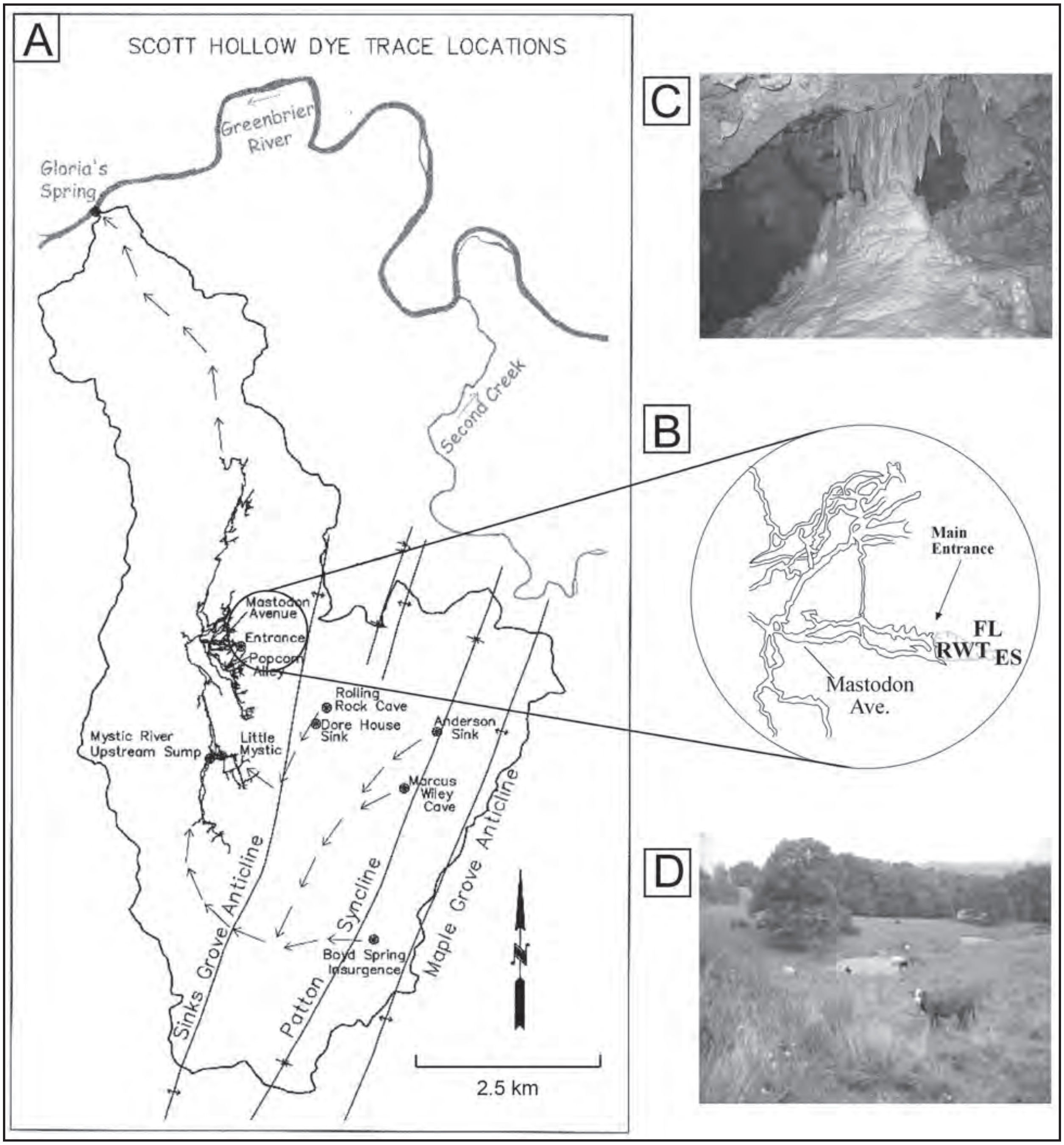

Figure 2: A. Map of the hypothesized drainage basin (unpublished map by Michael Dore 2009) illustrating dye traces conducted. Geologic contacts and structural features from Ogden (1976) B. Photo taken in the North South passage within Scott Hollow Cave (scale – about 3 meters) C. Inset of where the Scott Hollow dye trace was conducted D. Photo illustrating the local surface topography.

of southeastern West Virginia, which is a rolling limestone upland surface that hosts many of the long caves of North America (Fig. 1, inset). This karst plain is a rural area dominated by agriculture, mostly cattle grazing and feed crops (Figure 2D). The animal waste from pastures has the potential to seep into the soil or be carried underground by sinking streams and impact the aquifers below. Water samples were collected at 10 locations within the cave.

2. Location and Overview of Study Area

The Scott Hollow drainage basin is located in a moderately deformed portion of the Appalachian Plateau physiographic province. The stratigraphy consists of Mississippian interbedded limestones (Fig. 2B) and shales of the

Greenbrier Group (Reger and Price, 1926). Many of the extensive cave systems present in Monroe County occur within the Hillsdale and Sinks Grove Limestones, including Scott Hollow Cave (Fig. 1). The Scott Hollow drainage basin is a mature karst plain that drains an estimated 48.2 km^2 surrounding the small town of Sinks Grove (Jones, 1997). Overall drainage is towards the north, where the deeply incised Greenbrier River serves as local base level (Fig. 2A). Earlier work (Jones 1997) showed that the cave drains to Gloria's Spring on the south bank of this river.

The two dominant folds within the basin are the Sinks Grove anticline and the Maple Grove syncline (Fig. 2A), both trending to the NE (Ogden, 1976). Scott Hollow Cave developed in the west limb of the Sinks Grove anticline with its main passage, Mystic River, running parallel to strike (Davis, 1999). Many of the eastern tributaries of Scott Hollow Cave flow down dip before reaching Mystic River. Joints, faults and fractures also influence conduit orientation and morphology (Ogden, 1976).

Demrovsky (2003) discovered that nitrate levels in cave streams peaked when large quantities of snow melt saturated the overlying soil recharging the aquifer. This increase is attributed to the fact that nitrates are stored in soils during dryer periods and are released during wetter periods, indicating seasonal influences on concentration levels (Pasquarell & Boyer, 1996).

3. Methods

3.1 Dye tracing

A series of qualitative dye traces were conducted using a method based on that of Mull et al. (1988). This information is being used to 1) define the boundaries of the Scott Hollow drainage basin, 2) establish hydrologic connections between the surface and sub-surface, and 3) delineate groundwater flow paths. Three fluorescent dyes were used for this study; Sodium Fluorescein (CI Acid Yellow 73), Rhodamine WT (CI Acid Red 388), and Eosin (CI Acid Red 87). Background levels of fluorescence were checked with activated charcoal. All traps were switched with new ones every few weeks and sent to the Environmental Data lab in Warm Springs, Virginia to be analyzed using a spectrofluorometer. The traps were continually replaced until dye was detected.

First Dye Trace - Scott Hollow: The first dye trace was conducted in the closed valley entrance sinkhole of Scott Hollow Cave (Fig. 2B). Approximately 1 liter of each dye was injected in 3 different locations on March 22, 2008. Eosin was used at a stream coming from a wooded area at the east end of the entrance valley, Sodium Fluorescein was placed where the stream enters Scott Hollow Pond, and Rhodamine WT was used in the stream that exits the pond and sinks underground. Detectors were placed at the following 8 locations throughout the cave: Popcorn Alley, Root Canal, Mastodon Ave., Chris Trunk, upstream Mystic River across from Johns Flowstone, downstream Mystic River across from Craigs Creek, NS Sump, and Middle Earth. Two detectors were placed at Motel 8 and Main St., the upper Scoop City section of Scott Hollow Cave, in the event that the dye was to travel in that direction.

Second Dye Trace - Eastern Boundary: The second dye trace was conducted in the southeastern section of the study area. 0.7 liters of Rhodamine WT was poured into a sinking stream exiting the pond at Anderson Sink in the eastern section of the drainage basin boundary. 2 liters of Eosin was used in a small sinking stream near the entrance of Rolling Rock Cave, and the same amount of Sodium Fluorescein was used at Dores Sink on May 18, 2008, which are also located in the eastern portion of the basin.

Traps were placed in the upstream section of the cave. These locations include Mystic River across from Craigs Creek, Mystic River across from Johns Flowstone, Iceland, Land of Lost Footing, Greenwater Junction in Little Mystic River, and at the Upstream Sump. Three traps were placed on the surface along Second Creek at Hokes Mill, Nickels Mill, and at the mouth of Second Creek in the event that groundwater flow went in the opposite direction.

3.2 Water quality sampling

Water samples were collected on a monthly basis from 10 locations within the cave and 4 surface locations. Three of the surface locations are known insurgences into the cave system and the last location is the only known discharge location, Glorias Spring, along the Greenbrier River.

Each month water samples for nitrate analysis were collected, and analyzed using a Dionex DX-120 Ion Chromatograph. A coliform bacteria water analysis was performed alternate months from samples collected on the surface and within the cave. The Coliscan Easygel method (Micrology Laboratories) was used. The analytical mixture was placed in a small incubator at 35°C (95°F) for 24 hours. All pink and purple colonies were counted and reported as total coliform per mL of water used.

4. Results and Discussion

4.1 First dye trace - Scott Hollow

The first set of detectors monitoring background levels contained no dye. The second [9 days] and third [18 days] set of detectors tested positive for dye. The Rhodamine WT used in the sinking stream exiting the pond was detected at Mastodon Ave. and was visibly detectable within a few hours of injection in this stream. Rhodamine WT was also detected in Mystic River across from Craigs Creek, the NS Sump, and was also detected in the Scoop City section of Scott Hollow Cave at Popcorn Alley. The Sodium Fluorescein used at the stream entering the pond was detected in Mystic River across from Craigs Creek, and NS Sump. Rhodamine WT and Sodium Fluorescein were also detected at Popcorn Alley where there is a stream coming from the upper Scoop City section of the cave (Fig. 2A).

The detection of both Sodium Fluorescein and Rhodamine WT in the upper Scoop City section and the lower section of Scott Hollow Cave at Mastodon Ave. and at the NS Sump indicates that water from the same sinkhole drains into two different parts of the cave. Eosin was not detected on any of the traps. This was probably because a high concentration of Rhodamine WT may have masked a relatively lower concentration of any Eosin present in the sample. This was taken into consideration for planning the second dye trace.

4.2 Second dye Trace - eastern boundary

Dye was detected on the first [12 days], second [27 days] and third [41 days] set of traps. Rhodamine WT was detected at the Upstream Sump, Land of Lost Footing, and Iceland, which are all located in the upstream section of the cave. Dye was also detected at down stream Mystic River across from Johns Flowstone and across from Craigs Creek. Greenwater Junction was the only location that Rhodamine WT was not detected. The Eosin and Sodium Fluorescein were detected at Greenwater Junction, Land of Lost Footing, Iceland and downstream Mystic River across from Johns Flowstone and Craigs Creek. No dye was detected at any of the surface locations along Second Creek (Fig. 2A).

The Eosin used at Rolling Rock Cave and Sodium Fluorescein used at the Dores Sink were not detected at the Upstream Sump and were both detected at Greenwater Junction. All three dyes eventually made their way down Mystic River and were detected across from Johns Flowstone and Craigs Creek. It appears that groundwater could be flowing around the southern nose of the Sinks Grove Anticline from the Anderson Sink, eventually making its way to the Upstream Sump at Mystic River. Groundwater flow from Rolling Rock Cave and the Dores Sink seem to be taking a similar path, both ending up at Greenwater Junction in the Little Mystic River and eventually joining Mystic River. This Eastern boundary dye trace suggests that Scott Hollow Cave may possibly be much larger than originally speculated and the potential for the discovery of new cave passages is very probable.

4.3 Nitrate analysis

Nitrate in the groundwater from March through December varies between 0 mg/L and 47 mg/L (Fig. 3). It appears that subsurface water sample locations containing the greatest amount of nitrates originate from areas with a high intensity of cattle. Locations with lower concentrations are in sub-basins that are mostly wooded or have fewer cattle. It also appears that seasonality affects the amount of nitrates present in cave streams. Samples collected from March through May all have values that don't substantially vary. This can be attributed to steady amounts of rainfall common in the spring. Beginning in June, nitrate values start to rise and then gradually decrease in August (late summer) through October (fall) (Fig. 3). This time of year precipitation was rather low, allowing nitrates to become trapped in the overlying soils and can account for the decrease in nitrates in the groundwater. Sample locations Craig's Creek and Middle Earth values were 10 to 15 mg/L higher than all the other sample locations. Based on current cave survey data, aerial photos and topographic maps of this area it was possible to determine the headwaters for these 2 areas. The land use for these locations is primarily for cattle grazing and other live stock, indicating that runoff from these pastures is entering the cave system. The cattle are rotated to different parts of the farm throughout the year and could attribute to these higher values at these specific locations. In November and December, nitrate values increased substantially due to an increase in rainfall and snow melt occurring after a month with little to no precipitation, flushing nitrates from the surface into the aquifer.

4.4 Coliform Analysis

There are gaps in the total coliform data for this study due to analytical problems. Interpretation is based on 4 months of data; March, May, July, and December 2008 (Fig. 4). Coliform colony totals range from about 550 (per 3 mL of the water sample) to 0. Coliform levels in March and May are between 0 and 300 per 3 mL of sample and continue to decrease in July in correlation to low precipitation rates. Samples collected in December had the greatest amount of coliform present which was a result of increased precipitation, which flushes the microbes into the cave via swallets and sinking streams.

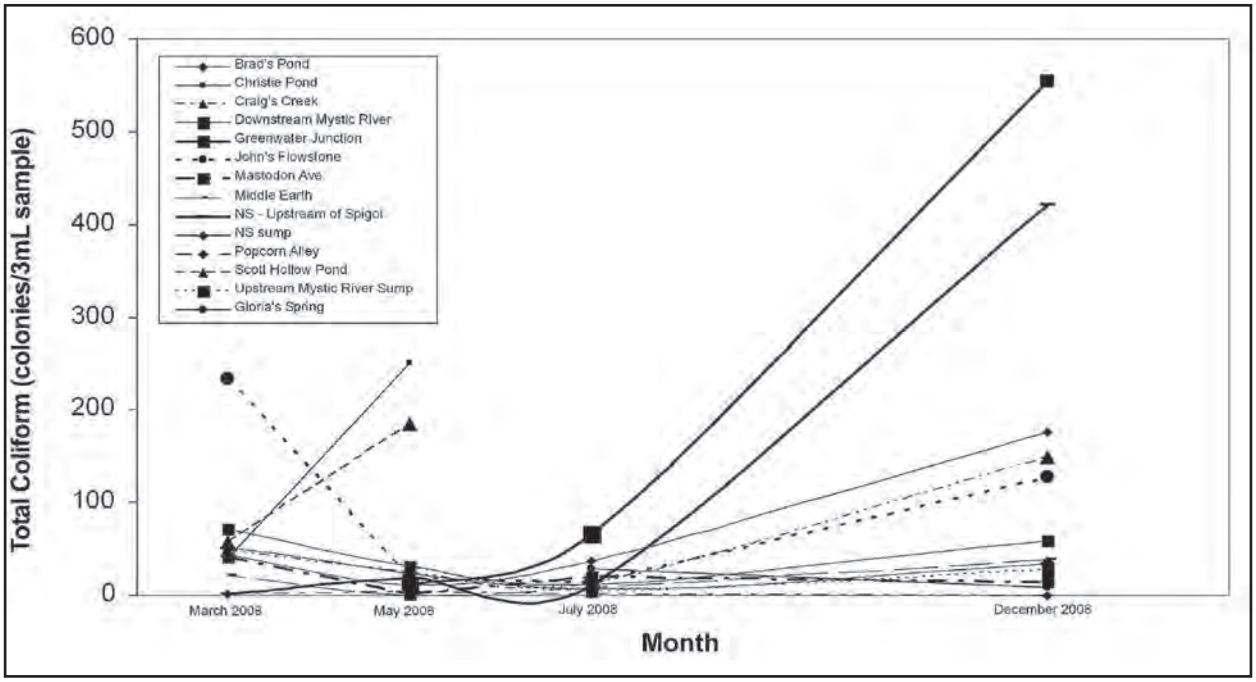

Figure 3: Graph of nitrate concentrations from March – December 2008 and total precipitation (in). Precipitation data provided courtesy of Doug Boyer (Lewisburg Airport station). Triangles indicate sampling days.

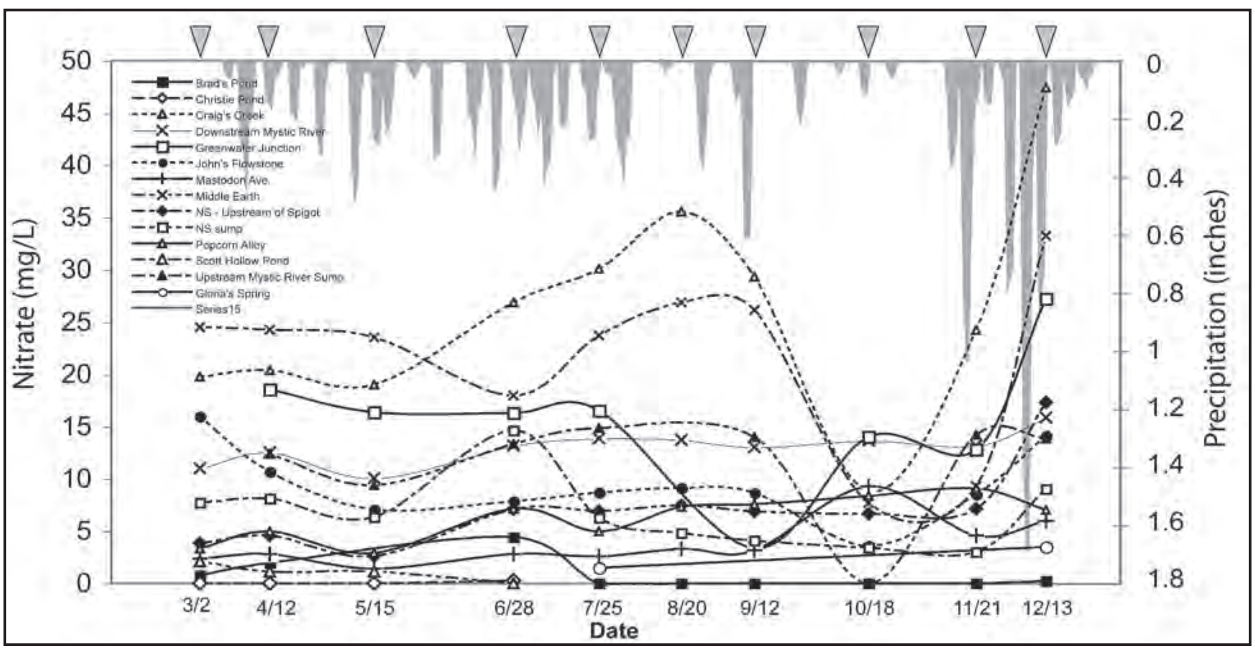

Figure 4: Graph of the total coliform data for March, May, July, and December 2008.

5. Conclusions

Subterranean drainage in the Scott Hollow basin is complex as a result of the local structure and stratigraphy. The first traces examined flow on the scale of a single sinkhole. They show that minor variations in position of an insurgence can result in flowpaths that diverge on the scale of 100s of meters. This is likely caused by the presence of multiple permeable bedding planes near the base of the Hillsdale Limestone. On the scale of the mapped cave, flow from sinkhole inputs is mainly downdip along bedding planes, with collected flow traversing northward along strike to resurgence at the Greenbrier River. The second set of traces examined portions of the drainage which go beyond the mapped cave. These results indicate that a) The basin may extend beyond the original estimated 48.2 km^2, b) It is likely that the cave has a much more extensive footprint than is currently mapped, and c) Flow appears to wrap around the plunging southern end of the Sinks Grove Anticline, going southward and then northward towards the Greenbrier River.

The nitrate and total coliform data collected within this drainage basin indicate that agricultural practices can have a direct affect on groundwater quality. The fluctuations in nitrate concentrations and total coliform values also illustrate how seasonality and precipitation rates have an effect on the groundwater quality of this area. During spring precipitation rates don't vary much. Nitrate concentrations during this time ranged from 0-25 mg/L, but each individual location didn't vary much due to the fact that nitrates were readily washed into the aquifer with every precipitation event. Late summer through fall, precipitation rates began to slowly decrease to almost no rainfall in October. October nitrate values range from 0 – 15 mg/L. November and December had significant precipitation events following a long dry period which allowed high quantities of nitrates to be flushed into the groundwater, yielding higher concentrations ranging from .2 – 37 mg/L.

Acknowledgements

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FLOW CHARACTERIZATION FROM EPIKARST AND SHALLOW BEDROCK SPRINGS ACROSS A RANGE OF HYDROLOGIC CONDITIONS, SAVOY EXPERIMENTAL WATERSHED, OZARK REGION, U.S.

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Abstract

This study describes the results of a series of spring-discharge measurements, continuous monitoring of field parameters, and tracer studies that were conducted at the Savoy Experimental Watershed (SEW), and it offers explanations for the observed variations in springflow for varying hydrologic, temporal, and extreme stress conditions. This specific study is part of a longer-term assessment of hydrologic budget components and speleogenesis at SEW, a long-term, well-instrumented karst research site in the Ozark region of northwestern Arkansas, midcontinent United States.

Discharge measurements for Pond, Tree, Woodpecker, Memory, Dribble, and Red Dawg Springs (epikarst) were conducted twice a day, during the early morning (7:00 A.M. during July and August; 8:00 A.M. during December because of late sunrise), and the early afternoon, at about 2:00 P.M. Data collection periods were chosen reflecting the growing season (21 days in July and August, 2005 and 2006) and the dormant season (5 days in December 2005). Volumetric measurements were made with 500 to 2000 mL graduated glass cylinders, accurate to +/- 2 mL; time measurements were made with a stopwatch readable to 0.01 seconds. The mean of 10 repetitions per spring (volume/time) for each measurement provided an accurate, reproducible assessment of discharge. Results indicate that (1) diurnal fluctuation of these epikarst springs is dominant during the growing season and minimal during the dormant season when deciduous trees have lost their leaves and transpiration is minimal. This loss of water from the shallow ground-water system is interpreted to be evapotranspiration from the ground-water system, and ranges from 5 to 25 mL/s over the course of a diurnal cycle for each spring; (2) extreme low-flow conditions are manifest differently in different spring basins, and these provide an understanding of the flow mechanisms that may be active in karst settings; (3) the wide range of hydrogeologic response in epikarst springs to identical stresses indicates that our models of these systems are likely grossly oversimplified.

Continuous monitoring and multiple tracer studies at Langle and Copperhead Springs (shallow bedrock) over long time periods and varying hydrologic conditions illustrate the varying hydrogeologic responses to differing ground-water levels in rapid-flow karst aquifers, and provide strong evidence that predictive numerical modeling in such settings at grid scales less than several kilometers is risky and misleading. Application of models to test hypotheses does seem apprpriate, but only within the range of hydrologic conditions that have been observed and used to develop the conceptual model.

FLUORESCENCE CHARACTERIZATION OF KARST AQUIFERS

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The fluorescent properties of natural dissolved organic matter (DOM) were investigated as indicators of organic carbon flux and pollutant/pathogen transport through groundwater basins. The study focused on the character and potential monitoring value of naturally-occurring fluorescence in karst aquifers typical of the Southern Appalachian region. Well and spring samples were collected during severe drought conditions, and provide a reference for DOM behavior at base flow. The evidence suggests that DOM fluorescence changes predictably on multiple temporal scales. In carbonate settings, DOM composition changes seasonally across the entire region, and more suddenly in response to local recharge events. Groundwater was dominated by fulvic acid-like in winter months, reflecting fresh inputs of leaf litter and woody plant material from leaf fall. Refractory, humic acid-type fluorophores were only detected after significant recharge events in a minority of the sources. Fluorescent DOM exhibited a compositional shift towards protein-like compounds during warmer weather, possibly due to increased soil microbial production, root exudates, and soil moisture deficits. The fluorescent properties of low-risk wells varied less than those of all springs. The fluorescent properties of some high-risk springs were observed to change over very short time intervals (hours), while others exhibited little fluctuation regardless of time frame. With more work, fluorescent DOM characterization could provide a useful tool for watershed monitoring and modeling, with benefits for the design of low-concentration dye tracer tests, and refinement of sampling strategies for organic pollutants and waterborne pathogens.

1. Introduction

Sampling groundwater for background fluorescence is recommended as to test the potential for analytical interference between tracer dyes and ambient fluorophores, both naturally-occurring and anthropogenic (Aley, 1999; Smart and Karunaratne, 2002). In practice, low-level fluorescent signals are subtracted from dye spectra without much consideration of the information being lost (Alexander, 2005). Natural fluorophores are ubiquitous in aquatic systems, consisting of dissolved organic matter (DOM) derived from decomposed plant litter and the exudates of roots and soil microbes (Chen et al., 2003; Zech et al., 1997). Humic acids (HA) and fulvic acids (FA), plus the tryptophan-like (P1) and tyrosine-like (P2) proteins make up the bulk of this complex mixture.

The fluorescent properties of DOM are attributed to reactive, oxygen-rich functional groups (carboxylic acids, phenols, amines) that help drive essential soil processes and biogeochemical cycles (Kramer et al., 1990; Mobed et. al, 1996; McDowell, 2003). DOM is a key player in the processes of metal complexation, immobilization of microbial pathogens, and the subsurface retardation and transport of radionucleides (Scott et al., 1998; Jardine et al., 1990), and though its specific role in the global carbon cycle is not fully understood, DOM is considered a major link in the transfer of carbon and nutrients between terrestrial and aquatic ecosystems (Smart et al., 1976; Jaffe et. al., 2008).

Fluorescent properties are expressed in terms of excitation and emission wavelengths ($\lambda ex/\lambda em$) and intensity (I) of the spectral peak. Natural fluorescence is most commonly observed in the long ultraviolet and blue parts of the spectrum, with λex in the 200–400 nm range, and λem from 350–500 nm (Newsom et al., 2001). Exceptions include algal products and chlorophyll which are detected by extending the scan range up to 650 nm, near the analytical limits of most instruments.

Fluorescent DOM has been distinguished in lake water samples from Antarctica to Colorado (McKnight et al., 2001), the Amazon River basin and Gulf of Mexico (Coble, 1996), peat catchments in northern England (Baker and Spencer, 2004) and caves in Hungary (Tatar et al., 2002). The position and intensity of spectral signals can be correlated with relative age, function, composition and origin of fluorophore solutions (Senesi, 1991; Mobed et al., 1996; Frimmel, 1990; Chen et al, 2003; Kalbitz et al., 1999).

Correlations between DOM and aquatic environments have been reported despite differences in analytical techniques and instrumentation, suggesting the need for wider applications of fluorescence characterization in monitoring karst watersheds. The objectives of this study were to examine the temporal and spatial variability of natural fluorescence in karst aquifers, and to assess the viability of fluorescence characterization as an environmental tracer and indicator parameter for assessment and compliance monitoring. The research was conducted in partnership with the Tennessee Department of Environment and Conservation (TDEC) Division of Water Supply under the auspices of the Source Water Protection Program.

2. Study Area

We sampled 23 groundwater-based community water supply sources in the Upper Tennessee River Basin (UTRB; Figure 1). The Tennessee portion of the watershed encompasses an area of about 2 million hectares between Johnson County (36° 33' N latitude) and Hamilton County, Tenn. (35° 12' N latitude). Altitudes in the northern part of the study area exceed 1200 m near Mountain City, TN and vary around 200 m in the south near Chattanooga. The climate is temperate and humid, with average annual temperatures from 9° C to 17° C. Mean annual precipitation (1935–1997) ranges from 988 mm in the north to 1244 mm in the south (Johnson, 2002). The sampling program was conducted from fall 2006 through fall 2007 during a period of severe drought.

The study area encompassed Paleozoic carbonate aquifer settings in the Valley and Ridge physiographic province. Bedrock generally dips 40° to 50° to the southeast, and is heavily folded and fractured by multiple thrust sheets aligned sub-parallel to the northeastward trend of the Appalachian orogen (Lloyd and Lyke, 1995). Subsurface drainage networks and direct surface water-groundwater connections are common, and most often manifested by karst topography. Karst aquifers are mantled by clay-rich soils (Order, Ultisols) ranging from very thin to more than 30 m thick.

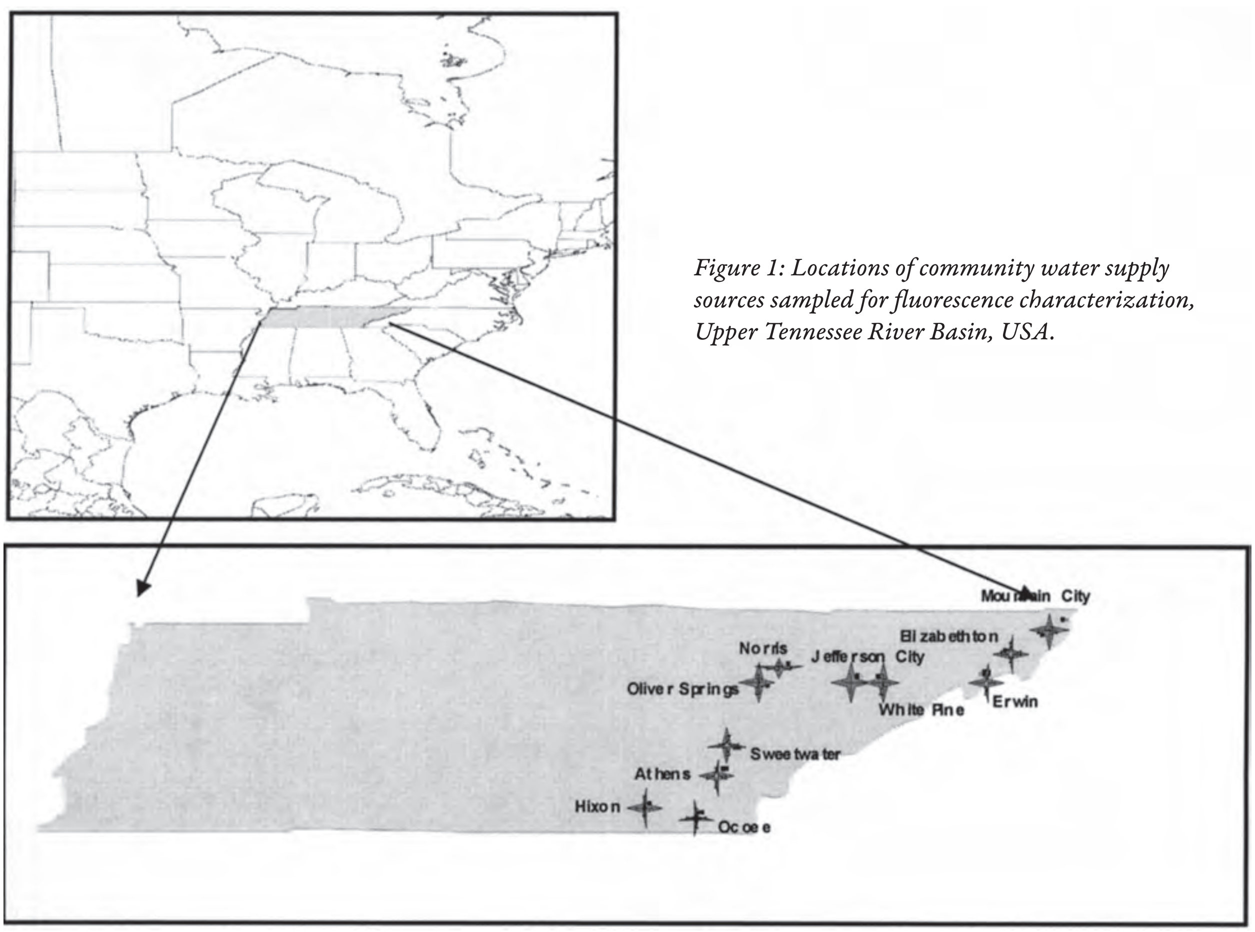

Figure 1: Locations of community water supply sources sampled for fluorescence characterization, Upper Tennessee River Basin, USA.

SPRINGS	pH	Temperature (°C)	Conductivity (µS/cm/s²)	Absorbance	TOC (mg/L)
Max	8.9	19.3	567	0.36	1.75
Min	7.1	11.0	112	<0.004	0.31
Avg	8.0	15.1	253	0.07	0.94
WELLS					
Max	8.6	19.7	573	0.16	3.36
Min	7.2	11.3	187	<0.004	0.37
Avg	7.9	15.6	332	0.02	1.11

Table 1: Summary of 2006–2007 Geochemical Data.

Spring and well waters are generally of the calcium-magnesium-bicarbonate type, with relatively high hardness measured as total dissolved solids (TDS) or Specific Conductivity (SpC; Lloyd & Lyke, 1995; Krawczyk and Ford, 2006). A summary of physical and geochemical field parameters measured during this study is presented in Table 1. Recent surveys by both the USGS and UT detected *E. coli* in up to half of all water supply wells and the majority of springs, along with low concentrations of enteric viruses (Johnson, 2002; Johnson et al., 2005). Despite their inherent vulnerability to surface-derived contamination, karst aquifers are the primary and most productive sources of private and community water supplies in the region.

3. Methodology

Raw water samples were collected directly from community water supply wells and springs on a quarterly basis, in addition to one week-long automated sampler study. Field parameters (pH, electrical conductivity, and temperature) were measured prior to sample collection with a multi-parameter meter (YSI Model 63). Replicate raw water samples were collected in pre-cleaned 40 ml glass vials for use in analyses, as field blanks, and for comparison of sample degradation and holding times. Samples were filtered in the field using 0.2 um glass fiber syringe-mounted filters and immediately placed on ice, protected from light, and transported to the UT Hydrogeology Program laboratory in Knoxville.

Samples were temporary stored in a dedicated refrigerator at 4°C. One replicate sample from each source was acidified to just above pH = 2.0 for total organic carbon analysis (TOC; Shimadzu) via EPA Method 5310. Ultra-violet (UV) absorbance (Beckman Coulter 640B) was measured at 254 nm and 270 nm per Standard Methods 5910B and others (Kalbitz et al, 1999). Fluorescence analysis was performed on a luminescence spectrophotometer (Perkin Elmer LS55) with a xenon lamp. Instrument settings are listed in Table 2. Samples were analyzed in both single scan and in 3-D mode to illuminate spectral details over a range of excitation wavelengths at fixed wavelength intervals (Δλ).

4. Results

Throughout the latter half of the study period, most sources exhibited the spectra of at least two distinct fluorophores, usually FA in combination with one or more proteins or HA. A snapshot of groundwater DOM under low base flow conditions was obtained by plotting excitation and emission wavelengths at maximum fluorescent intensity (single scan spectra) for August and September 2007 (Fig. 2). The data were grouped into five distinct components. Protein-like fluorophores, P1 and P2, plotted at the lowest λex/λem, reflecting their low molecular weight.and intense fluorescence. FA and HA compounds plotted near the center of the graph at higher and lower excitation wavelengths, respectively. A fifth component detected only in later summer samples (λex/λem= 275/600) was thought to be related to algal products (AL), since some spring-based supplies were experiencing nuisance algae problems at the time. Other possibilities include the introduction of anthropogenic material or vegetative signs of drought stress.

scan range:	200 nm - 620 nm
Δλ:	15 nm
ex slit:	4 nm - 5 nm
(dependent on maximum intensity)	
em slit:	3 nm - 4 nm
(dependent on maximum intensity)	
scan speed:	1000 nm/min
emission increment:	10 nm
number of scans:	1 - 15

Table 2: Instrument Settings for Perkin-Elmer LS55B Spectrophotometer.

The seasonal dynamics of DOM are evident from progressive changes in λex/λem, presented as scatter plots in Figure 3. The well data is generally more tightly clustered than the spring data, which is probably a function of the wells having smaller immediate recharge areas and less mixing. Humic acid only appeared in response to storm events in springs, and occurred in only one high-risk well. Fulvic acid dominated all groundwater DOM in winter,

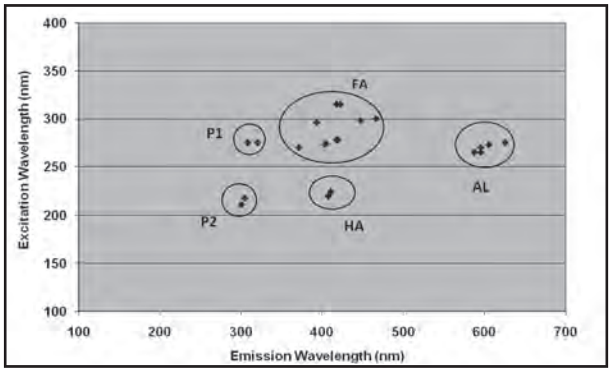

Figure 2: Typical DOM Components in East Tennessee karst aquifers (Late Summer 2007). Data points represent single synchronous scan fluorescence maxima labeled accordingly: P1 = Protein-like (Tyrosine); P2 = Protein-like (Tryptophan); FA = Fulvic acid-like; HA = Humic acid-like; AL = Algal by-products.

while warmer weather samples showed a distinct blue shift towards proteins. This pattern was mirrored in the absorbance data, a surrogate for dissolved organic carbon (not shown), which dropped over time as biodegradation progressed, temperatures increased and recharge events became increasingly scarce.

High FA fluorescent intensity occurred in winter and exhibited the most variability, apparently driven by the influx of organics from freshly fallen leaf litter during winter storms. High I values in summer were mainly related to nm), highly fluorescent pulse that appeared in response to the third and largest rain event, suggesting a contribution of algae or autochthonous turbidity (Pronk et al., 2005).

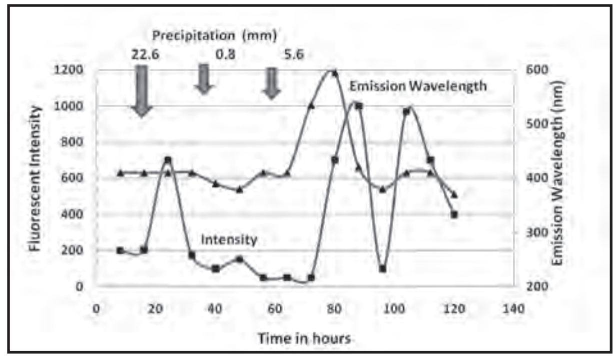

Figure 4: Short-term DOM Dynamics at Clear Creek Spring, June 2007.

5. Conclusions

This regional survey of the fluorescence properties of karst groundwaters revealed predictable, seasonal patterns in DOM evolution that could be exploited for water supply protection and management. While the annual trend was similar across the study area, local variations indicate the potential value of using natural fluorescence to trace pathways in specific groundwater settings. While annual to millennial changes in climate, vegetation and land use affect DOM source material and supply, short term fluctuations occur in response to recharge events and diurnal cycles. In well-characterized systems, the introduction contaminants such as detergents could be viewed tracers in and of themselves.

the entire spectral range in groundwater. Fulvic dominant fluorophore consistent with the and Genty, 1999; van et al, 2002; Lapworth et presence of intense protein months was unexpected. and springs, all closely supply sources, the proteins increased soil microbial al., 2001) rather than such as wastewater effluent, agricultural runoff (Baker Baker and Spencer, 2004). The humic acid fraction of fluorescent DOM

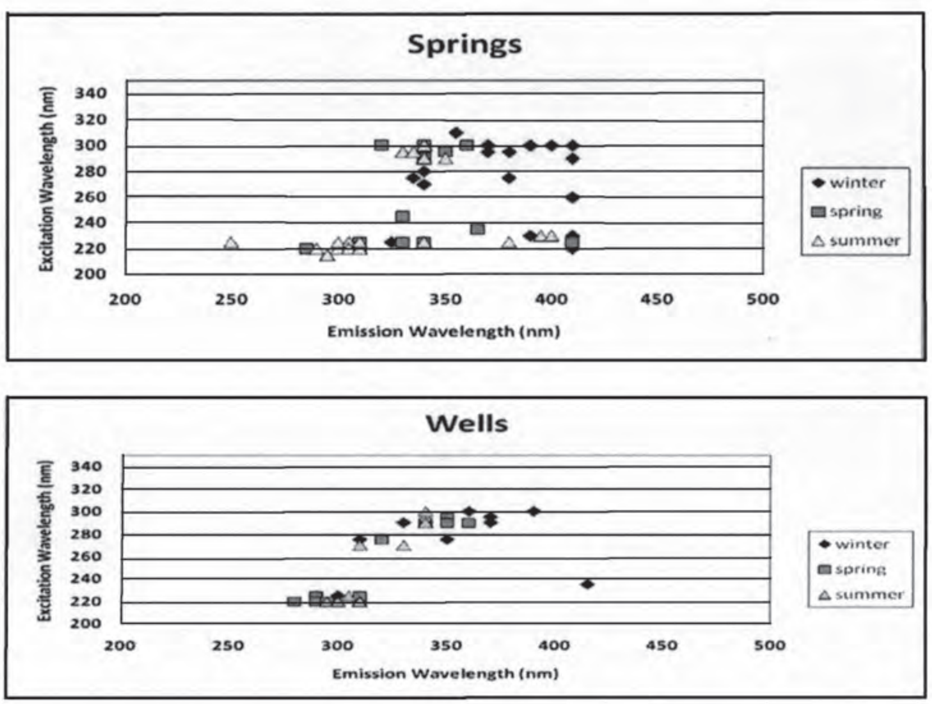

Figure 3: DOM Dynamics as Seasonal Fluctuations in Fluorescence Maxima.

occurred in groundwater in association with significant recharge events, and in keeping with its hydrophobic nature, appeared to remain bound by sorption and other mechanisms to clays and biofilms in the epikarst (Perrin et al., 2003; Kramer et al., 1990; McKnight et al., 1997).

The final segment of this study proved that some sources can be highly sensitive to very small recharge events, especially at base flow conditions. The lag time between baseline and elevated fluorescent intensity is expected to be unique to each source, depending on environmental and site-specific factors such as season, vegetation, ambient moisture conditions and position in the watershed. These short-term fluctuations in fluorescent intensity and DOM content have implications for the timing of low-concentration dye traces and the application of fluorescent biomarkers. Data analysis is incomplete and the final presentation of this paper will include correlations with geochemical parameters such as turbidity and temperature. The results suggest that with more work, fluorescence characterization at various locations throughout a watershed could be used as a natural tracer of suspected nonpoint sources and discrete inputs of pollutants and other organic matter.

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ATRAZINE CONTAMINATION AND SUSPENDED SEDIMENT TRANSPORT WITHIN LOGSDON RIVER, MAMMOTH CAVE, KENTUCKY, U.S.A.

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Understanding the potential for karst aquifer contamination by sediment-sorbed pesticides is important for cave conservation efforts in agricultural landscapes. Flow rate, water quality parameters and suspended sediment concentrations were measured in Logsdon River, a ~10 km karst conduit within the Turnhole Spring Groundwater Basin of Mammoth Cave National Park, Kentucky, U.S.A., to determine characteristics of storm-period transport of sediment-sorbed atrazine through a conduit-flow karst aquifer.

Analysis of two independent precipitation events occurring in the Spring of 2008 from May 2-4 and May 27–29 demonstrated the rapid response of the Logsdon River to precipitation events with detections of atrazine increasing during the initial turbidity peak and decline in specific conductance, indicating that the atrazine arrives with the initial flush of surface waters that enters the conduit. Distinct peaks of atrazine did not coincide with fine grained (silt and clay-sized) sediment peaks and concentrations of atrazine remained elevated on the falling limb of the hydrograph as turbidity declined. In addition, no systematic relation between filtered and unfiltered samples was evident. There was also exceedingly weak correlation between the concentration of atrazine and suspended sediment, suggesting that if atrazine is sorbed to fine sediment particles, this sorption involves only the fractions finer than 0.22 μm.

1. Introduction

This research was conducted to evaluate whether storm-period transport of atrazine through conduit-flow karst aquifers depends on the magnitude and characteristics (particularly grain size) of surface-derived fine sediment inputs. In addition, we evaluated the use of turbidity, a commonly measured water quality parameter, to provide an easily measured proxy of the characteristics of the suspended sediment load and an indication of probable atrazine contamination during the pesticide application season.

The Turnhole Spring Groundwater Basin constitutes the largest karst aquifer within Mammoth Cave National Park, Kentucky, U.S.A (Fig. 1). Land use is a mixture of forest (53%), agriculture (43%) and developed use (4%) (Meiman, 2006). It drains 245 km^2 that discharge into the Green River, including the Cave City and Pakota Creek sub-basins. The Cave City basin is drained by Logsdon River, a vadose stream with a total drainage area of 25 km^2 and a base flow rate of ≤ 100 liters/second. The Logsdon River parallels the Chester escarpment along the southern edge of the Mammoth Cave Plateau and is traversable for ~10 km before ending in a sump where it intersects the Hawkins River tributary inside the Mammoth Cave National Park boundary.

Anderson (2002) collected suspended sediment and water samples from the 145 m drilled well site that intersects the Hawkins River in Mammoth Cave and determined that atrazine was primarily associated with suspended sediments, thus indicating that adsorption to sediments can be a major mechanism for atrazine transport in karst conduit aquifers. After a one year study of hydrochemical changes within the Logsdon River, Raeisi et al., (2007) attributed initial minimums in specific conductance during full pipe conditions to the early movement of storm water through the conduit, while the second minimum was interpreted as the return of storm water that was temporarily stored in the aquifer adjacent to the conduit. In contrast, changes in specific conductance during partially-full pipe conditions were mainly controlled by external recharge conditions, such as the behavior of sinking streams (Raeisi et al., 2007).

2. Methods

To document patterns of atrazine transport in relation to suspended sediment flux in Logsdon River, continuous water quality monitoring and water sample collection were conducted for two storm events during the Spring 2008 pesticide application season from May 2-4 and May 27-29. The primary source of data collected was from water quality instrumentation installed in an active flow channel of Logsdon River approximately 100 m upstream from

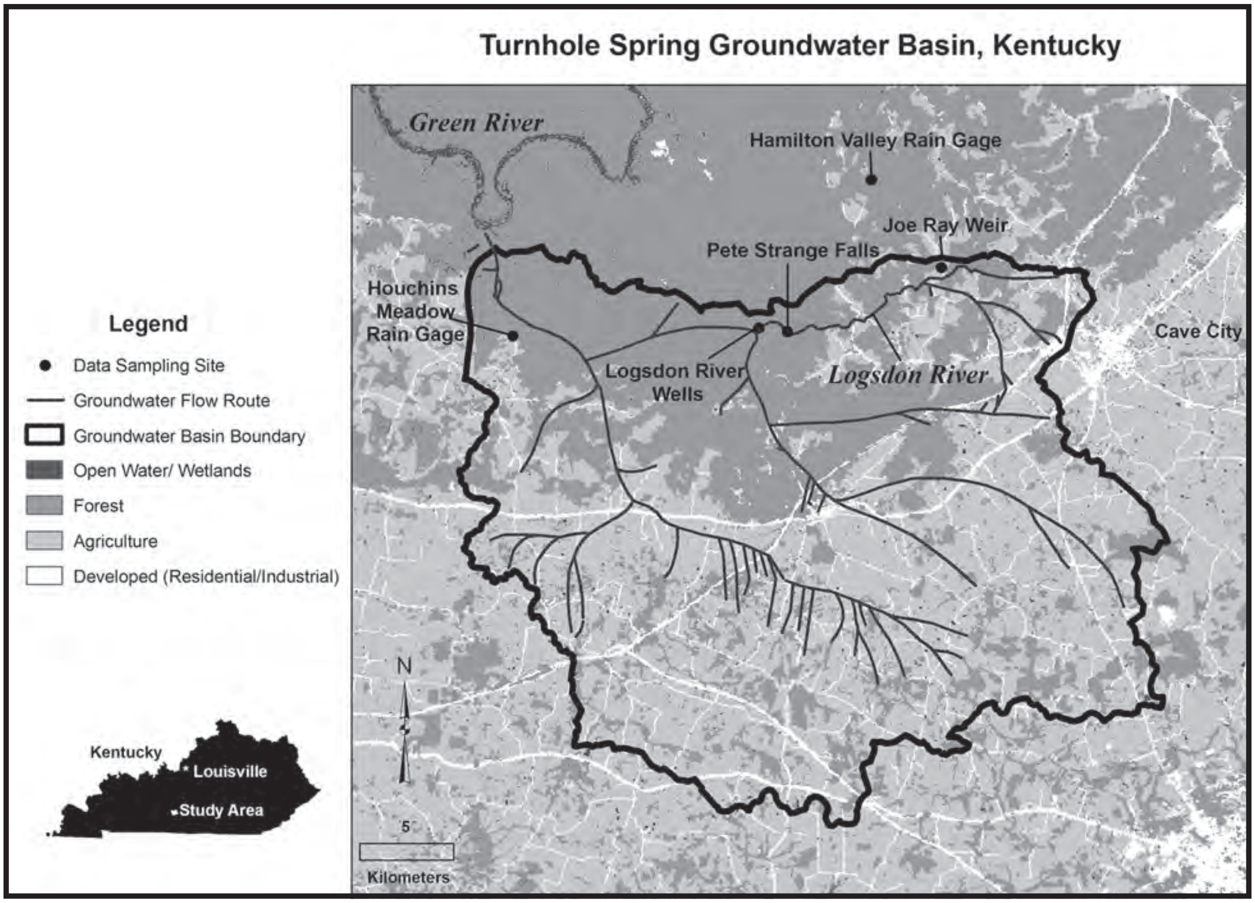

Figure 1: Map of study area (Based on NLCD 2001 data).

Pete Strange Falls. A Sontek Argonaut acoustic Doppler velocity profiler (aDcp) mounted on the river bed measured flow depth and velocity for estimation of flow rates. Water temperature, pH, specific conductance (spC) and turbidity were measured at 10 minute intervals with a Hydrolab MS5 multiparameter water quality sonde. Supplementary information on sediment concentrations and particle size was obtained from a Sequoia Scientific Inc. LISST 25-X laser diffraction sediment sensor. All instruments operated on battery power and were mounted to the cave passage to prevent movement during high flow conditions. Data collected from rain gages located near the Cave City sub-basin was used to estimate the timing and magnitude of precipitation inputs to the groundwater basin. Water quality data collected since the deployment of instrumentation in August 2005 were analyzed to establish baseline values and typical flood pulse responses for temperature, pH, specific conductance and turbidity.

Water samples for analysis of atrazine and suspended sediment concentration were collected by a Teledyne ISCO sampler that was programmed to collect samples at 40–60 minute intervals during flow events. Sample collection was triggered when turbidity readings exceeded a threshold value of100 NTU to capture data from larger runoff producing precipitation events. Additional samples for atrazine and total suspended solids were collected from a surface tributary sink point by a Teledyne ISCO sampler and from a pump below the 145 m well shaft that intersects the Logsdon River near the confluence of the Hawkins River. Analysis of atrazine levels within a 50 ml subsample was performed by the enzyme linked immunosorbent assay (ELISA) method. Water samples obtained from the Pete Strange Falls instrument site were filtered in the lab with a 0.22 µm syringe filter.

3. Results and Discussion

Hydrologic data for the two sampled events showed a rapid response typical of conduit flow karst aquifers (Figs. 2, 3). While the peak stage and flow rate were higher for the May 2-4 precipitation event, the hydrologic response was much quicker for the May 27–29 precipitation event due to the higher intensity of precipitation near the Cave City subbasin. Sudden drops in spC indicate the flushing of storm water through the conduit, followed by peaks and dips in spC that reflect subsequent pulses of storm water passing the instrument station. An overall correlation of spC reductions with increases in turbidity early on the flow hydrograph (before and immediately following the peak) suggests the arrival of one or more discrete inputs of relatively dilute, sediment laden water from the surface, followed by a secondary pulse of low spC, turbid water later on the falling limb (Figs. 4, 5). This pattern of spC and turbidity responses suggests the initial input of water arrives from land within or near the park boundary, while the secondary pulse arrives from areas further away from the observation point that has a lower proportion of forested land. An alternative explanation of the secondary water quality perturbation that occurs later on the falling limb is that it reflects the return of storm water temporarily stored in the aquifer adjacent to the conduit (Raeisi et al., 2007).

Atrazine values ranging from 12.4 ppb to >50 ppb at a surface tributary of the Logsdon River reflect the mobilization of atrazine from agricultural areas during

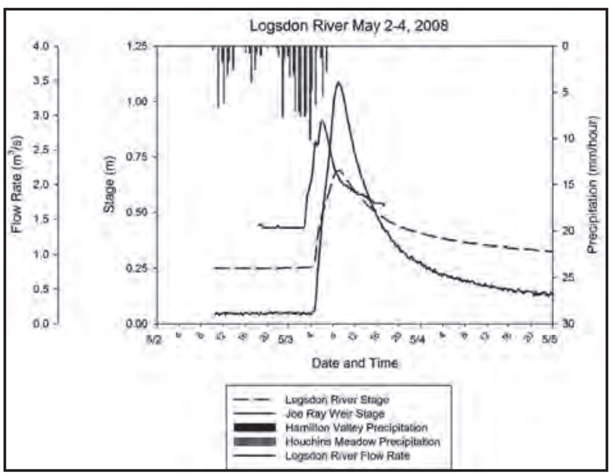

Figure 2: Precipitation, stage response and flow rate in Logsdon River and surface tributary: May 2–5, 2008.

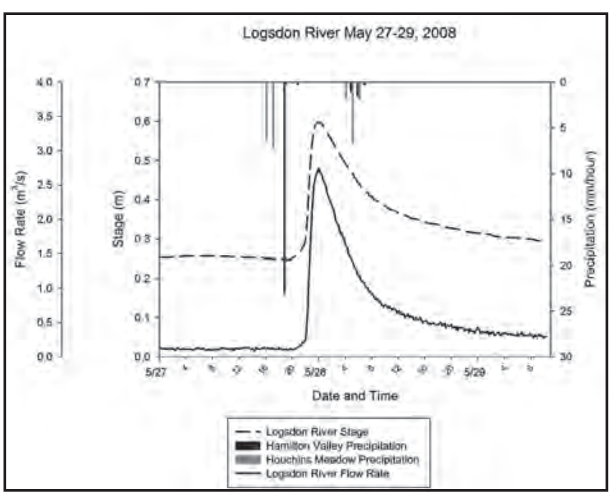

Figure 3: Precipitation, stage response and flow rate in Logsdon River: May 27–29, 2008.

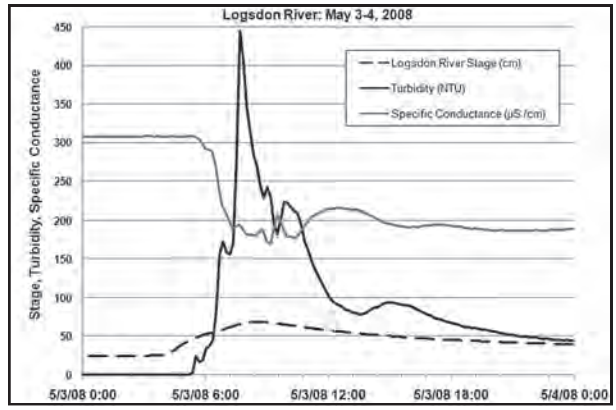

Figure 4: Stage, specific conductance and turbidity in Logsdon River: May 2–4, 2008.

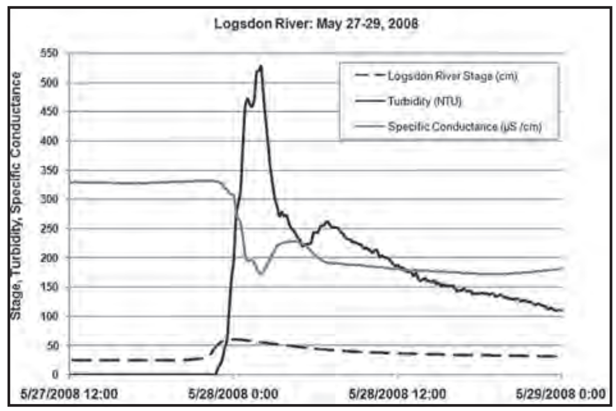

Figure 5: Stage, specific conductance and turbidity in Logsdon River: May 27–29, 2008.

the early May event (Fig. 6). Detections of atrazine during the initial turbidity increase at both in-cave monitoring sites (Logsdon River Wells and Pete Strange Falls) indicate the atrazine arrived before the secondary pulse of turbid water passed the sampling point (Figs. 7, 8). The increase of atrazine concentrations to near steady values between 2 and 3 ppb was correlated with the secondary pulse of fine sediment laden water for both precipitation events. However, distinct peaks in atrazine levels did not occur during periods of peak turbidity and continued to stay elevated on the falling limb of the hydrographs as turbidity declined. These observations are similar to results from Anderson (2002) who reported peak levels of atrazine after the turbidity peak in Hawkins River. The timing of atrazine transport relative to flow and other water quality variations in Logsdon River may reflect relatively low atrazine availability in surface recharge areas closer to the monitoring point. In addition, no systematic relation between atrazine concentration in filtered and unfiltered samples was evident, suggesting that if atrazine is sorbed to fine sediment particles this sorption involves only the fractions finer than 0.22 µm. Nor was atrazine positively correlated with measured concentrations of suspended sediment or the grain size distributions of samples for the May 27–29 precipitation event (Fig. 8). Therefore, increased atrazine levels do not correlate simply with fine sediment concentration, but may be related to the geochemical composition of materials in suspension or to other factors affecting sorption such as preferential association with particular mineral fractions or an increase in fine organic material, both of which were not evaluated in the present study. Additional work is required to establish whether such geochemical factors are important controls on pesticide transport in the Cave City basin or other conduit-flow karst aquifers in agricultural landscapes.

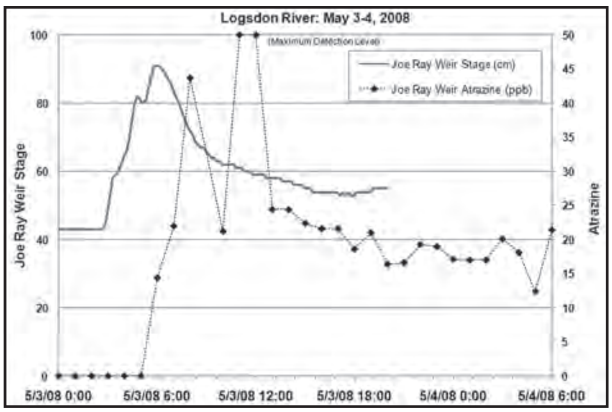

Figure 6: Atrazine levels detected at surface tributary of Logsdon River: May 3–4, 2008.

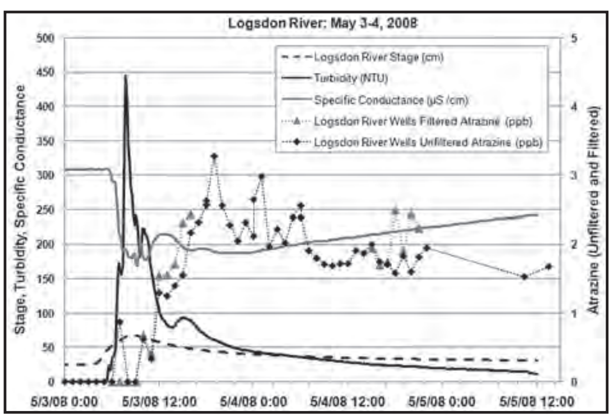

Figure 7: Atrazine levels, specific conductance and turbidity in Logsdon River: May 3–5, 2008.

4. Conclusions

Observed patterns of suspended sediment and atrazine concentrations were related to the transport of surface runoff through the karst aquifer and to patterns of agricultural land use within the Cave City subbasin. This study determined that storm-period transport of atrazine through a conduit-flow aquifer was associated with an initial peak of surface derived fine sediment inputs, but a commonly measured water quality parameter (turbidity) was not correlated to the

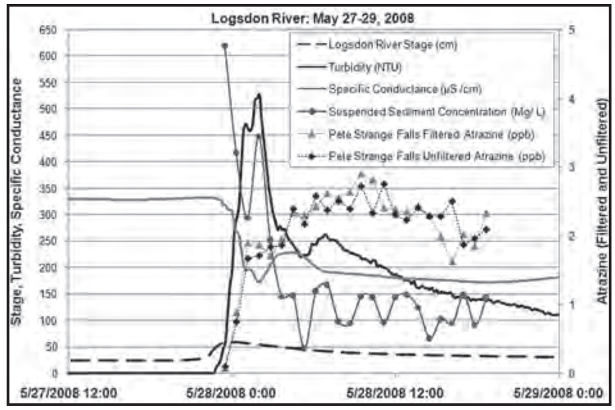

Figure 8: Atrazine levels, specific conductance, turbidity and suspended sediment concentration in Logsdon River: May 27–29, 2008.

concentration of atrazine and could not provide an indication of possible atrazine contamination during the pesticide application season.

Water quality monitoring within Mammoth Cave National Park clearly cites non-point source runoff from agricultural practices as the major cause of contamination in the Turnhole Spring groundwater basin (Meiman, 2006). Atrazine levels at a surface tributary of Logsdon River greatly exceeded the U.S. Environmental Protection Agency's (USEPA) maximum contaminant level (MCL) of 3.0 ppb which was detected in 81 percent of these samples. Only one of the in-cave samples from either event exceeded the MCL, but seventeen of the thirty-three samples from the early May event and twenty of the twenty-four samples from the late May event did exceed the USEPA aquatic life criterion of 1.8 µg / L. These findings support the need for on-going monitoring and mitigation of contamination within karst aquifers to protect cave fauna, particularly within areas that receive surface precipitation inputs from agricultural lands.

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TIANKENGS IN THE KARST OF CHINA

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China has the most extensive and diversified karst terrains in the world and most of them are rich in caves and dolines. The cone karst (fengcong) and tower karst (fenglin) developed in the humid climate in southern China form the most distinctive karst landscapes. Tiankengs are giant dolines that are a feature in some areas of the cone karst. In recent years, more than fifty tiankengs have been discovered in the cone karst in southern China, notably in the provinces of Chongqing, Guangxi, Sichuan, and Guizhou. Current research indicates that tiankengs develop in specific environments of geomorphology, geology, and hydrogeology, and are, therefore, distinguished from normal karst dolines.

1. Introduction

In carbonate rock terrains, one kind of negative karst landform has not previously been recorded because it is relatively rare and occurs only in more remote regions. It is the great or giant doline, with steep walls and several hundred meters in depth and diameter; it is a collapse doline distinguished by its very large size. This landform was first observed by geologists in China in the early 1980s, in the Xingwen karst in Sichuan, in an area that was being developed for tourism.

In the past 20 years, many more of these great karst dolines have been discovered in southern China. Some, including Xiaozhai, Dashiwei, Qingkou, and Haolong, have been found by vigorous tourism development that has been searching for spectacular features in the more remote karst areas. Others have been found during explorations by the China Caves Project, and this has led to considerable research to identify the special features of the giant dolines that distinguish them from more common, smaller, dolines.

This kind of giant doline is distinguished from normal dolines by its size, and also by major differences in basic characteristics, geomorphic evolution, and hydrogeologic conditions. The understanding of its geomorphology and its importance matured through the 1990s. In October 2001, it was proposed that this giant doline could be distinguished from "normal" dolines, and a new term, *tiankeng*, was proposed for the karst literature (Zhu, 2001).

There are two types of tiankeng - collapse tiankengs and erosion tiankengs. The former developed by dynamic underground water flow, while the latter were formed by allogenic surface drainage that fed into an underground river in the karst. Collapse tiankengs are much more widespread and more numerous than the erosional forms.

2. Distribution of Tiankengs in China

Current records show that the tiankengs in the karst of China are mainly in the south of the country, especially in the cone karst terrain, although some lie outside this core zone. The distinctive cone karst of southern China covers an area of about 150,000 km^2, mainly in northern and western Guangxi, southern Guizhou, around the Yangtze Gorges, and across southeastern Chongqing, northern Guizhou, southeastern Sichuan, western Hunan, and western Hubei, as well as in southeastern Yunnan. The important tiankengs discovered so far in China are those described below, and these are located on Figure 1.

Figure 1: Locations of tiankengs in southern China.

3. The Major Tiankengs in China

Tiankengs are best described as collapse dolines that are more than about 100 m wide and deep, and this is recommended as the internationally accepted definition of a tiankeng. There are, however, many more features that are between 50 m and 100 m deep and wide, and these are already widely known as tiankengs within China; they have been referred to as "small tiankengs" (Zhu, 2001). These include three small tiankengs in the Mengzi basin, within the karst of Yunnan. Though many of these smaller features are very significant karst landforms, they are all omitted from Table 1 and the descriptions that follow.

Except for the Xiaoyanwan and Dayanwan tiankengs in the Xingwen stone forest tourism area in Sichuan Province, which have been known for many years, the important discoveries of tiankengs have occurred since 1994. In that year, the largest tiankeng, Xiaozhai, was discovered near the Yangtze Gorges during the search for a new exploration site for British cavers in the China Caves Project. In 2001, a group of 26 tiankengs was discovered in the Leye karst in Guangxi during investigations for karst tourism resources and the search for another venue for cavers of the China Caves Project. The discoveries of this special karst feature generated interest in scientific research, which was pursued in subsequent years. Almost at the same time, Qingkou Tiankeng was discovered by the senior author in the Wulong karst, and was later explored by the Hongmeigui Cave Club. Around its vertical walls there are several hanging waterfalls and these converge on the floor and flow into a large cave passage. Qingkou Tiankeng was the first erosional tainkeng to be recognized. The 49 known tiankengs are listed in Table 1.

Tiankeng	Length x Width m	Area m^2	Depth max m	Depth min m	Volume Mm^3
Xinlong karst, Fengjie, Chongqing					
Xiaozhai	625 x 535	274,000	662	511	119.3
Xiaokeng	330 x 180	45,000	286	137	12.0
Chongtianyan	300 x 160	41,500	168	103	7.0
Luokuangyan	135 x 100	10,800	101	100	1.1
Wujiazhai	200 x 150	24,000	103	47	2.5
Daqinkeng	200 x 150	8,000	137	66	1.1
Qingshui, Yunyang, Chongqing					
Longgang	350 x 170	53,000	350	250	9.2
Houping, Wulong, Chongqing					
Qingkou	250 x 220	40,700	295	195	9.2
Niubizi	380 x 100	27,000	195	100	3.5
Taipingmiao	180 x 180	26,400	420	300	9.9
Daluodang	240 x 220	32,400	372	282	10.4
Shiwangdong	170 x 150	25,900	252	172	5.1
Sanqiao, Wulong, Chongqing					
Zhongshiyuan	565 x 555	278,200	214	75	34.8
Xiashiyuan	990 x 545	352,100	373	50	31.5
Qinlong	520 x 200	194,000	276	195	31.7
Shenying	300 x 260	51,200	285	190	9.7
Xingwen karst, Sichuan					
Xiaoyanwan	625 x 475	200,000	248	178	36.0
Dayanwan	680 x 280	164,000	110	40	15.0
Dashiwei group, Leye, Guangxi					
Baidong	220 x 160	22,000	312	263	5.8
Chadong	400 x 350	80,500	25	165	13.3
Chuandong	370 x 270	73,000	312	175	11.7
Dacao	300 x 140	30,000	92	56	1.3
Dalong	240 x 200	35,000	125	95	3.3
Dashiwei	600 x 420	167,000	613	511	75.0
Datuo	530 x 380	149,000	290	263	32.7
Dengjiatuo	370 x 240	128,200	278	222	26.2
Diaojing	290 x 280	86,300	170	145	12.6
Gaicao	440 x 95	24,700	120	90	2.2
Huangjing	320 x 170	51,700	161	140	6.3
Jiameng	90 x 80	8,800	271	211	1.6
Ladong	202 x 125	21,600	215	146	2.8
Laowuji	300 x 275	75,600	171	110	8.3
Longtao	210 x 175	14,400	115	95	1.4
Luojia	140 x 100	10,200	128	71	0.7
Lanjiawan	150 x 115	10,700	130	67	0.6
Shenmu	370 x 340	70,900	234	186	13.2

Shizilu	130 x 70	7,000	120	90	0.6
Shuijia	245 x 135	23,700	167	111	2.6
Xiangdang	310 x 230	45,000	146	80	12.6
Bama karst, Guangxi					
Haolong	800 x 600	320,000	509	185	110.0
Jiaole	750 x 400	220,000	325	283	67.0
Dongdang, Shuitang and Yijiehe groups, Guizhou					
Detian	200 x 130	20,000	145	115	2.5
Dachang	550 x 180	80,000	320	160	10.0
Bajiao	280 x 160	24,300	195	150	4.0
Tongtian	210 x 130	20,000	370	360	7.2
Xiaoshui	180 x 130	13,000	230	210	2.8
Dacaokou	920 x 240	140,000	220	160	25.0
Xiaocaokou	300 x 120	22,000	180	120	3.3
Bandong	190 x 100	15,000	240	225	2.0

Table 1: List of tianken.

3.1 Tiankengs of Xingwen, Sichuan

These two tiankengs are situated in the stone forest tourism area of Xingwen, in Sichuan Province. In September 1992, a British cave expedition team explored the underground river and cave systems to reveal the hydrogeological characteristics of the karst (Waltham and Willis, 1993; Waltham et al, 1993; Zhu et al, 1995). More than 30 km of passages were surveyed in 89 caves; the two longest caves Tianquan Dong (8100 m) and Zhucaojing (8800 m) both have passages opening directly into the sides of the Xiaoyanwan tiankeng.

Xiaoyanwan Tiankeng is roughly circular in plan, 625 m from east to west, and 475 m across; its vertical walls are 60-130 m round the entire perimeter. The maximum elevation on the rim is 870 m, and the lowest point in the tiankeng floor is at 622 m, giving a maximum depth of 248 m, and the total volume is 40M m^3. Dayanwan lies 400 m to the west of Xiaoyanwan, and is 680 m long east to west, 280 m across, 110 m deep, and 15M m^3 in volume. The Dayanwan and Xiaoyanwan tiankengs appear to be older than many of the other tiankengs in China, but cannot yet be dated; clearly Dayanwan formed earlier than Xiaoyanwan since it is so degraded.

3.2 Xiaozhai Tiankeng, Fengjie, Chongqing

Located near Xinlong town in Fengjie county, the Xiaozhai tiankeng is in the karst on the right bank of the Jiupan River, a tributary to the Yangtze River. Developed in gently dipping Lower Triassic limestone, the area is a typical cone karst at elevations of 1300-2000 m. Xiaozhai Tiankeng may rank as the largest tiankeng in the world, with an entrance diameter of 537 to 626 m, a depth of 662 m, and a volume of 119.35M m^3 (Fig. 2). In profile, it has a double nested structure; the upper bowl is 320 m in depth, and the lower shaft is a rectangle 342 m in depth and 257-268 m across; the sloping ledge between these two parts is formed at the level of a muddy limestone. Across the floor of the tiankeng, a cave river has a maximum discharge of 174 m^3/sec.

Within the karst around Xiaozhai tiankeng there are six other tiankengs of medium-size and 101–170 m deep; these are Chongtianyan, Luokuangyan, Wujiazhai, Houzishi, Xiaokeng, and Daqinkeng (Table 1). They all appear to have developed at an earlier stage than Xiaozhai Tiankeng, and all of them are of the collapse type.

Figure 2: Aerial view of Xiaozhai Tiankeng, Fengjie.

3.3 Dashiwei tiankeng group, Leye, Guangxi

The large group of tiankengs that includes Dashiwei lies in western Leye county, close to Tongle town (Zhu et al, 2003b). There are 26 tiankengs discovered so far. The largest is Dashiwei Tiankeng, which is pear-shaped in plan, 600 m long from east to west, 420 m wide from north to south, 1580 m around the perimeter, and 613 m at its maximum depth. It is surrounded by vertical cliffs (Fig. 3) and its floor is covered by a ramp of collapse debris more than 100 m high that slopes steeply down from east to west and is covered by flourishing secondary forest. The cave river is accessible at the lowest point of the tiankeng floor (Fig. 3), under its western wall; it emerges from a pile of collapsed rocks, and 6000 m of passage has been mapped downstream, as far as a point where the river drops into deep, narrow, and inaccessible fissures.

Figure 3: Aerial view of Dashiwei tiankeng, Leye.

All the tiankengs in the Dashiwei group are of the collapse type, though Huangjing Tiankeng has been modified by allogenic water since its collapse development, and is intermediate to an erosional type of tiankeng (see below). Of the 26 tiankengs in the Leye karst, Dashiwei is classified as a very large tiankeng. Chuandong, Datuo, and Dengjiatuo are all large, though only Chuandong Tiankeng has vertical walls on its entire perimeter, while the other two have degraded to leave debris slopes round about half their perimeters. These and 17 other tiankengs of normal size are listed in Table 1.

3.4 Tiankengs of Wulong, Chongqing

Around Wulong, the terrain along the banks of the Wu Jiang, a tributary of the Yangtze River, is a typical fengcong cone karst that is deeply dissected by a river valley. The major local relief creates a vadose zone up to 1000 m deep in the succession of carbonate rocks of Cambrian, Permian, and Triassic age.

Several collapse tiankengs have been recognized in the karst of Wulong county, in the natural bridges tourism area, and close by it. The most important are Zhongshiyuan, Xiashiyuan, Qinlong, and Shenying Tiankengs. Xiashiyuan is the largest of the tiankengs and is 1 km long. Both the Qinlong and Shenying Tiankengs (Fig.4) developed in the dry valley that originated as a major cave passage over 2 km long and is now spanned by three natural bridges.

Qingkou Tiankeng is the finest example of an erosional tiankeng yet discovered in China. It has been formed by a concentrated flow of allogenic surface water draining into karst with a deep vadose zone. The tiankengs of Qingkou, Niubizi, Daluodang, and Taipingmiao were developed at the sandstone-limestone boundary within a broad valley. Of these, Qingkou Tiankeng is the largest and most mature; it is 250 m wide and 295 m deep (Table 1). This type of tiankeng differs from the collapse form because it has been formed by erosion from the surface into the limestone vadose zone by an allogenic surface stream. It is the less common type of tiankeng. Caves have developed at different levels in the Qingkou tiankeng karst, and a cave system about 10 km long discharges southward to the Mawandong rising of the Muzong River.

Figure 4: Shenying Tiankeng, between the natural bridges in Wulong.

4. Nomenclature and Definition of Tiankengs

4.1 The definition of a tiankeng

Based on the research and conclusions outlined above, it is proposed that the definition of a tiankeng is - a large, steep-walled, pit-like, negative, karst landform that opened from beneath towards the surface, with both its depth and diameter more than 100 m, developed in a great thickness of continuous soluble rocks within a deep vadose zone of the aquifer and connecting with an active cave river at its foot. A tiankeng is characterized by its tourism values of rarity, grandeur, and spectacular magnificence, and also by its special ecological environment. These are all characteristics that differentiate between tiankengs and normal karst dolines. There are three size groups –

- Very large tiankengs, more than 500-600 m in diameter and depth, are very rare worldwide, and there are only three known so far in China - Xiaozhai, Dashiwei and Haolong.
- Large tiankengs, 300-500 m in diameter and depth, are also few around the world.
- Normal tiankengs, 100-300 m in diameter and depth, are more numerous and more widely distributed.

4.2 Two types of tiankengs

Current research suggests that tiankengs in carbonate rocks may be divided into two types - collapse tiankengs and erosional tiankengs. The former are much more widespread and numerous than the latter (Zhu et al, 2003a, 2003b).Collapse tiankengs have been formed in soluble rocks where massive amounts of rock material have been dissolved and eroded away at depth by a powerful and dynamic underground drainage system, notably through a large cave river passage. Under specific geologic and hydrogeologic conditions, a cave chamber evolved as its roof failed gradually while the fallen rock debris was carried away by water; eventually, the chamber roof opened out to the ground surface. Erosional tiankengs is developed in the vadose zone of soluble rocks by allogenic water that dissolves and erodes the rock in its vertical descent from the surface. They are rare because of their special environmental conditions.

4.3 Development environments of tiankengs

Collapse and erosional tiankengs have some features in common, but also have some important differences in their development conditions. There are five essential environmental conditions. 1) A great and continuous thickness of soluble rocks. 2) A deep vadose zone in the karst. 3) A favorable geologic structure. 4) A highly active hydrodynamic system with underground conduit flow in cave rivers. 5) Favorable climate and hydrogeology. These environmental factors are all optimally developed in the karst of southern China, especially in the cone karst areas with high relief - which include the most important tiankeng sites in the world.

4.4 The geologic age of tiankengs

Tiankengs provide data for research of karstification intensities and rates, and offer a new way to study time-scales of karst geologic processes. It is suggested that the tiankengs in China are among the youngest negative landforms of the karst. Ongoing research is relating the high intensities and rates of karstification to the relatively young geologic ages of the tiankengs. Tectonic uplift of the karst region of southern China dates only from the Himalayan orogeny in the early Quaternary. This caused the deep incision by surface trunk rivers (including the Yangtze, the Wu, and the Hongshsui, each with their deep gorge sections), and the consequent decline of the karst water table (and increase in vadose zone thickness) caused development of the underground rivers and development of the tiankengs. This suggests that the tiankengs in China formed mainly in the late Pleistocene, within the last 128,000 years.

5. Conclusions

The doline is one of the most familiar and distinctive landforms in karst terrains. There are several doline types that form in soluble rock terrains (mainly of carbonate rock and gypsum), including the solution, collapse, and subsidence dolines. Collapse dolines are karst bedrock collapses (and caprock dolines involve collapse of insoluble rock that covers a buried karst), but the sizes of all dolines do not match the size of a tiankeng. Dolines in carbonate rocks generally have diameters and depths up to about 100 m. Very large, vertical-walled, karst depressions differ from all the main doline types, though some have been called just large dolines or large collapse dolines. These are distinguished by not only their size but also by their development mechanisms and conditions, so it is proposed that they should be separated from dolines and referred to as tiankengs.

5.1 Distinctive features of a tiankeng

A very large doline is now called a tiankeng for certain basic reasons:

- A tiankeng develops in special environmental conditions that integrate aspects of geology, geomorphology, and hydrogeology, but a normal doline develops in a much wider range of karst environments. Consequently, dolines and collapse dolines are widespread while tiankengs are very few within the world's karst.
- A tiankeng differs greatly from dolines and collapse dolines in its development and erosional mechanisms. A collapse doline forms by dissolution and suffosion in normal geologic and

hydrodynamic environments. Collapse tiankengs have developed through an unusual hydrodynamic combination of erosion, dissolution, and collapse, where three evolutionary stages may be distinguished, from a cave river passage, to a large cave chamber, to a tiankeng open to the surface.

- A tiankeng is very much larger than a normal collapse doline. It is more than 100,000 m^3 in volume, 1000-100,000 m^2 in area at both the surface level and its floor, and more than 100 m in depth.
- A tiankeng differs from normal dolines in its development processes. Tiankengs have close relationships with the regional development of cave river systems, and their distribution, evolution, age, and development rates are not comparable to those of normal karst dolines.

5.2 The importance of the scientific study of tiankengs

The study of tiankengs has important scientific implications for karst hydrogeology and geomorphology, and for studies of karst processes and neotectonics.

Where tiankengs develop within a regional karst drainage system, they indicate the presence of a powerful karst hydrodynamic system, and they relate to the input and output balance of material and energy in a strong conduit flow or cave river in the karst aquifer. This can supply valuable data towards research into the basic characters of an aquifer and into the evolution and variance of conduit flow in drainage areas where tiankengs occur.

The evidence to date suggests that collapse tiankengs develop anywhere they can, and always destroy any surface karst landform, including depressions, dolines, wind-gaps, blind valleys, cones, hills, towers, and any other positive landforms. It appears that tiankengs are among the younger karst landforms, and a negative feature of 10 to 100 million cubic meters volume developed in a short geologic time gives us a new concept of intensity, mode, and rate of karstification. It appears that the tiankengs of southern China have largely or entirely developed within the later Pleistocene, and the oldest tiankeng appears to be no more than 128,000 years old.

Finally, local neotectonic uplift appears to have contributed to the critical environment for tiankeng development. Conversely, tiankeng research can supply important information for the study of the rates and characteristics of neotectonic movement.

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DELINEATING SPRING FLOW SYSTEMS IN THE TEXAS HILL COUNTRY, USA

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To improve our understanding of the spring flow systems in the Edwards and Trinity aquifers of the Texas Hill Country, we have examined more than 250 spring waters for their chemical compositions, estimated flows, and water temperature. Springs in the area arise along zones of weaknesses in the aquifer materials, such as, bedding planes, faults, karst features, and river bottoms due to gravity drainage or artesian pressure. Continued flow of recharge water under-saturated with respect to carbonate along these zones causes preferential dissolution of host carbonates creating cavities and facilitating rapid transport of groundwater discharging through springs. These springs are important to the area as they provide clean drinking water, maintain streamflow through baseflow discharges, nourish ecological habitats, and supply water for the survival of the rare, endemic, and common species. A good understanding of the origin of the spring waters can provide valuable information regarding their flowpaths and residence times and for evaluating vulnerability of these springs and the biota they support to drought and pumping.

We observed that most of the springs are mainly composed of calcium-magnesium-bicarbonate waters characteristic of shallow groundwater recharge. Some of the spring waters have sodium and chloride ions that are well correlated, and a few of the spring waters have chloride/bromide ratios in excess of 400 suggesting minor halite dissolution, possibly from halite contained in evaporites of the Upper Glen Rose Limestone or upward migration of deeper saline water. Sodium and chloride enriched spring waters preferentially occur to the north (south of the Llano Uplift) and northeast along the Balcones Fault Zone. About 80 percent of the springs have estimated flows that range from 270 to 2,700 cubic liters per day. Most of the spring water temperatures are less than 25 degrees centigrade similar to the adjoining groundwater in the aquifers.

We have also analyzed about 24 of these springs for detailed stable and radiogenic isotopes and chemical compositions. We observed that isotopic and chemical compositions of the spring waters vary with differences in elevations. Spring waters at higher elevations commonly have lower total dissolved solids and lighter carbon, oxygen, and deuterium isotopes suggesting shorter flow paths and residence times between recharge and discharge. At lower elevations, heavier carbon, oxygen, and deuterium isotopes in the spring waters suggest relatively longer flow paths and residence times. Strontium isotopes suggest that most of the spring waters are derived from various degrees of mixing of the shallow groundwater and rainfall. Nearly all of the springs have tritium as high as three tritium units and percent modern carbon content ranging from 70 to 110 percent, supporting a recent origin of these waters.

Our investigation suggests that most of the spring waters are modern in age and result from relatively rapid flow through the aquifer. The modern age of the waters suggest that the spring flows are highly vulnerable to short term climatic variations and pumping, such as the response of Jacob's Well Springs during the drought of 2000 and 2008.

1. Introduction

Springs are natural discharge points in a groundwater flow system. Groundwater from unconfined aquifers may naturally drain under gravity to spring orifices through bedding planes, faults, karst features, or river beds. Under artesian pressure, deeper groundwater may move vertically upwards to the land surface and discharge through springs. Duration and intensity of spring discharge may serve as clues to our understanding of shallow groundwater recharge, their role in maintaining streamflow, and hydraulic characteristics of the aquifer. In the Texas Hill Country, USA, springs are of significant importance as they are used for potable water supply sources, in shaping surface drainage and maintenance of streamflow, and sustaining ecological habitats for various rare, endemic, and common biological species.

Many of the larger springs in the study area, including Comal, San Marcos, and Hueco Springs have been extensively studied for their source waters, flow paths, and recharge characteristics (Guyton and Associates, 1979; Ogden and others, 1986; McKinney and Sharp, 1994; Brune, 2002; and Johnson and Schindel, 2008). Therefore, while we examined geochemical data for about 250 spring waters from the Hill Country area including the larger springs, we concentrated our investigation on the 24 smaller springs that were not studied earlier. In this study our objectives were: (1) determine the origin and ages of the spring waters, (2) better understand flow characteristics to these springs, and (3) determine vulnerability of these springs to drought or pumping from the shallow aquifers.

2. Methods

We examined about 250 spring water compositions from the Texas Water Development Board's groundwater database for this investigation. In addition, we selected 24 springs based on the spring flow amount and ease of accessibility for collection of chemical and isotopic compositions. We collected 24 spring water samples for deuterium (δ^2H) and oxygen-18 ($\delta^{18}O$), carbon-13 ($\delta^{13}C$), carbon-14 ($^{14}C_{DIC}$), tritium (^3H), and strontium ($^{87}Sr/^{86}Sr$) isotopes. All groundwater samples were analyzed by ion chromatography-mass spectrometry (ICP-MS) for chemical parameters at the Energy Laboratories in Wyoming. Isotopic analyses of $\delta^{18}O$ and δ^2H were carried out at the Coastal Sciences laboratory in Austin, Texas. Isotopes of $\delta^{18}O$ were analyzed on a VG Micromass SIRA Series II mass spectrometer using the carbon dioxide (CO_2) equilibration method (Epstein and Mayeda, 1953). Isotopes of $^{14}C_{DIC}$ were analyzed at the Beta Analytic Inc. using an accelerator-mass-spectrometer (AMS) and the results were presented as percent modern carbon (pmC). Isotopes of $\delta^{13}C$ were measured with reference to the PDB standard. Isotopes of ^3H were analyzed at the Tritium Laboratory of the Rosenstiel School of Marine and Atmospheric Sciences, University of Miami. Isotopic analysis of ^3H was performed by chromium or zinc reduction to hydrogen (H_2) gas on a Micromass 602D mass spectrometer. $^{87}Sr/^{86}Sr$ was analyzed by Thermal Ionization Mass Spectrometer (TIMS) at the isotope laboratory of Massachusetts Institute of Technology in Boston.

3. Hydrogeology of the Springs

Springs are fed by gravity or they may appear under pressure through natural openings (dissolved limestone along impermeable bedding contacts, caverns, and faults) in a confining unit. The Edwards and associated limestones form the most prolific springs in Texas (Brune, 2002). Certain sections of the vugular limestones that form the aquifers are interconnected to facilitate rapid infiltration and replenishment of recharge. The Edwards Group of rocks are characterized by a steep drop in land surface elevation allowing groundwater to drain under gravity along its slope through permeable parts of the aquifers and discharges along impermeable bedding contacts of the Upper Glen Rose Limestone. Springs also preferentially occur along many of the river beds as they occupy the lowest elevations in the land surface (Fig. 1). In addition, locations of many of the headsprings may move by tens of meters with changes in the duration and intensity of rainfall. Many of the springs are perennial sources of water to the creeks and rivers. For example, a well developed trend is observed between spring discharges at the Fessenden Springs and flow in the adjacent Johnson Creek located in the Upper Guadalupe watershed in Kerr County. When recharge is not available, such as during the droughts that affect parts of central Texas, water levels in the springs may decline, with some springs eventually drying up temporarily. For example, flow in the Jacob's Well Springs trickled down to nothing during the drought of 2000 and 2008, probably due to an absence of recharge that was further exacerbated by increased pumping in the shallow aquifer.

4. Results

Chemical and isotopic characteristics of the spring waters can help delineate the origin of the spring waters and their potential sources. We report chemical and isotopic characteristics of the spring waters in the following sections.

4.1 Chemical composition

The spring waters are dominantly composed of calcium-magnesium-bicarbonate waters except for about six spring waters that have higher sulfate and chloride. Springs in the north and northeast of the study area have higher concentrations of sodium and chloride.

A plot of sodium versus chloride to determine the source(s) of sodium and chloride indicates that they are well correlated ($r^2 = 0.74$) with most of the samples plotting on or close to the 1:1 line (Fig. 2). However, one sample plots above the 1:1 line showing excess sodium compared to chloride concentrations. Both sodium and chloride concentrations of these spring waters are much higher than the rain water. Most of the spring waters have low chloride/bromide (<400 molar) with only a few springs having values greater than 400. These values of chloride/bromide

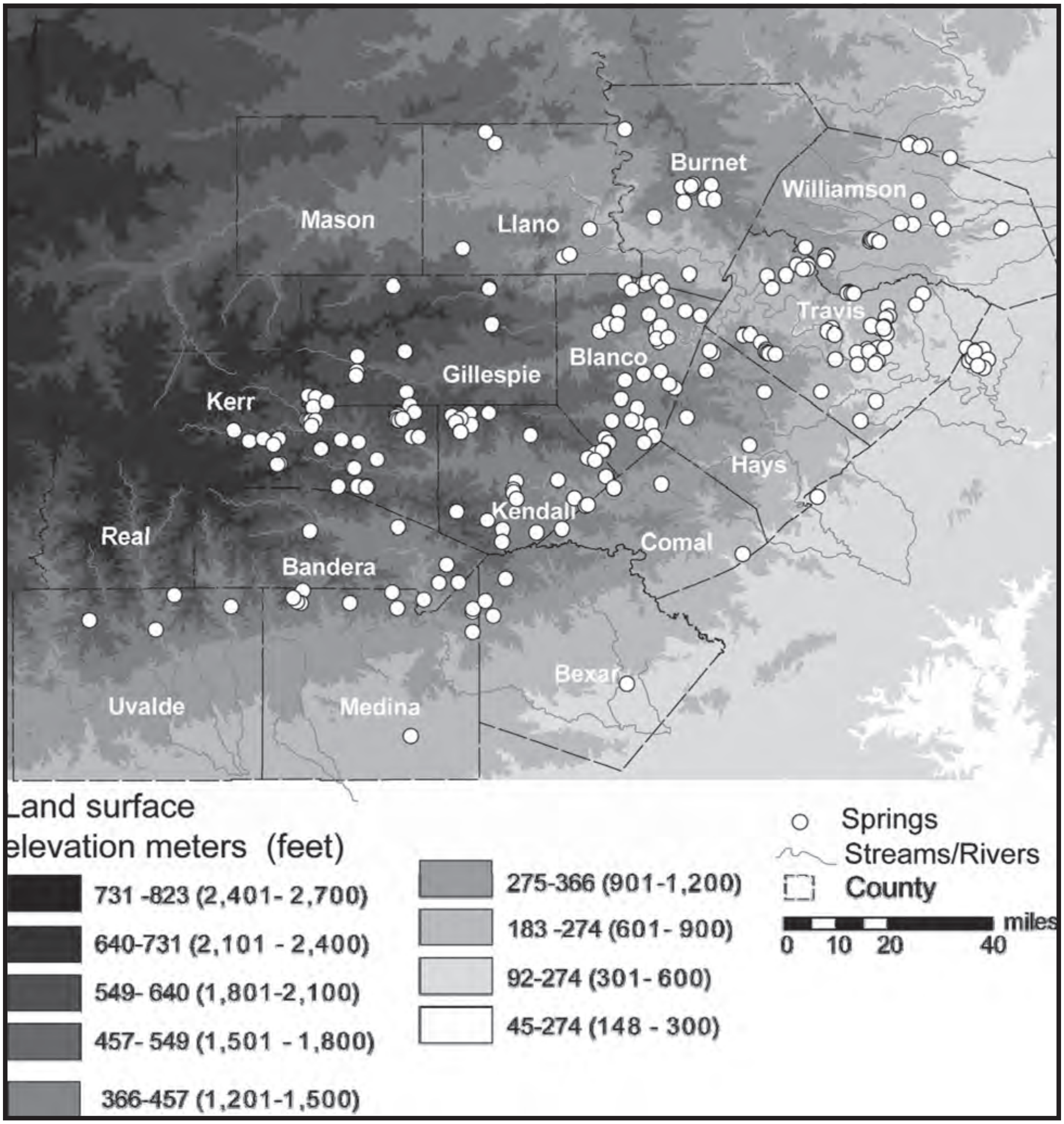

Figure 1: Map showing land surface elevation in the study area and spring locations.

ratios are much lower than groundwater from the adjacent aquifers where many samples have chloride/bromide ratios in excess of 10,000 (Chowdhury, 2008). A plot of land surface elevation versus total dissolved solids of spring waters indicate that salinity progressively increases in the springs from the higher to the lower elevations (Fig. 3)

4.2. Isotopic composition

Spring waters have $\delta^{18}O$ values that range from -3 to -6.1 ‰ SMOW similar to groundwater (Fig. 4). Springs in Bandera and Real counties have much lighter $\delta^{18}O$ compositions than the springs further to the east. A plot of $\delta^{18}O$ versus $\delta^{2}H$ values show that most of the spring waters fall along the Local Meteoric Water Line that represents average composition of local precipitation (Fig. 4). $\delta^{13}C$ isotopes of the spring waters range from -3 to -12.8 ‰ PDB with the lighter isotopes occurring at higher elevations in the west. Heavier $\delta^{13}C$ isotopes in the spring waters are more common at lower elevations (Fig. 5).

Most of the spring waters have ^{14}C isotope values containing more than 80 percent modern carbon with the exception

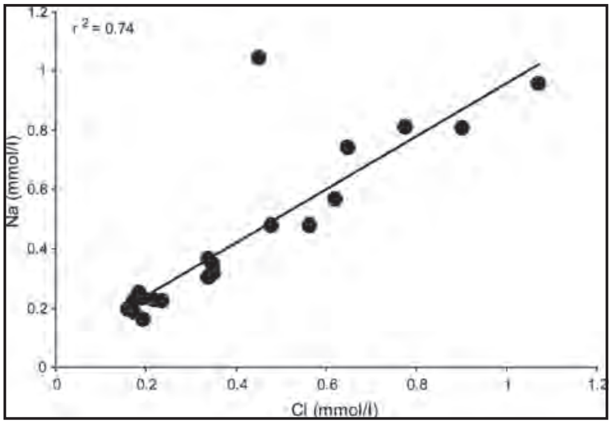

Figure 2: Plot of Na versus Cl of the spring waters. Note that most samples fall on the 1:1 line.

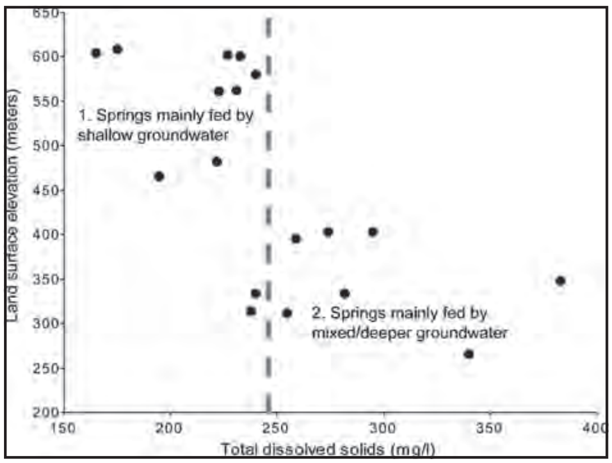

Figure 3: Plot of land surface elevation versus total dissolved solids. Note total dissolved solids in the spring waters increases at lower elevations.

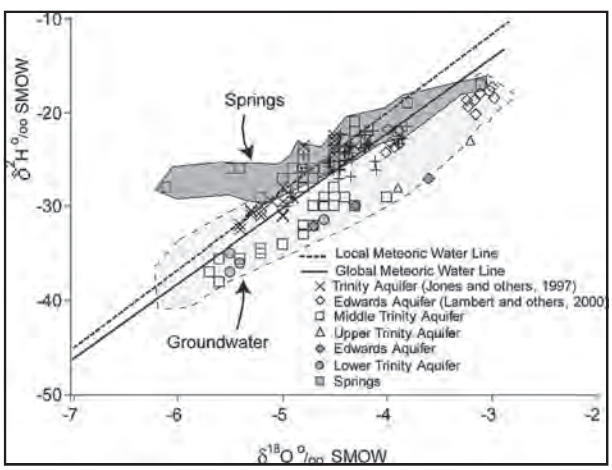

Figure 4: Plot of $\delta^{18}O$ versus δ^2H for the spring waters and groundwater. Note most samples plot along the Local Meteoric Water Line (part of the groundwater data from Jones and others, 1997 and Lambert and others, 2000).

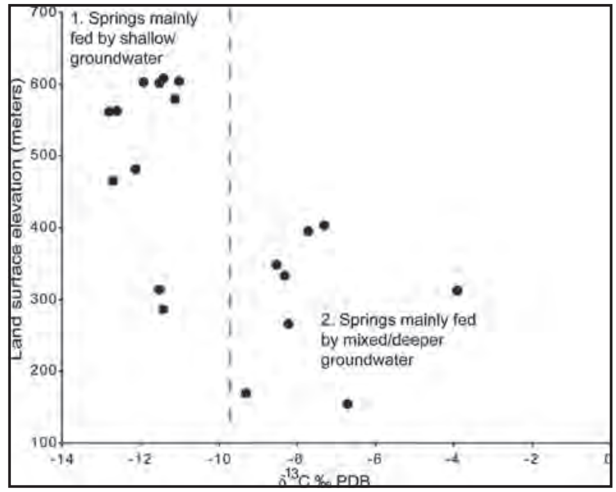

Figure 5: Plot of land surface elevation versus $\delta^{13}C$. Note $\delta^{13}C$ values in the spring waters gets heavier at lower elevations.

of one spring water which has as low as 40 percent modern carbon. Nearly all of the spring waters that we studied have tritium concentrations that range from 2 to 3 tritium units. Only three spring waters have concentrations less than 1.5 tritium units.

We note that most of the spring waters have $^{87}Sr/^{86}Sr$ values of 0.7076 to 0.7079 with a few samples having values of 0.7080 to 0.7086, and one spring located in the north near the Llano Uplift has an elevated $^{87}Sr/^{86}Sr$ value of 0.7098.

5. Discussion

Most of the spring waters have a dominant calcium-magnesium-bicarbonate composition with low total dissolved solids. This chemical composition is characteristic of waters derived from modern recharge from the shallow subsurface parts of a limestone aquifer. Higher concentrations of sodium and chloride in springs located in the northern-northeastern parts of the study area suggest some involvement of halite dissolution. This observation is further supported by (1) good correlation between sodium and chloride ($r^2 = 0.74$), (2) chloride/bromide ratios in excess of 400, and (3) low concentration of sodium and chloride in the rain water (Oetting, 1995; Musgrove and Banner, 2004). Higher concentrations of sodium and chloride in the springwater could potentially develop due to evaporation and accumulation of these elements in the soil zone with subsequent discharges under recharge events, but the spring waters do not show any significant effect of evaporation as observed from their depleted $\delta^{18}O$ isotopes. One sample with high sodium may suggest that the excess sodium is derived from dissolution of feldspars contained in the aquifer materials, supported from its proximity to the

Llano Uplift.

A subset of the spring water samples, with detailed analyses of chemical and isotopic data, shows moderate correlation ($r^2 = 0.61$) between land surface elevation and total dissolved solids (Fig. 3). This relationship may suggest that springs at higher elevations discharge rapidly due to a steep drop in elevations, have shorter flow paths, and thus retain fresh water compositions. Some of the groundwater that still recharges further from the springs, moves deeper into the aquifer acquiring more dissolved solids through water-rock interaction and finds its way as spring discharges along the contacts of the Edwards Group and the tighter Upper Glen Rose Limestone outcrop. Changes in $\delta^{13}C$ in the spring waters at different elevations are also observed. For example, lighter $\delta^{13}C$ isotopes preferentially occur in the spring waters at higher elevations and heavier $\delta^{13}C$ values at lower elevations (Fig. 5). Under open system conditions of the shallow groundwater, $\delta^{13}C_{TDIC}$ approach $\delta^{13}C$ values of soil CO_2 with values of -18 to -22‰ PDB. Considering a equilibrium fractionation factor of about ~ +8‰ PDB between soil CO_2 and $HCO_{3,}$ $\delta^{13}C_{TDIC}$ of the recharge water would range from -10 to -14‰ PDB as observed in the spring waters at elevations of 450 to 600 meters (Figure 5). On the contrary, some spring waters at elevations between 150 to 400 meters have $\delta^{13}C$ values of -4 to -8 ‰ PDB suggesting carbon contribution through carbonate dissolution from the deeper parts of the aquifer under close system condition.

Isotope values of $^{87}Sr/^{86}Sr$ in the range of 0.7076 to 0.7079, with a few samples having values of 0.7080 to 0.7086, suggest that the spring waters largely retain $^{87}Sr/^{86}Sr$ values of local marine limestones negating involvement of any deeper fluids. Variations observed in $^{87}Sr/^{86}Sr$ are probably functions of various degrees of mixing of the rainwater and the shallow groundwater. One spring water to the northern part of the study area shows $^{87}Sr/^{86}Sr$ values of about 0.710, suggesting flow from silicate-bearing rocks in the Llano Uplift aquifers.

Other lines of evidence, such as plot of $\delta^{18}O$ isotopes along the Local Meteoric Water Line suggest that the spring waters are largely derived from local precipitation with no significant effects of evaporation. However, three springs, with $\delta^{18}O$ values lighter than -5.5 ‰ SMOW fall to the left of the Local Meteoric Water Line, suggesting that they are not directly derived from local precipitation and were modified by subsurface processes during recharge. Most of the spring waters are also shifted to the left of the Global Meteoric Water Line (Fig. 4) whereas most of the groundwater plots to the right of the Global Meteoric Water Line indicating effects of evaporation. Given these differences between adjoining groundwater and the spring waters, it can be argued that the spring waters were largely infiltrated into the subsurface through fracture openings, and thus escaping evaporation.

Nearly all of the spring waters contain 70 percent or more modern carbon indicating that the waters are relatively modern. Tritium concentrations of as much as about 3 tritium units in several of the springs further suggest that the spring waters are derived from modern recharge. The above lines of evidence suggest that the springs are rapidly recharged and replenished by modern recharge and are therefore, highly vulnerable due to a reduction in rainfall during drought and/or excessive pumping of the shallow aquifer. Reduction in flow at the springs will threaten protection of the rare, endemic, and common species found in the springs as well as reduce instream flows to the receiving basin.

6. Conclusions

A modern, shallow subsurface origin for most of the spring waters is supported by their chemical and isotopic compositions as well as their compositional differences with land surface elevations. A moderate correlation between total dissolved solids and land surface elevation suggest that the length of the flow paths and groundwater residence time control spring water composition. For example, shorter flow paths between recharge and discharge at higher elevations result in fresher spring waters and longer flow paths for springs that recharge further from the springs and discharge at lower elevations result in greater water-rock interaction retaining higher dissolved solids. Similarly, lighter $\delta^{13}C$ values in the spring waters at higher elevations and their heavier $\delta^{13}C$ values at lower elevations support origin of the dissolved carbonates, and in turn, the host water that contains them, from shallow and deeper in the subsurface, respectively. Isotope values of $^{87}Sr/^{86}Sr$ further suggest that the spring waters retain characteristic isotopic signatures of local marine limestone aquifer and their variations are probably caused by various degrees of mixing of the rain water and shallow groundwater. Nearly all of the spring waters contain 70 percent or more modern carbon indicating that the waters are relatively modern. Tritium concentrations of as much as about three tritium units further support this. Given that the springs are rapidly recharged and replenished by modern recharge, they are highly vulnerable due to a reduction in rainfall during drought and/or excessive pumping of the shallow aquifer.

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KARST MICROCLIMATE MONITORING IN THE NORTHERN ALPS, AUSTRIA: INITIAL RESULTS

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An ongoing micrometeorological program was initiated in the summer of 2007 by the Cambridge Austrian Cave Science Expedition (CASCE) with the intention of characterizing the heat flux across the entrances of two caves on the Loser plateau in the Totes Gebirge mountains, Rundreishöhle and Steinbruckenhöhle. The relative importance of the diffusive, convective (airflow), and latent (condensation and evaporation) components of that flux were examined. Three weeks of intensive monitoring conducted in 2007 resulted in 105,500 temperature data points in Rundreishöhle and 64,000 in Steinbruckenhöhle, as well as surface meteorological data. The long penetration distance observed for the diurnal temperature cycle into the caves implies an entrance heat flux several orders of magnitude greater than could be explained by diffusive processes alone, suggesting dominance of convective and / or latent processes. 1.1 L/m of condensate was estimated in the entrance series of Steinbruckenhöhle, potentially transferring 34 kJ/day to cave walls.

1. Aims

The Loser plateau karst microclimate study seeks to characterize the heat flux between the caves investigated, Rundreisehöhle and Steinbrückenhöhle, and the external air mass in terms of the relative magnitude of its component processes. Viewing the cave entrance as a plane, the heat flux Q_{Ent} across that surface is expected to be the sum of the flux of three types of heat transfer across that plane. These are the advective sensible heat flux Q_S, the advective latent heat flux Q_L, and the diffusive heat flux Q_C through limestone, such that

$$Q_{Ent}=Q_C+Q_S+Q_L \qquad (1)$$

The relative importance of these components is assessed here using data from simultaneous datalogged measurements of cave and surface atmospheric variables, as well as visual observation by a team of cavers. To begin with, the importance of the diffusive flux Q_C is investigated. Because Q_C cannot be measured directly, I tested a theory that assumes all heat transfer in caves is via Badino's (2004) penetration length model by observing the distance from entrances at which diurnal temperature cycles are no longer visible. This zone of diurnal temperature variation is similar to the the "heterothermic zone" of Luetscher and Jeannin (2004) for a daily rather than annual periodicity. Evidence that Q_C alone is a very small component of heat transfer through the caves leads to a discussion of airflow through the cave and the "chimney effect" (Michie, 1997), representing Q_S. Likely latent heat flux (Q_L) is addressed through wet and dry bulb measurements of atmospheric water vapor content and visual observation of condensation. Existing theories are critically evaluated in the light of our data, to develop a conceptual model of heat transfer with empirical limits based on our observations.

2. Cyclical Variations and Penetration Lengths

Heat transfer across the cave entrance is investigated initially on the diurnal scale in this study. If the cave is modeled as rock, we would expect a sinusoidal temperature cycle that decreases in amplitude with distance into the cave. Longer period cyclicities (such as seasonal or even glacial cycles) would be expected to cause the same amplitude signal further into the cave. For each period length, there is a distance at which the amplitude approaches zero. This is referred to as the "penetration length," x_{cycl}, defined as

$$x_{cycl} = \sqrt{\frac{a}{\pi}\tau} \qquad (2)$$

where a is thermal diffusivity (m^2s^{-1}) of the cave air or limestone, and τ is the period of the forcing cycle (Badino, 2004).

Taking only diffusive heat transfer through cave walls into account, we can use values for a obtained for limestone through laboratory analysis, around 1.0×10^{-6} m^2s^{-1}. Using this value, the annual cycle (8760 hours) should disappear only 3.4 m into the cave, and glacial-cycle scale influences should be extend 339 m into the cave. Taking into account impurities such as water in the limestone, thermal diffusivity can be a factor of 10 higher, implying that the annual cycle would extend a more reasonable 10 m into the cave.

Measurements of air temperature at distances from cave entrances have found values of penetration depth much higher than those predicted by these values of limestone thermal diffusivity. For example, Forbes (1998) detected diurnal variation in both temperature and humidity 75 m into a cave. The present study found diurnal temperature variations 15 m into the cave. These cannot be accounted for by the thermal diffusivities of any of the components of the cave system. Therefore, other processes must be having a significant effect.

3. Diffusive Heat Transfer (Q_C)

To investigate penetration length in Rundreisehöhle, thermistors (labeled rA3, rA4, rB1, rB2, rB4, rC1, rC2, rC3), were placed roughly every three meters along the cave (their locations were surveyed to BCRA grade 5). Next, spectral analysis was carried out to determine whether the external diurnal temperature forcing cycle was observable at each distance into the cave, and if so its amplitude and wave energy (Fig. 1).

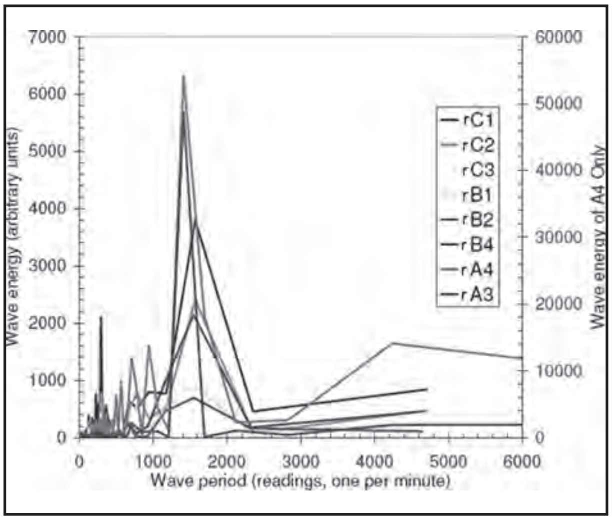

Figure 1: Fourier transform of Rundreisehöhle temperature timeseries.

If the (Badino, 2004) diffusive model of penetration length holds true for Rundreisehöhle, then, using the standard thermal diffusivity for limestone of $1.0 \times 10^{-6}\ m^2s^{-1}$, we would expect the amplitude of the diurnal cycle to approach zero at 0.08 m. Instead, all six in-cave thermistors on the plot demonstrated convincingly diurnal peaks in their spectral analyses. Referring to Figure 1, we see that the peaks occur at slightly longer periods of 1549 and 1570 minutes, or 25.8 and 26.1 hours. Noise is probably responsible for the deviation of these peaks from 24h. The surface weather station demonstrated peak wave energy at 23.75 h.

Because Rundreisehöhle is a simple 25 m tube of a cave with two entrances, and the thermistors extended the entire length of the cave, the diurnal cycle had a penetration length of at least 12.5 m. This is more than an order of magnitude further than would be predicted by conduction through limestone. Therefore, Q_c is only responsible for a very small portion of the total heat transfer into the cave.
However, the peaks do attenuate towards the center of the cave, as shown in Figure 2, effectively an east-west transect of Rundreisehöhle where the energy of the diurnal peaks from the spectral analyses has been plotted against distance along the cave. We can investigate the nature of the relationship between diurnal amplitude and distance into the cave by fitting regressions to our data. A parabolic regression fits best, and explains 98.4% of the data (adjusted R^2), well within the 95% confidence intervals displayed on the graph. This weakening of the diurnal cycle's wave energy with distance into the cave is a pattern that is not exclusive to a Q_c-driven system; it would be observed in a Q_S or Q_L dominated system as well. Before discussing these possibilities, we can consider the penetration length results for one entrance of Steinbrückenhöhle, an extensive cave system with nine entrances.

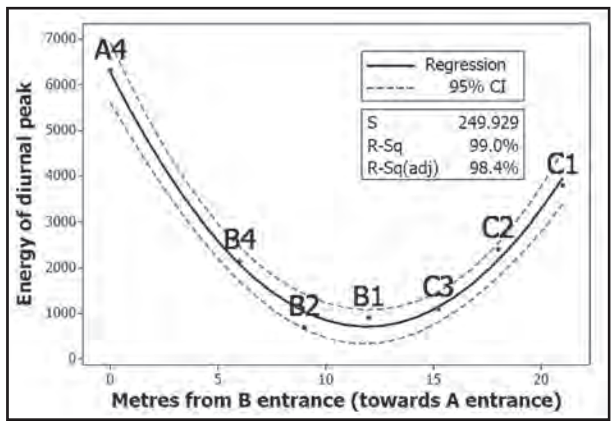

Figure 2: Amplitude of energy peak for diurnal wavelength from Fourier transform for each sensor, with distance into the cave. A parabolic regression, with the equation amplitude=6273934.8m into cave+ 39.26m into cave2 fits well. Entrances are at 0 and 25m.

The Rundreisehöhle measurements provided us with a lower bound for penetration length of 12.5 m, but no upper bound on that value because the cave was too short for the wave energy of the diurnal cycle to approach zero at any point. Because Steinbrückenhöhle is a larger cave, however, we were able to place thermistors as far as 180 m from any entrance. Table 1 shows the results of the spectral analysis, which raises our lower bound for penetration length to 15 m, and provides an upper bound of 35 m.

	sA3 & sA4	sA1 & sA2	sB1 & sB2	sB3 & sB4	sC1 & sC2	sC3 & sC4
Distance from 204e entrance	4	15	35	75	150	180
Spectral analysis peak period	23.8 hours	24.0 hours	None	None	None	None
Peak amplitude	795.8	719.8	None	None	None	None

Table 1: Spectral analysis of thermistors in Steinbrückenhöhle.

4. Airflow (Q_S)

Because Rundreisehöhle is nearly straight, we can test the influence of external, cave-parallel wind using weather station and cave thermistor data. If external wind controls air movement in the cave (rather than "chimney effect"), we would expect to see a temperature increase when a strong wind blows in a direction parallel to the cave, as this would increase Q_S, the advective flux of heat from the entrance of warm outside air into the cave. Rundreisehöhle runs almost exactly east-west.

A Pearson correlation matrix of the eight Rundreisehöhle thermistors with wind speed, north-south wind component, and east-west wind component showed that the temperatures are not controlled by surface airflow, suggesting either a lack of significant cave air movement or a dominance of the chimney effect. Correlations with p=0.05 for the wind variables occur for thermistor rA4, rB2, rB4, rC2 and rC3, and rA3 has one at p=0.08. rA4 and rA3 are the surface and entrance thermistors. It is interesting to note that rA3, located in the sheltered entrance depression but outside the cave entrance, shows a fairly strong relationship with north-south wind but not east-west wind. Thermistor rA4, on the surface but below the dwarf pine canopy, correlates with wind blowing in both directions. The remaining wind-correlated thermistors, rB2, rB4, rC2, and rC3, are correlated with wind but not cave-parallel wind.

External wind is almost certainly not a factor in Steinbrückenhöhle, where two transects of sensors were placed. Although this cave would be classified as a Type V (multiple entrances at different levels, chimney effect likely) cave according to the scheme of (Michie, 1997), for our purposes we can think of the specific sections we are monitoring as simpler caves. The E entrance transect can be approximated as a type III cave (single entrance, descending passage), and the CSB area can be viewed as a type IV (single entrance, ascending passage). In this case, we are merely considering the effect of entrances 204E and 204C on the nearby cave microclimate.

5. Condensation (Q_L)

Extensive measurements of condensation have been carried out in the caves of the Crimea and the Caucasus, reviewed by (Dublyansky and Dublyansky, 1998). In that paper, condensation was related to discharge of streams fed by karst aquifers, and several proposed formulas for predicting underground condensation were put forth. Corrosion in association with condensation is an agent of speleogenesis and has been discussed by Dreybrodt et al. (2005). Here, we are particularly interested in the latent heat transfer (Q_L) associated with cave condensation. (Michie, 1997) stresses that condensation always results in a net transfer of heat from the cave air to the cave walls. However, because cave air is eventually replaced, the cave as a whole is a net recipient of heat from condensation.

To observe condensation, expedition members were instructed to look for morphologies that suggest condensation corrosion (Dreybrodt et al., 2005). According to (Jameson, 2005), these include "drop dents," "rill trails," and "splash patches." However, despite 30 pairs of observant caver eyes inspecting the rock for these features, none were reported.

Direct, visual surveys of condensation itself proved more effective. Making use of the frequent trips to various parts of Steinbrückenhöhle, I asked expedition members to keep an eye out for any walls covered partially or completely in water droplets, and afterwards surveyed the cavers informally. Responses highlighted three main areas in which striking examples of the phenomenon were commonly observed. These three areas are shown in Figure 3. All three were near entrances, and conveniently, these happened to be in close proximity to our temperature transects: 204E entrance, CSB passage, and Crowning Glory. One caver described the fields of droplets as "really pretty," while another remarked that droplets were "quite extensive" and occurred "generally on `underside' surfaces." There was a general feeling that condensation on this scale is not typical of the UK caves in which expedition members did most of their caving, perhaps a confirmation of Dublyansky and Dublyansky's (1998) prediction that this altitude and latitude provides better conditions for condensation than those of Britain.

To an observer, the condensation droplets appear similar to the "reflective dots" described by Rowling (2001) (Fig. 4). Rowling held that such droplets are not caused

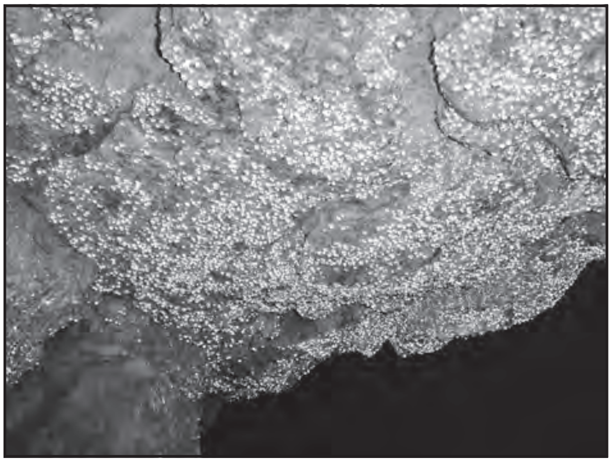

Figure 3: CSB passage, with condensation droplets.

solely by thermodynamic phase change but that bacteria colonies of the genus *Actinomyce* encourage nucleation of condensation droplets and attract water using hydrophilic fibers. This is in accordance with the increasing realization that bacteria are important agents in caves and that many geophysical processes that occur underground depend on microbiology, as evidenced in Barton (2006) and in a special speleological issue of Geomicrobiology Journal (v18, 2001). However, the condensation droplets that we observed do not show the features that Rowling considers indicative of the biological origin of these droplets. Rowling expects the droplets may exhibit a gold, yellow, or brown color, which Moore and Sullivan (1997) attributed to the presence of the pigment beta carotene in association with actinomycetes. Additionally, bacterial droplets should be small: 0.1 mm to 2 mm. Because our droplets are clear and range from 4 mm to 8 mm, it is unlikely that this bacterial mode of formation is involved.

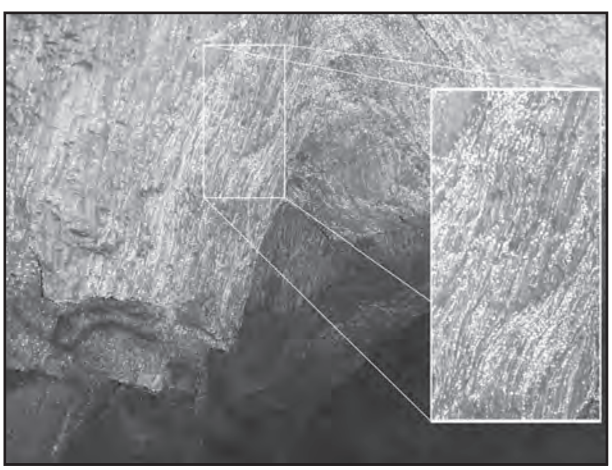

Figure 4: Condensation in Crowning Glory. Streaks detailed in inset are interpreted in the text as rivulets down which condensate slowly flows (although this is not visible on an observer's timescale.)

Two trips into Stienbrückenhöhle were conducted to photograph condensation. By measuring the pixel size of droplets and scaling with the use of a measuring tape included in the photos, we found that the vast majority of droplets were between 4.6 and 7.7 mm in diameter, and were spaced at one drop every 2 to 4 cm^2. With an average passage perimeter of 4 m, this amounts to about 1.1 L per one meter of passage. So, in the 170 m of passage we were observing, there was roughly 187 L of condensate present as droplets on the walls.

While it is possible to make these limited guesses as to the abundance of condensed water, the actual net rate of condensation rather than the amount visible at any one time is required in order to understand the thermal effects of the condensation. There are indications that the condensation process was active during our study period, and most of this condensation may have been formed each day. Condensation occurred on the Hobo datalogger in CSB passage during the period of investigation (Fig. 5). Surveys of cavers suggest that there is a diurnal cyclicity to the formation of this condensation. The majority of reports of extensive condensation occurred in the evening; cavers noticed condensation while leaving rather than entering the cave, and one caver remarked that there was "more in the evening/afternoon." Condensation in the 204E entrance passage, Germknödel's Revenge, was observed exclusively in the evening. According to the expedition logbook, few trips were underground during the period between 2 am and 10 am, however, so we cannot be certain that droplets were not present then, although it seems likely due to the absence of condensation from 11 am to around 2 pm .

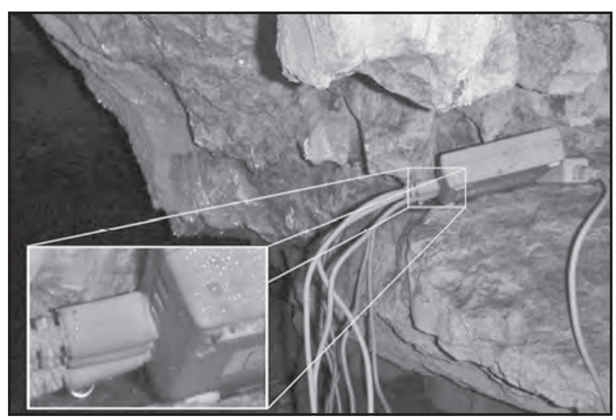

Figure 5: Condensation droplets in CSB Passage. Moisture on the logger (inset) demonstrates that the droplets formed during the study period.

This is not entirely in accordance with the predictions put forth by Dublyansky and Dublyansky (1998) with the "microclimatic method" for condensation estimation. They imagine a maximum at 10 am to 4 pm and a minimum at 10 pm to 2 am, corresponding with maxima of surface temperature and humidity. However, by observing condensation droplets, we are not observing the rate of condensation, but rather the cumulative volume since the beginning of the period t. Maximum visible condensation is likely to occur at the end of the period t, which is likely to be the afternoon through early evening.

If droplets were not present in the morning, this implies that not only are condensation processes more active during the evening, but crucially that the droplets were removed from the walls by another process during the night or morning. Evaporation is one possibility. de Freitas and Schmekal (2006) produced a "conceptual model" of the vapor flux between cave air and walls as a continuum, cycling sinusoidally between condensation and evaporation. Besides evaporation, it is also possible that the droplets are removed by mechanical means. Gravity is the most likely culprit. The majority are attached to the underside of rock by adhesion and surface tension, and appear to be stationary, without flowing or dripping, to casual observation. However, the droplets could be moving slowly, coalescing and flowing down the side of the rock. Dreybrodt et al. (2005) described such "flow from the rock surface down to the cave floor." Close observation of Figure 4, a photograph taken of the roof of Crowning Glory Passage, suggests this is such a case. One can clearly make out vertically aligned "stripes" in the condensation pattern, presumably representing long timescale rivulets. In addition to flow down the wall through these rivulets, it has been suggested that the limestone in our area is porous enough that the droplets could flow directly into the rock and enter the pore spaces, potentially another significant pathway for mechanical removal of the condensation water (Charles Self, personal communication, 2008).

Assuming that the droplets are removed nightly by a non-evaporative process, we can estimate the daily latent transfer of heat to the cave walls, using water's enthalpy of condensation, which is roughly -2.5 kJ g^{-1}. at the temperatures relevant here (near 0 degrees C)

$$228.6\cdot10^{4g}\ \mathrm{day}^{-1}\cdot\text{-}2.5\mathrm{kJ}\ g^{-1} = -555.6\ \mathrm{kJ\ day}^{-1} \quad (3)$$

If this much condensation is occurring each day, it may be a major control on the cave wall temperature. However, this is only a first order approximation at best, and it is very likely that a significant percentage of the condensation droplets remain in the cave overnight, reducing the daily heat transfer into the cave. To determine whether the droplets are removed by flowing, dripping or by evaporation, time-lapse photography could be employed.

6. Conclusions and Foundation for Continuing Research

This study provided a first look at the likely relative magnitudes of component processes in diurnal heat transfer at Rundreisehöhle and Stienbrückenhöhle. The wave energy of the diurnal cycle approaches zero at a distance greater than 15 m but less than 34 m from entrances, more than an order of magnitude further than would be expected if diffusive heat transfer through cave walls (Q_C) alone was responsible. The abundant condensation observed in Stienbrückenhöhle suggests that condensation on cave walls may be a greater factor. Disentangling the importance of airflow through caves is more complicated; at Rundreisehöhle, cave temperature correlated with surface windspeed, but not specifically in a cave-parallel direction. Future investigations in these caves should conduct anemometry at multiple entrances to measure the chimney effect.

Acknowledgments

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GEOMORPHOLOGICAL EVOLUTION AND DIGITAL MAPPING OF THE KSIROMERO REGION, WESTERN GREECE

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Ksiromero is a region in the northeast section of the Prefecture of Aitoloakarnania, in western Greece. The region has a total areal extent of 106.76 km^2 and ranges in elevation from 178 m to 1,314 m above sea level. The karst of Ksiromero is primarily developed on beds of 10-200 m thick Triassic carbonate breccia conglomerates which occupy 70% of the region; 200-300 m thick Upper Triassic to Early Jurassic limestones and dolomites occupy 20%, Quaternary deposits 17%, and 150 m thick Triassic gypsum 3%. The region is normally dry, but streams flow after strong rains. The Ksiromero region contains a dense network of dolines, and more than 75 water reservoirs, which include depressions excavated in terra rossa.

This geomorphic study is based on field research, laboratory analysis of water and rock samples, and work with Able Software R2V, ARCGIS 9.2, and ERDAS 9.1 geographic information systems software. We created an ArcGIS karst feature and geodatabase and developed a mechanism for symbolically identifying the ephemeral, temporal, or inferred features common for karst in this region. All 1:5000 topographic maps of the region were digitized at 2-m contour intervals to allow detailed visualization and analysis. Arc Info 9.2, with 3DAnalyst Tools and Spatial Analyst, were used to create .TIN, grid and 3D shapefiles and high resolution digital elevation models. We also created a digital geological map of the study area and examined Landsat satellite images using principal components analysis, where we could recognize, compare and measure karst landforms from the digital karst geomorphological map model with the satellite imagery.

Karst in the carbonate breccia conglomerates has dramatic features, including richly developed fields of dolines, uvalas, and poljes. The main karst drainage basin has three smaller peripheral basins. In some cases, it was difficult to categorize karst landform types by field research and the digital topographic model. From our parallel study of the digital karst geomorphological map with the satellite imagery, we conclude that the geologic structure of the carbonate breccia conglomerates does not provide the information needed to remotely classify small karst forms. Additionally, the gypsum-cemented clasts create relatively high uniform permeability throughout that outcrop, compared to most karst terrains, which minimizes runoff and development of additional karst features. Poljes of tectonic origin were easily recognized. The analysis yielded information to better evaluate field results for other possible poljes in the region. We identified 14 poljes; however, six previously identified poljes are now recognized as part of a larger compound basin. Residual hills are predominantly intercalated limestone and gypsum, likely the result of lesser solubility than tectonic factors. The system of solution dolines and terra rossa cisterns are adequate water reservoirs, but it is necessary to protect their water quality from pesticides used in the watershed. The karst geomorphological map with the geodatabase will be used to guide future land use in this region.

1. Introduction

Thirty-three percent of Greece is karst (Papadopoulou-Vrynioti, 2004), yet Greece has no specialized governmental or private karst research association. Consequently, knowledge is scattered, and hydrogeological karst investigations are often not based on a clear understanding of karst geomorphology. With this project, we try to provide a model for the country that integrates karst evolution with the study of the organization and origin of karst landforms, their influence on human activities, and the impact of those activities on karst.

Ksiromero is a 106.76 km^2 region in the northeast section of the Prefecture of Aitoloakarnania, in western Greece. It is geographically bounded by the mountainous area of Akarnanika Ori to the west (Psili Koryfi, the highest peak is 1,157 m above sea level), the basin of Lake Ambrakia to the east, Amvrakikos Gulf to the north, and the southern watersheds whose rivers flow to the Ionian Sea through the Department of Akarnania. The karst of Ksiromero is richly developed with different types of dolines, poljes, and uvalas. Since ancient times, it has been sparsely populated, and agriculture is limited due to small water supplies. Animal husbandry, mainly sheep-herding, is the population's primary livelihood; farming of cultivable karst surfaces is secondary.

In this paper we present some of the puzzling questions of our karst geomorphological research of Ksiromero, and answers we developed through the creation of a karst geomorphological map and geodatabase, with insights from Landsat satellite images. Karst geomorphological research that focuses on the resolution of land use problems, combined with an understanding of the natural history and development and functions of karst features is necessary to sustainably live with karst (Veni, 1999).

2. Regional Geological Setting

The Ksiromero region is within the Ionian geotectonic zone, part of the large External Hellenides Platform that extends west from mainland Greece and appears on the western edge of Peloponnesus and in some of the Dodecanese Islands. Primary tectonic features of the Ionian Zone are long thrust faults that trend east-west and northeast-southwest, and long reversed and normal faults that trend northwest-southeast. The faults' configurations have created the large tectonic basin of Ksiromero and other basins in western Greece. Geologic mapping of the region is provided by the Institute of Geology and Mineral Exploration (1986, 1987). Figure 1 illustrates these units and karst geomorphic and hydrologic features.

During Permo-Triassic time, the Ionian Zone was a shallow, restricted, marine basin which accumulated over 150 m of evaporites (Karakitsios, 1992), of which gypsum is notably exposed. Their episodic deposition may have allowed the development of a paleointrastratal karst, as described in other regions by Bosák et al. (1989), although no direct evidence has been found. Triassic Tryphos Formation carbonate breccia conglomerates were deposited over the evaporites, followed by up to 200 m of dolomite and as much as 300 m of the Pantocrator Limestone into the Early Jurassic. At that time, the shallow Thethos Sea covered a continental platform which extended throughout nearly all of western Greece. The carbonate breccia conglomerates are epigenetic, formed during the Triassic from major tectonic activity, diapiric deformation, and dissolution of underling evaporites. These conditions continued with small modifications up to the end of the Jurassic. From the Pliocene to the Quaternary, more recent gypsum deformation occurred at the surface due to underlying diapiric movement along prominent faults (Underhill, 1988).

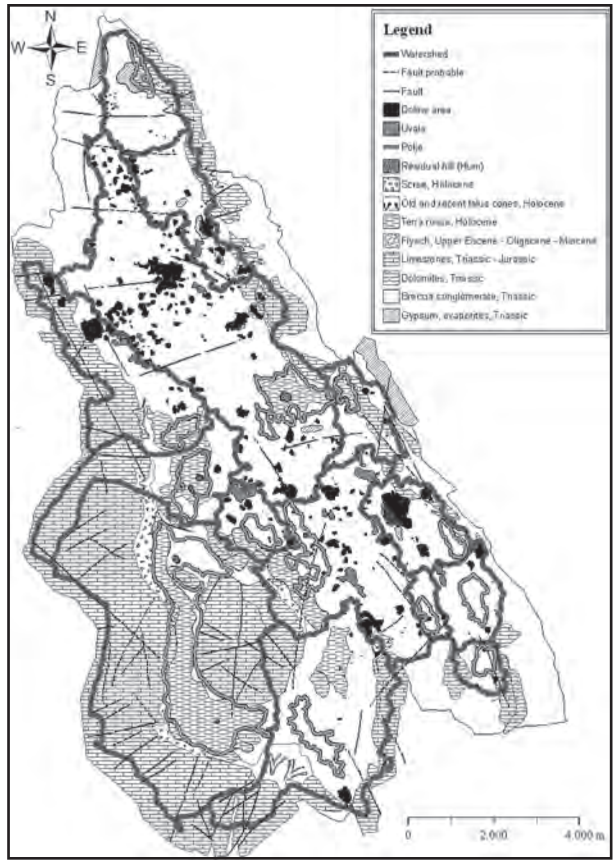

Figure 1: Geomorphic and hydrogeologic map of Ksiromero, Greece (geology based on Institute of Geology and Mineral Exploration, 1986, 1987).

The Tryphos carbonate breccia conglomerates are the main karstified rocks of the region. They range from 10-200 m thick and cover 70% of the area. Petrographic analyses, the geological mapping, and studies of hand samples identify them as microcrystalline to sparry calcite limestone and dolomite breccia and pebbles, up to 30 cm in diameter. In some places, the carbonate clasts have become marble. Traces of pyrite and quartzite are present. The clasts occur in a cohesive to slightly cohesive gypsum matrix that weathers into a terra rossa matrix.

3. Local Karst Hydrology

The word "Ksiromero" is Greek for "dry place." From a geographic perspective, the region internally drains water to where it is not exploitable for use. Hydrogeologically, it is a system of closed karst watersheds whose recharge characteristics are poorly defined and where the downgradient destination of its groundwater is unknown. While recharge occurs through the higher elevation limestones and dolomites, most of it is transmitted though the Tryphos breccia conglomerate and the underlying gypsum. The highly soluble gypsum matrix of the conglomerate produces a relatively uniform high-permeability surface that minimizes surface runoff. While most karst features of the region are developed in the Tryphos, their density may have been greater if the matrix had been carbonate. Additionally, the few open caves and conduits in the region likely result from the high production of residual terra rossa soils from the gypsum. The soils accumulate on all surfaces, especially in dolines, and runoff is insufficient to transport them through the karst to create more open caves.

In some lower-central elevation areas, groundwater occurs in two horizons, separated by a thin bed of clay and marl. One is 4-12 m below the surface and the other between 15-30 m. They serve as small, local water supplies where they pool in some dolines. Deep wells in the region are not known to yield usable quantities of water because they either do not reach the water table, and/or possibly because most groundwater is restricted to conduits which are unlikely to be intersected by drilling. Generally, water is supplied to Ksiromero from neighboring regions and stored in more than 75 reservoirs. Some are natural solution dolines fed by groundwater, and others are natural or excavated depressions in terra rossa. To prevent loss of water into the ground, the bottoms of some of the terra rossa reservoirs are cemented. Chemical analysis of the imported water shows it is usually within drinking water standards, although due to vulnerability to contamination, it is more suitable for irrigation.

4. Karst Geomorphology and Geographic Information System (GIS) Analysis

To better evaluate the morphologic and hydrologic characteristics of the region, we used ArcGIS Info 9.2 to create a detailed geodatabase of karst landforms, and geographic and hydrologic features that represent and/or influence karst development. We digitized surface water flows, which exist only following periodic rain. Topographic contours were digitized at 2-m intervals above mean sea level. We used Spatial Analyst to create a digital elevation model (DEM) to calculate surface area, flow direction, flow accumulation, flow sinks, stream networks, stream links, and watershed boundaries.

We created a database with all existing karst forms and their sub-groups in different layers. We identified 14 poljes in the region; six were previously identified but we recognized them as part of a larger compound basin. Through watershed delineation, we identified one large compound karst basin, which includes nine smaller polje watersheds,

Doline	Elevation above mean sea level (m)	Depth (m)	3-D surface area (m²)	Type of doline (per Čar, 2001)
Amuistra	323.8 – 352	28.2	1,080,500	shallow, near-fault, point recharge
Stadopigado	135.4 – 240	104.6	481,400	funnel-like, near-fault, point recharge
Palaiofrazata	243.5 – 284	40.5	265,900	funnel-like, near-fault, point recharge
Mpoimo	337.9 – 376	29.1	262,600	funnel-like, fault doline, point recharge

Table 1: Morphometric characteristics of major dolines in Ksiromero.

Polje	Elevation above mean sea level (m)	Watershed 3-D surface area (m²)	Polje 3-D surface area (m²)	Type of polje	Residual hills (Hum)
Fraksias	178.8 – 200	20,518,200	1,397,900	tectonic, evolved from dolines and uvalas	1
Geladomandra	235.2 – 240	5,627,200	860,700	tectonic, border	2
Kserolagia	210.3 – 246	10,160,600	854,600	border, evolved from dolines and uvalas	6
Spilia	246.4 – 288	10,673,500	278,500	tectonic, structural, point recharge, ponor	0
Stinadia	200 – 230	27,489,300	5,259,800	radial, tectonic, structural, point recharge	3

Table 2: Morphometric characteristics of polje watersheds in Ksiromero.

and five smaller separate watersheds for poljes. We found 17 residual hills in the poljes, comprised predominantly of limestone intercalated with gypsum and likely the result of lesser solubility than tectonic factors. We identified a total of 278 dolines with funnel, shallow, and a few collapse morphologies. We also identified 12 uvalas. Ponors are rare but exist at the contact of the limestone with the breccia conglomerates and follow faults. Using Čar's (2001) classification scheme, Ksiromero primarily has broken, broken collapse, near-fault, and fault dolines.

Our database included different layers for each type of karst features, and using the DEM, we applied Spatial Analyst and 3D Analyst to calculate surface areas and slopes. Some results are summarized in Tables 1 and 2.

5. Satellite imaging

We adapted Landsat satellite imaging of Ksiromero, using ERDAS Imagine 9.1 software, for principal components analysis (PCA). This linear transformation technique in image processing reduces data redundancy between spectral bands (Sabins, 1996). Using PCA for this study, standardized principle component transformations were conducted using the six bands of the Landsat image (excluded the thermal band to recognize karst morphologies. We determined: PC1 = 92.7%, PC2 = 4.2%, PC3 = 2.4%, PC4 = 0.4%, PC5 = 0.25% and PC6 = 0.05%. Figure 2 is an example of PCA-examined imagery, specifically PC2. In combination with PCA, we used ArcMap 9.2 to compare, evaluate, and further reduce image noise and better recognize karst features. With that technique, we evaluated a combination of stretched symbology values while changing color schemes to best accentuate the features.

Both PCA and color scheme methods produced the same results. The first principle component looks like a panchromatic image and corresponds to the brightness, providing information about topography and albedo. This principal component contains most of the information needed for recognizing large karst features (the largest poljes) on the breccia conglomerates. PCA and color scheme analysis also identified parts of the largest polje's watershed where limestone pavement and smaller karst features like dolines or uvalas are otherwise difficult to impossible to remotely discern.

6. Conclusion

Ksiromero is a region of carbonate karst, with morphologic and hydrologic characteristics complicated by underlying evaporites and preferential dissolution of the gypsum matrix

Figure 2: Hydrologic and geomorphic Landsat image of Ksiromero examined for second level principle components analysis (original imagery was evaluated in color).

in the carbonate breccia conglomerate. Its features cannot be adequately understood based on carbonate karst conditions alone.

The size of a doline's watershed is often roughly proportional to the size of the karst conduit at its base. In contrast, the more uniform high permeability surface of the breccia conglomerate in Ksiromero recharges water more diffusely than a well-cemented limestone, resulting in less runoff and more sediment deposition in dolines to effectively reduce conduit size. However, the high, though diffuse, permeability suggests that groundwater fed by such recharge, as well as through open conduits, is highly vulnerability to contamination from the drained surface. The system of solution dolines and terra rossa reservoirs are adequate for the area's modest water demand, but water quality must be protected from pesticides and other agricultural contaminants. The GIS-based map and geodatabase from this study can be used to assess vulnerability, plan protective measures of individual sites of outstanding vulnerability, test future regional groundwater recharge models, and develop supplemental water supply and conservation plans.

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MORPHOLOGICAL RELATIONSHIPS BETWEEN ERRATIC BOULDERS AND ASSOCIATED BEDROCK LIMESTONE FINS OR "ROCK COMETS," MADRE DE DIOS ARCHIPELAGO, CHILE

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Rock comets are apparently unique karst landforms composed of glacial erratic boulders and bedrock limestone fins from the Madre de Dios Archipelago, Chile. Fins form due to differential erosion under conditions of prolific rains and strong frequent winds. We measured 50 erratics at two sites as well as their proximal bedrock fin, fin orientation and grooves adjacent to the windward side of the erratic boulders and analyzed this data with standard statistics. Comet orientation varied 29˚ at Suplador Pass while on Tarlton Island comet orientation varied 52˚ due to the wider distribution of the comets across a ridgeline. Erratic width was a good predictor of fin width and groove width. But, these were the only strong relationships demonstrated. Erratic height is not a good predictor or fin height or length and erratic average dimensions are also not a good predictor of fin length. Erratic height also does not predict groove depth. Overall comets seem to develop based upon more specific and localized conditions such as the overall shape of the erratic, location relative to other comets, bedrock features, or vegetation and specific location along the ridge line or pass area all of which effect wind flow and rain fall.

1. Introduction

The Madre de Dios Archipelago of Chile at 52˚ south latitude hosts the karst-rich Tarlton Limestone of Pennsylvanian to Permian age. This rock has been heavily altered and includes many folds, faults, thrust faults, localized marble, and sills and dikes of volcanic rock. Outcrops of Duchess of York Sandstone also occur across the karst (Forsythe and Mpodozis, 1983). This region of Chile is extremely wet with annual rainfall between 6 and 10 m and as few as three days per year with no rainfall. The region also routinely has very strong winds – gales are common and local ports are often closed due to the high winds. The islands and adjacent fiords are entirely glaciated, although the specifics of glacial activity and timing are unknown (Jalliet et al., 2008).

International cave and karst researchers have travelled to the area on four major expeditions over the past 10 years. Based at the open-air limestone mine on Guarello Island, the caver teams have explored many caves and pits as well as the amazing surface karst of the islands.

One of the most interesting discoveries in 2000 were rock "comets" – small erratic boulders of volcanic rock or sandstone behind which a bedrock limestone tail or fin had developed (Figs. 1 and 2) originally described in Jalliet and Hoblea (2000). In addition a groove of varying size, but generally a few centimeters deep, is eroded into the bedrock at the windward margin of each erratic. Comets occur in groups only at the most windy sites in the archipelago – on flat benches at the tops of passes and along narrow ridges and where erratics have also been deposited during glacial retreat (Fig. 2). A handful of comet sites have been recorded and most have only a few comets. The sites used in this study on Tarlton and Madre de Dios Islands contain the densest concentrations of comets known.

Figure 1: Comets on Tarlton Island looking along the axis of the bedrock fin. Joel Despain, Centre Terre.

Figure 2: Comets at Suplador Pass on Madre de Dios Island that weremeasured for this study. Joel Despain, Centre Terre.

Previous work has shown that erosion rates of the Tarlton limestone are very high with a possible down cutting rate of 16 mm per century (Centre Terre, 2007). Winds on the islands are associated with frequent periods of heavy rain and the rain does literally move sideways across the passes and ridges during storms. Observations and photos of the comets during rainstorms revealed that the limestone fins at times remain dry while adjacent areas are exposed to rain and subsequent erosion (Fig. 3).

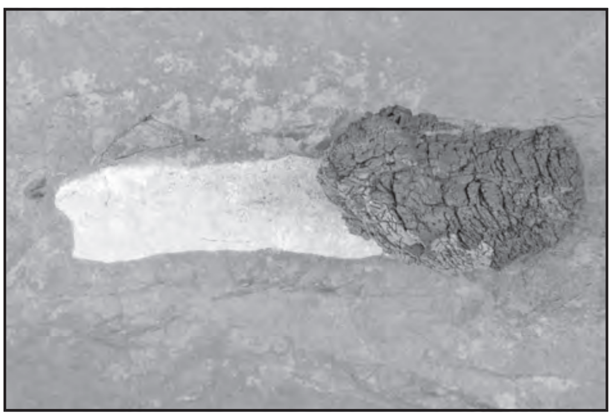

Figure 3: Rock comet on Tarlton Island after a light rain with strong winds and with a prominent dry area along a small limestone fin in the lee of the erratic. Joel Despain, Centre Terre.

2. Methods

To understand the relationship between the erratic boulders and their adjacent bedrock fins, we measured their respective sizes. Eighteen comets were measured along a ridge on the northwest corner of Tarlton Island and 32 comets at a single site were measured at Suplador Pass on Madre de Dios Island, for a total of 50. For each the maximum width, height, and thickness of each erratic, the length, and maximum width and height of each limestone fin, and the depth and width of the bedrock groove on the windward side of the erratic were measured using a fiberglass measuring tape to an accuracy of 0.5 cm except for groove depths, which were measured to the nearest millimeter. In addition, the azimuth orientation of each fin was recorded. Some comets at both sites were not appropriate for this study such as those formed by two erratics or those that merged into each other and, as such, were not included. Standard statistical analysis was applied to these data.

3. Results and Discussion

Comets are oriented differently at the two sites reflecting a variation in the direction of the prevailing winds. On Tarlton Island comet azimuths vary from 245˚ to 297˚ with a range of 52˚ and a mean orientation of 273˚. At Suplador Pass, comet orientations vary from 305˚ to 334˚ for a range of 29˚ and a mean of 324.5˚. The comets on Tarlton Island are across a larger area compared to Suplador and are within several flat exposures of limestone that are proximal but at different elevations up a ridgeline. With varied locations comes an increasing likelihood of localized variations in the wind direction and variation in comet orientation.

Erratics vary in width from 11 to 105 cm while the bedrock fins vary from 7.5 - 93 cm. Forty five of 50 erratics are wider than their adjacent bedrock fin. Width variations between fins and erratics range from 0.5 - 19 cm with a mean of 4.5 cm. A linear polynomial regression of erratic width versus fin width produces a fit and r^2 of 0.844 demonstrating a strong relationship between the width of erratic boulders and bedrock fins (Fig. 4).

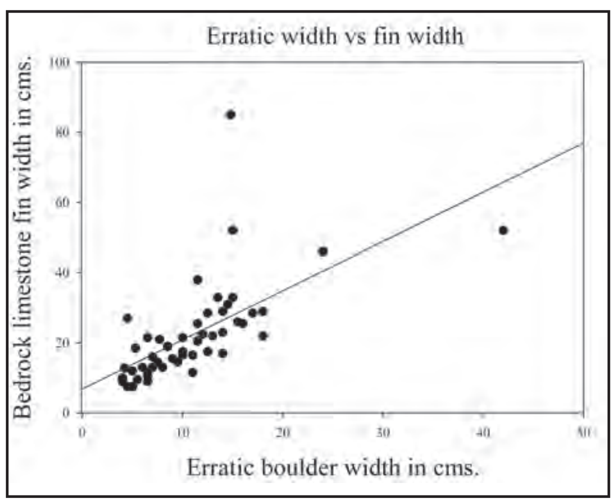

Figure 4: Regression between the width of erratic boulders and their adjacent bedrock fin. The fit is an r2 of 0.844.

Erratics range in height from 11.5 to 105 cm. and bedrock fins vary in height from 4 to 42 cm. All of the erratics were taller than their proximal fins. The average difference between erratic and comet height is 11.3 cm. with a range of 3 to 70 cm. Linear polynomial regressions between the height of the erratics and the fins produce a resulting r^2 of 0.382 showing that erratic height is a poor predictor of comet height.

Unlike the other dimensions, the length of the comet does not have a direct corollary in the size of the associated erratic. We compared erratic height and width and the average of erratic height and width (mean dimension) to fin length. Both erratic width and height are poor predictors of comet length. The regression of erratic width versus fin length produces an r^2 of 0.322 and for erratic width the fit is an r^2 of 0.187. The mean of the two is no better with a fit of 0.25 (Fig. 5).

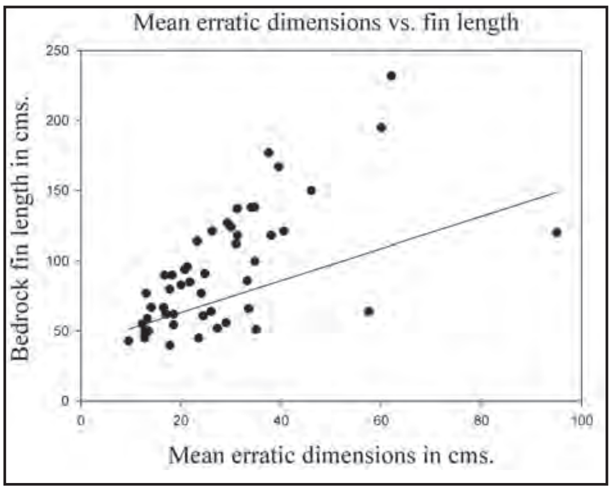

Figure 5: Mean erratic boulder size versus bedrock fin length with a poor r2 of 0.25.

The grooves parallel to the front of the erratic boulders are variable. Fifty-eight percent of grooves are 0.5 - 6 cm wider than their adjacent erratic, but 25.5% are shorter and a few comets lack the feature entirely. A linear polynomial regression with erratic width versus groove width produces an r^2 of 0.74 showing a relationship between the widths. Groove depths range from 0 - 7 cm with a mean of 1.37 cm. A regression between erratic height and groove depth produces a poor fit with an r^2 of 0.255.

While comets themselves are uncommon, related landforms are throughout the islands. Differential erosion along volcanic dikes and sandstone units at varying orientations and angles and vertical erosion below erratic boulders in areas of low wind have been widely noted (Centre Terre, 2007). Forty meters from the comets at Suplador Pass, volcanic rock 0.1 m thick and 0.7 m in diameter shielded a bedrock "arm" in its lee from erosion. The bedrock limestone arm is 2 m in length and projects upward and into the prevailing winds (Fig. 6).

Figure 6: Bedrock arm at Suplador Pass. Joel Despain, Centre Terre.

While the width of the erratics has a clear effect on the width of the limestone fin and groove for each comet, only general predictions on other bedrock parameters can be made from an examination of the erratic. Small variations in the shape of the erratic and the adjacent ground surface, the proximity to adjacent comets, the shape and slope of the bedrock surface, and likely other factors that effect wind velocity and direction wield significant and localized influence on the size and shape of the bedrock fins, making these features highly variable.

Acknowledgments

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EXTREME INCREASE OF CO_2 IN BELGIAN CAVES

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We began making CO_2 measurements in Belgian caves in 1966. Analyses were conducted in cave halls, galleries, fissures and shafts. They were collected during various seasons and at different levels above the floors of the conduits, and in the absence or presence of other human beings. Our first results were published in 1968. From that time on, we have carried out studies in Poland, Quebec, China and other countries. However, we have focused most of our work in Belgium. We have discovered over these forty years of study, a strong increase in the observed values of CO_2 in Belgian caves.

For example, a few of our observations follow. "Trou Joney" (Comblain-au-Pont, province of Liege) is a small and shallow cave. We measured at the central point of the main gallery, 1870 ppm CO_2 in July 1966, and 13,800 ppm at the same location in July 2007. At the bottom of the shaft of the "Comblain-au Pont" cave, we measured 600 ppm in July 1966 and found 1500 ppm in July 2008. In "La Merveilleuse" cave (Dinant, province of Namur), we measured 800 ppm at the central point of the Big Hall in August 1990, rising to 1700 ppm in August 2008. In the main gallery of the "Fontaine de Rivire" cave (Hamoir, province of Liege), we found 5000 ppm in August 1972, increasing to 12,000 ppm in 1991.

We conclude that the CO_2 content of the atmospheres of many caves in Belgium (at least) has become higher . The increase is very variable, but omnipresent. Are our measurements significant? We believe that we have validated our instruments and our methods. The increase is probably not a result of local industrial activities. The CO_2 curves of Mauna Loa Observatory (Hawaii) and "Mace Head" (Ireland) both show an increase of atmospheric carbon dioxide during the last half century. However, the upsurge of CO_2 observed in the caves is proportionately much greater than the increase in those well-known surface measurements.

There is a very complex interrelationship between temperature, vegetation and biomass activity, and CO_2 in the soil and underground. The increase of any one of these three parameters can induce changes in the two others, and hence in the partial pressure of CO_2 in cave air.

Inflation du CO_2 dans les grottes de Belgique. Nos premières mesures de dioxyde de carbone dans les grottes de Belgique datent de 1966 et les premiers résultats furent publiés en 1968. Nous avons mesuré le CO_2 dans les salles, les puits, les galeries et les fissures, en différentes saisons. Au fil de ces quelque quarante années, nous avons observé dans toutes les grottes une forte augmentation des concentrations de l'air en dioxyde de carbone au cours du temps.

Ainsi, par exemple, dans le fond du Trou Joney, une petite grotte peu profonde située à Comblain-au-Pont (province de Liège), nous avons mesuré 1870 ppm de CO_2 en juillet 1966 et 13800 ppm au même endroit en juillet 2007. Dans la grotte La Merveilleuse à Dinant (province de Namur), la teneur en CO_2 dans la grande salle était de 800 ppm en août 1990 et en août 2008 elle était passée à 1700 ppm. Dans la grande galerie de la grotte de Fontaine de Rivîre à Hamoir (province de Liège), nous avions trouvé 5000 ppm en août 1972 et nous en avons mesuré 9400 en octobre 2008.

Les teneurs en CO_2, dans les grottes belges en tout cas, sont donc en forte hausse. Cette augmentation est très variable mais elle est très générale et, à notre avis, elle n'est pas influencée par l'activité industrielle locale. Certes, les courbes de l'observatoire de Mauna Loa et de Mace Head montrent une augmentation du CO_2 dans l'atmosphère au cours du dernier demi-siècle, mais, dans les grottes étudiées, nous sommes en présence d'un phénomène beaucoup plus important.

Les relations entre les paramètres climatiques, biologiques (tels la respiration de la biomasse) et le dioxyde de carbone dans les sols sont complexes et les variations de chacun de ces paramètres peuvent influencer les deux autres et par là la pression partielle du CO_2 dans les grottes.

1. Introduction

Our CO_2 measurements in cave air began in 1966. They were conducted in galleries, chambers, shafts, fissures; we analysed the air near the entrances and in remote parts, near the ceiling and near the floor. The first publication of our results appeared in the *National Speleological Society Bulletin* (Delecour et al., 1968). It showed that there is much more carbon dioxide in cave air than in the open air, much more in fissures than in galleries or chambers, and more in remote parts than near the entrances. Other results were published the same year in the *Annales de Spéléologie,* showing that CO_2 in caves mainly comes from the surface soil through fissures (Ek et al., 1968). In 1985, we described the seasonal rhythm of CO_2 partial pressure with a summer maximum and a winter minimum, and the slow decline of carbon dioxide from the soil to lower and lower levels in the caves (Ek & Gewelt, 1985).

Six Belgian caves have been selected here to display our results. All of them are located in the Paleozoic limestones south of Liège (Belgium), close to the 50th parallel North (Fig. 1). All caves exist in an oceanic temperate climate, with a mean temperature of about 10°C and an average annual rainfall of 800 mm. They are in a covered karst, under grasslands and woods, at elevations ranging between 80 and 240 m. The thickness of the roof between cave and surface ranges from 15 to 90 m. We have conducted analyses in several other countries (i.e., Canada, Poland, China), but those are not dealt with in this paper. Some of our measurements done between 1966 and 1990 were repeated in several caves in similar conditions between 2000 and 2009. This has allowed us to discover that carbon dioxide in these cave atmospheres has strongly increased in the recent decades, considerably more so than in the outer atmosphere.

Figure 1: Location of the caves studied in Belgium. C: Comblain-au-Pont. D : Dinant. E : Esneux. H: Hamoir. R : Remouchamps.

2. Instruments and Methods

The first measurements of CO_2 were made in 1966 by C. Ek and his colleagues with an electrolytic field device (Ek et al., 1968). The analysis was based upon the titration of the carbon dioxide in a known volume of air absorbed in a 0.1 N NaCl solution. The time necessary to neutralize the absorbed carbon dioxide is measured. The CO_2 content of the sample is computed from the current (mA), the time (seconds), and the air sample volume (mL). The apparatus, packed in a wooden case, weighed 15 kg, and was thus relatively heavy; however it worked in caves for several years (Fig. 2).

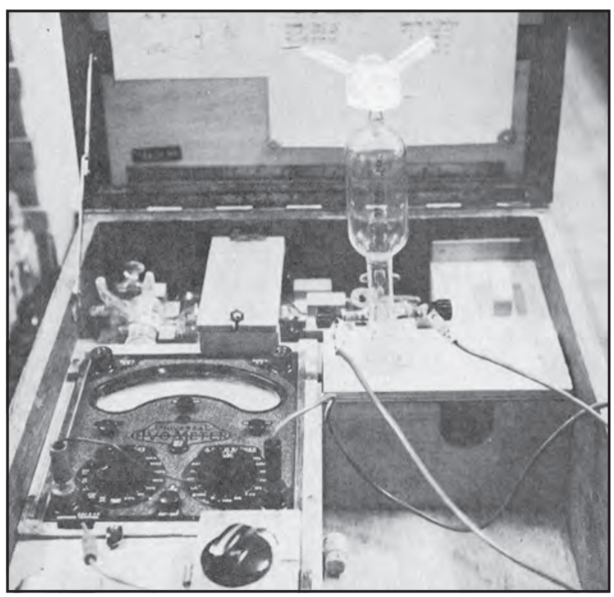

Figure 2: Electrolytic field device for measuring atmospheric CO2, by Koepf (Ek et al., 1968).

From 1981 onward, we used the gas pump Precision Detector (by Gastec) which is lighter and faster but working with single use detector tubes. In these tubes, carbon dioxide reacts with hydrazine or, for higher concentrations, with potassium hydroxide; in both cases, the CO_2 concentration is given by a direct reading on the graduated scale of the tube. The minimal precision guaranteed by the manufacturer is +/-25% but the effective precision is much better and the reproducibility is about +/-10%. In some cases, for example in confined places, the operator used a carbon dioxide absorbing mask in order to avoid human CO_2 exhalation (Fig. 3).

Figure 3: Gastec pump detector giving a direct reading of CO2 concentration (Ek & Gewelt, 1985).

Current surveys (since 2008) are conducted using a X-am 7000, a portable gas measuring and monitoring instrument by Draeger equipped with an IR (infrared radiation) probe ranging from 300 ppm up to 50,000 ppm CO_2 which has been the most suitable device for our purpose (Fig. 4). This equipment, weighing 1.6 kg (one tenth that of our first device), is also able to record data from remote places thanks to its pump sampling function, thus avoiding human contamination. Before each working day, the device was calibrated in the open air against the known concentration of CO_2. Whenever we changed measuring instruments we checked several times the concordance of the techniques.

Figure 4: X-am 7000 by Draeger, infrared portable device.

3. Results

Six caves have been selected here to display our results (Fig. 1). All of them are located in the Paleozoic limestones south of Liège (Belgium). The carbon dioxide content of the air of all the caves displays seasonal fluctuations, with a summer maximum and a winter minimum, as exemplified in Figure 5.

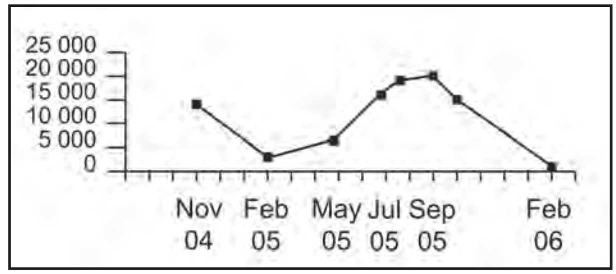

Figure 5: Seasonal variation in the CO2 concentration in the atmosphere of Comblain-au-Pont Cave.

Over the course of the 40 years covered by this study, the values of CO_2, and particularly the summer maximums, have been on a noticeable increase. Here are a few examples of these rises:

3.1. Fontaine de Rivîre Cave in Hamoir

This cave lies in Devonian limestones, in the province of Liège, some 40 km south of the city of Liège. Its entrance opens at 135 m a.s.l. It is about 1100 m long. The rock above the cave is about 85 m thick. It is a phreatic maze connected to a wide gallery ending in a large chamber (20,000 m^3) with a lake (Godissart, 1994). Between 1972 and 2008, the summer concentration of CO_2 increased from 5000 to 9000 ppm (Fig. 6.1).

3.2. Trou Joney in Comblain-au-Pont

Trou Joney is a small cave, 30 km south of Liège, in the same province. It lies in Carboniferous limestone, at an elevation of 185 m. Its length is only 60 m and the rock above the cave is about 15 m thick. The single gallery is choked at the bottom with gravel and fine sediments. We carried out a carbon dioxide survey in July 1966, and a monthly survey all along 1978 (Ek, 1979). At the bottom of the cavity, the CO_2 rose in summer from 1715 to 13,800 ppm between the first and the last date (Fig. 6.2).

3.3. Sainte-Anne Cave and Brialmont Caves in Esneux

These two caves are located 9 km south of Liège, in Devonian limestones. The entrance of Sainte-Anne is at an altitude of 85 m a.s.l. whereas Brialmont, which is situated above the first one, opens at 180 m a.s.l. They are probably

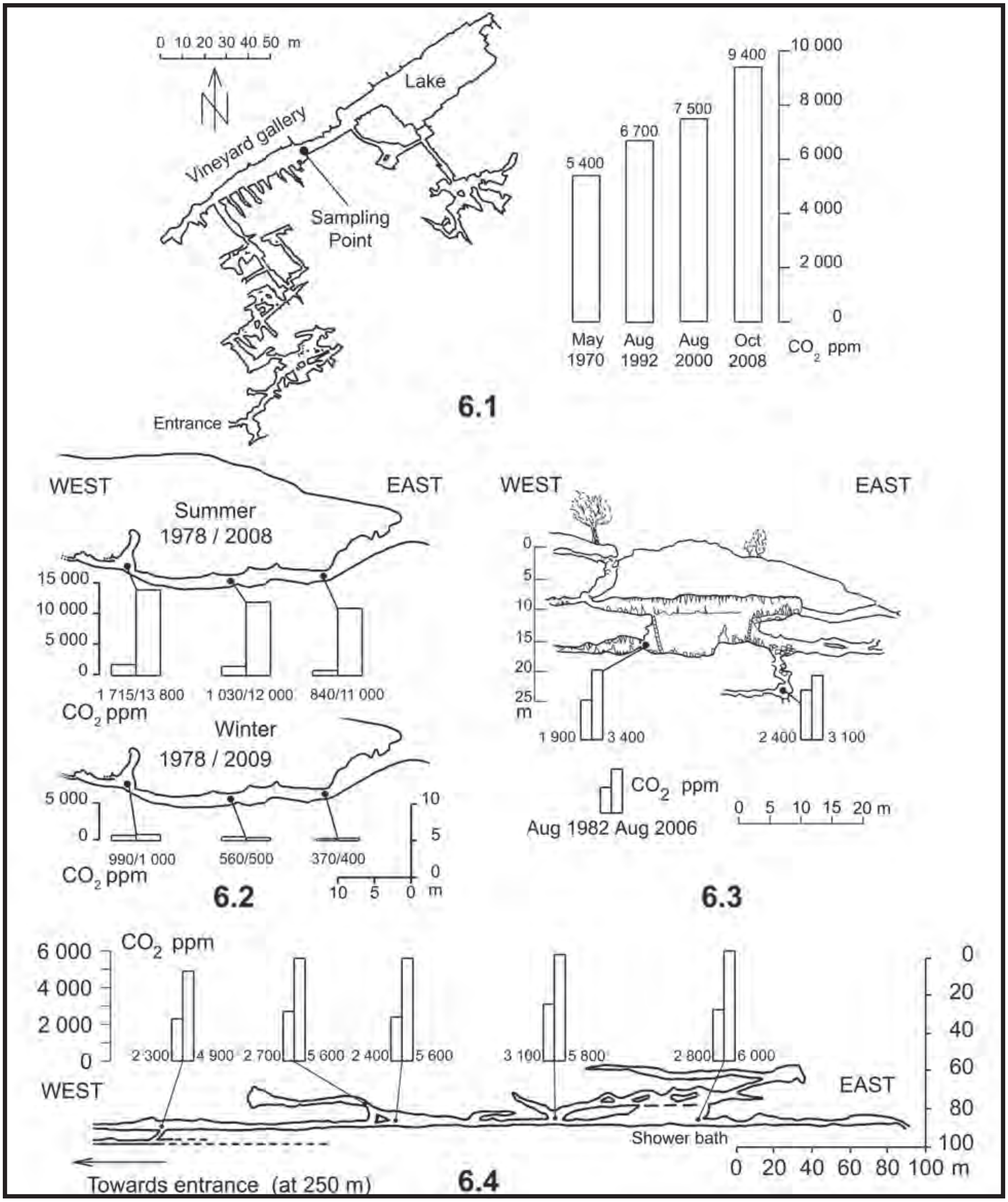

Figure 6: Carbon dioxide in cave air.
6.1. Rivîre Cave, Hamoir. Sketch map and location of the principal point of CO2 measurements.
6.2. Trou Joney, Comblain-au-Pont. Long profile and comparison of CO2 values in summer 1978 and 2008 and in winter 1978 and 2009.
6.3. Brialmont Cave, Esneux. Long profile. Location of comparative CO2 measurements. Topographical survey by Naveau, S.S.D., 1971.
6.4. Ste-Anne Cave, Esneux. Long profile. CO2 concentrations in January 1983 and January 2008.

parts of the same system, but to date the connection has not been made by cavers. Both caves consist of subhorizontal galleries. Brialmont is two-tiered. Beneath it, Sainte-Anne is four-tiered. The galleries are spacious and connected by shafts and fissures. The total development of Sainte-Anne is about 1500 m and an underground river flows in its two lower levels. Above it, Brialmont, with 180 m of development, is dry (Figures 6.3 and 6.4). It is in this cave system in 1984 that we discovered the slow diffusion of carbon dioxide from the soil to the successive lower levels of the caves. We also established the strong annual rhythm of CO_2 concentration (Ek & Gewelt, 1985). Returning to these caves a quarter of a century later, we discovered a strong rise in carbon dioxide. In August 2006, the galleries of Brialmont showed an increase of much more than 30% (Fig. 6.3). In January 2008, Sainte-Anne displayed values approximately double those of 1982 (Fig. 6.4). In these caves, although the measurements of 1982 were carried out each month, unfortunately we have only single values in 2006 and 2008.

3.4. La Merveilleuse Cave in Dinant

La Merveilleuse lies in the Carboniferous limestone, 75 km south of Brussels as the crow flies. It opens at about 150 m a.s.l. and its development measures about 750 m. We analyzed the CO_2 there in 1990, 2003 and 2008. The values measured in the halls and galleries in August of each of these three years are displayed in figure 7.1. It is clear that between our first and last measurements, the CO_2 concentration in the cave air has approximately doubled, except at the aperture of two shafts, where carbon dioxide variations are probably related to a deep underground stream (Fig. 7.1). In August 2003, we carried out a detailed survey of a small confined chamber: the Temple de Diane (Fig. 7.2 and 7.3). We measured 4000 ppm CO_2 near the ceiling and 5100 near the floor. In August 2008, these figures had increased to 15,400 and 18,000 ppm respectively!

4. Conclusions

We observed in the caves of Belgium a huge rise in pCO_2. This generally has been an increase of around 100% in forty

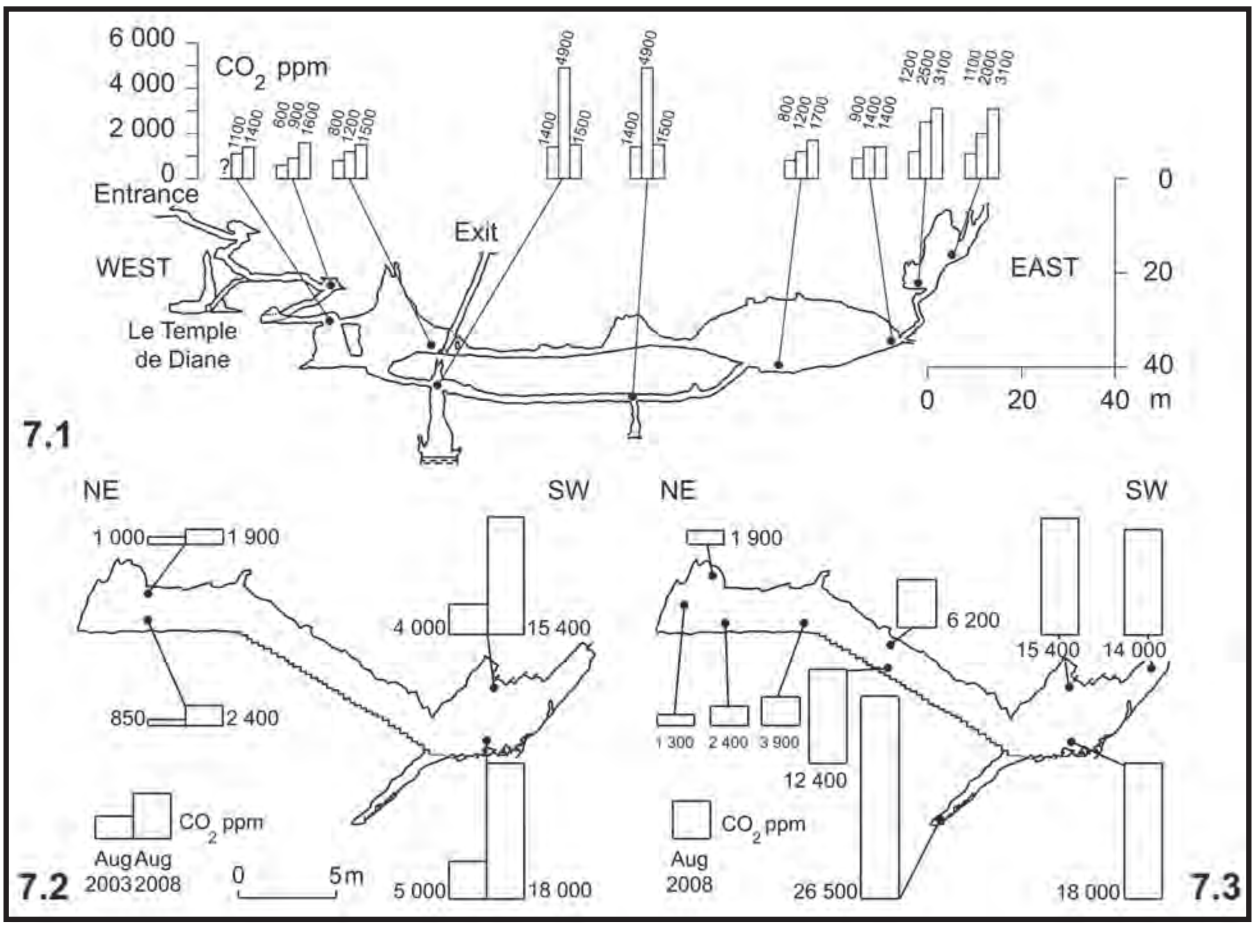

Figure 7: La Merveilleuse Cave, Dinant. Carbon dioxide in air.
7.1. La Merveilleuse. Long profile. CO2 measurements in August 1990, 2003 and 2008.
7.2. Le Temple de Diane. Long profile. Comparison of some CO2 measurements in Aug. 2003 and Aug. 2008.
7.3. Le Temple de Diane. Long profile. Detailed CO2 survey in August 2008.

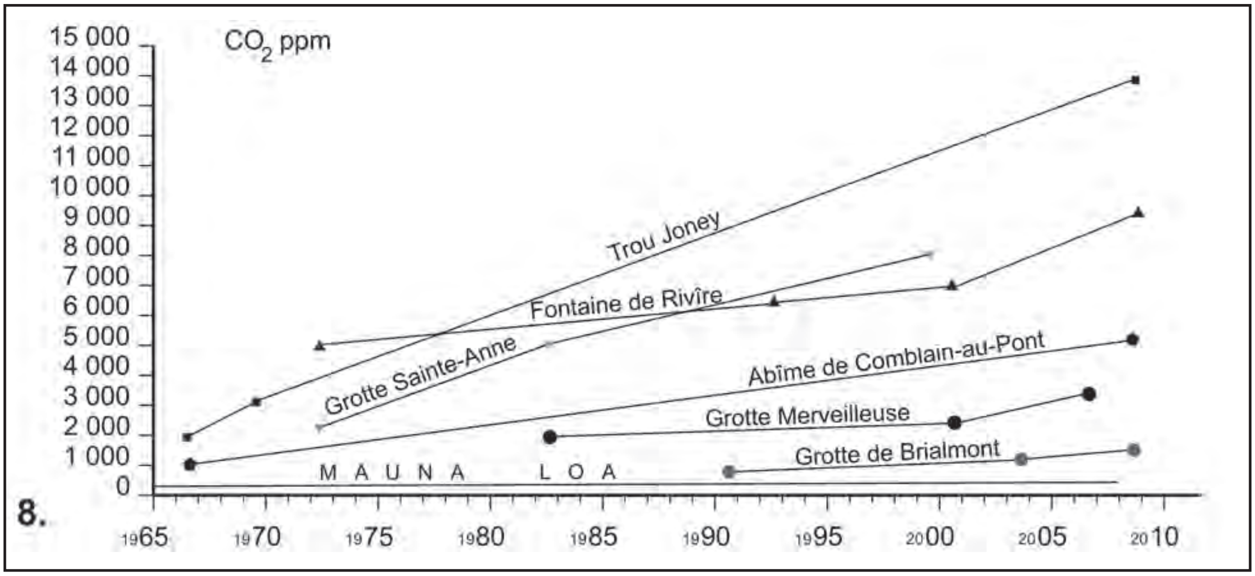

Figure 8: Changes in CO2 concentrations in some Belgian caves between 1966 and 2008. Below, Mauna Loa curve of CO2 evolution.

years, and in some places even more. This increase is variable, as shown in Figure 8, but all of the caves visited showed some increase.

Of course the pCO_2 curve of Mauna Loa (Machta, 1972), from 1960 to 2008 displays a slight increase, but this is much less significant: rising from 314 ppm in 1960 to 387 ppm in 2008, about 22% in a half-century. From 1960 until now, the rate of rise at Mauna Loa has increased from 0.9 ppm per year in the nineteen sixties to 2.0 ppm per year during the beginning of the third millennium. Closer to Belgium, Mace Head (Ireland) shows the same slope. The worldwide rise of atmospheric CO_2, although sharing the same trend, is much too small to explain the inflated values observed in the caves.

Carbon dioxide in most caves mainly originates from the soil. This idea is supported by investigations by Bourges et al. (2001), Calmels et al. (2005) and Baldini and colleagues (2006). It is the emission of CO_2 by the soil biomass which is the presumed cause of the increase observed in the caves. A slight rise of temperature has been observed in Belgium, which can favor increased activity by the vegetation. The year of 2006 was the warmest since the beginning of meteorological surveys (1833), and 2007 was warmer than 2006. On the other hand, the general rise of atmospheric pCO_2 induces a rise of the rate of photosynthesis which leads, in turn, to an increase of root respiration and of microbial activity in the soil (Koerner et al., 2005). This could certainly enhance the carbon dioxide concentration in soil air, hence in the caves.

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OVERVIEW OF THE NON-KARST CAVES IN HUNGARY

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Hungary is a country in central Europe with a land area of 93,030 km². The greater part of its territory consists of a plain and a low hilly landscape. A moderately high mountain range, with a highest point of 1014 m comprises a third of the country. These mountains are mainly composed of limestone, other sedimentary rocks, and volcanic formations. In Hungary, 2800 karst caves and 892 non-karst caves have been recorded. The majority of the non-karst caves developed in basalt, andesite, rhyolite, and their tuffs, as well as in sandstone, conglomerate and a variety of metamorphic rocks. A significant part of the karst limestone caves are large and well decorated. The length of 30 of these caves varies between 1 and 25 km. However the non-karst caves are shorter - the longest being the 428 m long Csörgő Hole - they represent various types of cave development. The syngenetic caves in volcanic rocks include gas bubbles, steam explosion caves, fumarole caves, and crystal chambers. Typical syngenetic caves formed at the same time as the deposition of calc-tufas. The caves that originated postgenetically formed by four major effects: mass movement, erosion (physical weathering), fragmentation (physical weathering), and chemical weathering. These four main processes have resulted in the development of about 25 different types of non-karst caves. The 892 non-karst caves are located in 20 regions. The number of caves varies greatly from region to region. There is one area with nearly 300 caves identified, while in other regions only have one or two caves documented. Generally the Hungarian non-karst caves are poor in secondary mineral deposits and speleothems, although silicate speleothems and other mineral formations occur in some caves. Ice remains until the summer in some smaller caves. In the caves 198 species of fauna and 18 species of flora - some very rare - have been found and classified. In some non-karst caves, significant archaeological and palaeontological remains have been discovered.

1. Introduction

In Hungary, 892 natural non-karst caves have been listed. Organized research began in 1983 with the launch of the Volcanspeleological Collective. Their comprehensive activity is still ongoing. The present study summarizes the development, the number and location, the mineral occurrences, the climatological and biological observations in the non-karst caves in Hungary (ESZTERHÁS 2005, ESZTERHÁS-SZENTES 2004, OZORAY 1952).

2. Geographical Sketch of Hungary

Hungary is situated in the center of Europe in what is known as the Carpathian Basin (BULLA 1964, JUHÁSZ 1987). The total surface area of Hungary is 93,000 km². Its largest river, the Danube, runs through the country.

The main geographical units of Hungary: are the Great Hungarian Plain, the Little Alföld, the North Hungarian Mountains, the Transdanubian Mountains, the Transdanubian Hills and Island Mountains and the pre-Alps.

The *Great Hungarian Plain* lies at an average of 100 m a.s.l. and comprises of lowland which covers nearly the half of the country. Its surface is made up of alluvial flat and low ridges covered with sand dunes. Structurally, the lowland represents a cauldron subsidence, which has been filled up with loose sediments. The Variscan crystalline basement and the Mesozoic sequence is overlain by 1,000–3,500 m thick Pannonian and Quaternary sediments such as clay, clayey marl and sand. The *Little Alföld* is a plain in the north-western part of the country. Its landscape has been moulded as a result of the influence of the Danube River. The sunken fault-blocks of the basement are covered by Miocene limestone and 1500- 2500 m thick Pannonian limnic sediment, above which has been deposited a 20–250 m thick sandy-pebbly sediment of the primal Danube River. The *North Hungarian Mountains* are a part of the inner range of the Carpathian Mountains. The main ridge is the highest summit in Hungary, the 1,014 m high Mount Kékes. Small basins and tectonic-erosion valleys form a strongly dissected landscape. The geological history can be traced back to the Carboniferous Age. In the Triassic thick limestone layers were deposited in the Bükk and Aggteleki Mountains.vvolcanic activity occurred, which has created the Börzsöny, the Cserhát, the Mátra and the

Tokaji Mountains. The basalt plateaux and cones of the Medves-Ajnácskői Mountains were formed at the end of the Pliocene. At the end of the Tertiary the mountains underwent a peneplanation, resulting in further uplift. The *Transdanubian Mountains* are a 200 km long, 40 km wide SW-NE trending fault-block range mainly composed of Mesozoic sequences. The range includes the following Visegrádi, Budai, Pilis, Gerecse, Vértes, Velencei and Bakony Mountains, which are divided by tectonic valleys and wider basins. In the Mesozoic formations the Velencei Mountains are composed of Carboniferous granite, the Visegrádi Mountains of Miocene andesite whilst a part of the Bakony Mountains are covered by Pliocene basalt flow. The *Transdanubian Hills and Island Mountains* lie west of the Danube River. The crystalline basement and the Mesozoic sequence is overlain by Tertiary sediment several thousand metres thick. The most significant are the Pannonian formation and the extensive loess cover. From this hilly landscape rise two distinctive mountains, the *Mecsek* and the *Villányi Mountains*. Above the granite basement they are composed of Permian sandstone, Triassic and Jurassic limestone. The easternmost foothills of the Eastern Alps, the Soproni, Kőszegi and the Vas Mountains form the *pre-Alps* on the western border of Hungary. They are mainly composed of metamorphic sequences (Fig 1).

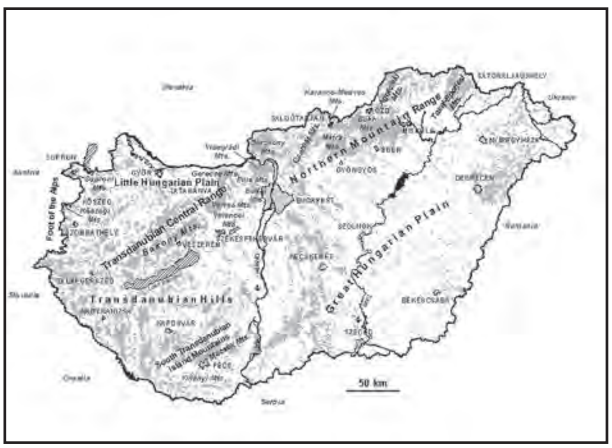

Figure 1: The main geographical units and the mountains in Hungary.

3. The Number and Location of the Non-Karst Caves

Before beginning the discussion of the non-karst caves we should mention briefly the karst caves of Hungary. Approximately 2800 karst caves are known in the karstic limestone ranges of the Bükk, Aggteleki, Bakony and the Budai Mountains. Some of them are extensive and spacious cave systems. In the Aggteleki Mountains the longest cave, the 25 km long *Baradla-Domica System,* is to be found. This runs under the border into Slovakia. In the Bükk Mountains the deepest cave in Hungary is located, the 253 m deep *István-lápai Cave.*

4. Rsearch History of the Non-Karst Caves

The first written reference to a non-karst cave, the Likas-kő near the village of Lovasberény, dates from 1295. The cave has developed in quartzite and it was mentioned in a charter as a border reference point. Thurzó György, Palatine of Hungary had visited the Pokol-lik near the village of Kapolcs in 1610. From the middle of the XVIIth century more and more descriptions and data appeared in the archives concerning non-karst caves. In 1869 the geologist József Szabó led the first scientific expedition to the Mátra Mountains in order to explore the Csörgő Hole. It was many years late in the1930's, that various researchers again investigated non-karst caves. In the 1950's and 1960's explorations revived further. Organized research began in 1983 with the launch of the Volcanspeleological Collective. Their comprehensive activity is still ongoing. The organization, led by István Eszterhás, consists of a nucleus of 15 persons, who are occasionally joined by several more cavers. They have listed many new caves and in the last 25 years they have dug and discovered nearly 1000 m of new cave passages in 43 caves. They have studied the development of the non-karstic caves, and have identified several new types of cave development, identified as the consequence caves, holes formed by alkaline solution and the fumarole cavities. They have discovered, and described, some speleothems previously unknown in Hungary, such as silica stalactites and isingerit discs. They have solved the problem of the reasons for ice development in low elevation basalt caves. They have classified 198 species of animals and 18 species of fungi (some of them are unusual) which are to be found in the caves. The results have been summarized in seven separate volumes and in 160 articles mainly in Hungarian, but occasionally in German or in English (ESZTERHÁS 2003). In 2004 the digital list of the non-karst caves in Hungary, was completed. This can be viewed on the website http://geogr.elte.hu/nonkarstic using either Netscape or Mozilla browser. The list is updated every year (ESZTERHÁS - SZENTES 2004).

5. Genotypes of the Non-Karst Caves

The development of the non-karst caves is a complex process in both space and in time. Several influences, of varying importance, prevail, related to the formation of these caves. The most important of these influences are described below (ESZTERHÁS 1993, OZORAY 1952, SZENTES 1971).

The *syngenetc cavities* formed *concurrently* with the processes of the rock formation. In Hungary only a few syngenetic cavities are known, because the youngest lava flow of the country is over one and a half million years old. Thus the cavities near to the surface, for instance the lava tubes have fallen victim to denudation. In some lava rock, steam explosion cavities can be found, for example in Explosion Cave near the village of Gödrös. In syngenetic caves in the magmatic rocks, gas bubbles occurred (Gyula Cave in the Mátra Mountains). Crystal caves, which have been opened by mine workings (e.g. Andsite Cavity of Rózsa Mine in the Börzsöny Mountains) also formed. Additionally, in magmatic rocks, holes formed by alkaline solution can be found, as well as fumarole cavities and hollows (Kámori Fox Hole in the Börzsöny Mountains). At the same time as the deposition of the calc-tufas, characteristic syngenetic caves formed (Anna Cave in the town of Miskolc).

Most of the non-karstic caves in Hungary have *postgenetic* origin. These caves were formed after the development of their surrounding rock. The formation of these caves can be divided into four major categories namely *mass movement*, *erosion (physical weathering), fragmentation (physical weathering) and chemical weathering,* representing about 25 different types of the cave development.

The caves which originated through *mass movement* were formed as a result of the shifting of the rock mass. This type of tectonic cave falls into one of four groups, which are dependent on the rock structure and the tectonic features of the region, namely: *caves which have developed perpendicular to the rim of the outcrop* such as the Fissure Cave of Mount Tátika, *caves which have formed parallel to the rim of the outcropping rock formation* such as Pokol Hole near the village of Kapolcs, *the combined fissure cave such as the* Tűzifás Cave in the Kőszegi Mountains which developed along several vertical faults and caves which have formed along the bedding plane such the Lena Cave near the village of Bozsok. *Atectonic caves* which were formed by the equalization of tension as the rock mass moved down the slope. In the talus deposits of the basalt cones, typical *extensional atectonic pseudocave* such as the „Vadlán-lik" in the Mount Kovácsi are to be found. The other type of the atectonic cave that such as the Csörgő Hole in the Mátra Mountains. The development of this cave can be traced back to the continuous sliding of the rhyodacite tuff and the consequent *aggradation.* As a natural cavity breaks down, realignment of the hollows forms a high level *collapsed labyrinth* (e.g. Basalt Cave near the village of Pula). The *consequence caves* are a particular example of caves which originated through collapse. The collapse of ceilings in artificial cavities may form apparently natural holes in the higher elevations of a system (e.g. a Szilvás-kői Cave near the town of Salgótarján). Rock drift has resulted in the formation of smaller cavities, resulting in the formation of the *leaning pseudocaves* (e.g.Asztag-kői Hole in the Mátra Mountains) and the *talus caves* (e.g. Csörgő-pataki Pseudocave near the village of Mátraszentimre).

The *erosion* (*physical weathering)* has created three different types of caves in Hungary. C*hannel erosion* has formed the Szarvas-kői-kőlyuk in Tarnalelesz village. The Görgeteges Rock Shelter near the village of Domoszló was formed by the lateral erosion. Near the town of Bátonyterenye the Macska Rock Shelter was shaped by *evorsion* in rhyodacite tuff below a waterfall. D*eflation* has not formed caves in Hungary, but the influence of deflation can be seen in several rock shelters (e.g. the Peskő Cave near the village of Tarnalelesz). A further cave developing process caused by physical weathering is *fragmentation*, which has come as a result of the influence of *temperature and moisture variation*. Examples of such caves are the cavities between basalt columns (e.g. „Sziklakonyha" near the village of Somlóvásárhely) and woolsack caves which have developed in granite (e.g. Zsivány Cave near the village of Pákozd).

C*hemical weathering* has resulted in the formation of different types of solution caves. A*cidic solution* forms cavities in the rock, which has a high lime content, such as in the Kurta-völgyi Cave near village of Velem which has formed in calcareous phyllite. In silicate rocks, *alkaline solution* is able to dissolve cavities. In siliceous conglomerate Mókus Bácsi Cave in the Mátra Mountains is an example of this type of dissolved cave development. Alkaline solution has been partly responsible for the formation of the Aranyház Hole – a small cave in geysirit - in the Tihanyi Peninsula. *Hydratation*, *hydrolysis*, *oxidation* and *biological weathering* are not decisive in the development of non-karst caves in Hungary. These effects have only minor secondary influences in cave formation (e.g. Iker-kő Cave near the village of Pákozd and the Lyukas-kő-völgyi Cave near the village of Ivád).

6. The Most Important Non-Karst Caves

Below we try to give a short introduction to some non-karst cave in Hungary. These caves are either the longest or are of particular genetic, mineralogical or archaeological importance. All of the non-karst caves can be found on the website http://geogr.elte.hu/nonkarstic.

Csörgő Hole, the longest non-karstic cave in Hungary in the Mátra Mountains. This cave has recently been extended to 428 m long and 29.6 m deep. The development of the

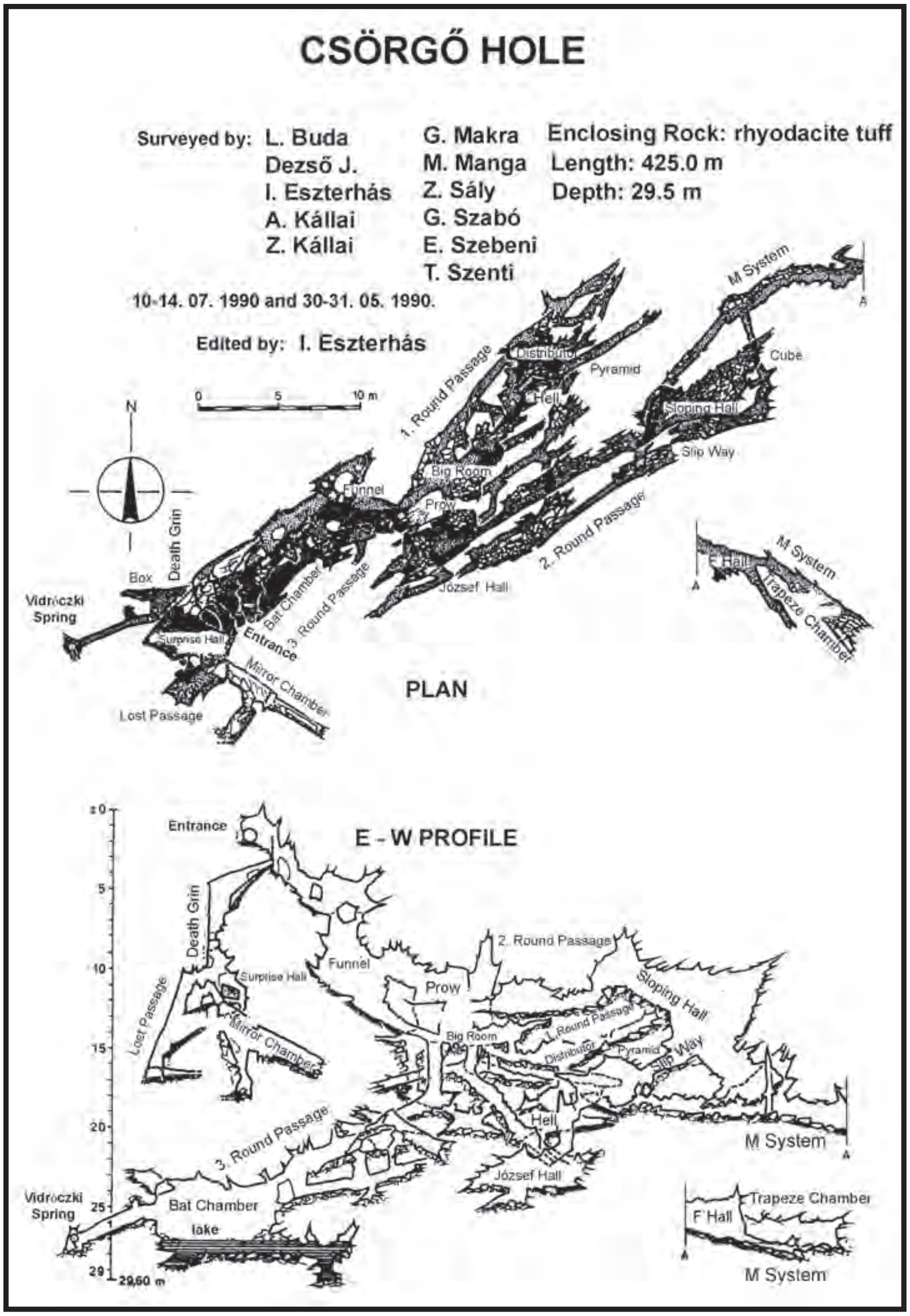

Figure 2: Survey of the Csörgő Hole, the longest non-karst cave in Hungary (Mátra Mts.).

cave can be traced back to the continuous sliding of the rhyodacite tuff boulders on a 20 ° slope and the consequent aggradation.. As a result of this, the cave is a complicated labyrinth, consisting of several chambers, passages of varying length and shafts (Fig.2., Fig. 3). At the deepest level of the cave a perennial spring emerges and in the Bat Chamber an intermittent lake can sometimes be found. In the cave 18 species of animal have been identified. In the Lost Passage large colonies of Lesser Horseshoe bats roost throughout the winter.

The *Pulai Basalt Cave* opens in the Bakony Mountains. The cave is a 151 m long and 21 m deep break down cave. The 25-30 m thick basalt is underlain by soluble limestone. Along cracks in the basalt, seeping water has dissolved holes in the limestone, into which the basalt layer has broken. The cave is accessible through a narrow shaft, which leads to a bigger chamber. From this chamber various small passages and shafts open in different directions. The cave wall shows nicely the different basalt layers, which are the witness to the several thousand years of volcanic activity. In the cave a rare silicate mineral can be found, the disc-shaped isingerit.

The 51 m long *Pokol Hole* is also to be found in the basalt of the Bakony Mountains. The basalt is overlain by a loose sandstone layer and its rim has broken away. The basalt blocks have not slid down on the slope, but leant against the bedrock, forming a leaning pseudocave. In the sandstone, thick basalt blocks dam up the seeping water, which emerges in the cave as a spring. This spring feeds a small lake. The size of the lake varies, because after the water reaches a certain level a siphon system drains it.

The 32 m long *Nagy Sárkány Ice Cave* can be found in the basalt of the Mount Szent György in the Bakony Mountains. This cave is unique in that the annual average temperature is +10 °C . The entrance is 270 m a.s.l. The cave consist of a narrow labyrinth, which has developed in the debris of the collapsed basalt columns. Ice (ice coating, icicles) can be

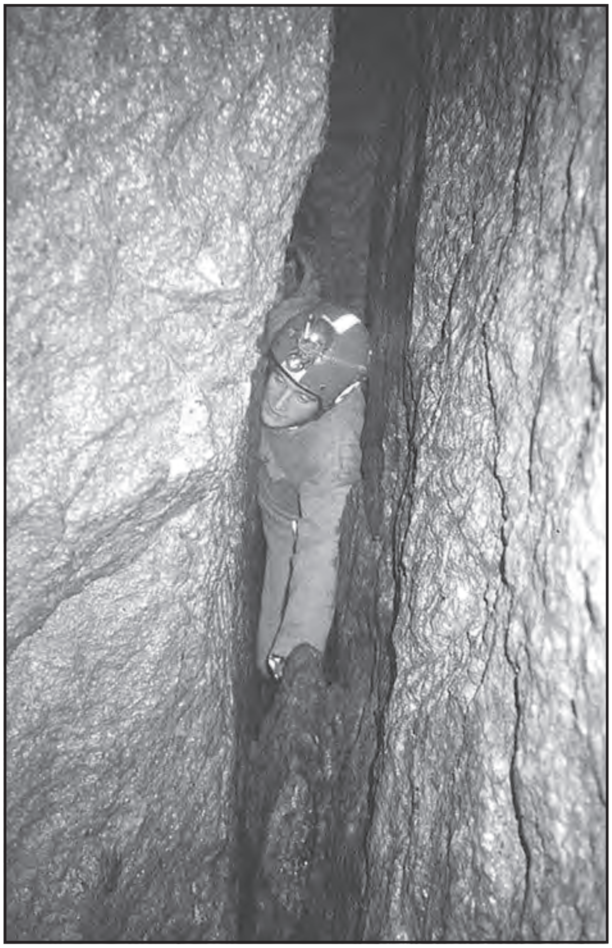

Figure 3:.A very narrow passage in the Csörgő Hole (Mátra Mts.).

observed only in summer. During this time the air flows over the stone slope outwards from the cave. Evaporation on the extensive surface of the moist basalt blocks causes so much heat extraction, that the surroundings are cooled to below the freezing point.

The *Gyula Cave* is a gas bubble cave in the andesite of the Matra Mountains. Erosion by the nearby stream opened the cave, which originally had an entrance about 7 m in diameter. Now only a quarter of the sphere shaped hole exists, the rest having been eroded away with the lower part being filled in by gravel. The excavations in the gravel found potsherds from the Bronze Age and the Middle Ages. This suggests that, the cave was a transient shelter for people in those times.

The 24 m long *Fuló-hegyi Big Cave* has developed in hydroquartzitic rhyolite tuff in the southern part of the Tokaji Mountains. The Miocene rhyolite tuff was percolated by the alkaline, silicic water of the hot springs, which silicified the tuff. In a later period, when the reaction of the water exceeded the pH 9, which has precipitated earlier, dissolved. This solution formed several cavities in the Mount Fuló region. The excavations of the infill of the Big Cave revealed many potsherd and tools from the Neolithic times to the Middle Age.

The *Szilvás-kői Cave* opens in a basalt inselberg in the Medves-Ajnácskői Mountains. The 68 m long and 15 m deep cave is a so called consequence cave. In the early 20th Century, below the basalt, a 3 m thick coal seam was mined out. In May 1917 the mine collapsed. As a consequence of this collapse the 80 m thick basalt layer downfaulted about 1 m and a 300 m long 20–25 m deep crevice developed. The basalt blocks formed part of the ceiling of this fissure system and 30 known consequence caves were created. The largest of these is the Szilvás-kői Cave (Fig. 4)

Figure 4: Large collapsed basalt boulders in the Szilváskői Cave (Medves-Ajnácskői Mts.).

The *Betyár Cave* in the Cserhát Mountains is 87 m long, and is the longest sandstone cave in Hungary. The cave was formed in calcareous sandstone as a result of different types of cave development. It is has formed along a fault line. Along the fault, the seeping water has dissolved the limy cementing material and the sand has peeled off from the loose rock surface and accumulated in the lower level of the distended fissure. This iterative process has resulted in a gradually widening fissure cave filled with loose sand. Excavations in this sand have revealed a large number of Pleistocene mammal bones and potsherds dating from the Middle Ages to modern times.

The 50 m long *Arany Cave* opens in the Tokaji Mountains in rhyolite tuff. The way in which this partly collapsed horizontal cave has developed is complex. Originally it was formed along a fissure by an underground stream. The natural passage was widened in the 17th century for an ore prospecting mining tunnel. Later, the first part of the tunnel was collapsed and was subsequently dug out again in 1993. In the cave there is a slow running knee deep stream. The roof is nicely decorated with a large number of 20–40 cm long silicate stalactites. The *Mókus Bácsi Cave* can be found in the Köszörű Valley in the Mátra Mountains. This 14 m long, tubular shaped cave was formed in siliceous conglomerate by the alkaline solution. The alkaline solutions originated from the geysers, which were active above the cavities long ago.

7. Mineralogical, Climatological, Biological and Archaeological Observations

Generally, the non-karst caves in Hungary are poor in *mineral content*, but in some caves various mineral formations occur. (ESZTERHÁS 2003). Calcite speleothems can be found in those caves, which are covered or surrounded by calcareous rock formation (e.g. Remete Cave near the village of Zalaszántó, Explosion Cave near the village of Gödrös). More common are the siliceous speleothems. Large quartz, amethyst and celestine crystals are to be found in those caves, which were opened by deep ore mine operations. The roof of the Arany Cave near the village of Tállya is nicely decorated with a large number of 20–40 cm long silicate stalactites. Thermal water has resulted in albite, anorthite and kaolinite covering the walls in the Felső Cave near the town of Sárospatak and in the Baglyas Hole in the town of Salgótarján. Siliceous pisolites are fairly common (e.g. Galérias Cave near the village of Háromhuta and the Smirgli Cave near the village of Regéc). However, the large number of isingerite disks on the wall of the Basalt Cave near the village of Pula are a rarity.

The *climatic conditions* in the relatively small non-karst caves in Hungary do not show significant deviation from the surface climate. The exceptions are those caves, which have developed in porous or detritic rock formations. Here the evaporation on the large rock surface causes such significant a heat extraction, that the surroundings are cooled below freezing point. Five small ice caves are known in Hungary. Each of these caves have developed in detritic volcanic rocks which open at a low elevations (270–625 m) (ESZTERHÁS 1999-a).

One hundred ninety-eight species of *animals* and 18 species of *fungi* which were classified, which are to be found in the non-karst caves. The fauna and the flora do not show significant differences from those found in karst-caves, although variations in proportions found can be observed. For instance the proportions of the penicillin flora and the lepidoptera fauna are higher than in the karst-caves. In almost every caves springtails (*Collembola)* occur, as do rove beetles (*Staphylinidae),* humpbacked flies (*Phoridae*), spiders (*Araneidae*) and b**utterflies and moths** (*Lepidoptera*). Furthermore some unique species were identified, such as for instant the *Niphargus hungaricus*, the *Holoscotolemon jaquet*, and the *Orobainosoma hungaricum* (ESZTERHÁS 2003).

The *palaeontological* findings in the non-karst caves are poorer than in the karst-caves, due to the lack of the lime to preserve them. The most ancient finds were rodents (*Cricetus cricetus major, Ochotona pusilla*) from the Riss-Würm interglacial period from the Seybold Cave near the town of Kőszeg. The most spectacular find was a cave bear (*Ursus spelaeus*) skeleton, from the Würm period in the Betyár Cave near the shrine of Szentkút. *Archaeological* remains occurred in 20 non-karst caves. The oldest findings, Neolithic potsherds and lithic tools (flint obsidian), were excavated from the Nagy Cave near the village of Legyesbénye. The finds from the metal ages, from the ancient times and from the Middle Ages occur in many caves all over the country. Many artefacts and documentation prove that, the non-karst caves and artificial cavities were used for dwellings, resting-places, sanctuaies as economic or military objects (ESZTERHÁS 1999-b, 2003).

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FROM THE PLAINS OF ABRAHAM TO DODO CANYON: REMARKABLE DOLOMITE KARST IN PERMAFROST IN THE MACKENZIE MOUNTAINS, NORTHWEST TERRITORIES, CANADA.

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Abstract

Along a west-to-east transect across the Canyon Ranges at Lat. 66º N in the Mackenzie Mountains (Northwest Territories, Canada) there is a remarkable variety of karst landforms. The host rocks are Upper Proterozoic - Devonian in age, consisting of two thick-to-massive platformal dolomite formations with salt and redbeds below and a dolomite-gypsum megabreccia above. Only the most easterly sector of the transect experienced any glacierisation (Laurentide Continental Icesheet), conditions in the mountainous interior being too arid. Modern ecoclimatic conditions range from polar desert at >1500 m above sea level in the west to taiga-boreal ecozone transitional at ~300 m asl in the east. Technically there is “continuous permafrost” >50 m deep along the transect but groundwater recharge is common wherever the geohydrologic conditions are favorable. Despite the cold and aridity, and the low solubility generally associated with dolomite in comparison with limestone, etc. karst groundwater circulation and landform development are widespread along the transect, including extensive solutional pavements, steephead valleys and cirques (*reculées*), dolines, dry canyons, a large structural polje, fresh and salt springs, and a fantastical “dissolution drape” topography on the breccia. Protection of a representative corridor along the transect is proposed under the aegis of of the new UNESCO “International Geopark” program.

NEW RESEARCH IN THE SOUTH NAHANNI KARST, MACKENZIE MOUNTAINS, NORTHWEST TERRITORIES, CANADA

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Abstract

Karst developed in platformal limestones and dolomites of Devonian age in the Mackenzie Mountains appears to include some of the most rugged and distinctive topography known in any arctic or sub-arctic region. The karst straddles the basins of the South Nahanni and Ram rivers, centered at 61º–61º 45' N and 124–125º W. Elevations range from 300 m asl at the lowest springs (in a great antecedent canyon on the South Nahanni River) to 1800 m asl on sharply dissected plateaus to the NW. Mean annual temperatures range from -5 to -11º C or colder; permafrost is discontinuous at the lower elevations, becoming generally continuous above ~1000 m asl.

Ancient karst is preserved at all elevations above 600 m asl in both limestone and dolomite. U series measurements of speleothems in relict caves in the 1970s established that most is greater or much greater than 350 ka in age. However, a proglacial lake dam burst of probable mid-Wisconsinan (Wűrm) age has modified landforms in a central corridor into a composite of scablands and karst, with giant bogaz, shafts and solution dolines, plus three small but beautiful poljes.

Investigations were renewed in the summer of 2006 as part of a program to extend the area of the existing South Nahanni National Park Reserve. Using a helicopter it was possible to survey the highest and most remote karst in terrain that escaped any cover by flowing glaciers because of its aridity under full glacial climatic conditions. The karst consists of plateau remnants that have been much reduced in extent by cliff recession consequent upon canyon incision over deep permafrost. Nevertheless, there are many expanses of limestone pavement and some larger (>50 m diameter) dolines with subterranean drainage via taliks. The remnants convert into castellated tor topography where they become very narrow. Felsenmeer prevail on the less soluble dolomite plateaus but the more extensive remnants of them contain solution dolines that appear to be active.

Several new karst springs with melt season discharges ≤10 $m^3 s^{-1}$ were discovered. Dye traces of sinking streams determined that there was conduit groundwater flow through dolomites to the major springs at mean velocities >4000 $m d^{-1}$, indicating that fully mature karst aquifers can be established and maintained in these adverse climatic conditions.

DNA ANALYSIS OF FECAL BACTERIA TO AUGMENT AN EPIKARST DYE TRACE STUDY AT CRUMPS CAVE, KENTUCKY, USA

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A rainfall simulation experiment was performed to investigate the transport behavior of fecal-derived bacteria through shallow karst soils and through the epikarst. The experiment was conducted at Cave Springs Cavern located south of Mammoth Cave National Park on the Sinkhole Plain of south central Kentucky. Using a rainfall simulator, water containing 514 ppm sulforhodamine B was applied at a rate of 6.6 cm/hr for 4 hrs to 150 kg cow manure spread over a 7.5 m^2 plot on the surface. Water was then sampled from a waterfall within the cave predetermined to be hydrologically connected to the surface area where the manure was applied. Fecal and *E. coli* MPN numbers were determined by standard culturing procedures and total DNA was extracted from each sample by direct lysis measured by fluorometry. DNA was further analyzed by quantitative Real-Time PCR (qRT-PCR) with specific primers to specifically amplify and quantify *Bacteroides* DNA (fecal-specific bacteria) and Eubacterial DNA (all bacteria) in the samples. Both methods show a bimodal distribution of fecal bacteria as it infiltrated through the soil and epikarst. Fecal bacteria and DNA levels peaked in samples collected approximately 90 min. ahead of the tracer dye followed by a second peak of fecal bacteria and DNA which roughly corresponded to the dye peak. DNA analysis also revealed that a surge of non-fecal bacteria was carried along just ahead of the dye front. These data suggest that a mobile population of non-fecal bacteria in the soil was carried along with the rain event, and that the fecal bacteria followed two routes of transport through the soil and epikarst; some fecal bacteria applied to the surface reached the waterfall quickly by way of preferential flow paths through the soil while other fecal bacteria infiltrated through the soil matrix along with the dye front.

1. Introduction

Karst aquifers are extremely vulnerable to microbial contamination due to thin soils, groundwater velocities that can exceed 200 meters per hour, and direct communication of groundwater with surface water. Microbial contamination of karst groundwater in agricultural areas from manure application is widespread and often severe (Boyer and Pasquarell, 1999; Ryan and Meiman, 1996). An important component of many karst flow systems is the epikarst region. Epikarst is a specialized vadose zone with high capacity for storage and transport. Standard models of epikarst structure depict a soil horizon several meters deep with high CO_2 concentrations due to microbial activity. The surface zone is influenced by agricultural activities, acidic rainfall, wind, and weather. The lower zone is rich in dissolved CO_2 causing large fractures to form at the bedrock interface resulting in aquifer recharge through fissures, often emerging as shafts in underlying cave systems (Bauer et al., 2005; Trček, 2007; Pronk et al., 2008). Because epikarst flow is concentrated into preferential flow paths to form a porous conduit network, water and contaminants can be rapidly transported downward through the active conduit network and into cave systems during storm events (Boyer et al., 2003; Groves et al., 2005; Pronk et al., 2008). Evaluating the impacts of epikarst flow and storage is critical for understanding the fate and transport of pathogens and indicator organisms through karst aquifers.

Use of microorganisms as tracers has a long history that has become more sophisticated as our ability to detect, quantify, and discriminate them has advanced. As far back as the 1800's bacteria that produce red or yellow pigments were utilized, and later bacteriophages and inoculations of known bacteria were analyzed with classical micrbiological techniques. Today, culturing techniques for fecal coliforms and *E. coli* that use colorimetric and fluorescent substrates to distinguish bacteria according to biochemical pathways are the standard techniques used to monitor presumptive fecal contamination and migration of pathogens in groundwater and for testing the purity of municipal drinking water (Harveya, 2006; Göppert and Goldscheider, 2007). Recent studies of bacterial transport through epikarst at karst springs according to particle size distributions substituted fluorescent microspheres representing pathogens the size of bacteria (1 µm) and *Cryptosporidium* (5 µm) to simulate transport and recoveries of bacterial cells (Pronk et al., 2007; Pronk et al., 2008). Modern techniques employing DNA analysis of bacteria with the polymerase chain reaction

(PCR) have been used to demonstrate fluctuations in epikarst microbial community composition in response to storm events with PCR followed by denaturing gradient gel electrophoresis and DNA sequencing (Pronk et al., 2009).

The purpose of this study was to demonstrate the practical application of rapid and quantitative DNA analysis using quantitative Real-Time PCR (qRT-PCR) in parallel with conventional dye trace data to better understand transport of fecal bacteria and other constituents of cow manure through the epikarst. As part of the dye trace study reported in this volume by Ham et al., aliquots of the water discharged into the cave were assayed for total DNA concentration as well as specific bacterial DNA sequences using a quantitative and discriminatory assays for specific bacterial genes. Microbial source tracking studies have established that fecal bacteria of the genus *Bacteroides* are favored for fecal DNA analysis because they are the most abundant bacteria in the intestines of mammals. Another advantage is that different species and strains of *Bacteroides* tend to be associated with particular hosts therefore DNA analysis of *Bacteroides* can be used to identify the source from which the fecal contamination originated (Bernhard and Field, 2000; Field, 2002; Dick et al., 2005; Layton et al., 2006). *Bacteroides* are anaerobic and difficult to culture in the lab, while fecal coliforms and *E. coli* are very easy to culture in the laboratory. Although fecal coliforms and *E. coli* have been used as indicators of possible fecal contamination for over 100 years, the presence of *Bacteroides* in water is unequivocal evidence of fecal contamination. At temperatures typical of natural waters, *Bacteroides* persists in streams for four to five days (Field, 2002).

In our study, DNA sequences from fecal-specific bacteria (*Bacteroides*) correlate with conventional assays for fecal contamination plus they reveal additional information about epikarst bacterial transport: DNA analysis of Eubacteria in general suggests that a large component of non-fecal bacteria, probably resident in epikarst soil storage, was mobilized and discharged into the cave during the simulated storm event. Rapid parallel DNA analysis can augment the information retrieved during a conventional dye trace and contribute to a deeper understanding of epikarst bacterial transport.

2. Experimental Procedures

2.1 Study Site

Crumps Cave, A.K.A. Cave Spring Caverns, has been used as a field site for research and education by Western Kentucky University (WKU) and the Hoffman Environmental Research Institute (HERI) to generate a large body of data including hydrological maps and chemical parameters during storm events (Groves et al., 2005). The cave contains 2 km of large horizontal passage lying 25 m beneath mostly agricultural land with three percolation waterfalls 5 - 8 m in height numbered 1, 2, and 3 on the east side of a 160 m section of passage. Waterfall 1 is in a recessed dome 40 m from the entrance equipped with data loggers, a tipping bucket, and two ISCO fraction collectors. Sample collection bottles and caps were rinsed with 70% isopropanol and dried before transport and installation to minimize bacterial contamination. Samples were packed in ice while in the ISCO units and transferred on ice to WATERS Laboratory for analysis within 24 hours after collection. Samples returned to the lab in these bottles were subdivided for chemical and biological analyze related to the dye trace. On the surface a small plot that was hydrologically mapped to Waterfall 1 was mowed and fitted with a soil data logger and three lysimeters. At the time of the experiment , land use around the plot was residential and immediately down slope from agricultural wheat production. Before application of manure to the surface, samples were taken every 30 min for 24 hrs during passive discharge at Waterfall 1 to establish background conditions.

2.2 Simulated storm event sample collection

At the beginning of the experiment 150 kg of dairy cow manure was spread evenly over the 7.5 m^2 site. A rainfall simulator consisting of an enclosed shower approximately 3 m tall by 2.5 m long by 3 m wide was placed over the plot. Previous comparisons of sulforhodamine B (SRB) with Fluorescein and Tinopal showed that SRB did not interfere with colorimetric or fluorescent analysis. Water containing 514 ppm SRB was pumped at a constant rate of 6.6 cm/hr for 4 hrs (2000 L total volume). Cave samples were delivered from Waterfall 1 to ISCO fraction collectors using a flushing bucket, and fractions were collected at 15-minute intervals starting from the beginning of the simulated rainfall (t = 0). Background data was collected for 24 hours prior to the start of the experiment.

2.3 Quantification of fecal coliforms and *E. coli*

Fecal coliforms and *E. coli* were measured with the Colilert method using Quantitrays (IDEXX Corporation, Rockport, ME) to determine the most probable numbers (MPN) of viable cells per 100 ml (equivalent to cfu/100 ml). Trays were incubated at 44.5° C in order to inhibit total coliforms and limit growth to fecal coliforms and *E. coli*. Tenfold dilutions were simultaneously analyzed when higher concentrations were expected.

2.4 DNA extractions by direct lysis

ISCO fractions of 250 ml were centrifuged at 3000 x g for 10 min. to sediment all particulate matter including bacterial cells (Murray and Hampton, 1980). Supernatants were decanted and the pellets were resuspended in 30 ml (3 x 10 ml rinses) of 10 mM Tris-HCl, 1 mM EDTA pH 8.0 (TE buffer) and transferred to 50 ml conical centrifuge tubes. Suspensions were centrifuged to recover particulate material and resuspended in 1.5 ml (3 x 0.5 ml rinses) of 0.1x TE buffer and transferred to microcentrifuge tubes with volumetric graduations. Those suspensions were centrifuged at 10,000 x g for 5 min. and the final volumes of the compacted pellets were noted after decantation of the supernatant. Pellets were resuspended in 10 volumes (minimum 100 µL) LyseN'Go direct lysis solution (Pierce) and processed according to the manufacturer's protocol to lyse cells and release a complex mixture of lysates containing environmental DNA. These lysates were used to measure total DNA concentrations and for PCR amplifications.

2.5 Measurement of total DNA concentrations

Aliquots (10-20 uL) of lysates were assayed with the Qubit fluorimetric DNA quantification platform (Molecular Probes Division, Invitrogen Corporation, Eugene, Oregon) according to the manufacturer's protocol. The Qubit assay uses a selective DNA fluorescent dye to quantify double stranded DNA with high sensitivity and specificity even in complex mixtures (http://probes.invitrogen.com/media/pis/mp32851.pdf). Total DNA concentrations represent the bulk DNA from all cellular debris eluted through the epikarst, including fecal material applied to the surface as well as soil and interstitial organisms mobilized by the applied hydraulic gradient.

2.6 Quantitative Real-Time PCR (qRT-PCR) analysis

A Bio-Rad iCycler system was used to carry out thermocycling while monitoring SYBR Green fluorescence at 490 nm to measure the increase in fluorescence in proportion to a logarithmic increase in the concentration of specific double stranded fragments of *Bacteroides* 16S SSU-DNA (Malinen, et al., 2003; Ponchel et al., 2003). Fecal-specific *Bacteroides* 16S SSU-DNA was amplified from lysates with primers Bac-32F and Bac-708R as described by Bernhard and Field (2000). Similar conditions were used to amplify Eubacterial 16S SSU-DNA with universal Eubacterial primers 27F and 1492R (Fowler et al., 2003). Finished qRT-PCR products were characterized by melting point analysis and agarose gel electrophoresis. Standard curves were for quantification of *Bacteroides* or Eubacterial 16S SSU-DNA were generated with p-GEM plasmids carrying a copy of the homologous fragment from *B. thetaiotaomicron* or Eubacterial cave clone BCTP21 (Acidobacteria), respectively (both plasmids were constructed in this laboratory and confirmed by DNA sequencing). Threshold fluorescence was set at 100 relative fluorescent units (RFU) above background, and the number of cycles required to reach 100 RFU (threshold cycle, C_t) was plotted against the log of the starting quantity (SQ) of DNA added to the PCR reaction. This relationship allowed calculation of the concentration of a specific sequence of 16S SSU-DNA (*Bacteroides*, Eubacteria) expressed as the number of 16S SSU-DNA gene copies (DNA molecules) per L of original sample.

2.7 Melting point analysis

A cycle was added to the qRT-PCR thermocycling protocol to measure the disassociation temperature, or melting point, of the double stranded DNA fragments ~700 bp in length generated during q-RT-PCR. Temperature was increased from 65° C to 95° C in 0.1° C increments while emission at 490 nm was averaged over 10 sec. at each temperature.

3. Results and Discussion

A period of roughly two hours elapsed between the start of the simulated rainfall and the visible presence of SRB in the waterfall. The dye concentration increased over a period of two hours to a maximum in the 4.0 hr sample and steadily decreased over the following two hours to SRB concentrations comparable to those at the dye breakthrough. Monitoring of Waterfall 1 for fecal coliforms, *E. coli*, and physicochemical parameters continued for two weeks (Ham et al., this volume). The SRB curve represents the behavior of solutes in the infiltrated water as the rain event displaced epikarst storage water.

Fecal coliforms (Fig. 1A) and *E. coli* (Fig. 1B) were quantified using Idexx Colilert assays. Both graphs show two peaks in bacterial concentration representing two separate transport routes through the epikarst. A large proportion of the bacterial contamination on the surface was discharged at Waterfall 1 ahead of the infiltrated water (2.25–5.0 hrs, filled arrows) while another large increase in fecal bacterial contamination was discharged along with the SRB (3.75–4.0 hrs, open arrows). Lower concentrations of fecal contamination were observed as the SRB concentration decreased.

For extraction of total DNA, fractions collected from Waterfall 1were centrifuged at 3000 x g for 10 min, sufficient to precipitate suspended material including bacteria and other colloids (Murray and Hampton, 1980).

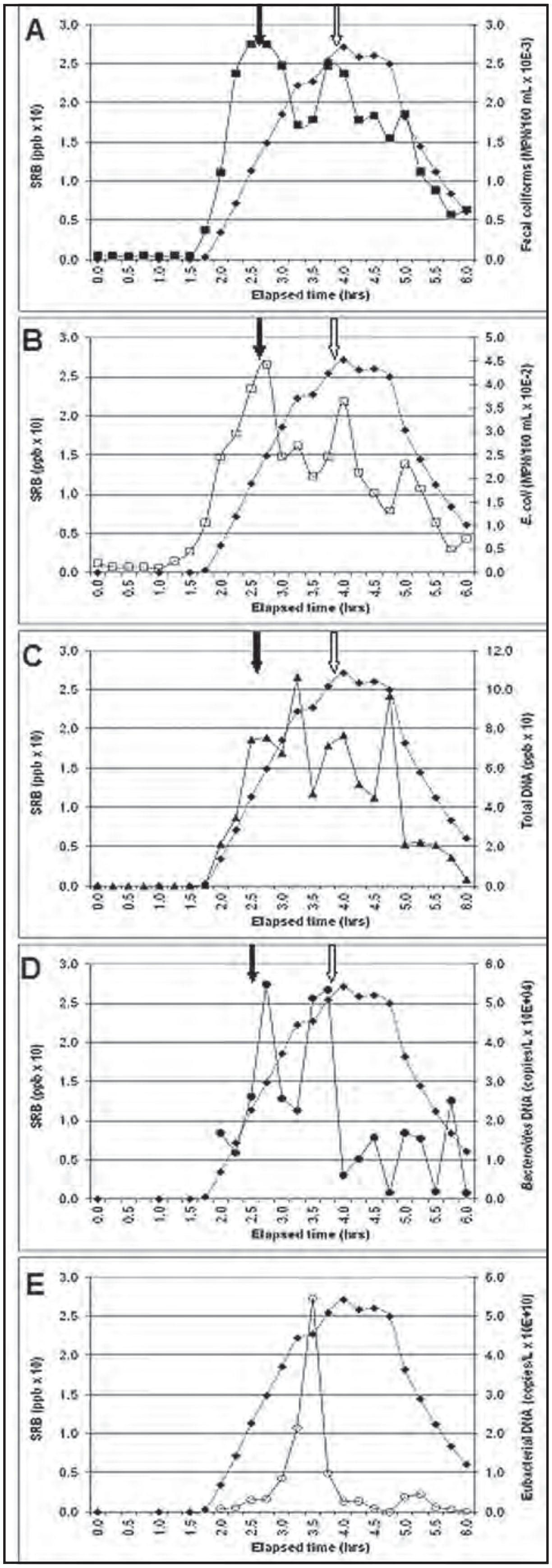

Figure 1. Graphs showing concentrations of fecal coliforms, E. coli, total DNA, Bacteroides DNA, and Eubacterial DNA in 15 min fractions taken over a six-hour period during simulated storm conditions inside Crump Cave at Waterfall 1.

Simulated rainfall containing 514 ppm sulforhodamine B (SRB) dye was applied at a rate of 6.6 cm/hr for 4 hrs to 150 kg cow manure spread over a 7.5 m2 plot on the surface above Crump Cave. SRB dye was visible in Waterfall 1 fractions beginning two hours after the start of the experiment.

All methods agree that during storm conditions, surface application of cow manure results in rapid transport of fecal contamination to karst aquifers through two transport routes resulting in appearance of bacteria before (filled arrows) and during (open arrows) emergence of the tracer dye. DNA analysis also suggests that a large displacement of non-fecal soil bacteria accompanies the storm event. SRB (♦) is shown on each graph for reference.

***A. Fecal coliform concentrations*(■)** *measured using the Idexx Colilert assay show an early peak (2.25-–2.50 hrs) followed by a later peak (3.75-–4.0 hrs). A later peak of fecal coliforms (5.0 hrs) was also seen.*

B. E. coli concentrations *(□) measured using the Idexx Colilert assay show an early peak (2.25–2.5 hrs) followed by a later peak (3.75 hrs). A later peak of E. coli (5.0 hrs) was also seen.*

C. Total DNA concentrations *(▲) measured by the Qubit fluorimetric DNA assay show two early peaks (2.25-2.5 hrs, 3.25 hrs) followed by two later peaks (3.75–4.0 hrs, 4.75 hrs). The higher peaks in DNA concentration late in each phase (3.25 hrs, 4.75 hrs) do not correlate with any of the bacterial data. Those peaks presumably represent DNA contributed by other biological constituents of manure.*

D. Bacteroides 16S SSU-DNA concentrations *(●) measured by qRT-PCR show an early peak (2.75 hrs) followed by a later peak (3.75 hrs). Later peaks in Bacteroides DNA concentration (4.5, 5.0, and 5.75 hrs) were also seen.*

E. Eubacterial 16S SSU-DNA concentrations *(○) measured by qRT-PCR show an intense peak (3.5 hrs) early during the peak concentrations of SRB. This assay quantifies any kind of bacterial 16S-SSU-DNA from fecal material as well as soil and epikarst storage water. Due to the large magnitude of the Eubacterial peak (3.5 hrs) and the fact that it does not correlate with the other indicators of fecal bacteria, we hypothesize that the peak represents mobilized indigenous soil bacteria displaced from storage in the epikarst zone by the simulated rain event.*

Total environmental DNA from all particles suspended in the fractions (manure, soil organisms, colloids, sediments) was extracted from the precipitated material by a direct lysis procedure and quantified by a sensitive fluorimetric assay for double stranded DNA. Similar to the results using standard culture assays, peak concentrations of total DNA (Figure 1C) were discharged ahead of the infiltrated water (2.25–2.5 hrs, 3.25 hrs; filled arrows) and later concurrently with the SRB (3.75–4.0 hrs, 4.75 hrs; open arrows). The total DNA peaks at 3.25 hrs and 4.75 hrs do not correlate with any of the other four bacterial indicators plotted in Figure 1. These results indicate that manure contaminants containing DNA in the fractions taken at 3.25 and 4.75 hrs also show two peaks representing two routes of transport. Manure constituents contributing this DNA discharge later than fecal bacteria thus they are inhibited during transport relative colloidal particles the size of bacteria (~1 μm).

Aliquots of DNA lysates were used as templates in qRT-PCR reactions with primers specific for bacterial targets of interest in order to quantify the contribution of the target organism(s) to the total DNA. The concentration of fecal-specific target DNA is expressed as the number of *Bacteroides* 16S-SSU-DNA gene copies per liter. *Bacteroides* 16S SSU-DNA concentrations measured by qRT-PCR (Figure 1D) show an early peak (2.75 hrs) followed by a later peak (3.75 hrs). Later peaks in *Bacteroides* DNA concentration (4.5, 5.0, and 5.75 hrs) were also seen, in agreement with the fecal coliform and *E. coli* Colilert assays above (Figures 1A, 1B). Note the highest numbers of *Bacteroides* are in the range of 10^4 copies per liter.

DNA lysates were analyzed in another qRT-PCR reaction using universal primers known to amplify 16S SSU-DNA from Eubacteria (the subkingdom of true bacteria, excluding subkingdom Archaebacteria) to estimate the number of all bacterial cells in each fraction, represented by the number of Eubacterial 16S SSU-DNA genes per liter (Figure 1E). Eubacterial 16S SSU-DNA concentrations measured by qRT-PCR show an intense peak (3.5 hrs) early during the maximum concentrations of SRB and represent any kind of bacterial 16S SSU-DNA from fecal material as well as soil and epikarst storage water. Note the highest numbers of Eubacteria are in the range of 10^{10} copies per liter. Due to the large magnitude of the Eubacterial peak (3.5 hrs) and the fact that it does not correlate with the other indicators of fecal bacteria, we hypothesize that the peak represents mobilized indigenous soil bacteria displaced from storage in the epikarst zone by the simulated storm event. The dye trace will be repeated without the application of manure to test this hypothesis.

4. Conclusions

A rapid DNA analysis technique was used to quantify specific bacteria in up to 72 samples simultaneously. DNA data agree with traditional culturing techniques for monitoring fecal coliforms and *E. coli*. Collecting DNA data as part of a dye trace reveals information about bacterial transport that otherwise would not be apparent. Samples with peak concentrations may be analyzed in detail after qRT-PCR to reveal detailed information by cloning and sequencing or other molecular techniques if warranted.

The bimodal behavior of bacterial transport from the surface during high flow conditions suggests that a large proportion of fecal bacteria are transported rapidly through larger fissures and fractures due to size exclusion processes. These bacterial cells interact very little with soil particles or other materials lining the porous network in the epikarst soil and become mixed with water stored in large fissures below the soil horizon. Other fecal bacteria are transported through the epikarst along with the infiltrated water marked by SRB. These cells could be retained in the porous network through interactions between the cells and soil constituents through electrostatic forces or structural features lining the pores. In addition to the fecal bacteria applied to the soil surface, high flow conditions elute a large number of nonspecific bacterial cells as a single peak along with the dye front. These cells do not enter the fast transport route thus suggesting they were resident in the epikarst soil prior to the high flow event. Furthermore the quantitative signal is six orders of magnitude greater than that produced by *Bacteroides* suggesting the infiltrated water mobilized those bacterial cells from storage in the large mass of epikarst soil between the surface and the bedrock interface. Soil is known to harbor a dense and complex population of bacteria responsible for nitrogen fixation, bioremediation, and other processes important to agriculture.

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DATING A BIBLICAL LADY: AN UNROOFED SALT CAVE GIVES BIRTH TO LOT'S WIFE

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Trying to explain the origin of peculiar geological features has led ancient societies to develop narratives of mythical transformations. Dating geological features supposed to be related to ancient narratives has been virtually impossible until now, because of either the lack of identified, dateable field evidence, or the doubted historicity of the narrative. For at least two thousand years historians and travellers attributed a relict salt pillar in the Dead Sea area to the biblical myth of Lot's Wife, who "became a pillar of salt" (Genesis 19:26). The formation of the salt pillar and associated cave is analysed and radiocarbon dated, complemented by measurement of its rising rate. Contrary to earlier assumptions that the salt pillar was formed by direct rainfall, the current results attribute the salt pillar to the remains of a wall of a karstic salt cave that collapsed during the period commonly proposed for the Sodom and Gomorrah upheaval. The new evidences suggest that the myth of Lot's Wife was originally based on one of the earliest geological observations: The sudden appearance of a salt pillar following a catastrophic earthquake which unroofed the cave. The continuous observation of the pillar by travellers must have been coupled with the formulation of the myth which was later documented in the book of Genesis. This is the first field evidence for the origin of such an ancient biblical narrative.

1. Geologic Setting

Mt. Sedom is the exposed top of an actively rising salt diapir (ZAK, 1967) at the southwestern shore of the Dead Sea (Fig. 1). Mt. Sedom comprises vertical layers of latest Miocene to Pliocene(?) salt, covered unconformably by residual caprock, composed mainly of anhydrite. The diapir has been rising throughout the Quaternary along its marginal faults (WEINBERGER et al., 2006). Measured mean rising rate for the diapir has been 6–7 mm/yr during the Holocene, and 6.9±0.3 mm/yr for southern Mt. Sedom during the previous decade (PE'ERI et al., 2004; WEINBERGER et al., 2006). This indicates that the present rising rate has persisted for at least thousands of years. The rising is driven by tectonics and buoyancy of low density salt, cutting through the overburden of denser sediments (ZAK, 1967).

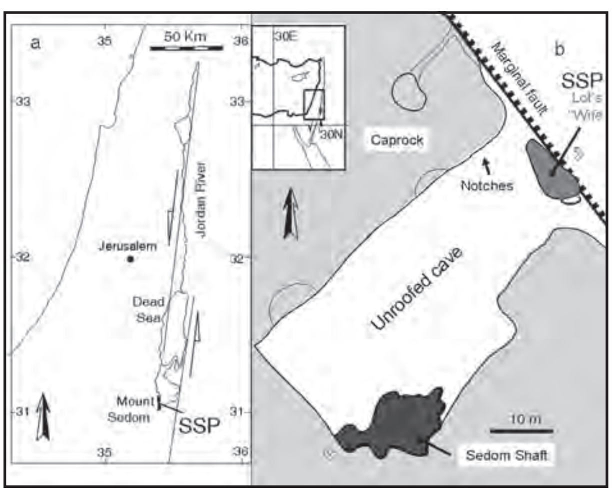


Figure 1: (a) Location of Mt. Sedom salt diapir; (b) Plan of the study site, showing SSP as a relict between the unroofed cave and the marginal fault. Figure 3 section line is marked.

During the Holocene, salt dissolution has been concentrated mainly where ephemeral streams carrying runoff water sink into the extremely soluble salt (FRUMKIN, 2000), forming (ephemeral) river caves. These underground voids usually comprise (1) vertical shafts close to the stream-sink; (2) active sub-horizontal channels, often discharging at the foot of the marginal escarpment (Fig. 2); and (3) high, dry cave passages hanging above the active channel (Fig. 3). The oldest, uppermost cave level relates to the initial exposure of salt above base level. As the diapir rises, caves are downcutting, adjusting rapidly to base level changes (FRUMKIN AND FORD, 1995). Subhorizontal dissolution notches are common features in Mt. Sedom caves, formed where flowing aggressive water dissolves the salt wall (in addition to precisely horizontal notches formed by standing water). Low-gradient cave passages accumulate alluvium and some dateable plant remains, derived from the surface of Mount Sedom.

2. Biblical Events

Several geologic events, some associated with caves, are described or alluded to in the Bible (BENTOR, 1989). One of the earliest, the biblical story of Sodom and Gomorrah,

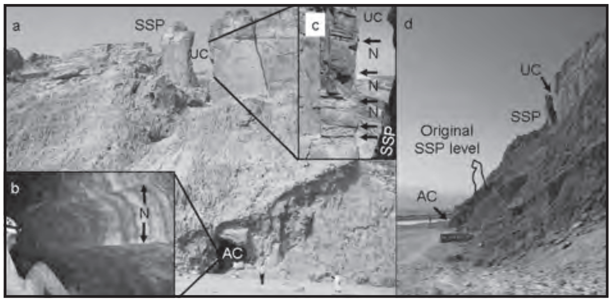


Figure 2: (a) View of thestudy area from the east with the active outlet (AC) of Sedom Cave at the foot of Mt. Sedom below SSP and the upper cave (UC). Note people right of the cave entrance for scale; (b) a notche in salt wall of the active Sedom Cave; (c) paleo-nothches (N) in the salt wall of the unroofed upper cave. SSP is in the right; (d) SSP and its eastern wall—a marginal fault, as seen from the north, with SSP resembling a human statue. The original level of SSP, 4000 yr ago is indicated to emphasize the rising of Mt. Sedom. No horizontal movement is implied.

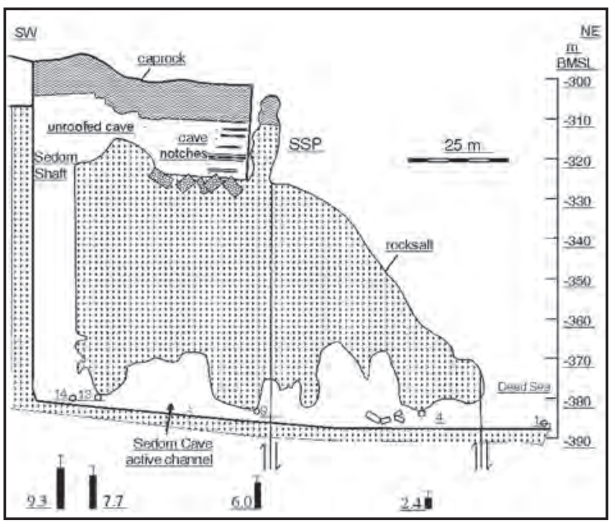


Figure 3: Vertical section of the study site. The notches to the left of SSP correspond to the remains of the unroofed paleo-cave whose upstream uncollapsed northern branch was radiocarbon dated using deposited wood remains (Figure 5). Ephemeral runoff enters the cave today through the Sedom Shaft flowing along the active channel to the Dead Sea base level. Leveling benchmarks and their numbers are shown in the active channel of Sedom Cave. Their measured rising rates (in mm/yr, relative to benchmark 1, are shown at the bottom, presented also by black bars. Blocks of rock, detached from the cave roof (shown schematically), litter both the active and unroofed levels of the cave. Altitude is given in m below Mediterranean Sea level.

is argued by geologists to reflect a natural calamity that took place in early historical times (BEN-MENAHEM, 1991; BENTOR, 1989; BLANCKENHORN, 1898; BLOCK, 1975; HARRIS AND BEARDOW, 1995; ISSAR, 1990; NEEV AND EMERY, 1995; TRIFONOV, 2007). However, no clearly dated geologic evidence has been presented.

Within the general framework of the Sodom and Gomorrah narrative, the myth that Lot's wife "became a pillar of salt" is unique in several ways: (1) it is a very early description of both the morphology and lithology of a geologic feature (a pillar composed of salt); (2) if such a feature really exists, it can be located geographically, because the scene must be at the vicinity of the Dead Sea, and there is only one salt outcrop in the Dead Sea region, namely Mt. Sedom salt diapir. Mt. Sedom (Hebrew name), preserving the biblical name Sodom (Greek - Sodoma; Arabic - Usdum) is known near the Dead Sea at least since the 2nd century CE (e.g. Claudius Galenus, quoted and translated by REINACH (1895)). (3) Within the southeastern face of Mt. Sedom, a distinct salt pillar (termed here Sedom Salt Pillar – SSP, Figs. 1-4) resembling a human statue in profile (Fig. 2d), has traditionally been called "Lot's Wife".

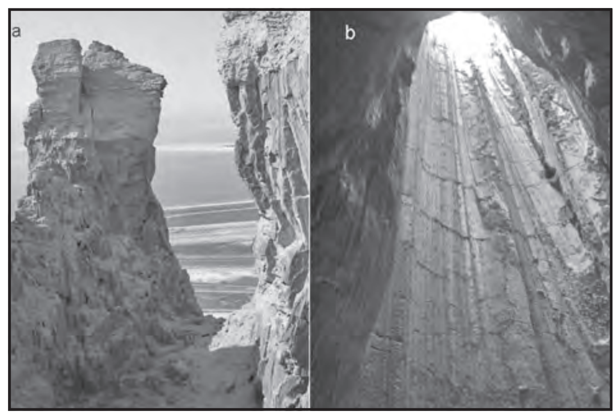


Figure 4: (a) the unroofed cave and SSP as seen from the west. Note paleo-notches on the right wall; (b) the active 70 m high Sedom Shaft in rocksalt.

A mid-19th Century pioneering expedition to the Dead Sea initiated a new era of realistic geologic observations: "we found the pillar to be of solid salt... Its peculiar shape is doubtless attributable to the action of winter rains" (LYNCH, 1849). SSP has been attributed to erosion by rainfall until recently (BENTOR, 1989). Here the nature of SSP is discussed, following a wider analysis of this salt pillar published in the geologic literature (FRUMKIN, 2009).

3. Results and Discussion

The following observations have been made during the present study: SSP is a 20 m high, 5-10 m wide pillar, standing within the upper part of the 87 m high eastern escarpment of Mt. Sedom. The upper third of SSP is composed of anhydrite caprock (Fig. 3); the lower two thirds comprise vertical salt layers. The caprock head of SSP protects it from being rapidly dissolved by rainfall.

The eastern wall of SSP is an almost vertical bedding plane acting as a major marginal fault along the eastern border of the diapir (Figs. 1, 3). SSP is separated from the northern extension of the escarpment by a deep chasm. In the present study, subhorizontal paleo-notches were found in the walls of the chasm (Figs. 1, 3), similar to those observed in the active Sedom Cave passage. Collapsed boulders are piled on the bottom of the chasm. The base of SSP and its associated notches are hanging ~60 m above the associated active level of Sedom Cave. Closely associated with SSP, the 1799 m long Sedom Cave is one of the largest known salt caves (Figs. 2a, 3).

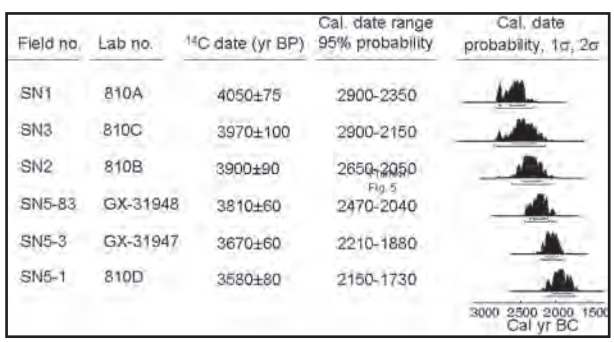
On the western side of SSP is a continuation of the chasm, forming a 25-m deep roofless depression (Figs. 1, 3). Its south-western part is the active Sedom Shaft (Fig. 4b), one of four active stream-sinks of Sedom Cave. The combined features clearly show that the depression is an unroofed cave, formed by the collapse of paleo-Sedom Cave, whose outlet had been at the chasm to the north of SSP. SSP is a remaining part of the eastern wall of the unroofed cave.

As an integral part of the eastern escarpment of the diapir bedrock, the rising rate of SSP was monitored, for the first time, by direct geodetic leveling across the eastern escarpment. A 100-m long leveling traverse, using an automatic tripod-mounted level (BOMFORD, 1985), has been measured yearly three times, over a set of benchmarks through the lower level bedrock of Sedom Cave (Fig. 3). Point 9 is located within the same vertical salt layer of SSP. The mean measured rising rate is 9.3$\pm$3.5 mm/yr across the entire traverse (Frumkin, 2009). The mean measured uplift rate of SSP layer in respect to the foothills is 6$\pm$1.5 mm/yr. The rising rate measured in this study is relative to the foothills, thus it combines two components: (1) the absolute rising rate of the diapir, and (2) the absolute subsidence rate of the eastern foothills plain, associated with the subsidence of the southern Dead Sea basin. This combined effect is reflected in the high relief of the eastern Sedom escarpment and border faults location (Figs. 2, 3).

Cave level age is well represented by radiocarbon dates of wood fragment deposits, because the wood residence time on the surface before being swept underground, as well as the life span of a single cave level are smaller than the error of the date (Frumkin et al., 1991). Six radiocarbon dates, ranging from 4050 to 3580$\pm$80 yr BP (Fig. 5), were obtained from four wood fragments (SN1,2,3, and 5) in the upstream part of the upper levels of Sedom Cave, where the upper levels of the cave are well-preserved, with no major collapse. After calibration, the calendar dates within 95% probability indicate that the upper levels associated with SSP started forming between 2900 and 2350 calendar yr BCE.

A probable (but not necessary) trigger of a cave collapse in cohesive salt within this tectonically active region is an earthquake. The dimensions and form of the studied unroofed cave suggest that SSP could become a distinct isolated pillar following a major earthquake. Other collapse dolines Mt. Sedom are discussed by FRUMKIN and RAZ (2001). The collapse terminated the functioning of the cave channel as an active stream. The maximal likely age for this event is given by the youngest calendar date of the drift wood, ranging between 2150 and 1730 BCE (95% probability, Fig. 5).

The elapsed time (~3950$\pm$100 yr) multiplied by the measured rising rates suggest that SSP was ~38$\pm$14 m lower when it first became an isolated pillar. This was much closer to the foot of Mt. Sedom, rendering it easily observable by anybody travelling along the foothill. The radiocarbon–dated disturbed sedimentary layers of the Dead Sea contain the best long-term record of Dead Sea earthquakes (MIGOWSKI et al., 2004). Within this record, the largest cluster of relevant seismic events occured between ~2100 and 2000 BCE, represented by three disturbed sediment sequences. The intermediate one, ~2050 BCE, was suggested to reflect a magnitude 8 earthquake, the strongest in the entire Holocene record of the Dead Sea (MIGOWSKI et al., 2004). This date agrees with the latest Sedom Cave dates, suggesting that the same high-magnitude earthquake may have triggered the collapse of paleo-Sedom



Field no.	Lab no.	^{14}C date (yr BP)	Cal. date range 95% probability	Cal. date probability, 1σ, 2σ
SN1	810A	4050±75	2900-2350	
SN3	810C	3970±100	2900-2150	
SN2	810B	3900±90	2650-2050	
SN5-83	GX-31948	3810±60	2470-2040	
SN5-3	GX-31947	3670±60	2210-1880	
SN5-1	810D	3580±80	2150-1730	

Figure 5: Radiocarbon dating of wood remains from Sedom Cave, upper level of 'Shual Natush' branch. Conventional radiocarbon dates are reported with ±1 σ. Calibration is determined by OxCal (Bronk-Ramsey, 2001). Age range of calibrated dates represents 95% probability, corresponding to the lower horizontal lines in each probability graph (right).

Cave, bringing about the formation of SSP. The present explanation and dating of Lot's wife is independent of the explanation of the Sodom and Gomorrah narrative, although the two events may be related, as implied by the biblical narrative (Genesis 19) and the following discussion.

Scholars who adopt the historical view of Genesis 19 usually relate it to the late Early Bronze or early Middle Bronze Age, ~2000 BCE, based on independent reasoning (e.g. ALBRIGHT et al., 1944; GRINTZ, 1983; MEITLIS, 2006; NISSENBAUM, 1994; RAST, 1987; SPEISER, 1964). This age is consistent with the present study. It may thus be suggested that the biblical narrative of Lot's Wife originated from the collapse of the ancient Sedom Cave followed by an observation of the sudden appearance of a salt pillar ~2000 BCE. The measured rising rate of the diapir suggests that the salt pillar formed close to the eastern foothills plain, attracting travelers. Evoking an explanation, SSP was perceived as a testimony for God's wrath on moral grounds. The early observers transferred the narrative as a living memory through time, until the evolved myth was recorded in the book of Genesis. Their morphological-lithological observation ("pillar of salt") withstood the tide of time as it was continuously supported by new observations. This is probably the oldest narrative that can be geologically attributed to a particular dated geologic feature.

Acknowledgements

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GEOLOGIC AND HYDROGEOLOGIC CONDITIONS IN SPELEOGENESIS OF THE LONGEST AND DEEPEST CAVES IN KARST OF CROATIA

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In Croatia about 54% of territory has characteristics of karst relief (with sea floor about 73% of territory). Between two basic kinds of speleological features in Croatia (caves and pits), pits prevail in about 70% cases. In Croatian karsts are 53 caves and pits with depth over -250 m (three pits with depth over -1000 m, one over -750 m, one over -650 m, nine over -500 m, five over -400 m, sixteen over -300 m, eighteen over -250 m). There were presented few speleological features with the largest depth in the Croatian karst. Their basic geomorphological characteristic were analyzed and compared: location, depth, kind, morphological type and basic conditions of speleogenesis (geology and hydrogeology conditions). The review of the most perspective areas for further speleological exploration in Croatia was made on the basic of above given facts.

There more than 11,000 caves explored in the Croatian karst areas, and it is assumed that several times more exist. In some kinds of calcareous breccia called "Jalar" from Paleocene geological period, mostly vertical and deep caves are present. For example System Lukina jama - Trojama with depths of -1392 meters, Slovacka jama, depth of -1320 m, than System Velebita pit -1026 m, with world's deepest underground free-fall vertical step, at -513 m, than Pit Patkov gust with entrance vertical of -553 m (the second in the World).

The longest cave system Đulin ponor -Medvedica near Ogulin is 16,396 m long. It had mostly developed through erosion and corrosion activities of the underground sinking Dobra river.

The deepest karst springs are in Crveno jezero (Red lake) at -281 m, Una river spring at -205 m, Kupa River at -154 m, and Cetina river spring at -115 m, etc.

All the Dinaric karst system is affected by neotectonic movements and this is one of the main reasons for the many vertical speleolological features found in the region..

1. Types and Forms of Speleogenesis in Croatian Karst

The correlations between the initial, main and fossil phases of speleogenesis, the karstification types (gravity, regression, or complex karstification) and the place of occurrence (internal, central and peripheral karst zone), provide new information and scientific data, and point to the conclusion that the examination of caverns, which outnumber by far the speleological structures with natural entrance, can be regarded as the very foundation for the study of karst. The speleogenesis of caverns is directly related to their lithostratigraphic, hydrogeological and tectonic predispositions. These occurrences are dominantly vertical speleological structures (pits), of knee or column shaped morphological type, assuming the hydrogeological function of intermittent or permanent springs, and are now going through the main phase of speleogenesis. Caverns are not affected by atmospheric influences, or by surface waters via natural entrances, and so they reveal the "veritable condition" of underground cavities.

2. Classification of Speleogenesis

The extensive study of genesis of speleological structures in Croatian karst, as based on a considerable number of examples, shows that such structures are located in the immediate vicinity of fault planes or paraclases, or along fault zones. Traditionally, speleologists have been using various techniques in the study of speleological structures, but were limited to structures having natural entrance at the ground surface (Beck, 2005). A significant breakthrough was made by the study of caverns discovered during construction of motorways, bridges, tunnels viaducts etc., which has in fact enabled investigations along fault paraclases or in fault zones. It was noted that speleological structures always occur in several groups at a single fault (vertical or horizontal sequence), depending on the type of rocks, intensity of karstification, neotectonic activity, etc.

2.1. Along the neotectonic outcrops of rock complexes

The correlation of absolute displacement (neotectonic activity) measurements shows that the frequency of speleological structures at the same fault (or fault zone) is the greatest in vertical direction in case of neotectonic outcrops, and when there is a smaller deviation from the direction of neotectonic impact in relation to the predisposed fault significant for speleogenesis.

2.2. Along the neotectonic downlift of rock complexes

On the other hand, the faults on which horizontal “continuations” of caverns are formed are generally found in the zone of neotectonic downlift, or in the zone of change of direction of neotectonic impact in relation to the predisposed fault. The probability of occurrence of vertical or horizontal continuations of caverns was statistically calculated based on 3877 identified and registered faults and 845 caverns formed on their paraclases, or on paraclases of neighboring parallel or subparallel faults or fault zones. These values range from 30 to 35 percent and, when neotectonic predispositions of faults are taken into account, the probability of occurrence of a speleological structure assumed in advance varies from 55 to 65 percent. The neotectonic activity was determined by direct measurement of absolute displacements in the surrounding speleological structures, or based on prognostic maps of neotectonic uplift or downlift. This method could be used to assume the spreading of many speleological structures in our karst and, of course, in the zones when construction activities are undertaken. By comparing the neotectonic (present-time) orientation and intensity of displacement, it would be possible to compare, with a relatively high level of accuracy, the speleological structures in similar rock formations and, combined with comparison of their karstification rates, the resulting correlation data would be very indicative. The intensity of karstification is currently measured and compared in some caverns. The influence of seismic waves is also measured and related to constantly measured neotectonic displacements.

3. Regressive (Inverse) Karstification

In the course of study of caverns in our karst, it was noted that, in all phases of speleogenesis, many structures tend to intensively develop towards the ground surface, which is due to the mentioned neotectonics, but also to the ground water influence. This has resulted in formation of some large-size speleological structures which are internationally known as sinking valleys or sinkholes, and we have defined them as speleological structures formed by regressive karstification. In the first two phases, the cavern is widening along the fault paraclases towards the ground surface. In the third phase the cavern is already a speleological structure with its entrance at the ground surface, while the fourth phase is characterized by the start of intensive rock weathering activity and backfilling of the speleological structure.

The tectonic predisposition of the area in which speleological structures develop is actually of highest significance for speleogenesis (Herak, 1984; Garašić, 1984a; 2002). It is known that karstification in horizontal or slightly inclined layers advances more slowly when compared to steep or vertical layers. More interesting conclusions can be derived from the results obtained by systematic study of all caverns in tunnels along the Rijeka - Karlovac Motorway where the data about the intensity of karstification, as well as the morphospeleological and hydrogeological data, were continuously monitored and compared. In some tunnels (Tuhobić, Vrata, Sopač, Veliki Gložac) the tectonics has played a crucial role in speleogenesis. These are speleological occurrences of mostly tectonic origin, and are exclusively dependant on the closeness to fault surfaces (Garašić, 2002). These occurrences are relatively rare.

Less than 3 percent of structures registered so far in Croatian karst were formed exclusively by tectogenesis, i.e. without a significant erosive or corrosive influence of ground water (Garašić et al., 1993, 1994). Other than in fault zones, they can also be found in the apexes of local anticlines (Sopač Tunnel) where ground water has subsequently exerted a secondary role in the speleogenesis.

The hydrospeleogenesis is always a complex process in which water has a dominant role. The erosion and corrosion (mechanical and chemical speleogenesis) act together in the development of speleological structures (Trailkill, 1968; Garašić, 2002). In fact, about 93 percent of structures registered in our karst have been formed, to a lesser of greater degree, through the influences of erosion and corrosion.

4. Other Types

Some other rocks present in our karst (particularly near the town of Knin) also have exceptional hydrogeological conditions. These rocks are gypsums and evaporites. Other than on carbonate rocks (which are best known to us), the karst also develops on some other rock types which are soluble and have a good secondary porosity. Evaporite rocks are a good example. They are formed by chemical leaching from highly-concentrated solutions, as a result of a very strong evaporation. The most important and most frequent evaporite sediments are gypsum, anhydrite and salts. The chemical composition of the gypsum mineral is $Ca(So_4)$ x $2H_20$ and, just like other evaporites, it is highly soluble in water. The main difference in the karstification of gypsum and carbonate rocks lies in the fact that the gypsum is more soluble. For that reason the surface denudation of gypsum is very intensive. The surface morphology of karst lying on gypsum is generally similar to morphology of carbonate terrains, although some specific features do exist. Concave forms are mostly less often pronounced, i.e. they are wider and shallower. The occurrence of gypsum is related to the so called interstratal karstification as, when found in nature, gypsum layers are often clenched between other sediments. They can thus be protected with a less permeable or impermeable overburden formations. The karstification of gypsum underneath such overburden results in creation of underground cavities which are responsible for the cave-in ad settlement of terrain which is otherwise not susceptible to karstification. The study of speleogenesis in gypsum has revealed that such caves form if two basic conditions are met: a transverse flow of water between the roof and floor aquifers via the gypsum layer, and lateral discharge of water via the insoluble but porous aquifer situated underneath the gypsum layer (Klimchouk, 2000, 2007).

Anhydrites and gypsums are sedimentary rocks of purely chemical genesis, unlike carbonates that can also be of organic genesis, while conglomerates and breccias may be of mechanical (clastic) genesis. As according to its specific weight, the gypsum is lighter than carbonate rocks, we have here the so called diapiric uplift. In fact, the gypsum rocks rise from the carbonate or other massifs and form, during this movement, diapiric folds with numerous fissures (leptoclasms, diaclasms and diastroma). They are sometimes interbedded with fault paraclases. These movements are measured in hundreds of meters and the uplift can sometimes measure several kilometres in length. In Croatia, diapiric gypsum deposits and gypsum-based speleological structures are found only in the Kninsko polje area. These are mostly smaller-size speleological structures that have been degraded to present dimensions (20 to 50 m at the ground surface) through subsequent orogenetic movements and gypsum solubility. The uplift occurrences are estimated at more than 1500 meters. That is why it is quite possible that bigger speleological structures in gypsum do exist, but at greater depths (caverns).

The neotectonic activity has been registered in several structures (peripheral karst belt), e.g. in the tunnels of Hrasten, Sveti Rok, Tuhobić and Učka. There some speleothems have been disrupted by neotectonic movement of blocks. These displacements are measured in millimetres and are of local type, and thus not detrimental to the roadway.

All morphological properties of speleological structures (form, length, depth, orientation, inclination, etc.) are closely related to the factors of speleogenesis, its type, phase, intensity and location (various karst belts). It is today a known fact that the most complex karstification processes (karstification, corrosion, erosion, abrasion, denudation, accumulation, secondary and tertiary sedimentation, etc.) act in different directions depending on hypsometric position, geological (lithostratigraphic) predispositions and hydrogeologic conditions. Although most speleological occurrences/structures have been formed through karstification by gravity, some twenty percent of them have in effect been formed through the so called reverse or regressive karstification. An example of the so called complex karstification has been identified in a cavern in the Učka and Vrata tunnel (influence of impermeable rocks).

The karstification by gravity advances quite intensively in the downward direction, the reverse or regressive karstification advances in the upward direction, and the complex type of karstification advances at a similar rate in all directions. The karstification by gravity or surface karstification is always influenced by gravity water, i.e. by precipitation rate. It can be observed quite easily and is very pronounced in Jurassic and Cretaceous carbonate sediments. Tectonic fracturation is favorable for its development (Garašić, 1986a). The reverse or regressive karstification can be observed only in the underground (in caverns) and is due to hydrogeological conditions (change in the ground water level, its continuous presence in the underground in the first and second phases of speleogenesis, etc.) and lithostratigraphical factors (it develops intensively in easily soluble formations, in Jurassic and Cretaceous fine-grained breccias, in Plio-Quaternary breccias, and in blocks with neotectonic uplift). Its presence has been noted in the area of neotectonic uplift (e.g. in the Jablan - Sušica zone and in the South Velebit area), and its intensity is proportional to the intensity of the uplifting action. The signs that clearly point to the reverse or regressive karstification are, for instance, the so called air cushions found on cave ceilings (in the area of Fužine, Josipdol and Brinje). Unlike karstification by gravity, the intensity of reverse karstification is less dependent on tectonic fracturation, and more on special hydrogeological conditions (Garašić, 1993, 2002). A complex type of karstification has been found in the cavern at the contact between the Palaeozoic clastic impermeable formations and the Mesozoic complex of dolomitic limestones in the Vrata Tunnel and at the contact with flysch at the Učka Tunnel. It is however quite rare to find karstification which is advancing at a similar rate in all directions.

The need to have the roadway and/or tunnel above a spring is the biggest possible engineering-geological, hydrogeological and civil engineering challenge. Significant examples are those above the Jadro spring (Mravinci), in flysch materials or above the Zvir spring in Rijeka (Katarina Tunnel), and in fractured Mesozoic carbonates.

5. List of the Longest and the Deepest Caves in Croatia

The longest caves are listed in Table 1.
The deepest caves are listed in Table 2

The biggest vertical shafts:

Patkov gust -553 meters (entrance vertical shaft) and Velebita -518 meters (inner vertical shaft)...

The deepest and longest siphons:

Crveno jezero (depth - 281 m /ROW/, - 181 m cave diver), Una river spring (-205 m), Kupa river spring (-155 m), Sinac spring (- 151m), Cetina river spring (-115 m), Gacka river spring (- 105 m, length 950 meters)...

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No.	Name:	Location:	Length (m):
1.	Sustav Đulin ponor - Medvedica	Gorski kotar, Ogulin	16.396
2.	Sustav Varicakova (Muškinjska) - Panjkova spilja	Kordun, Rakovica	12.385
3.	Jama Kita Gacesina	Velebit, juzni	10.603
4.	Špilja u kamenolomu Tounj	Kordun, Tounj	8.487
5.	Veternica	Medvednica, Zagreb	7.128
6.	Sustav Jopiceva spilja - Bent	Kordun, Brebornica	6.710
7.	Jama Munizaba	Velebit, juzni	5.993
8.	Sustav Vilinska spilja - Ombla	Dalmacija, Dubrovnik	3.063
9.	Gospodska spilja	Cetinska krajina, Vrlika	3.060
10.	Donja Cerovacka spilja	Lika, Gracac	2.779

Table 1: The longest caves in Croatia.

No.	Name:	Location:	Depth (m):
1.	Sustav Lukina jama - Trojama (Manual II)	Velebit, sjeverni	1.392
2.	Slovacka jama	Velebit, sjeverni	1.320
3.	Jamski sustav Velebita	Velebit, sjeverni	1.026
4.	Amfora	Dalmacija, Biokovo	788
5.	Meduza	Velebit, sjeverni	679
6.	Stara skola	Dalmacija, Biokovo	576
7.	Vilimova jama (A-2)	Dalmacija, Biokovo	572
8.	Patkov gust	Velebit, sjeverni	553
9.	Jama Olimp I	Velebit, srednji	537
10.	Ledena jama u Lomskoj dulibi	Velebit, sjeverni, Lom	536

Table 2: The deepest caves in Croatia.

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PROBLEMS WITH CAVERNS WHICH WERE FOUND ON THE ROUTE OF THE HIGHWAYS IN CROATIAN KARST REGION (DINARIC KARST)

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While building highways in karst regions of Croatia during the last eighteen years, over 945 caverns (speleological features without natural entrance) were discovered and thoroughly explored. All of them were geologically mapped , surveyed and photographed in details. Research were carried out systematically on sections of roads, highways, cuttings, slides, tunnels, bridge foundations, viaducts, etc. while building about 500 km of highways in Croatian karst region, e.g. Dinaric Classical Karst area (Zagreb-Rijeka highway, Zagreb-Split Highway, Epsilon of Istria semi-highway, Rijeka-Rupa highway, Zagreb-Zadar semi-highway, Rijeka by-pass, etc). Some of these caverns have big chambers like in tunnel "Sveti Rok" tunnel and in some of them like in tunnel "Vrata" there were necessary built bridge over cavern. It is the first bridge over cavern in tunnel in the world. Special protection of the stability of cavern roofs has been done with hundreds of anchors and jet grouting. Groundwater is well protected in all of new founded caverns.

1. Introduction

Regardless of the quantity, type and quality of primary geologic, geophysical or geotechnical investigations, it is difficult to positively identify most of the caverns in karst areas. In many cases, caverns are discovered during the construction process, without prior indications pointing to their existence, or with indications based on qualitative forecast only. Preliminary investigations rarely provide information about locations of a cavern and even less so about its shape and size. Caves are natural holes in the lithosphere and according to their size they may be ranked among diaclases and/or diastromas. They may have an entrance at the ground surface although, more often, they do not as they are fully buried in the interior of the karst massif. Entrance-less caves at the ground surface are called caverns. Almost one thousand caverns have been investigated in Croatia so far, and the total number of such occurrences exceeds 11,000.

In Croatian karst, speleological sites are defined as diaclases wide enough to be penetrated by a human at least 5 m in depth, or 10 m in the horizontal direction. As geologic processes are characterized by permanent activity in the course of time, changes in the number of speleological sites are also possible (Garašić, 2008). Caverns are exclusively found during construction and/or mining activities namely in cuts, side cuts, quarries, during excavation of bridge and viaduct foundations or, most frequently, during tunneling works. During construction of infrastructure facilities, these occurrences are always regarded as technical problems but, on the other hand, they also provide us with new knowledge about complex karstification processes. Some commonalities in the occurrence of caverns have been noted and it may be concluded that they outnumber by 20:1 the caves with the opening at the ground surface. This means that in Croatia there may be as many as 100,000 caverns reaching down to several hundred meters in depth. In our country, the deepest traces of caverns were found in deep boreholes in the Adriatic, where dripstones (speleothems) were found in zones reaching down 3125 m. Karstification depth exceeds 7 km in this region, as all preconditions favoring such karstification depths are in place (i.e., solubility and fracturing of rocks, and groundwater). Here we also have a Mesozoic geosynclinal carbonate basin ranking among the thickest in the world. All these data lead us to believe that caverns are common in this part of the world, where we can find many types and species of speleogenesis in all its phases.

Since 1991, systematic speleological, speleogeological, and hydrogeological investigations of these occurrences are mandatory in Croatia, and are routinely carried out during construction of transport facilities in karst regions. So far, more than 945 caverns have been inspected in full detail along our motorway routes. Proper remedial measures are taken with respect to caverns encountered during such investigations, taking into account the safety of the transport facility, the need to preserve groundwater quality, and construction costs. A correlation has been noted in the present and shape of caverns, lithostratigraphy, neotectonics, and hydrogeology, which is the effect of various forms of speleogenesis and karstification.

2. Karst zoning in Croatia

According to the Zoning and Classification of Karst, Croatia's motorway areas should be considered separately, as the speleogenesis is different in each area (Fig.1). This has also been proven by detailed speleological investigations along motorway routes that have been conducted continuously since 1991. The Zone between Zagreb and Karlovac is a valley type no-karst terrain, mostly made of Quaternary and Plio-Quaternary formations. There are no speleological sites in this area. In the area from Karlovac to Bosiljevo, the motorway runs through the Internal Karst Belt where speleological occurrences are mostly related to Plio-Quaternary and Triassic formations.

Figure 1: Karst zones in Croatia.

Rijeka route: On the stretch from Bosiljevo to Fužine the motorway passes through the Central Karst Belt, which is characterized by numerous speleological occurrences/ structures in Mesozoic carbonate formations. From Fužine to Rijeka the motorway is in the Peripheral Karst Belt, which is characterized by the exclusive occurrence of vertical speleological structures with signs of strong fault tectonics. The zone from Rijeka to Rupa is the transitional Ćićarija zone, dominantly with vertical but with some horizontal speleological structures.

Istria: In the hydrogeologic sense, the Istrian area is within the almost horizontal layers of the Vrsar Anticline, which has been fractured by local tectonics and which carries water vertically towards the rivers Raša and Mirna, or towards Istria's main karst sources. The Ćićarija zone is related to reverse faults and overthrusts with water-impermeable flysch barriers, while the Učka zone is characterized by the contact between the flysch and carbonate sediments. In this area, all caverns transport groundwater into the Kvarner Bay where the water emerges as numerous sub-sea water springs.

Split route: The zone from Bosiljevo to the Mala Kapela Tunnel, including the boundary area along karst fields in Lika, is characterized by horizontal speleological structures that are greatly influenced by groundwater. From the Mala Kapela Tunnel to the Sveti Rok Tunnel, the road traverses the Central Karst Belt abounding in groundwater, with vertical but with dominantly horizontal or inclined movement of ground water. The area is characterized with many estavelles. The area from the Sveti Rok Tunnel to the Maslenica Interchange is characterized by rapid vertical circulation of groundwater and by slow movement in horizontal directions. The area of Ravni Kotari is extremely significant in the vertical and also more importantly in the horizontal circulation of groundwater as sometimes the impermeable flysch substratum is located in the immediate vicinity of roadways. The Dalmatian Hinterland area (Dalmatinska Zagora) is similar to the area of Lika, groundwater is more intensive as the Adriatic drainage basin in this area receives an additional supply of groundwater from Herzegovina. At this point, special attention must be paid to the vertical circulation of groundwater. A speleological structure with the highest minimum to maximum groundwater amplitude of as many as 236 m, which ranks it among the highest in the world, was registered in the zone between Zagvozd and Vrgorac. It is expected that a considerable number of vertical caverns will be found in the tunnel underneath the Biokovo mountain.

The area to the south of the Neretva in the direction of Dubrovnik is characterized by dominantly vertical (less often inclined) speleological structures from which groundwater arriving from Herzegovina is eventually discharged into the sea, via the subsea springs and other water springs. Analysis of simplified speleogenetic peculiarities of the area traversed by main transport routes in Croatian karst shows that in the main phase of speleogenesis, the caves have a big potential for transporting groundwater, both in vertical and horizontal directions. The groundwater changes, through its karstification activity, the engineering geologic and geotechnical properties of rock formations it traverses, which should undoubtedly be taken into account during construction in karst zones in Croatia.

The Croatian karst ranks among the better known "locus tipicus" of the world's karst. The underground karst forms are represented with over 10,700 speleological structures

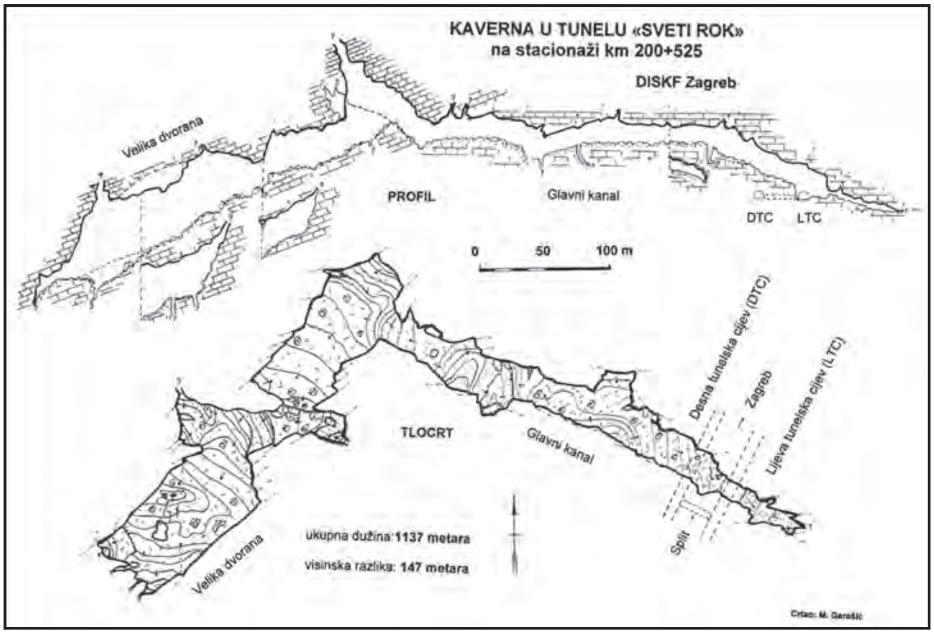

Figure 3: Map of cavern in the tunnel Sveti Rok.

(Garašić, 1991) with varied morphological and morphogenetic features and hydrogeological functions. The study of speleogenesis of this area can be an indicator of karstification index and can also be applied to many other karst areas in the world. Although very many caverns have been discovered and studied in this karst region, a relatively small number of papers have so far been published in this field of speleology. The following authors have published papers about caverns (i.e., about speleological structures without a natural entrance at the ground surface): Malez (1956) - Drenovac Cavern in the Gojak Tunnel; Božičević (1985) - cavern in the Učka Tunnel, caverns in the Obrovac Tunnel; and Garašić (1993; 2002) - caverns in the Učka Tunnel (Milanović, 2004) and in all tunnels along the Rijeka - Karlovac Motorway and Zagreb - Split Motorway (Sveti Rok Tunnel) (Garašić, 2002, 2004, 2008). The latter author personally participated in the study of all caverns in Croatia since 1975 to this day.

Caverns along motorway routes have been systematically studied since 1991 and, to this day, the total of exactly 945 caverns have been fully investigated. Although all of these caverns vary by their genesis, morphology, depth and length, they still confirm the scientific assumptions about differentiation of karstification level, which is dependant on the level, type, quantity and aggressiveness of groundwater, and on tectonic predispositions and lithostratigraphic properties of environment in which they were formed. In all big road tunnels (Učka, Tuhobić, Sveti Rok, Mala Kapela), there was at least one large-size speleological structure that had to be remediated, and in some cases there were more than 70 of them (Brinje Tunnel). In some tunnels, the issue was solved by designing smaller bypasses above the caverns (Veliki Gložac, Plasina), while in some cases veritable bridges had to be built (Vrata) (Figs.2, 3). The groundwater from some caverns encountered during the tunnelling work is now used in water supply (Učka), and some tunnels actually pass above the well field (Mravinci, Katarina, Grič, Vrata). Interestingly, sea water was found in some caverns (e.g., Pećine Tunnel). All these and many other hydrogeological problems have successfully been solved by builders either during preliminary investigations, construction or use of the transport facilities.

Figure 2: Cave chamber in highway tunnel.

The piers or abutments of the following viaducts and bridges are actually situated above caverns: Anđeli, Vela Draga, Delnice, Golubinjak, Hreljin, Severinske Drage, Osojnik, Zečeve drage, Bijakuše, Maslenica Bridge, bridge over the Krka River, bridge over the rivers of Dobra, Bistrac, Kamačnik, Rječina, etc. All caverns discovered along our transport routes have been investigated in full detail, and these investigations were in all cases backed by an appropriate documentation (reports submitted to the employers). If we compare the above hydrogeological problems in karst - encountered during construction of transport facilities in Croatia - with similar ones in other countries, we can be no less than pleased. In fact, we have had no environmental problems in Croatia due to incompetent handling of hydrogeological issues in karst and in speleological structures (caverns). On the other hand, many examples can be cited of road construction projects in Trieste hinterland, in Austria, in France, and in the USA, where some changes occurred in the movement, quantity, and quality of groundwater following construction of transport infrastructure projects in karst zones.

Several levels can be differentiated in speleogenesis. Various authors point to three basic and several special levels in the generation of speleological structures. These three levels are: initial level (or phase I), principal level (or phase II) and fossil level (late level or phase III).

All three levels of speleogenesis are present in areas traversed by the Rijeka - Karlovac (Zagreb) Motorway. The ratio of principal to fissile level varies on individual parts of motorways, but an average value for the entire Croatia is 3.11:1. A completely different situation has been established for the internal karst belt, i.e. for the area from Karlovac to Bosiljevo. Here the ratio of principal to fossil level of speleogenesis is 1:6.89, which is an indication that the voids are in most cases filled with detached material, calcite, or most frequently with highly plastic, very firm, red to brown-red clay. In the Central Karst Zone, i.e., in the zone from Bosiljevo to Fužine, the motorway traverses the area in which the speleogenesis is characterized by the principal phase to fossil phase ratio ranging from 2.36:1 to 3.05:1. In the Peripheral Karst Zone, i.e., in the zone from Fužine to Rijeka, this ratio is 4.20:1. All known and investigated structures on the route of the mentioned motorway, and structures in its immediate vicinity were taken into account when calculating proportions of individual phases of speleogenesis (Garašić, M. 2003a,b).

All three levels of speleogenesis are present in the area traversed by the Zagreb - Split Motorway. An approximate ratio of principal to fossil levels varies along individual parts of the motorway and generally amounts to 3.05:1. The situation is completely different in the Internal Karst Zone, i.e., in the zone from Karlovac to Bosiljevo. Here the ratio of principal to fossil levels of speleogenesis is 1:6.89, which is an indication that the voids are, in most cases, filled with detached material, calcite, or most frequently with highly-plastic, very firm, red to brown-red clay. In the Central Karst Zone, i.e., in the zone from Bosiljevo to the Sveti Rok Tunnel, the motorway traverses the area where speleogenesis is characterized by the principal phase to fossil phase ratio ranging from 2.21:1 to 3.22:1. In the Peripheral Karst Zone, i.e., in the zone from the Sveti Rok Tunnel to the Maslenica Interchange, this ratio is 4.44:1. All known and investigated structures on the route of the mentioned motorway, and structures in its immediate vicinity, were taken into account when calculating proportions of individual phases of speleogenesis.

If we compare the above two most significant roadways, a good correspondence can be established in the sphere of karst zoning, i.e., with respect to the dominant influence of individual types of speleogenesis. The initial phase of development of speleological structures is present in all areas under study, and the karstification process is in progress in all these areas. However, it was impossible to directly monitor this phase of development of caverns because of the narrowness (low width) of cracks and initial fissures. Nevertheless, in the Internal Karst Belt, i.e., in the zone from Bosiljevo to Fužine (or to the Sveti Rok Tunnel on the Split roadway), the parallel presence of initial, principal, and fossil phases of speleogenesis in the ratio of 1:1:1 was noted in some fifty speleological structures. If this information is compared with the overall picture of all known speleological structures in Croatia, it can be concluded that this is a relatively rare occurrence. In Croatian karst, there are 183 speleological structures (or about 1.58%) for which it can be claimed with high level of certainty that the speleogenesis is in all levels of development, and this without great horizontal or vertical spacing among individual structures (no more than 100 m).

Following analysis of a large number of studies and data processing results, it can be concluded that most speleological structures in Croatian karst have not as yet passed through all three levels of development. This is due to geologic, tectonic, hydrogeologic, and climatic factors, i.e., the structures in high mountainous massifs, although affected by the gravity karstification process, have not as yet "reached" less permeable or impermeable substratum, and so the fossil phase of speleogenesis has not as yet been attained.

It is of special interest to compare speleological structures having natural entrance at the ground surface with those without such entrance, i.e., with caverns with entrances that were revealed in the course of construction works. In 825 samples, all three phases of speleogenesis have not been established in any of the studied structures. They can be statistically classified as follows: 599 (or 64.75% of the studied caverns) are now undergoing the principal phase of speleogenesis, 223 (or 24.10%) are in the fossil phase of speleogenesis, and 103 (or 11.15%) of caverns have a similar ratio of initial and principal phases of speleogenesis. For caverns, the ratio of principal phase of speleogenesis to fossil phase is: 599:223 or 2.68:1. This can be observed in the zone of intensive occurrence of caverns in the Central Karst Belt, where the percentage of fossil phase is higher. The reason for this can be found in the intensive tectonics and the great quantity of precipitation replenishing the groundwater in the Central Karst Belt (Gorski kotar, Lika). The fossil phase is particularly present in caverns found in tunnels with a low overburden (Brinje, Hrasten, Sopač).

If we consider the position of caverns with respect to the ground surface (thickness of overburden), it can be concluded that in the Internal Karst Belt, the fossil speleological structures are dominant down to about ten meters from the surface, while in greater depths this phase is replaced with the principal phase of speleogenesis. In the Central Karst Zone (Bosiljevo - Fužine, Bosiljevo - Sveti Rok Tunnel; Dalmatian Hinterland), the principal phase is encountered after several meters in depth, while the fossil phase occurs between -100 to -300 m. In the peripheral karst zone (Fužine - Rijeka, Sveti Rok - Maslenica Interchange, and locally in Ravni kotari) this situation is less often encountered and, when present, the overburden is thicker and ranges from 200 to 500 m deep.

The following conclusions can be made by analyzing the above results and by taking into account the types of karstification processes in individual areas:

- Due to additional regressive karstification, the Central Karst Belt (Bosiljevo - Fužine; Bosiljevo - Sveti Rok Tunnel; Dalmatian Hinterland) is characterized, in addition to the principal phase of speleogenesis, by a higher number of structures that are currently in the fossil phase of speleogenesis. From the standpoint of civil engineering activity, this area is exposed to the greatest number of speleological occurrences that may hinder or prove detrimental to construction activity. This is why caverns are sometimes unstable, and may greatly vary in size.
- Because of dominant karstification by gravity in the Peripheral Karst Belt (Fužine - Rijeka; Mala Kapela Tunnel - Maslenica Interchange - Ravni kotari), the speleological structures are generally vertical and are going through the principal phase of speleogenesis. From the standpoint of civil engineering activity, this area is exposed to a considerable number of speleological structures, but they may be quite big in size and cause some problems in remedial work.
- The simultaneous occurrence of the karstification by gravity and regressive karstification in the Internal Karst Belt (Karlovac - Bosiljevo) brings about a higher incidence of fossil structures when compared to the principal phase of speleogenesis. From the standpoint of civil engineering activity, such speleological structures are likely to cause problems because of varied engineering geologic and geotechnical properties of rock formations in which they were generated or deposited. The number of such structures is relatively small when compared to other karst zones.

Such occurrences are also dominant on the Zagreb - Rijeka Motorway. Karrens have been found in structures situated in the Peripheral Karst Belt and, to a lesser extent, in the Internal Karst Belt. These karrens are one of the indicators of an intensive underground karstification (Grabovšek, 2000; Gunn, 2004). Some other forms of erosive or corrosive action of water in the underground have also been noted in the biggest caverns investigated so far (i.e., in the Tuhobić Tunnel and along the Vrbovsko - Kupjak section) . Such forms include turbulence pots as well as the hieroglyphs and leopard skin. The force of chemical or mechanical groundwater action has been proven beyond any doubt in places where the rock is highly polished (Sljeme Tunnel area, foundations of the Dobra Bridge, foundation of the Zečeve Drage Viaduct).

Carbonate rocks (milestones, calcareous dolomites, dolomitic limestones and dolomites) of various textures and age react quite differently to erosion and corrosion at the ground surface (Ford, 1970; 1971; 2007). The different reactions have been proven in the underground as well. The most intensive karstification along the mentioned roadway has been registered in the limestones of Jurassic to Lias origin, and then in the Dogger and Malm sediments, and in the Upper Cretaceous limestones.

The Jelar and Promina formations are of particular interest in the differentiation of various types of speleogenesis. Carbonate clastites of Lika, Velebit, Mala Kapela and Hrvatsko Primorje were initially described as facies with the Promina strata. However, their unclear correlation and the difference in composition have resulted in the introduction of the name "Jelar formation." Their origin was later attributed to significant tectonic disturbances (reverse faults and overthrusts), which was followed by vertical faults. Promina strata, found in Ravni Kotari area and at the Promina mountain, and also the area characterized by Jelar formation, are always in transgressive contact with older formations. These are the carbonate breccias that dated back to Paleogene - Neogene. In these formations, karstification is highly intensive. It should be noted that the spring of the world's third largest sinking stream - the Gacka River - is actually situated in Jelar strata, and that the Zrmanja River partly cuts through Promina formations. In addition, the largest underground cavities in Croatian karst are situated precisely in Jelar formations in the South Velebit area. These underground halls may sometimes reach even more than 100 meters in diameter. Also, the deepest speleological structures in this area pass, either partly or fully, through Jelar formations, which points to subsequent intensive karstification (sometimes more than 450 meters in depth). The karst is intensively developed in Jelar and Promina formations, and better solubility of breccias has enabled creation of a number of karst phenomena. Recent speleological and hydrogeological investigations, conducted in the scope of the Zagreb - Split Motorway construction, have revealed a great intensity of karstification and a variety of speleological occurrences that could not have been detected in earlier times through investigations conducted from the ground surface. Thus, these occurrences were discovered during excavation of tunnels (Grič, Plasina, Sveti Rok, etc.) bridges (over the Gacka), cuttings, etc. According to the number of speleological structures per km2, Jelar formations come after Lias - Jurassic limestones, and locally after Senonian - Cretaceous limestones.

3. Conclusions

Detailed speleological and speleogeologic investigations, topographic survey, and photographing of structures, and hydrogeological observations within the structures, were undertaken by the team of experts headed by Prof. Mladen Garašić, Ph.D. during construction of the Zagreb - Rijeka Motorway and Zagreb - Split - Dubrovnik Motorway in the period from 1991 to 2008. Out of 945 caverns subjected to detailed investigations, 791 or 85.5% are vertical speleological structures, and 134 or 14.50 percent are horizontal speleological structures. No combined or complex speleological structure has been registered. As the motorway routes along which the investigations were made pass mainly through the Peripheral and Central Karst Belts, it is logical that the data slightly differ when compared to general data for the whole of Croatia - vertical : horizontal : complex (V : H : C = 78 : 21 : 1).

An average cavern depth is 35 m, which is more than an average value for 11,000 speleological structures registered so far in Croatia (with the exception of min/max peaks) The average cavern length is 53.5 meters (without peak values). The deepest cave reaches -196 m and the longest one measures 1490 m (Garašić, 2004). A big cavity is the cavern in the Sveti Rok Tunnel (registered in the left-side tube) at KM 200+525 where 1137 meters of channels, with the altitude difference of 147 m, were subjected to speleological investigations and topographic surveys. Another significant cavity is the cavern in the Učka Tunnel measuring 1490 m in total length, and 151 m in depth. The extensive study of speleological structures newly opened along the route of the Zagreb - Rijeka Motorway and Zagreb - Split - Dubrovnik Motorway has contributed to the better understanding of the process of karstification, speleogenesis, and speleomorphology of karst areas. An invaluable experience and scientific knowledge gained in this way will certainly enable easier and safer remediation of caverns to be encountered during road construction in karst areas.

The volume occupied by these caverns varies from several tens to several tens of thousands of cubic meters. According to their orientation, they mostly follow the Dinaric Line of Spreading (northwest - southeast) with about 67% of caverns. Some 29% of structures are oriented almost perpendicular to that line of spreading (northeast - southwest), while the remaining 4% of the caverns have no dominant spreading. During the detailed speleological investigations made in the Tuhobić Tunnel, a certain correspondence, i.e. a systematic occurrence of three vertical caverns, spaced at no more than 50 m from one another, was established. These caverns are situated in Jurassic limestones. Similar occurrences were later on observed in the Sveti Rok Tunnel, also in Jurassic limestones (Garašić, 2002).

In the Internal Karst Belt, the karstification depth ranges from 50 to 100 m, in the Central Karst Belt from 150 to 600 m, and in the Peripheral Karst Belt from 500 to 1000 or more meters. Zones with inclined or even horizontal circulation, from which the water is transferred to various drainage areas, were also registered.

The preparation of cavern remediation design solutions was greatly facilitated by speleological investigations. A certain regularity of occurrence, as related to types of karstification and speleogenesis, was noted. At some points, the roadway route had to be partly modified, but the groundwater flow patterns discovered during speleological investigations have in no case been altered. The results obtained in the course of these investigations will prove valuable in future infrastructure development activities (e.g., realization of tunnels, cuttings, side-cuts, viaducts, bridges) in our karst which occupies as much as 54% of territory of the Republic of Croatia.

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DYE TRACING OIL AND GAS DRILLING FLUID MIGRATION THROUGH KARST TERRAIN: A PILOT STUDY TO DETERMINE POTENTIAL IMPACTS TO CRITICAL GROUNDWATER SUPPLIES IN SOUTHEAST NEW MEXICO, USA

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Rapid oil and gas exploration, drilling, and production in karst terrains in southeastern New Mexico are posing increased potential for contamination of critical groundwater sources. The area of primary concern is the Capitan Reef aquifer and the gypsum karst lands of the Delaware Basin. These aquifers provide critical drinking water supplies to the City of Carlsbad, Carlsbad Caverns National Park, White's City, several ranching families, and water wells for domestic livestock in the area. The aquifers are also the source of water for numerous springs and resurgences in the area that provide the basis for critical riparian areas and wildlife habitat. These fresh water sources are vital in sustaining life along the northern edge of the Chihuahuan Desert ecosystem.

There has not been a systematic analysis of karst ground water in this region. Gathering baseline data on ground water quality and proving the connectivity between oil and gas drilling operations and critical water supplies is crucial in understanding, detecting, and mitigating undesirable events associated with oil and gas drilling and production operations. A pilot study was initiated by the Bureau of Land Management in the summer of 2005 to begin gathering field data. The study area was expanded in 2007 to keep up with the expanding oil and gas development. Oil and gas drilling operations are required to put water tracing dyes into their drilling fluids before they start drilling and then again before they case and cement the well bore. Dye receptors are placed in several springs and water wells. Dye receptors are sent to a laboratory for analysis. The results of the dye tracing of drilling fluids help fill some of the voids in our understanding of karst groundwater flow in the Southern Guadalupe Escarpment study area and place greater emphasis on developing better methods of karst groundwater protection.

1. Introduction

As the price of oil and natural gas continued to rise in 2004 the demand for drilling of new oil and gas wells increased dramatically. The central portion of the Capitan Reef and the gypsum karst lands of the Delaware Basin in southeast New Mexico overlays rich deposits of oil and natural gas. This is the boundary of the study area (Fig. 1). Within these boundaries are critical groundwater recharge zones and numerous springs and resurgences. The aquifers in this area supply drinking water to the City of Carlsbad, Carlsbad Caverns National Park, White's City, several ranching families, and water wells for domestic livestock in the area. These aquifers are also the source of numerous springs that provide the basis for critical riparian areas and wildlife habitat. The largest is Blue Springs, with an outflow of 10 to 15 cubic feet per second. Also included are numerous springs that give rise to the Black River. These fresh water sources are critical in sustaining life along the northern edge of the Chihuahuan Desert ecosystem.

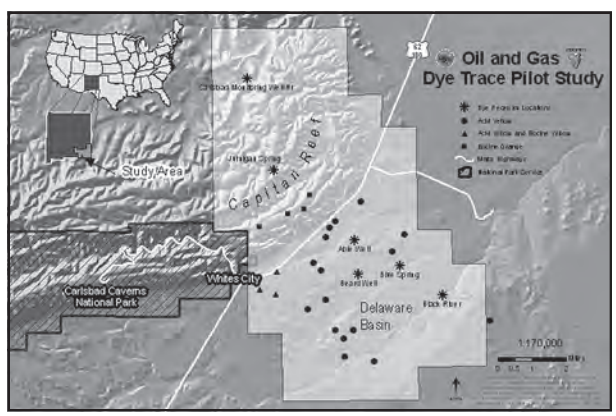

Figure 1: Oil and Gas drilling fluid dye trace area, southeast New Mexico, USA.

Groundwater research conducted by G.E. Hendrickson and R. S. Jones (Hendrickson, 1952) for Eddy County, New Mexico indicate that recharge of the groundwater associated with the Capitan and Carlsbad limestones is largely through the joints and fractures in the bottom of gravel filled arroyos. Water that enters the gravel and boulders in the arroyo bottoms moves downward into the underlying bedrock. The amount of water that enters the underlying rock and into the aquifer depends on the permeability of those rocks. Where the gravels are underlain by limestones all the water probably enters the underlying bedrock. Movement of groundwater after it reaches the bedrock is controlled chiefly by fractures and bedding planes, more or less enlarged by solution in limestone and dolomite.

They further state that the flow of the Black River, Rattlesnake Springs and Blue Springs is sustained chiefly by discharge near the base of the Capitan reef escarpment. The principal source of these springs is almost certainly discharged from the Guadalupe Mountains area, as the recharge in the area between the reef escarpment and the springs is not enough to provide their flow. In addition to the water discharged by the springs, groundwater probably moves from the Capitan limestone and other underlying limestones into the alluvium and underlying Castile formation and may supply water to several of the other springs located in the gypsum karst lands of the Delaware Basin. Perched aquifers may be present in the Quaternary piedmont alluvial deposits and the Quaternary alluvial deposits which are underlain by the Castile formation.

Recent studies by Snow (Snow and Goodbar, unpublished paper, 2007) indicate the critical recharge areas of the Capitan Reef aquifer are within one mile of the reef front and along the contact zones of the Yates and Seven Rivers formations in addition to the recharge into fractures in the alluviated canyon bottoms.

2. Potential Oil and Gas Impacts

The reasonable foreseeable development of the study area has yet to be determined. There have been several geophysical studies conducted in the area that indicate the potential for oil and gas exploration is high. The 1997 Bureau of Land Management Carlsbad Resource Management Plan Amendment for Oil and Gas (DOI 1997) shows the area as having a high potential for oil and gas occurrence. To date there have been 103 wells drilled in the study area. Of these, 76 are oil or gas wells drilled on federal land. The remaining 27 wells were drilled on state or private land. Based on the maximum allowable number of wells per section (16 oil wells and 4 gas wells) the maximum number of wells that could be located in the study area is 1,680 wells if maximum production were achieved.

Drilling in the study area could affect both the perched aquifers and the underlying Capitan aquifer. Potential groundwater impacts from drilling can be divided into those caused:

(1) <u>During drilling and cementing</u>; Drilling and cementing fluids may spill or leak into formations at any lost circulation zone.

(2) <u>During testing and production</u>; If the inner and intermediate casing strings fail following installation due to inadequate cementing or long term (50 + years) corrosion, drilling fluids, brine, oil,or gas could be released directly to the subsurface anywhere along the casing string.

(3) <u>Following plugging and abandonment of the well</u>; Because the atmosphere in the unsaturated part of the aquifers contain elevated concentrations of carbon dioxide and trace amounts of sulfur compounds as well as oxygen, the steel well casing could slowly become corroded and eventually fail in zones not protected by cement. (DOI, 1993)

A more complete description of oil and gas impacts on caves and karst can be found in the *Dark Canyon Environmental Impact Statement, US Department of Interior, Bureau of Land Management, 1993.* (DOI, 1993)

3. The Pilot Study

Identification and monitoring of karst areas includes gaining a better understanding of the underlying groundwater flow paths and their associated erosional features. To monitor the integrity of subsurface groundwater a program capable of identifying potential sources of contaminates entering the aquifers needed to be established. To begin this study the Bureau of Land Management in cooperation with the oil and gas industry, local land owners, the City of Carlsbad, and the Center for Cave and Karst Studies at Western Kentucky University initiated a die tracing pilot study to help identify areas of potential concern. The purpose of the dye tracing study was to determine if contaminates could enter the ground water through drilling and cementing operations, or during later phases of production or abandonment in the event of casing failure. Any positive results from the dye tracing study would then indicate that the BLM in conjunction with the oil and gas industry needs to ensure that all possible down-hole mitigation measures are being taken to protect these vital water resources.

As a pilot study a small area was selected to begin with. That area extends north from Whites City to Dark Canyon and east of Whites City to Black River. In August of 2005 activated charcoal dye traps (bugs) were place in six locations, three in perennial springs, two in domestic water wells, and one in the outflow of a Carlsbad city water monitoring well. These bugs were retrieved after one month to ensure that samples were taken before any dye was introduced into the system. New bugs were then installed prior to dye being added to drilling fluids during oil and gas drilling operations. New oil or gas wells drilled in the gypsum karst planes were then required to add 16 ounces of Fluorescein dye (Acid Yellow 73) to their surface interval drilling fluid. For wells drilled in the Capitan Massive or Carlsbad limestones 16 ounces of Orange (Eosin Y) dye were added. For wells that were drilled through the gypsum karst overlying the Capitan Massive both dyes were required to be added to the drilling fluid. Due to the large number of wells being drilled and the complexity of the project it was decided to use only two types of dye, one for the gypsum karst and one for the Capitan Limestone group. The amount of dye to add to the drilling fluid was calculated based on the amount of water needed to fill a standard reserve pit for drilling oil and gas wells in that area. This began during the fall of 2005. The bugs were changed out bi-monthly and sent to the Western Kentucky University Crawford Hydrology Lab for analysis. In addition to the dyes that were required to be added to the drilling fluids, analysis was also run for Rhodamine WT. This dye is often used by the industry as a marker dye when conducting pre-flushing operations of the well bore before casing is cemented. During the "pre-flush" the dyed water may also enter karst aquifers.

In 2007 the amount of dye was increased to 32 ounces of 100% powered dye to be added during the initial spudding of the well and to the preflush fluids before casing was cemented. This was done to ensure the amount of dye was sufficient for detection after being diluted by the waters of the aquifers. Additionally, to ensure that dye would be added to both the top and bottom of the karst zones. If dye were only added to the initial spud fluids it could be lost into the perched aquifers in the shallow surface interval and not reach the lower intermediate drilling interval of the Capitan Reef Aquifer.

4. Initial Results

To date 23 wells have added dye to their initial drilling fluids. Fourteen of these wells are in the Castile formation in the gypsum karst planes of the Delaware Basin. Five wells have been drilled in the transition area containing both gypsum karst and the Capitan Reef Aquifer and four wells have been drilled on the crest of the Guadalupe Ridge anticline. Lost circulation has been reported in five of the wells drilled that were using dye. That is not to say that lost circulation zones were not encountered in the surface intervals of other wells, only that it was not reported to the Bureau of Land Management.

All the dye receptors were sent to Western Kentucky University, Center for Cave and Karst Studies, Crawford Hydrology Lab for analysis. All the dye receptors sent in before dyes were introduced to the drilling fluids came back with no Fluorescein detected and a weak background of Eosine and Rhodamine WT dyes detected. After 16 ounces of dye were introduced to the drilling fluids the Able water well came back with a detectable concentration of Eosine of .952 ppb which is nearly 2 orders of magnitude greater than the previous back ground concentration of .042. The dye receptor for this reading was put in on 9/07/05 and taken out 11/20/05. During that time the Estell AD #3 gas well was drilled with both Eosine and Fluorescein dyes being added to the drilling fluid. This would indicate a definite connection between that well and the Able water well but would not explain why there was not a similar recording of fluorescein dye in the same dye receptor.

The Carlsbad City Water Monitoring Well in Juniper Canyon showed a similar increase in detectable Eosine moving from a low back ground level up to .563 ppb. The dye receptors showing the increase was put in on 9/7/05 and taken out on 8/20/06. During that time, four wells were drilled through the Capitan Reef aquifer using Eosine dye. Subsequent dye receptor analysis produced concentrations of .508 ppb and .930 ppb. of Eosine dye in this location. Background levels of Rhodamine W/T have been consistently recorded. No detectable levels of Fluorescein dye were recorded.

Another location that showed significant increases in detectable fluorescein dye was Blue Springs, moving from none detected, up to low background levels (.068), and then up to .601 ppb. Additionally, the detectable concentrations of Rhodamine WT increased from a background level of .049 ppb up to a concentration of 1.017 ppb. This occurred during the fifth sample period. The dye receptor was put in 10/20/06 and collected 5/02/07. It is not known what wells in the area were drilled on private or state lands and which of those wells may have used Rhodamine WT during their drilling operations. Another interesting hit came in June, 2008 with a Fluorescein (acid yellow-73) detection of 1.937 ppb. It was during that time the Hot Seat well #2 was drilled using fluorescein dye.

The Jurnigan Spring location showed none to very low background concentrations of Eosine and Fluorescein dyes during the first three samplings. The fourth sample showed a possible positive detection of Fluorescein dye of .528 ppb. The Fluorescein dye could be from one of the wells drilled in the transition zone of the reef escarpment to basin margin.

At this time the Beard home and Black River locations have only shown below detection levels or background levels of dye concentrations.

5. Technical Questions and Solutions

It appears that there are no "solid" positive (+), very positive (++), or extremely positive (+++) concentrations of dye detected in any of the dye receptor locations. This may be attributed to the increased dilution of the dyes as they move into the aquifers. A second possibility is that once the drilling operation looses circulation into the first open zone all or most of the drilling fluid and dye are lost into that zone. Any other lost circulation zones connecting to aquifers that were encountered below that point that may not receive any dye.

To compensate for these two possible issues the dye amounts were doubled to 32 ounces of 100% powder and a second addition of dye was required to be added after the completion of the surface drilling interval. The dye is added to the pre-flush fluids prior to casing and cementing the well bore. In this way dyes can be pushed into the lower portions of the drilling section and enter the bottom levels of the lost circulation zones.

Another unanswered question is what the residence time of the dye in the aquifers is. This question may be answered as the project progresses but more probably by the design of a different study.

6. Conclusions

Dye tracing oil and gas drilling fluids in the Castile gypsum and Capitan Reef aquifers appears to be a viable way of determining if drilling fluids can enter the aquifers. If dyes are detected, it suggests that failures in the production casing and cementing may also allow hydrocarbons to enter the aquifers. With this in mind, it then becomes incumbent on the land managing agencies and the oil and gas industry to ensure that the best possible drilling, casing, and cementing programs are put into practice. The initial results are conclusive that the drilling fluids do enter the aquifers. The changes in procedures of adding additional dye during the initial spudding of the well and before the casing and cementing of the surface string may aid in producing more detectable concentrations of dye in the collection locations.

The pilot study should be continued and built upon. A more definitive study should be designed and considered to monitor and document the potential impacts in the shadow of impending oil and gas development in the karst areas south of the pilot study area.

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CAVE DEVELOPMENT INFLUENCED BY HYDROCARBON OXIDATION: AN EXAMPLE FROM THE POLISH TATRA MTS

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Abstract

The development of caves influenced by the deep circulation of water has received increasing interest for last thirty years. Deeply circulating waters are characterized by elevated temperature and chemical composition different from meteoric water, which results in its aggressiveness against carbonate rocks, and thus influences the rate of karstification.

In the cave Dziura Wyżnia located in the northern slopes of the Tatra Mountains, huge crystals of calcite spar have been found. Distribution of the crystals shows that they grow during the primary, phreatic stage of cave development. Analyses of the stable isotope composition of the crystals prove that successive growth zones were build up in different conditions. The values of $\delta^{13}C$ increase systematically upwards starting from values as low as -28.8 ‰ (vs. VPDB). Such a low value strongly suggests origin of carbonate deposits due to CO_2 generated by oxidation of methane. It is in line with results of inclusion analyses, which show the trend in crystallization temperature of subsequent zones of the crystals and chemistry of their parent fluids. At the beginning the temperature grew up to ca. 300° C, which is associated with the presence of liquid hydrocarbons in the inclusions. Subsequently the temperature rapidly decreased and oscillated between 162° C and 174° C.

The facts listed above suggest that the parent solutions were composed of two components mixed in different ratios: (i) ascending component of deep circulation containing the carbonate molecules produced during oxidation of methane and, in some stages, also liquid hydrocarbons, and (ii) component of shallow origin which chemical and isotopic characteristics may have been related to meteoric water. The trend of the stable isotope content coupled with the record of temperature changes indicates decreasing influence of the former component during the crystal growth.

As the lower zone of the crystals postdates the origin of the cave itself it suggests that the isotopically light CO_2 derived from methane oxidation played the crucial role in the origin of Dziura Wyżnia cave as well as neighboring Dziura cave with famous ceiling cupolas. The oxidation was driven by mixing of the above described two components of carbonate solution which in turn led to creation of karst caves in the mixing zones. Bearing in mind the common occurrence of methane and its ability to migration the above conclusion have widespread implication. Similar mechanism may be responsible for creation of other hypogene caves all around the world.

STUDY OF TEMPERATURE AND AIRFLOW IN THE SCHELLENBERGER ICE CAVE (BERCHTESGADENER LIMESTONE ALPS, GERMANY)

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Abstract

In contrast to many other European countries, limited research activities in German ice caves have been carried out, notably by several scientists in the 19th century. Recently speleologists have again undertaken such work.

The Schellenberger ice cave has been known for a long time and was first mentioned in 1826 in the Bavarian ordnance map. It is the biggest accessible ice cave in Germany (total length: 2815 m) and is located in the Untersberg massif (1570 m a. s. l.), Since 1925 the cave has been run as a show cave. It is, to this day, only illuminated by carbide lamps, because there is no electricity in this part of mountains. A big entrance leads to the largest hall in the cave with a dimension of 70 x 40 m ("Josef-Ritter-von-Angermayer-Halle"). The entire floor of this hall consists of an approximately 30 m thick and 60000 m^3 ice block. The block is surrounded by the show cave trail. At the deepest point of the show cave trail ("Fuggerhalle") the ice was dated through a pollen analysis to an age of 3000 years b.p. In addition, to the 500 m portion of the cave with ice, there is also one main non-ice part. This non-ice part leads through several shafts to the deepest point of the cave (-210 m).

Although the cave is known since the late 19th Century, only few investigations about the cave climate, glaciology, etc. have been carried out. In this presentation we present a new study and the results of the first year of investigations, which were part of a master thesis at the Ruhr-University Bochum, Germany. In October 2007 three temperature data loggers were installed in three different microclimate zones and different levels of the cave. Because there is no access for electricity and no possibility to enter the cave during the winter time because of danger of avalanches, it has not been possible for us to install sonic anemometers. In June 2008 two more temperature data logger were installed. In October 2008, another datalogger was installed directly on the surface of the big ice block; this logger will be freeze inside the ice during the winter season 2008–2009. The aim of this campaign is to characterize different seasonal aspects of the temperature and airflow regime, to define the climatic behaviour of the cave and its interaction with the ice block, and to define possible reasons for the strong melting of the ice block in some specific parts of the cave. These measurements are the beginning of a long-term monitoring campaign in German ice caves, which shall help develop an idea or even a model of processes, dynamics and controls in German ice caves.

The first results show a partly dramatic "overheating" of the cave during long periods during the year, which cause a strong melting in several parts of the ice cave. They show a warming tendency in the cave during the different seasons. Interior and exterior factors influence the microclimate inside the cave in all zones.

DIFFERENTIATING KARSTIC AND PSEUDOKARSTIC CAVES AND CLOSED DEPRESSIONS IN THE AMERICAN SOUTHWEST, USA

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From Meteor Crater (Arizona) to Devils Hole (Nevada), home of the famous endangered pupfish, a perplexing variety of sinkholes and other closed depressions and related caves exists in the American Southwest (USA). Included are spectacular "punched-out" sheer-walled pits in alluvium, volcanic vents, craters and calderas, crevice caves and pits penetrating through carbonate, volcanic and clastic formations alike, ordinary-looking sinkholes in Pleistocene basalt flows underlain by cavernous formations, and many others. Differentiation of karst from pseudokarst and non-karst often is especially difficult because of (1) superposition of cavernous karstifiable and pseudokarstifiable rocks and (2) occurrence of large and small depressions and caves in various poorly consolidated, poorly soluble materials.

In intensive followup of sporadic observations beginning in 1949, three week-long studies of such features were undertaken in contiguous parts of Arizona, California, Nevada and Utah in 2007 and 2008. Excluded were (1) volcanic craters and calderas, (2) obviously karstic features in carbonate spring deposits (e.g., Dianas Punchbowl, NV), (3) well-known karstic caves, (4) well-known karstic sinks clearly overlying salt or gypsum deposits (e.g., Chevelon Creek Sinks and others in the Holbrook Basin, Arizona), and (5) well-known, previously visited volcanic pseudokarsts in southern Utah and northern Arizona. Not all the areas and individual features planned for these studies could be visited within time constraints. Nevertheless, the variety of observed features initially of uncertain origin was much greater than expected. Among the findings were one lava tube cave of pre-Holocene origin, and the nature of one open vertical volcanic conduit was confirmed. Some slot caves in alluvium were found to be analogous to headward migrating domepits in dense limestone in the southeastern USA. Alluvium Cave, Nevada, was found to be identical with karstic White Beds Cave, but shallow to deep piping has produced caves, "punched-out" sinks and pits in alluvium in widely dispersed areas. In other cases, dissolution of carbonate rocks has produced somewhat similar landforms. Some so-called sinkholes in or adjacent to Pleistocene basalt flows on the "Arizona Strip" appears to be merely surface drainage channels obstructed by the basalt flow, but others are the result of collapse into dissolution or piping cavities. The previously proposed origin by piping of shallow saucer-shaped depressions in outwash gravels of Utah's Cricket Mountains could not be confirmed. The pseudokarstic nature of extensive Bloomington Cave (Utah) was confirmed; it is a three dimensional maze of crevice passages aligned along the strike of a monocline in Permian Kaibab limestone. One small cave entirely in salt was visited; it is close to the location of Jedediah Smiths Salt Cave, destroyed by Lake Mead, but is unrelated to it. Additional studies in these and adjacent states are needed.

1. Introduction

Scattered throughout the American Southwest are closed depressions of varying sizes and types. They range from Devils Hole, Nevada (the much publicized home of the endangered pupfish, most of which is tectonic and, thus, pseudokarstic rather than solutional), to Meteor Crater (Arizona) and large "punched out" sinks along the margin of the Virgin River, Utah, and the Holbrook Basin, Arizona. Some of the largest and most intriguing sinkholes are in thick alluvium. In many cases, it is difficult to differentiate karstic from pseudokarstic depressions (and even to differentiate evaporate karsts from carbonate karst). I began to observe such landforms in 1949 and, with the assistance of several experienced western cavers in 2007 and 2008, I undertook three week-long field investigations in the western part of the region (Fig. 1). A narrative account of these investigations has been published (Halliday, 2008). Here, specific findings and conclusions are correlated with findings and conclusions of George W. Billingsley and other geologists who have studied extensive gypsum karsts of the "Arizona Strip" (the part of Arizona north and west of the Colorado River) and the Hualapai Indian Reservation with particular reference to breccia pipes. Heretofore, breccia pipes generally have been considered karstic in origin.

Billingsley and co-workers term them "solution-collapse features" (e..g., Billingsley et al, 1999: p.1). Because most of their volumes consist of or represent downward-piped clastic material, I include them here as pseudokarstic whether or not they are cavernous.

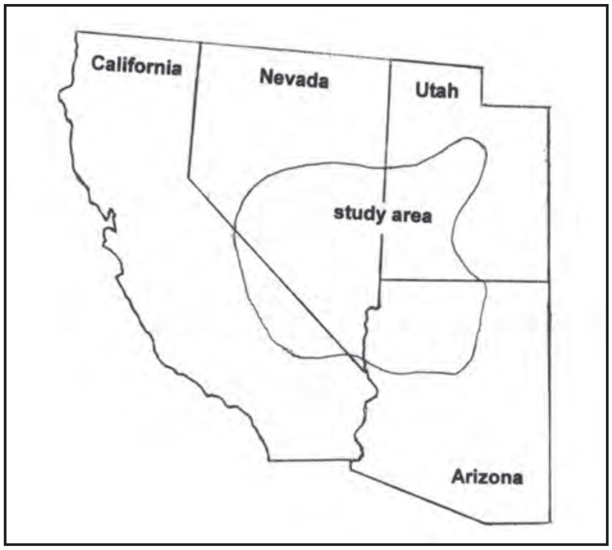

Figure 1: Study area in Arizona, California, Nevada, and Utah.

2. Pits and Sinks in Alluvium and in Thinly Mantled Gypsum

Innumerable individual and compound sinks are present in widespread gypsum karst and in alluvium in this vast, semi-arid area. They vary widely in size and form. Some of the largest and most spectacular are punched-out sinks seemingly entirely in alluvium (e.g., Devils Throat, Nevada, and Mystery Hole, Utah). Yet, numerous publications of the U.S. Geological Survey (e.g., Billingsley et al, 1999) indicate that the diameter of the average breccia pipe in this area is still larger.

Using Billingsley's criteria (e.g., Billingsley et al, 1999), we encountered three closed depressions that appear to be surface manifestations of breccia pipes: Eskdale Sink ("Hole in the Ground"), Utah, Dantes Descent, Arizona, and Littlefield Sink, Nevada. Eskdale Sink is a large, cup-shaped cavity in bleached, limonite-stained limestone, with an incomplete terrace of fine-grained clastics that may represent reworking of alluvium by spillover from Lake Bonneville (Fig. 2). Located in a low ridge of limestone at the western edge of Utah's desert ranges, it is about 200 m in diameter and 35 m deep. Dantes Descent is a vertical shaft about 30 m in diameter and 90 m deep, in dense basalt and underlying Permian red, mostly clastic units, with a funnel-shaped collar of alluvium. It is in gently sloping terrain near Ash Fork, Arizona. Located in alluvium just west of a major fault that demarcates the Great Basin from the Colorado Plateau, Littlefield Sink (Fig. 3). is the smallest of the three examples. It is notable for a hanging plug of characteristic breccia. The rear wall of its terminal grotto is injected by mineral stringers.

Figure 2: Utah's Eskdale Sink ("Hole in the Ground") looking westward into Nevada. For scale, Dale Green is barely perceptible, standing on the rim in the center. The ledge of fine-grained clastics may have resulted from overtopping and reworking by Lake Bonneville. The bedrock is altered limestone and the feature probably is the surface manifestation of a breccia pipe.

Spectacular Devils Throat and Mystery Hole are not as clearly downward piping structures but it is difficult to hypothesize any alternative form of speleogenesis in the alluvium in which they descend. A 1975 map showed the freefall depth of Devils Throat (Fig. 4) as 29 to 46 m, and its maximum width as 43 m (McLane, 1976). Its floor slopes westward (the direction of surface drainage) in an overhanging alcove to a total depth of 71 m. By 2008, block slumping and spalling had reduced its freefall depth to 20 to 38 m. Previously considered to be entirely in alluvium, favorable lighting conditions in 2008 showed that red sandstone is exposed in its overhanging alcove (Fig. 5). Any remnant of piping structures has been covered by sand and gravel. Large salt deposits are present farther west, but major faults associated with two mountain ranges exist in the interval and piping into cavities in local deep-lying gypsum (presumably in the Permian Muddy Creek Formation) appears more likely. Two similar but smaller pits in alluvium recently have been found nearby. Mystery Hole (Fig. 6) appears to be slightly smaller than Devils Throat, and only alluvium is visible in its "punched out" walls. It is located in the mouth of an alluvium-filled canyon of the House Range and its floor slopes toward that range rather than toward Sevier Lake, the local base level. Extensive Paleozoic

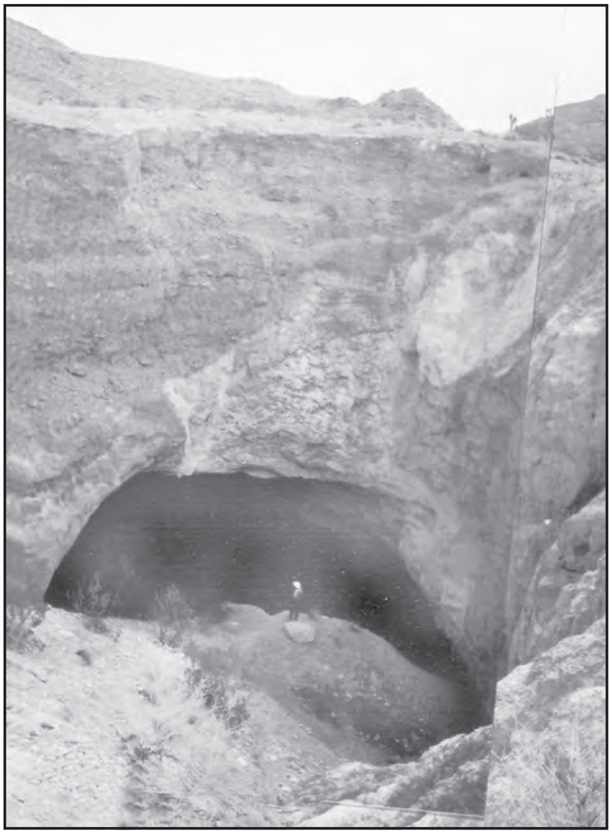

Figure 3: Littlefield Sink is located just west of a major fault demarcating the Basin and Range Province from the Colorado Plateau. The large light gray formation in the center of the photograph is a hanging clastic breccia and the feature appears to be the surface manifestation of a comparatively small breccia pipe.

Figure 4: The northeastern end of Nevada's Devils Throat appears to be entirely in alluvium.

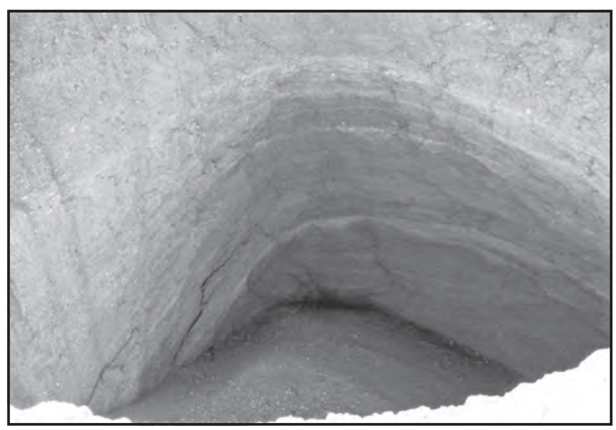

Figure 5: Red sandstone is exposed in the deeper western end of the Devils Throat, within an overhung alcove.

limestone crops out nearby and Mystery Hole presumably formed by downward piping toward buried dissolutional caverns in the House Range.

Smaller closed depressions in alluvium also were investigated. In Nevada's Amargosa Desert, "Alluvium Cave" was found to be well-known White Beds Cave, a karstic dissolution cave in dark grey limestone entered through an overhanging funnel-shaped pit. It apparently was developed by ordinary karstic processes in a presumably Paleozoic limestone, now buried by outwash gravels. Heaton Knolls Cave in the Arizona Strip is at the downslope end of a sizeable sink in alluvium notable for its fill of tumbleweeds. The cave itself is a single low room in the gypsiferous Harrisburg member of the Permian Kaibab formation. Its burrow-sized extensions are utilized by local wildlife. A similar sink adjoining the Larimore Tank basalt flow (see below) ended in impassible channels. U.S. Geological Survey maps of the Cricket Range in southwestern Utah show numerous small closed depressions variously labeled "sinkhole", "sinkholes/pipes" and "Big Sink". All are in outwash gravels in both sides of the range (Hintze, 1984), close to or in the highest terrace of ancient Lake Bonneville. Dale Green (oral communications, 2007 and 2008) previously had investigated nearly all of these shallow features. Neither he nor I found any evidence of lateral or downward piping in this area but without drilling, the possibility of downward piping into two or more unique

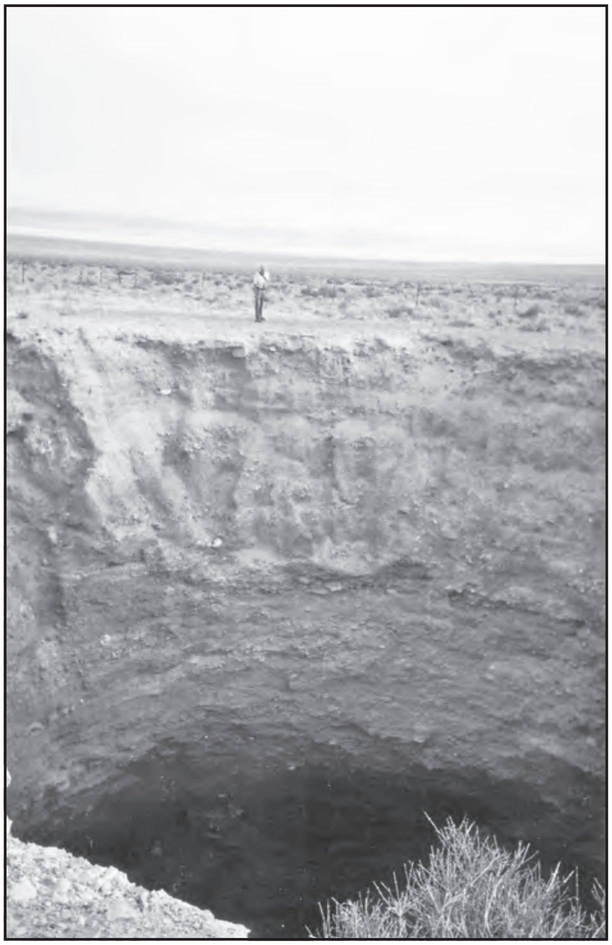

Figure 6: The walls of Utah's Mystery Hole appear to be entirely in alluvium. Sevier Lake is seen in the middle distance, but the feature's floor slopes in the opposite direction, toward limestones in the House Range.

series of dissolution caverns along the buried flanks of this range cannot be excluded. Another possibility is that they are compaction features of Lake Bonneville's reworking of outwash gravels, but similar closed depressions have not been reported in Lake Bonneville terraces elsewhere. They are much too small to be surface manifestations of breccia pipes as the term is generally used.

3. Crevice and Talus caves

Both karstic and pseudokarstic crevice and talus caves exist in this study area. Near Walnut Canyon National Monument, Arizona, in 1949, Dr. Edward Held and I descended into Bottomless Pit (Rio Frio Sink) in a calcareous facies of the Permian Kaibab formation., one of many so-called "limestone solution cracks" in this general area. In the 2007-2008 studies, I confirmed that well-known Bloomington Cave, in a similar facies south of St. George, Utah, is tectonic and, hence, pseudokarstic. It is an extensive three-dimensional maze of crevice passages oriented along the strike of a local monocline. During the 2007-2008 studies, we also encountered crevice and/or talus caves in travertine in Death Valley National Park, CA (Traverkeane Cave), and in basalt flows in the Arizona Strip (Mt. Trumbull Ice Cave and Hoarfrost Cave, a new discovery). Mt. Trumbull Ice Cave is an important biological site.

4. Stream-Cut and Eolian Caves

Two notable stream-cut grottos were visited during these studies and their precursors. Both are locally termed caves but do not fit the scientific definition of this term. The larger is Cottonwood Cave in Death Valley National Park, in a cobble fanglomerate. Its single chamber is 29 m wide and 19 m from the drip line to the rear wall. Height was estimated at 10 m. Also in easternmost California, Whipple Wash Cave is a gaping grotto in a thick Tertiary pyroclastic sequence consisting mostly of welded volcanic ash but with a detached clast of mylonized gneiss along one wall. No special effort was made to investigate individual pocket caves in sandstone, but inverse spheroidal exfoliation was noted in one such sandstone pocket in Lake Mead National Recreation Area, Nevada.

5. Piping Caves in Poorly Consolidated Material

Important caves formed by lateral and other piping in poorly consolidated material were encountered in and near Death Valley National Park, California, and in Cathedral Gorge State Park, Nevada. While the best-known examples in and near Death Valley are the Mustard Canyon group and the Tecopa Caves, those in Cow Canyon near park headquarters are considerably more varied. In addition, important non-cavernous pseudokarstic features were photo-documented in Twenty Mule Team Canyon. These consisted of blind gullies and pseudokarstic dimples. None of the Cow Canyon caves is as much as 50 m long, but they vary from horizontal to vertical, with notable vertical lapies (karren) in Mammoth Well Cave, located at the top of a comparatively steep pitch in the canyon floor. The entrance room of nearby Furnace Cave has an unusual fanglomerate roof. Also in Cow Canyon, No Snakes Cave is primarily a maze of breakdown from collapse of a stream-cut alcove. A few small halite stalactites are present. Three horizontal piping caves near Tecopa, California, previously were known to be up to about 50 m long, with some walking passage. In a nearby gully in borate-rich lakebed deposits, several smaller examples are together with radial crevices at its head, suggesting that piping speleogenesis is an important geomorphic process here. In Cathedral Gorge, similar but smaller piping caves are numerous. In addition, three extremely narrow, extremely contorted "slot caves" are tourist attractions of this park. Their up-slope ends are partially roofed. Characteristically their alluvium walls have well-developed lapies and resemble small migrating domepits in dense limestones of the southeastern U.S. Well-developed but miniature subterranean drainage systems also are present in these alluvial pseudokarsts, with many swallets and well-formed resurgence channels (Fig. 7). Beneath a sloping rhyolite flow, Arizona's Lake Havasu Bat Cave is a wide, spacious piping cave in welded Tertiary volcanic ash. On its sloping ceiling is an unusual multicellular structure several centimeters in height and width. It has the appearance of a fossilized nest of Tertiary wasps.

Figure 7: Most well-developed drainage systems in poorly consolidated material in Cathedral Gorge, Nevada are too small to penetrate. This small cavernous resurgence is alongside the entrance of one of its three "slot caves."

6. Caves and Closed Depressions in Pahoehoe Basalt

Flows of pahoehoe and other basalts are widespread in the Arizona Strip and elsewhere in the study area Here, Pleistocene basalt flows characteristically overlie the Harrisburg member of the Permian Kaibab formation, notable for extensive gypsum karstification. U.S. Geological Survey geological maps (e.g., Billingsley and Priest, 2003) show innumerable individual sinkholes in a variety of Pleistocene basalt flows (and a few breccia pipes as discussed above). The greatest concentration of these features is shown on and adjacent to the Pleistocene Larimore Tank basalt along Mohave County Highway 5. At least three lava tube caves were reported here. We investigated all of these caves and a total of 15 features shown as individual sinkholes. The U.S. Geological Survey Hat Knoll topographic map also shows large, compound depressions within the boundary of this flow, largely unrelated to the relatively small individual sinkholes shown on the geological maps. We attributed the larger depressions to gypsum karstification and did not investigate them specifically. We also investigated the smaller Heaton Knolls lava flow where another lava tube cave (Red Blanket Cave) was reported. All four of the supposed lava tube caves were found to lack characteristic features of such caves (e.g., Larson, 1993). Instead, they were interpreted as volcanic talus caves formed by collapse or subsidence of non-cavernous pahoehoe lava into cavernous spaces in the gypsum karst in the underlying Kaibab formation. The largest of these is Paiute Cave (not to be confused with a breccia pipe near Marble Canyon, also called Paiute Cave). It is an important site for aboriginal art. Most of the designated sinkholes also are collapse or subsidence features, but a few are complex depressions, formed when lava overran or surrounded sections of pre-existing stream gullies. One is the mouth of a deep crevice cave on the edge of a compound sink, and one appears to be a small volcanic vent. The sinkholes originally shown on the geological maps necessarily were identified by stereoscopy rather than by field investigations (George Billingsley, e-mail communication, 2008). The special concentration of such sinkholes on the Larimore Tank basalt may be due to preferential flow of its lava into pre-existing wide, shallow depressions in the gypsum karst. To determine if some other volcanic caves not hitherto visited in the study area also might be volcanic talus caves, the Tabernacle Caves and the Snow Canyon caves in southwestern Utah also were visited. These were confirmed as lava tube caves.

7. Other Caves and Features

Gneiss Cave, a pre-Pleistocene lava tube cave in Death Valley National Park, California, is discussed in a companion paper. The caves of Old Caves Crater, Arizona, are cavernous remnants of a small multifocal eruption center in rhyolite breccia or tuff, modified by prehistoric Native Americans (Barrett, 1923). Salt Cave, Nevada, is in the interface between karst and pseudokarst. Its main room is dissolutional but the entrance passage area is tectonic. In central Nevada, a vertical shaft near the summit of the compound volcanic hill just south of Lunar Crater was confirmed as an open vertical volcanic conduit about 10 m deep and half as wide; the first identified in Nevada. Its ejecta contain many xenoliths. Notable kaminitzas on Permian Toroweap sandstone were photo-documented at Toroweap Point, high above the Colorado River.

Acknowledgments

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USING CONSERVATIVE AND BIOLOGICAL TRACERS TO BETTER UNDERSTAND THE TRANSPORT OF AGRICULTURAL CONTAMINANTS FROM SOIL WATER THROUGH THE EPIKARSTIC ZONE

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Agriculture contamination is very common in karst systems due to the vulnerability of these aquifers. Animal waste is often spread across crop land to enrich the soil with nitrates and phosphates. Herbicides and pesticides are also applied to the crops. The transport of these pollutants through the soil and epikarst is a difficult process to monitor due to the complex, heterogeneous behavior of the groundwater as it makes its way down to the aquifer below.

An experimental site at Crumps Cave lends a unique opportunity to monitor the vadose zone at a waterfall in the cave below. A previous dye trace established the connection of a 11.15 m^2 grass plot to the waterfall mentioned above. This field design, accompanied by a rainfall simulator, allows researchers to control the input of precipitation in an effort to understand more about the movement of stormwater infiltrating the soil and the differences in transportation of solute particles and bacteria in the epikarstic zone. Two particle transport experiments were used to better understand these processes. The first trace involved the rainfall simulated injection of fluorescein dye and sodium chloride. A 2650 liter solution with an average concentration of 60 ppm fluorescein and a conductivity of 10,000 microseimens was injected over a period of 3.6 hours at a rate of 6.6 cm/hr. An electrical resistivity traverse perpendicular to the straight-line path between the established dye trace connection showed a peak in lower resistance at the upper epikarst layers 4 hours and 15 minutes after the beginning of the injection. Dye concentrations reached a peak of 1600 ppb 3 hours and 15 minutes after the beginning of the injection. The conductivity also peaked at this time with a value of 814 □S. This first trace showed that rapid transportation of solutes takes place in localized conduits causing a peak of both solutes in the cave before the widespread mobilization of sodium chloride is seen in the epikarst by the resistivity images an hour later.

The second trace involved a rainfall simulated injection of sulphorhodamine dye over 180 kg of dairy cattle manure spread on the 11.15 m^2 plot of grass. The 2650 L solution with an average concentration of 240 ppm sulphorhodamine was injected over a period of 3.6 hours at a rate of 6.6cm/hr. Dye concentrations reached a peak of 27 ppm 4 hours and 10 minutes after the beginning of the injection. Fecal coliform reaches its first peak of 2755 MPN (most probable number of viable cells per 100 mL of water) 90 minutes prior to the dye peak and a second peak of 2481 MPN 15 minutes prior to the dye peak. These results show that solutes travelling through the soil and epikarst follow similar paths while bacteria prefer conduits that offer more rapid transmission to the resurgence.

1. Introduction

This research aims to resolve some of the ambiguity associated with contaminant transport in the epikarstic zone. The uncertainty of capacity and flow within the epikarst is most certainly due to the fact that this realm straddles the disciplines of karst hydrogeology and soil science. Despite these hurdles, scientists have experimented with the intriguing nature of the epikarstic zone.

Much attention has been given to the topic of epikarst hydrology and geomorphology. Researchers have recognized the differences and overwhelming similarities between epikarst networks around the globe (WILLIAMS, 1983;VENI et al., 2001). Water on its way to the epikarstic zone infiltrates the ground surface and travels through the soil matrix as well as preferential flow paths such as macropores (RAY et al., 1997). The preferential flowpaths in the soil and epikarst enable flashy recharge of the aquifer below while the consolidated soil matrix along with the fractured and inundulating bedrock surface define the storage capabilities within the vadose zone. The flow regimes and storage capabilities of epikarst has been examined by JENNINGS (1985). He emphasized the importance of soil properties and vegetation with respect to vadose zone flow. JENNINGS (1985) asserted the significance of vertical infiltration promoted by colluvial soil structures. Sediments are an important part of understanding groundwater hydrology in karst terrains. LEGRAND (1973) explained the "inversion of soils" in karst which occurs when the majority of the soils in an area are stored in sinks and the subsurface. The ability of the bedrock void to accommodate the sediment from above lends itself to the maturation of macropore networks.

Component separation of spring hydrographs has become a useful approach to studying the factors that affect recharge within karst groundwater basins (EINSIEDL, 2005). This method has allowed researchers to distinguish between vadose and phreatic recharge waters. This important step was necessary for understanding the karst systems since springs are the most accessible and convenient place to monitor a groundwater basin. Many studies have involved monitoring water quality parameters at springs in order to characterize the karst system upstream (HESS and WHITE, 1988; RYAN and MEIMAN, 1996; RAEISI and KARAMI, 1997).

Modeling of karst aquifers has been an important tool in understanding the transportation of contaminants within these systems. WHITE (2003) outlined the differences in many types of karst systems with his conceptual models. Water quality monitoring and particle transport experiments have enabled scientists to evaluate the physical and chemical characteristics of karst aquifers (GROVES et al., 2005; FLOREA and WICKS, 2001; EINSIEDL, 2005). Recent improvements in monitoring techniques and equipment have allowed researchers to become more confident in their conclusions and spread their study areas to a wider radius encompassing many different types of karst systems.

Research has also been conducted investigating the transportation of colloids such as fecal coliform (BOYER and PASQUARELL, 1999; AUCKENTHALER et al., 2002; GÖPPERT and GOLDSCHEIDER, 2007). Cave Spring Caverns has been established as an experimental site to study particle transport and flow within the subcutaneous zone (GROVES et al., 2005). It was previously established that slow and rapid recharges of the epikarst aquifer depend primarily on antecedent moisture conditions and intensity of rainfall. A significant amount of storage in the epikarst aquifer above Waterfall 1 was recognized due to the hydrochemical response of the water at this site.

2. Site Description

Crumps Cave is a well-known cave located about 1.5 km northeast of downtown Smiths Grove, Kentucky. The property is situated in the sinkhole plain 4 km south of the Chester Uplands. The cave, formerly known as Crumps Cave, is a Native American historic site and also protects gray bats, an endangered species. It was featured on a PBS television program emphasizing the cave's archeological significance and praising the conservation efforts of cavers. The previous landowner had been running a respectful historic bed and breakfast operation also making the new name of the cave recognizable to many. The cave has now been purchased by Western Kentucky University with money from a state conservation grant. The cave will now become an outdoor classroom where students will gain hands-on experience with environmental research.

Crumps Cave is contained within the Mississippian St. Louis Limestone Formation and the Lost River Chert Bed is estimated to be located between the land surface and the cave roof. The regional geology dips to the west at one to two degrees. Groundwater flow from the cave has been dye traced traveling to Wolf Sink, Grant-Palmore Cave, Mill Cave, and finally Wilkins Blue Hole in the Graham Springs Groundwater Basin. Vadose recharge within the cave appears mainly along the east wall inside the first section of the cave. These waterfalls will are referred to as Waterfall 1, 2, and 3. Waterfall 1 is the predetermined tributary draining the injection recharge area. This has been determined by previous dye tracing (GROVES et al., 2005).

Soil surveys of the area show that the site is covered with two predominate types of soils. The Pembroke soils of the area are described as being moderately permeable, well-drained soils that formed in loess underlain by residuum of limestone. The soil is generally a reddish-brown silty clay loam which increases in acidity with depth. Chert fragments range from five percent in the upper portions to fifteen percent in the lower portions. Pembroke soils are often found in the same setting as Baxter soils. This is the case at Crumps Cave. The area around the entrance sink is dominated by Baxter soils and the area of the injections is near the boundary of the two soil types. Baxter soils are also moderately permeable, well-drained soils. The parent material of this soil is a weathered cherty limestone. This type of soil is often found in the sinkhole plain where sinkholes have breached the Lost River Chert Bed. The subangular structure of the soil in this case is weak as seen in many colluvial soils. The color of the Baxter soils is yellowish red turning to red with increasing depth. Chert fragments range from about ten to thirty percent. These soils are noted to be strongly acidic to very strongly acidic. Below thirty-eight centimeters, the soil survey notes that there are few fine continuous pores.

3. Methodology

The first trace was on March 5, 2008 (Julian day 64), following the initial background establishment, involving an injection of 1360 grams of fluoresceine and 14.74 kilograms of sodium chloride, both dissolved in 2650 liters of tap water. The dye and sodium chloride was mixed in a large water tank mounted on a flatbed trailer. A hose was mounted on the output drain of the tank and connected to a small water pump. This pump then led to the rainfall simulator where the pressure can be manipulated by the user. The solution was pumped from the tank at an estimated flow rate of 6.6 cm/hr. The injection began at 11:45 and ended at 15:20. A subsequent flush was also done with 757 liters of tap water from a clean tank. The 3407 liters were evenly distributed over a 11.15 m^2 grass plot at the boundary of the Pembroke and Baxter soil types.

Waterfall 1, the predetermined subsurface destination for the tracers was equipped with two automatic water samplers gathering twenty-four samples on a time interval basis of two hours. When these are offset, the combined samples allow one hour resolution over two days. This offset pattern also ensures that water samples were collected if one of the autosamplers failed to perform its program. The bottles were retrieved and replaced by clean ones when the forty-eight hours passed.

A second location for detection of the conservative sodium chloride tracer was a resistivity traverse which was located at an estimated perpendicular slice of the subsurface between the injection location and Waterfall 1. A system of twenty eight electrodes and Sting R1 by Advanced Geosciences Inc. was used. The electrodes were placed every 4.6 meters for a total distance of 123 meters. This layout allowed for a vertical profile depth of 20 meters. Monitoring of this traverse at two hour intervals before, during, and after the injection allows a unique visualization of the subsurface hydrologic conditions.

The second trace on May 6, 2008 (Julian day 127), was another experiment analyzing the upper flow regimes of the system. The precipitation rate remained the same but this trace involved the injection of 1360 grams of sulphorhodamine b. Prior to the injection, 181,437 grams of dairy manure was spread on the ground surface. The amount of fluorescent tracer and volumes of injection and flush water were preserved from the first trace to allow for comparison of the results. The only independent variable was the antecedent soil moisture conditions. The amount of manure was calculated based on statistics for different crops' needs for nitrogen. We used estimates for cool season grasses requirements for nitrogen and eventually calculated that 181,437 grams of manure was needed for the 11.15 m^2 injection area.

Water samples from waterfall 1 were analyzed for dye concentration and fecal coliform. These samples were collected at Waterfall 1 with automatic water samplers using a sampling interval of fifteen minutes for the initial portion of the trace. This interval was accomplished by offsetting two samplers with sampling programs that collect every thirty minutes for twelve hours. The bottles were collected and replaced after the program was complete and the autosamplers were programmed to continue this sampling regimen until the dye peak had clearly past. The interval was then adjusted to sample every thirty minutes between the two samplers.

The bottles used for this trace were cleaned for dyes and sterilized with alcohol to ensure the absence of bacteria prior to the collection of the samples. This is necessary due to the fecal coliform analysis during the trace. Ice was also placed within the bottle carousel and fecal coliform IDEX analysis were ran within 30 hours of collection to follow standard protocol for this type of bacteria analysis.

4. Laboratory Analysis

Charcoal dye receptors were brought to the Crawford Hydrology Lab and released into the custody of the technician that was working at the time. Each receptor is removed from the individual plastic bags and washed thoroughly with tap water. The receptor is shaken until the excess moisture is removed and placed on a drying rack covered with aluminum foil. When all of the receptors have been prepared in this fashion the rack full of receptors is placed in the convection oven for drying overnight.

The next day the technician removes 0.5 grams of charcoal from each receptor and places the samples in small labeled cups. These samples are then eluted with Smart solution prior to analysis in the Shimadzu Spectrafluorophotometer. Water samples in small vials are ready for analysis after rinsing and labeling. Results are reported for each dye in parts per billion.

The IDEX fecal coliform analysis relies on the fact that certain fluorophors will fluoresce when combined and incubated with the fecal coliform. For analysis a fluorophor named Coililert 18 was used which incubates with the water sample for 18 hours at 44.5 degrees Celsius before the sample may be visually analyzed. Samples with a limited volume were diluted in this process with deionized water and the alternate volume was recorded on the sample for later calculation of the concentration.

5. Results

The first trace began at 11:45 on Julian Day 64, 2008. The conductive salt was first recognized on the resistivity images on Julian day 64 at 16:00. The resistivity images show a lower resistance over an area measuring approximately 50 meters. The lower resistance anomaly began to gain resistance in the image that followed at 18:00, until the image reached the approximate background resistance at 20:00. This anomaly was not seen as one localized conduit, but is instead represented by a large area within the estimated top, weathered portion of bedrock. The soil/bedrock interface is estimated to be between 2 and 3 meters below the ground surface. A void is presumed to be beneath the traverse at a 54 meter distance from the beginning of the traverse and is estimated at its greatest height to be about 22 meters below the ground surface. The dimensions of the void cannot be assumed since the feature extends beyond the depth of the measured traverse.

Conductivity measurements of the water samples inside the cave first elevate at 13:00. The peak of the water sample conductivities was at 15:00 with a value of 814 µS. The elevated conductivity curve lasted for approximately twelve hours, ending at 23:00.

Fluorescein dye concentrations were very similar to the conductivity measurements. The first breakthrough of dye in the cave was seen at 13:00 with the peak of dye concentrations at 15:00. This peak concentration of dye was 1660 ppb. The main dye curve reached a lower value of 47 ppb at 19:00 before a small rise in concentration to 69 ppb before falling again and resting at values around 10 ppb at 5:00 on Julian day 65.

The second trace began at 12:20 on Julian day 127, 2008. The first significant rise of dye concentration occurred at 14:15 on Julian day 127 with a concentration of 305 ppb. The dye concentration in the water samples continued to steadily rise until 16:30 where the concentrations reached a peak of approximately 27000 ppb. The dye concentration then began to steadily fall to a concentration of 6093 ppb 2 hours later. The dye concentrations then rose to a peak value of 9359 ppb, 45 minutes later. The concentrations again fell steadily reaching values below 3000 ppb at 21:15, when the values were still consistently dropping but at a lower rate of decline for the rest of the monitoring period.

Background levels of fecal coliform prior to the introduction of the manure average 40 MPN. The first significant increase in fecal coliform count occurred at 14:15 on Julian day 127 when the MPN count jumped to 373. The MPN counts continued to steadily rise to a peak of 2755 MPN, 45 minutes later (15:00). Fecal coliform reached a second peak of 2481 MPN, 75 minutes after the first peak (16:15). Another small peak in the fecal coliform with an MPN of 1860 occurred at 17:30. The last significant peak in fecal coliform occurred at 20:15 with a value of 612 MPN. After this, the fecal coliform MPN values started to steadily retreat towards background levels.

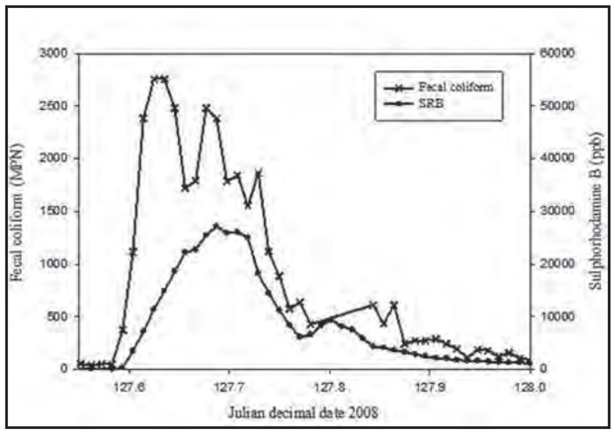

Figure 1. Fecal coliform and SRB concentrations at waterfall 1after the injection on Julian Day 127. Notice the two peaks in fecal coliform prior to the intial dye concentration peak.

6. Discussion

The two traces conducted at Crumps Cave give insight to the transport of solutes and bacteria, as demonstrated by the introduction of salt, dye, and manure. The trace on Julian day 64, 2008, evaluated the epikarstic zone with the additional aid of a resistivity profile. This unique opportunity of geophysical imaging during the trace allowed visualization of the transport process. The tracing experiments have shown that particle transport through the epikarst is rapid when rainfall intensity is very high. While 6.6 cm/hr is a very high value for rainfall intensity, this is a good starting point for understanding how the system will react under high flow conditions.

The first trace results show that solute particles, dye and salt, are detected at Waterfall 1 seventy-five minutes after the beginning of the trace. A peak in these concentrations occurs two hours later at 15:00. The resistivity data collected during the 16:00 hour suggests a widespread mobilization of injected salt passing below the resistivity electrodes. Since the main peak of solutes at Waterfall 1 occurred 1 hour prior to this image, it is assumed that the majority of the sodium chloride mass was transported through localized conduits and preferential flow paths while spatial distribution of the solutes within the epikarst reached its peak after small conduits and fissures had time to fill with the solution.

The results from the second trace highlight the preferential flow paths within epikarst that bacteria travel within. The first peak of bacteria occurred 90 minutes ahead of the initial dye peak. While the concentration curve of dye resembles a uniform recovery, the fecal coliform curve infers that the bacteria are able to choose different paths of greater transmissivity.

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THE KARST HYDROGEOCHEMICAL FEATURES IN THE CATCHMENT OF BAIYANDONG UNDERGROUND RIVER, BAOJING, HUNAN, CHINA

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Abstract

The planning developing project to Baiyandong underground river system, Xiangxi, Hunan is to resolve the potential water supply for the county. Based on the large numbers of field measured data on hydrochemistry, this paper gives a brief t analysis on the features and their dynamical changes of the karst springs water, surface water and underground river water. The results reveal that there are two kinds of karst spring waters in the catchment area, one is related to deep source CO_2 and distribute along with the regional faults, and their main hydrochemical indexes are controlled by the CO_2 concentration. Another is epikarst spring waters which are greatly influenced by the surface environment and the rainfall, the dynamical change of their hydrochemical indexes are obvious in three different measuring periods. The features of hydrochemical indexes of the water in main underground conduit and its branches are in the interposition between of epikarst spring waters and surface water, the data shows that the HCO_3^- , Ca^{2+} and Mg^{2+} content, electric conductivity, and so on is controlled by the diluting processes of rainfall, that is, the more the rainfall the low the concentrations of the indexes.

Moreover, the series of methods often used to study karst dynamical systems and also applied in this research have solved some factual problems, theses method character on obtaining large and exact data expediently.

RECENT OBSERVATIONS IN A REMARKABLY DYNAMIC, SULFIDE-RICH, HYPOGENIC CAVE IN SOUTHERN MEXICO

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Observations over the last decade in a two-kilometer long cave in southern Mexico have revealed a remarkably dynamic hypogenic karst system. During this time, both mineral and microbial wall coverings markedly changed and, at two test sites where material had been completely removed, areas have re-populated to the point that the previous damage is no longer identifiable. These observations suggest tantalizing opportunities to directly observe, test, and quantify some forms of speleothem deposition, passage development, microbial participation in both processes, and hydrologic system dynamics. These observations also document compelling evidence that unique sulfur folia form subaerially, a finding that contrasts with the hypothesized origins of more common calcite folia or mud folia.

1. Introduction

Cueva de Villa Luz (aka Cueva de las Sardinas, Cueva del Azufre) is a two-kilometer long cave in Tabasco, Mexico, currently undergoing aggressive physical and biological speleogenetic processes that have resulted in rapid changes observable over the last decade. The mostly air-filled passages are fed by dozens of small hypogenic, sulfidic, brackish inlets that contribute to an anastomotic, shallow stream which flows through most passages of the cave (Fig. 1). Hose and Pisarowicz (1999) discuss the general characteristics of the cave, and Hose et al. (2000) provide more detailed information on the environment.

Over 12 years of intermittent observations in the cave have

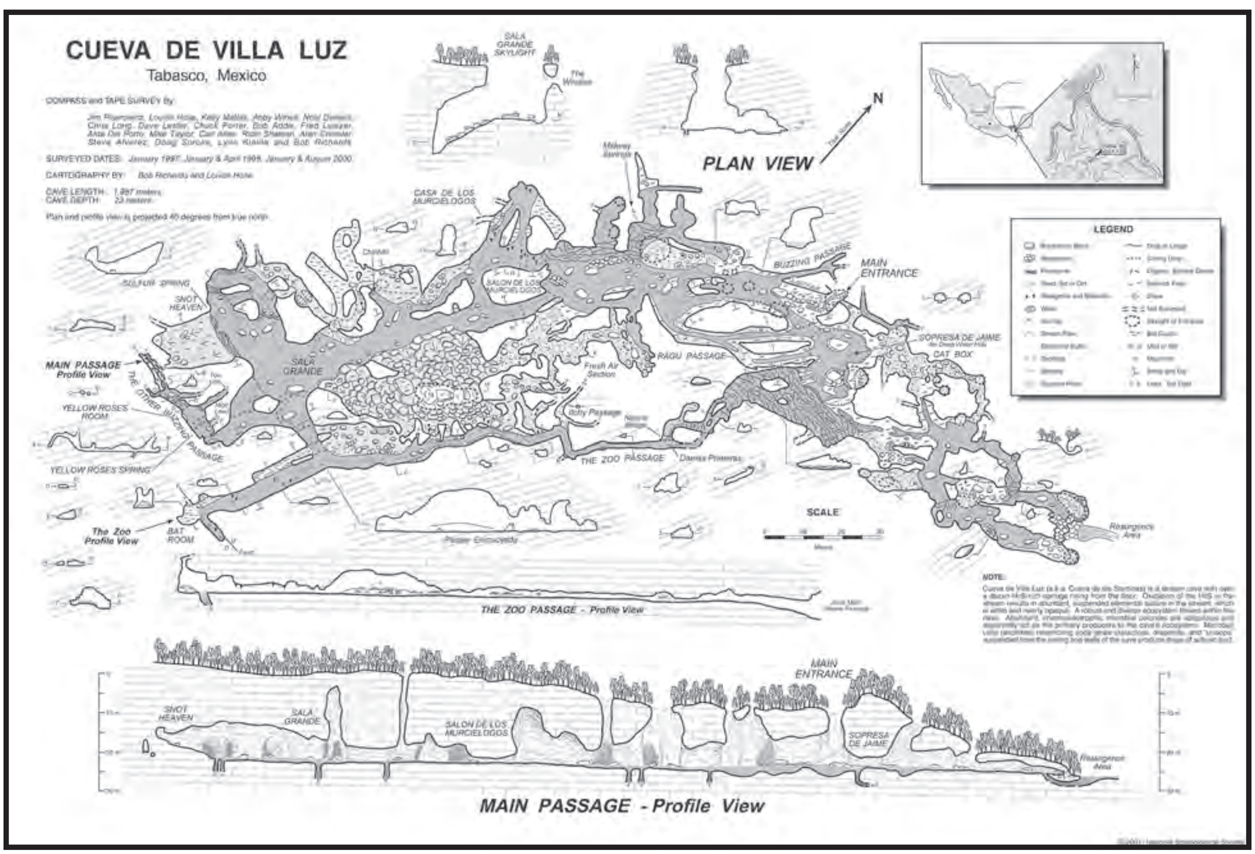

Figure 1: Map of Cueva de Villa Luz.

revealed many remarkable, and some unique, features. Perhaps most curious among these observations have been the rapid change in both mineral (i.e., sulfur crusts, sulfur folia, gypsum paste, and gypsum crusts) and biological (i.e., snottites, biovermiculations) wall deposits as well as changes in water inlet locations. These observations suggest that subaerial speleogenesis in high-sulfide environments may be measurable in a human time scale and that this cave offers an outstanding opportunity to observe and quantify this form of cave development.

2. Hydrology and Atmospheric Chemistry

Twelve years of intermittent observations in all seasons and rainfall conditions has demonstrated that the discharge from the cave to the surface does not fluctuate much from an average base level of approximately 270 L/sec. The stream level will rise a few centimeters immediately following intense, local rain storms but drops within a few hours while the nearby surface river continues to rise ten or more meters. During extended seasonal droughts, the cave stream continues to flow at base level. Stream temperature remains nearly constant at 28° C, as was also reported by Gordon and Rosen (1962) for conditions in 1946. Short-lived temperature drops of several degrees immediately follow heavy rains when meteoric water enters the cave through skylights and fissures.

Initial mapping identified about 20 inlets (subterranean "springs") feeding the cave stream. Over the ensuing decade, more than twelve additional inlets have been identified. The mapping team probably failed to recognize some of these inlets. However, two large upwellings appeared within the last four years at the base of the stairs, in the Main Entrance room where teams commonly stage for entry and clean up following exploration. These inlets have clearly changed since initial mapping in the latter half of the 1990s. Other inlets in the cave have decreased their discharge over the past 20 years.

Two ephemeral environmental factors appear to impact many of the changes described below. First, water chemistry at the various inlets varies temporally. In particular, changes in dissolved gases, particularly hydrogen sulfide, at the inlets result in changes in atmospheric hydrogen sulfide levels throughout the cave. Second, increased rainfall almost immediately results in increased infiltration of meteoric water into this shallow cave. This infiltration provides films of well-oxygenated, fresh water to the cave walls. The moisture mixes with the atmospheric hydrogen sulfide and facilitates several physical and biological processes, resulting in seasonal or temporal changes in the interior of the cave.

3. Changing Snottites

Stalactite-like deposits comprising mostly microbial colonies that drip potent sulfuric acid (pH typically 0–1) were first recognized and named "snottites" by Pisarowicz (1988a; 1988b). Initially considered unique, snottites have since been reported in a few locations elsewhere, including nearby Cueva de Luna Azufre and the Italian Frasassi and Grotta Nuova del Rio Garrafo Caves (Hose, 2005; Macalady, 2007). Typically suspended from selenite crystals and commonly following spider webs, the ephemeral snottites can grow several centimeters in 24 hours. While some specific locations in the cave commonly hold snottites, particularly the area called Snot Heaven, snottite distribution, abundance, location, and size vary dramatically from visit-to-visit, and even day-to-day. Empirical observations indicate that high atmospheric sulfide levels throughout the cave as well as abundant surface water infiltration (i.e., recent rains) promote a healthy crop of snottites.

4. Biovermiculations

Hose et al. (2000) coined the term "biovermiculations" to represent irregular, discontinuous wall mats of mostly organic material that resemble clay vermiculations (Hill and Forti, 1997). Northup (Hose and Northup, 2004) recognized fungi and different types of bacteria including *Acidobacterium* and actinobacteria in Villa Luz's biovermiculations. Jones et al. (2008) found an extremely diverse community of 48 representative phylotypes in Frasassi's biovermiculations. Observations in Villa Luz have shown biovermiculation deposits to be dynamic with significant, visually observable changes occurring over a few months. While changes in vermiculations have been noted in other caves (Jeannel and Racovitza 1929; Parenzan 1961; Jones et al., 2008), we now have a 10 year continuous photographic record of changes at one biovermiculation site in Villa Luz (Fig. 2). All surface coating was removed by scraping with a sterilized knife blade to expose a 3 cm by 3 cm square of bare bedrock limestone in 1999. The changes to that site and the surrounding growth of biovermiculations have been recorded on an approximately annual basis for the last 10 years. By spring 2008, the test square was no longer distinguishable.

Biovermiculations appear to be "pioneer" organisms that colonize nearly all bare limestone in the cave that is not regularly washed by infiltrating surface water or the cave stream. Biovermiculation excretions (pH ranging from 3.0 to 7.8, but typically in the lower, more acidic end) convert the limestone to gypsum. Initially, a veneer of gypsum

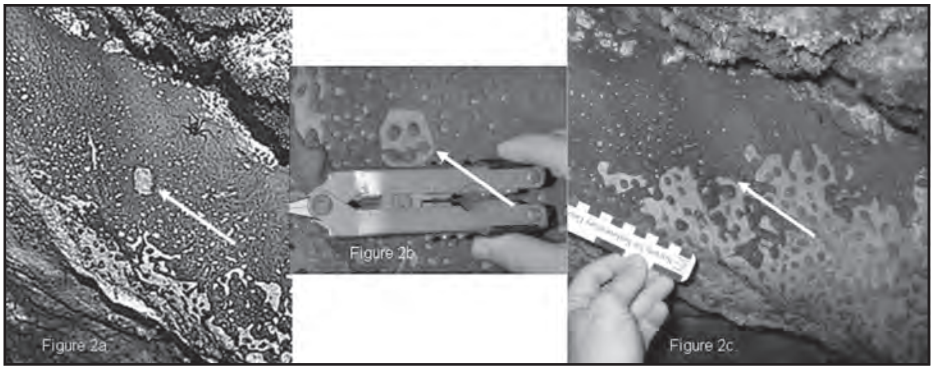

Figure 2: Biovermiculations at a test and monitoring site in the Ragu Passage. a. Site in April 1999, immediately after the 3 cm by 3 cm test patch was formed by scraping away all biovermiculations and any surficial gypsum coating with a sterile knife blade; b. June 2001 close-up photograph shows the test patch during the "happy face" stage of biovermiculation re-population; c. March 2009 photograph shows the test patch area has completely blended with the rest of the biovermiculation growths. It also shows dramatic changes to the general area over the past decade. (White arrows point to the test patch site in all photos.

forms. Interestingly, the biovermiculations will shrink and, in some cases, disappear during dry seasonal conditions to leave subtle "ghosts" that appear to be gypsum powder and clay. Desiccated-looking biovermiculations at the test site during a particularly rainless period (spring 2007) appeared to be coated with a white powder that was interpreted as gypsum. When the biovermiculations "plumped up" the following year, the surface mineral deposit was no longer evident.

Villa Luz's biovermiculations display a wide variety of colors and forms. Locally, dense biovermiculation sites grade into massive mats. When biovermiculations lie below a red clay seam in the bedrock limestone, or where surface clays and silts infiltrate from the surface, the growths are commonly brilliant red and prompted the name "ragu."

5. Sulfur Crust/Mammillaries and Folia

A subaerial sulfur crust that resembles cave mammillaries and folia coat portions of the above-water walls in the most remote passage, named The Other Buzzing Passage. The sulfur deposits begin approximately 15 cm above the stream's standard level and extend several meters up. Direct and instrumented observations along with indirect evidence (e.g., highest level of clastic material) provide compelling evidence that the stream in this area has never risen more than about 12 cm in recent times. The sulfur deposits are most dense on the wall within about one meter of the stream and become progressively sparse upward. The coatings display crystal faces, commonly about 1-1.5 cm across, but have a mushy consistency. P.J. Boston (personal communication, 2005) reported abundant microbial material within the deposits.

The morphology of the sulfur folia strongly resemble calcite and mud folia (Davis, 1984; Green, 1996; Hill and Forti, 1997) but the sulfur form has not been reported outside of Villa Luz. Sulfur folia, like calcite and mud folia, are found on vertical and overhanging walls in hypogenic caves. Adjacent, upward facing slopes display mammillary-like crusts of the same composition. All sulfur and mud folia have relatively small diameters of one to five centimeters, while some calcite versions are much larger. Sulfur folia occur in patches, particularly higher on the walls. This differs from the typically contiguous displays of calcite and mud folia. In addition, while there has been no agreement on the specific mechanism(s) of folia formation, there has been consensus that both calcite and mud folia form subaqueously. The sulfur folia are clearly subaerial deposits.

The massive sulfur deposits grow on selenite crystals, which ubiquitously coat the walls in this area. Some of the folia engulf the selenite (Fig. 3). In 1999, a visitor unintentionally put his hand on the wall and broke off a large (approximately 15 cm x 20 cm) section of the sulfur deposit along with some of the selenite. Most of the chunk of sulfur broke up and (presumably) dissolved in the underlying stream within minutes. This careless, but ultimately fortuitous, act provided a test laboratory to demonstrate the subaerial origin of these sulfur folia. Over the following decade, the site developed a new coating of sulfur. By 2007, incipient sulfur folia were observed and by 2009, the entire area had recovered and distinct folia had developed (Fig. 4).

The water inlets that rise in The Other Buzzing Passage have the highest concentrations of H_2S in the cave, and there is no free oxygen (Hose, 2001). This relatively confined area also consistently contains the highest concentration of atmospheric hydrogen sulfide (H_2S), which has rarely been measured at less than 50 ppm and commonly exceeds 70–100 ppm when visitors are present. These observations lead to the hypothesis that the warmer, sulfidic air rises from above the sulfidic inlet (Lake of the Yellow Roses), mixes with the higher and slightly cooler, oxygenated air

Figure 3: Sulfur folia engulfing selenite crystals.

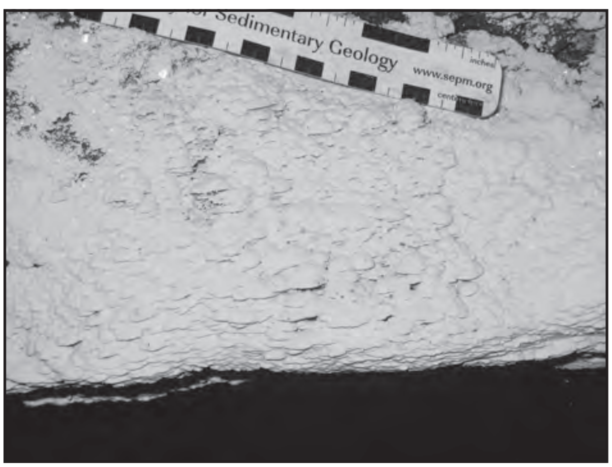

Figure 4: Sulfur folia and crust in March 2009. Ten years earlier, all sulfur was removed from this site when a careless visitor broke off the previous deposit of sulfur. Only the underlying gypsum crystals remained at that time. Subaerial deposits of sulfur progressively developed until the damaged area is hard to identify. Sulfur folia were first noted at this site in 2007.

that circulates into the area from the surface, resulting in the subaerial precipitation of sulfur crystals. The sulfur may precipitate directly on the surface of selenite crystals on the walls or in the air, then drift down onto the walls to form the distinctive folia form. Whether the microbial inhabitants of the sulfur deposits participate in the process or exploit an attractive habitat is unclear with our present knowledge.

6. Gypsum Paste and U-Loops

A gypsum "paste" forms as a weathering rind on some strata in Villa Luz cave. The material has the consistency, texture, and appearance of toothpaste with a typical pH of 3. This rind results from limestone bedrock converting to microcrystalline gypsum and is common in sulfidic caves worldwide. Villa Luz's gypsum coatings, both selenite and paste, are a step along a dynamic process of passage enlargement in which the gypsum regularly sloughs from the walls and ceiling (Palmer and Palmer, 1998; Hose et al., 2000). This process is so active that investigators have experienced spontaneous and, apparently, natural "paste-falls" from the cave ceiling on several occasions.

The gypsum paste also flows as a viscous liquid and can form small stalactite-like features. Common spider webs in the cave can direct flowing gypsum, resulting in "U-loops" of gypsum paste (Fig. 5). While previous researchers have proposed snottites as a possible model for the origin of calcite u-loop speleothems (Northup et al., 2000), these U-loops of gypsum paste provide an attractive alternative. The conversion of gypsum to calcite is well-documented in natural systems and seems more likely than conversion of an ephemeral, mostly microbial material to long-surviving calcite.

Figure 5: U-loop of gypsum paste. Microcrystalline gypsum has flowed down and engulfed spider webs, forming "u-loop" features.

7. Conclusions

Ten years of observations have demonstrated that Cueva de Villa Luz is a dynamic, high energy system producing rapid changes that are unparalleled in most limestone cave systems. Preliminary records of growth and changes in folia deposits over only a decade provide tantalizing possibilities for better understanding the mechanisms and conditions leading to folia development. More detailed studies of dynamic biovermiculation growth may also lead to a better understanding of the role biovermiculations play in speleogenesis as well as possibly providing clues to the origin of more common clay vermiculations. More generally, this active, sulfidic cave system, balanced with an environment that allows direct exploration and study by humans, provides unparalleled opportunities to learn about hypogenic speleogenesis in a redox environment dominated by accelerated subaerial processes.

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THE BIG CAVE AND CHAMBERS IN POYUE UNDERGROUND RIVER DRAINAGE IN SOUTH CHINA AND ITS CONTROLLING FACTORS

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Based on the statistics to the caves developed in Poyue underground river drainage, the authors found that there exist several large passages and 25 huge chambers with the area over 5000 m^2 in the karstic terrain developed the Poyue underground river system. The authors analyzed the controlling factors, such as the geological aspects and the climate and hydrological factor. The results show that the allogenous water may play a key role in the formation of the big passage and huge chambers.

1. Introduction

Abundant huge passages and chambers have been discovered in the karst terrain of the Poyue underground river system drainage. The features do not share the same developmental history with the large caves in the world. In order to explain the speleogenesis, we discuss the characteristics of the large passage and chambers and their developmental history to find the controlling factors.

2. The World Class Big Caves and Chambers in Poyue Underground River Drainage

As one of the four largest underground river system drainage in Guangxi, South of China, Poyue underground river system drainage covers an area of 1484.55 km^2, including the 708.35 km^2 within the clastic rock mountains that surround the 776.20 km^2 carbonate terrain. The subterranean river system is composed of several ramifications and is recharged by inflows that originate from the non-karstic rocks along the contact zone between the carbonate rock and clastic rocks, with a mean flow rate of 5796.8 L/s at its resurgence in dry season. As the source of the underground river, they disburse in the karst terrain of the Poyue underground river system drainage. The caves featured by their huge passages and big chambers may be among the largest caves in the world.

According to the geologic and geomorphic analysis and the survey results of cave exploration made by several sino-foreign joint expeditions since 1988 ,the authors deem that more than 500 caves had been generated in the drainage, and most of them may be big caves or be developed with big chambers.

2.1 The large passages

At present, there are several classifications of cave size. Generally, we can determine the size of a cave from some basic parameters, such as the length, width, height, and bearing, obliquity,etc. But, it is not easy to contrast the size between/amongst two or more caves to determine which one is 'bigger' from the survey parameters mentioned above. On scientific research, one must compare exactly cave size so as to contrast their dynamic condition of formation. We prefer to use the parameter "specific volume" (J.Gunn, 2003) to describe the size of a cave for it is more scientific for comparing different cave with different lengths. In addition, we still appreciate other parameters. But, in accordance with our primary research results (Zhang et al, 2008), the specific volume is the key parameter to describe the size of cave, especially the cave developed in the big drainage of subterranean river system. Here, we give the definition of the specific volume as the ratio of cave volume to horizontal length.

Intuitively, the big passage of the caves in Poyue underground river system hit us between the eyes for most of the passages are much greater than 20m in wide and high. From the data on Table 1,we found that the specific volume of the caves varies from 57 to 13380 m^3m^{-1} , most of them is more than 600 m^3m^{-1}. In order to evaluate the size of these caves, owing to the paucity of the similar data, we select two gigantic caves to compare. One is the Skocjanske jame caves in Slovenia and another is Deer Cave in Malaysia. The total length of the former cave is 5800 m. Only two section—Hankejev kanal and Mariniheva jama are the main big passage. Hankejev kanal is a gravitational canyon passage, 1 km long, with the maximum width of 55 m, height of 98 m, its volume is 2.000.000 m^3. So, the specific volume is 2000 m^3m^{-1}. Mariniheva jama is a passage with the length of 200 m, maximum width of 65 m, maximum height of 37 m, and volume of 230,000 m^3, then we can get the specific volume of 1150 m^3m^{-1}. Deer Cave in Malaysia is famous for the 162,700 m^2 chamber—the largest chamber in the world. It is 2160m long with the volume of 13,170,000 m^3, so its specific volume is 6097.2 m^3m^{-1}, the big digital is owing to the gigantic Sarawak Chamber, which is 600*300* 100 m. So, most of the caves in the Poyue underground river system drainage can compare favorably with the largest caves in the world.

Name of Cave or Section	Horizontal Length /m	Depth /m	Mean Height /m	Mean Width /m	Slobe /°	Floor Area /m²	Cave Volumn /m³	Surface Area /m²	Surface Volumn /m³	Specific Volumn /m³.m⁻¹	Specific Length /km.km⁻²	Area Ratio /%	Volumn Ratio /%
Jiangzhou System													
The whole	37939.7	281	49.7	27.6	9.7	1141188.9	28944498	26412398	7421976952	762.9	1.4	4.32	0.39
Section A	11349.2	212.4	23.1	26	10.5	334875.3	7671950.3	6760888.1	143600968	676	1.7	4.95	0.53
Section B	4705.6	84.9	22.6	29.5	5.8	124504.7	4100804.7	2170575.1	184273804	871.5	2.2	5.74	2.23
Section C	3337	64.9	53.4	15.3	7	74806.8	783374.5	407686.8	26470030.5	234.8	8.2	18.35	2.96
Section D	3592	76.6	59.5	29	6.5	127787.5	3024965.4	1356827.8	103980874	842.1	2.6	9.42	2.91
Section E	4366.1	179.5	40.3	41.2	11	202327.1	7397150.3	1068647.8	191817230	1694.2	4.1	18.93	3.86
Section F	6822.2	230.1	32.2	25.8	11.2	216855.7	4549134.1	2033263.7	467886195	666.8	3.4	10.67	0.97
Section G	252.9	22.6	7.3	9.6	12.4	1415.9	23277	6261.8	141294.6	92	40.4	22.61	16.47
Section H	500.2	80.5	25.9	42.4	15.7	14363.6	899790.9	34948.2	2813413.8	1798.9	14.3	41.1	31.98
Other Caves													
Dadong	1092.9	117	19.1	9.7	10.4	13006	102488.6	100354.4	11740816.1	93.8	10.9	12.96	0.87
Shendong	673.5	33.6	20.3	17.8	5.4	13971	213185.2	148787.6	4998678.5	316.5	4.5	9.39	4.26
Sifang	1532.8	58	14.4	20.9	7.4	37087.3	671091.3	242554.2	14074975.4	437.8	6.3	15.29	4.77
Dongli	749.1	55.3	23.8	26.8	4.5	28659	537855.3	133171.1	73673334.9	718	5.6	21.52	7.3
Mayoni	1625.6	58	21.3	43.5	6.2	68091.3	3076728.7	544860.8	31625772.6	1892.7	3	12.5	9.73
Maguai	738.2	38.5	18.9	15.3	12.2	16200.9	173076.8	73764	2839192.4	234.5	10	21.96	10
Green River	3235.2	90.4	10.6	37	6.8	134639.1	4423095.9	1630317	145511253	1367.2	2	8.36	3.04
Longshi Shaft	841.5	169		20	23.9	18280.6	336812.1	117927.6	1930018.8	400.3	7.1	15.5	1.69
Dashan	1447.1	172	22.5	36.2	13.9	64067.1	1892014.5	231343	39795633.9	1307.5	6.3	27.69	4.75
Crystal	794.4	40.2	19.3	20.3	9	22006.9	327930.9	88610.8	3560685.4	412.8	9	24.84	9.21
Cemetery	1319.9	43.2	11.9	7.6	6.9	8502.1	75892.5	401940.4	17351102.9	57.5	3.3	2.12	0.44
Feilong	192.5		70	55		10930	2575600			13379.7			
Shegeng	220		68	110		24200	2584900			11749.5			
Mawang	6620		100	50		2940000	32234400			4869.2			
Yuanyang	260		30	90		22500	1071000			4119.2			
Chuanlong	370		42	120		41500	1453200			3927.6			
Yunfeng	514		25	33		38600	1007400			1959.9			
Yulong	1350		40	40		61350	2454000			1817			
Siccily	1021		30	36		27950	839430			822.2			
Poxia	1112	□	34	20	□	22400	727700	□	□	654.4	□	□	□

Table 1: Some Representative Passages of Caves Developed in Poyue Underground River System Drainage.

2.2 The huge chambers

Besides the big passages, there still exist lots of enormous halls developed in the caves. A cave chamber is a special passage in a cave that is prominently larger than the adjoining areas. The results of statistics on 50 chambers over 5000 m² from 14 caves developed in the upriver reach of the Poyue underground river system drainage show that half of the chambers are over 10,000m² in area. Four of them are more than 20,000m² (Table 2) and six of them are over 25,900 m², accounting for one-sixth of the 24 world-class cave chambers over 25,900 m² in area. So, we can call the terrain located in Fengshan county one of the huge-chamber-area and the densest-distributing district of cave chamber in the world. For example, there are 24 chambers over 5,000 m² in area distributed within the 37.9 km of passages in the Jiangzhou System, which is currently the third longest explored cave in China. Nine of the chambers are over 10,000 m² in area.

3. The Geological Setting of the Huge Passage of the Caves

The research area is one of the isolated carbonate platforms in the Youjiang Depositional Basin formed during the Hesian—Indo-Sinoian Stage. The isolated carbonate platform was surrounded by big faults. Continuous deposition of the 3156 m thick sequence of carbonate rocks took place from Middle Devonian to Early Triassic. During the middle Triassic, the whole area was again submerged into a marine environment, then was covered by the 3000 m thick sequence of clastic rocks. During these stages (D_2-T_2), tectonic activity was not prominent, dominated by small-scale vertical activity. Since Late Triassic, all strata was folded

No.	CHAMBER NAME	CAVE NAME	LENGTH /m	WIDTH /m	AREA /m^2	MAXIMUM HEIGHT /m	MEAN HEIGHT /m	VOLUMN /m^3
1	Fengshan museum	Chuanlong	372	96-140	41,500	45	30	1,245,000
2	Nantianmen	Mawang	320	88-260	38,400	200	150	5,760,000
3	Zhuanwan	Gantuan	320	60-160	31,200	87	50	1,560,000
4	Luxi	Green river	240	100-110	26,220	105	90	2,359,800
5	Yuanyang	Yuanyang	260	45-130	29,250	130	107	3,129,750
6	Dongkou	Gantuan	375	45-131	25,900	135	80	2,072,000
7	Chuandong	Shegeng	220	78-142	24,200	76	70	1,694,000
8	Yangguang	Yunfeng	220	53-120	20,960	32	20	419,200
9	Dongdong	Mayoni	210	80-120	20,450	100	60	1,227,000
10	Creaked Mud	Jiangzhou system	264	40-83	18,500			
11	Maguai	Maguai	340	45-74	17,000	50	30	510,000
12	Nanfang	Mawang	240	40-88	16,800	165	150	2,520,000
13	Longhuai zoulang	Jiangzhou system	200	50-90	16,500	55	40	660,000
14	Xiepo	Jiangzhou system	228	36-96	16,461	65	40	658,440
15	Moduan	Gantuan	155	120	15,000	54	30	450,000
16	S.Junction	Jiangzhou system	165	24-130	14,920			
17	Dongfang	Mawang	200	60-80	14,500	78	40	580,000
18	Mud	Dongli	260	40-65	14,300			
19	Zhonglian	Jiangzhou system	212	58-95	13,992	95	60	839,520
20	Xiagu	Jiangzhou system	225	31-68	13,050	54	40	522,000
21	Liangdong	Liang	271	27-67	12,500	47	35	437,500
22	Dinner Time	Jiangzhou system	284	14-54	10,792			
23	Wuyan	Green river	150	40-85	10,670	49	40	426,800
24	Colossus	Jiangzhou system	188	32-70	10,524			
25	Terragotta	Jiangzhou system	164	44-90	10,168			
26	Houduan	Liangfeng	160	40-60	9,650			
27	Gloopsville Junction	Jiangzhou system	160	24-57	9,600			
28	Minaret Stal	Jiangzhou system	130	38-86	9,320			
29	Hijack Junction	Jiangzhou system	214	18-56	9,202			
30	Longhuai	Jiangzhou system	135	48-94	9,108	48	30	273,240
31	Monumentale	Siccily	130	45-80	9,000	60	42	378,000
32	Zhongduan	Yunfeng	120	50-104	8,800			
33	Cauliflower	Yulong	160	30-80	8,800			
34	Stal Graveyard	Jiangzhou system	122	37-110	8,549			
35	Gours I	Yulong	160	30-73	8,500			
36	Jianduan	Liangfeng	120	60-80	8,500			
37	Football Pitch	Jiangzhou system	135	28-67	8,100			
38	Pink Pyjamas	Jiangzhou system	110	25-95	7,920			
39	Fishing Pitch	Jiangzhou system	176	14-70	7,392			

40	Zhongjian	Mawang	120	40-75	7,200			
41	Xuezhu	Jiangzhou system	90	56-93	7,146	39	20	142,920
42	Piste	Jiangzhou system	156	16-56	7,020			
43	Entrance	Siccily	90	45-77	6,400	50	40	256,000
44	Shaobing	Jiangzhou system	94	26-80	6,288	55	40	251,520
45	Shiqiao	Jiangzhou system	150	30-60	6,145	95	60	368,700
46	Rukou	Hei	105	55-60	6,000	31	30	180,000
47	S.Herb Garden	Jiangzhou system	97	22-90	5,459			
48	Gours II	Yulong	115	20-80	5,400			
49	Cave Pearl	Jiangzhou system	90	45-64	5,035			
50	Tapehandle Junction	Jiangzhou system	148	23-54	5,030	□	□	□

Table 2: Some Cave Chambers in the Poyue Underground River System Drainage.

and faulted by the Indo-Sinoian Tectonic Movement and the whole structural framework was formed. Furthermore, it was lifted as a land environment and suffered from large-scale weathering for eighty million years. Eventually, during the Middle Jurassic, the clastic cover above the isolated carbonate platforms was eroded and exposed the carbonate rocks. According to the paleo-geomagnetics research result, the latitude was one to two degrees lower than now. Karstification in the tropical climate began but the karst forms were later erased away.

In the Cretaceous Period, a large lake basin formed in Guangxi in the arid or semi-arid climate conditions, depositing a set of red or morassic sediments, but it has since eroded in research area. From the Cenozoic on, a tectonic history of intermittent crustal uplift and karstification may be divided into three stages:

The first stage is from the latest Cretaceous to Early Tertiary when the crust was in steady state, after long-term erosion, an old land surface leaning southeastward was formed and only a few part of them can be found on the oldest the clastic peaks because most of it has been erased away. But, the present drainage system (including the surface and underground river system) had not been created at that time. The stream was in a disperse state.

The second stage is called the Fengcong Stage (Peak-cluster Stage) and dates back to neo-Tertiary to Eocene. The Qinghai-Tibetan Plateau rose rapidly due to the collision between the Indian Plate and the Euro-Asian Plate. Development of the lake basin in the whole Guangxi Region was finished and erosion restarted. The climatic condition was transformed into a regional monsoon climate by the planetary wind system, resulting in a humid tropical and sub-tropical climate. The activity of the surface stream was strengthened and the ancient hydrological net was generated. Then the fengcong (peak-cluster) was formed in the bare carbonate area as downcutting led to the formation of underground rivers and caves. In this stage, the geomorphic forms were dominated by the fengcong-depression/valley owing to the vertical movement of water.

The third stage begin in Quarternary. Yunnan-Guizhou Plateau continued to be lifted, Hongshuihe river—the key erosive base—incised more deeply, the research area was relatively uplifted, the caves formed previously were lifted up gradiually, their passages were enlarged due to the synergetic balance amongst the velocity of downcutting surface and underground rivers, and erosion (including dissolution) took place.

4. Controlling Factors to the Formation of the Big Caves and Their Chambers

A cave is the combination of dissolution, erosion, and collapse (Bogli,1980). In south China, most caves belong to the rainwater-type of speleogenesis. It is generated by the rain water and its secondary seepage flow (Zhu, 1988). According to our research, the caves in the research area originated with underground rivers in the phreatic zone (Ford, 1988). So, the water may play an important role in the formation of the big passages of the caves. The controlling factors of the development of the huge passages and chambers may comply with those controlling the growth of relatively small caves, such as base level and dynamics condition.

4.1 Rock condition

The bedrock of the cave in research area come mainly from Carboniferous and Permian strata. The old, pure, and solid carbonate rock are more favorable for karstification, with the consecutive thickness of 1077–3156 m, than “soft,” ”young,” and “high-void” carbonate rocks, such as those along the Mediterranean Sea, London Basin, and the East Europe (most of them are Mesozoic), those in Nallorbour Plain, Paris Basin, and Caribbean area (most of them are Tertiary), so there exist a huge passage in the research area. The rocks are strong enough to support and maintain any landforms, even large scale, for a long time.

4.2 Geologic structure and hydrogeological condition

Faults and joints are favorable for the transportation of water and dissolution of carbonate, facilitating cave passage development. Furthermore, a passage collects more and more water flow from the contiguous area, making the Poyue underground river more and more competent to carry more and more substance. Eventually, the passage get larger and larger. The junction of different fissures is favorable for the big chambers for the mixing-corrosion by two or more flow.

The intermittent uplift of the crust may be favorable for the velocity balance amongst the crust uplift, dissolution, and erosion at some part of the passage to form the gigantic hall and enormous passage. The most important point must be emphasized that the structure of karst and non-karst area (i.e., the relative low density of karstic terrain) is surrounded by the clastic mountains comprising the materials bearing the pyrite and other sulfate minerals depositing mainly in deoxidizing environment in deep water .The oxidizing of sulfate may supply more acidic matter to make the water more acidic, the karstification may be strengthened. Besides, the contact zone between the carbonate rock and non-carbonate rock is always the regional fault where some sulfate-bearing hot liquids were easily transported and stored or enriched as ores. The sulfate can play the same role in the formation of big passage. In addition, the allogenic flow generated from clastic rocks is always more acidic and erosive, the analyzing result of water sample has attested to this.

4.3 The synergetic water – heat condition of monsoon climate

The major karst forms in the research area were formed consecutively from Pliocene to Quaternary owing to the humid and warm, tropical and subtropical climate. According to the analyzing result of spore and pollen in neighboring areas, heat tolerant members account for over half of the sample, which show that it was a humid and rainy climate, and the temperature in the Pliocene was higher than present. In the Quaternary, the climate was still humid subtropical and tropical in spite of the fluctuation of ice period.

At present, a subtropical monsoon climate with mean annual precipitation of 1400 mm and mean annual air temperature of 17°C prevails. The hot season corresponds with the rainy season. The synergetic water-heat climate condition is favorable for the dissolution of carbonate rock.

5. Conclusions

The Poyue underground river system drainage is the premier place for the development of the largest cave chambers and passages in the world. The enormous passages and gigantic chambers are a production of the Poyue underground river system under special geologic structural and hydrogeologic conditions. In the world, most of the largest passages developed in the areas with the most abundant rain precipitation. For instance, rain falls up to 5000 mm in Malasia. So, it is significant for scientific research on the genesis of big caves and for cave expedition.

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TWENTY YEARS OF MONITORING, TESTS, AND EXPERIMENTS IN THE MILANDRE CAVE, JURA MOUNTAINS, SWITZERLAND: INPUTS FOR KARST HYDROGEOLOGY

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Abstract

The Milandre cave is a 10.5 km long cave with an underground stream, which can be followed from the spring upstream for 4.6 km (3 km as the crow flies) with an entrance at both ends. The cave is one of the most decorated ones in Switzerland and the spring is used as a drinking water supply by the community.

The construction of a freeway on top of the cave implied a lot of studies concerning engineering issues, groundwater protection and cave protection. Fundamental research on karst hydrogeology and geophysics was also carried out. Concerning karst hydrogeology, this research makes this site one of the most studied in the World.

A really interesting aspect of this test-site is that many experiments and measurements could be undertaken to verify in the field, whether the real karst system behaves the way we expect it to from spring data interpretation of from models. For instance the respective effect of soil, epikarst, vadose zone, cave stream and phreatic zone on the generation of hydrographs, chemographs and isotopic variations could be investigated with a high degree of detail.

Also, the realization of various experiments (e.g. tracer tests or infiltration tests) and their related interpretation models could be compared to models derived from other types of data (e.g. chemographs or isotopic variations) and to direct observation of the expected processes in the cave. This leaded us to revise our own interpretation models several times along those 20 years of experience. A critique of many models found in the literature is being prepared with this sum of experience.

For instance the storage component feeding the system during draught periods has been much better understood, as well as processes occurring inside the conduit system, which are responsible for many unexpected variations of the water quality. As an example, mechanisms controlling particle transport and water turbidity could be understood in a quite different way than what can be expected from the literature. Observation and development towards cave biology and its relation to the respective parts of the aquifer (soil, epikarst, vadose zone, underground stream and phreatic zone) is one topic we just started to develop. Collaboration in this domain is welcome.

This cave could be considered as a real laboratory and could be used in the future for experiments at a more international and interdisciplinary scale.

IMPACT ASSESSMENT OF A TUNNEL ON TWO KARST SPRINGS, FLIMS, SWITZERLAND

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Abstract

In October 2002 a karst conduit was cut by the road tunnel next to the Flims village in the eastern Swiss Alps. A discharge rate of 800 l/s was measured shortly after. In winter the discharge rate decreased down to about 200 l/s, but increased again with the snow melt.

Fifteen months later (in February 2004) the Lag Tiert karstic spring located 2.2 km away dried up. For more than 40 years, the spring has been used for an electricity power plant and it never dried up. Is the tunnel responsible for this drying up? Why did the spring dry up only 15 month after the tunnel hit the conduit? The year 2003 was extremely hot and dry in central Europe, could it be the reason for this drying up? How much water does the spring miss?

The owner of the electricity power plant asked us to answer those questions. Another spring was later identified to belong to the same system. The Lag Prau Pulté spring is an overflow spring of the Lag Tiert feeding a beautiful lake which is very attractive for the tourists in summer. The community asked us to study the effect of the tunnel on the lake.

We asked the civil engineers building the tunnel to make a dam in order to be able to raise the pressure of the karst conduit in the tunnel and to see if the springs respond to such pressure steps.

A large series of pressure tests were run by low and high water situations between November 2004 and September 2008. During the first tests (at low water stage) Lag Tiert spring responded 1 minute after the pressure steps. The same tests made in 2008 evidenced a clear difference in discharge rates in the tunnel, showing an increase in permeability towards the tunnel (erosion of infillings). However, the Lag Tiert spring as well as the Lag Prau Pulté spring did not show any reaction (or very slight) during tests at high water stages.

As these results could hardly be understood a numerical pipe flow model was applied. It could reproduce measured results with a fair precision and could explain why springs react at low water stage but not (or hardly) at high water stage. It was also possible to evaluate the impact of the tunnel on the spring's discharge.

TRACING GROUNDWATER FLOWPATHS IN THE EDWARDS AQUIFER RECHARGE ZONE, PANTHER SPRINGS CREEK BASIN, NORTHERN BEXAR COUNTY, TEXAS USA

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Abstract

The Edwards Aquifer Authority injected non-toxic organic dyes into six caves within the recharge zone of the San Antonio Segment of the Edwards Aquifer to trace groundwater flowpaths and measure groundwater flow velocities. The monitoring system consisted of 32 public and private wells, including irrigation wells completed in either the Edwards Aquifer or the underlying Trinity Aquifer.

Results of the tracer tests revealed discrete groundwater flowpaths associated with Panther Springs Creek. During most tests, dye was detected in well 68-28-608; however, dye was also detected in seven additional wells. Groundwater velocities to well 68-28-608 ranged from 1134 to 5283 m/day; velocities to the seven other wells where dye was detected ranged from 13 to 2330 m/day. These are apparent or minimum groundwater velocities since velocities can only be calculated between injection and detection points. The results demonstrate the high groundwater velocities that are characteristic of karst aquifers. The results also indicate that groundwater flows freely between injection points in the upper member of the Glen Rose Formation, the stratigraphic unit that comprises the Upper Trinity Aquifer, and detection points in the Edwards Aquifer. Dye was injected into the upper member of the Glen Rose Formation through Boneyard Pit, Genesis Cave, and Poor Boy Baculum Cave, which penetrate the Edwards Aquifer. Dyes traveling along the flowpaths between the caves and wells crossed several northeast-southwest trending faults in which members of the Edwards and Glen Rose formations are juxtaposed. Faults with up to 104 m of vertical displacement did not impede groundwater flow. Consequently, the tracer tests show excellent communication between groundwater in the Upper Trinity Aquifer and the Edwards Aquifer. One trace through soil, in a 1-m^2 interstream upland area where no karst features were evident, was shown to accept 180,000 L (250 L per hour) of recharge over a one-month period that flushed dye to at least two Edwards Aquifer wells. This trace demonstrates that aquifer vulnerability to contamination is not limited to recognizable karst features. The study revealed the three-dimensional groundwater flow system in the Edwards Aquifer in the Panther Springs Creek area. Groundwater flowpaths shift laterally and vertically in response to changing aquifer conditions. These tests also highlighted the anisotropy such as discrete groundwater flowpaths, aquifer characteristics that change with water levels, wide-ranging groundwater velocities, vertical groundwater flow, and rapid response to precipitation that exists in karst aquifers that is often underrated or even ignored while characterizing groundwater systems. Finally, this study demonstrated the diverse data necessary to characterize a karst aquifer system, including tracer tests, hydrophysical surveys, continuous water level measurements, and cave mapping.

URBAN KARST DRAINAGE PROBLEMS IN THE ENSOR SINK – TIRES-TO-SPARE SYSTEM, COOKEVILLE, TENNESSEE, USA

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Ceiling failure in a cantilever dome produced a 30 m long, 13 m wide, 10 m deep collapse sink entrance to a cave in the Warsaw Fm. (Mississippian) beneath the city of Cookeville, Tennessee. Exploration and mapping of the 630 m long virgin cave revealed urban debris in prodigious quantity and variety, including 30+ automobile tires, hence the name Tires-to-Spare Cave (TTS). Prior to the collapse, the cave stream transported tires and other large debris items through the entrance room; after the collapse, access to the upstream 380 m of passage was nearly blocked. A breakdown pile now acts as a strainer removing debris from cave floodwaters. A shopping cart and truck cargo seals of known provenance indicated the input point for the debris to be Ensor Sink (ES), 1.2 km straight-line distance from TTS, but access to most of this underground conduit is blocked by permanent sumps at the ES swallet and in the upstream section of TTS.

ES, sinkpoint for Breedings Mill Branch (BMB), is the larger of two sinks which form a composite sinkhole. The surface drainage basin of ES, delineated with detailed contour maps (CI=2 ft), is approximately 325 hectares and that of the combined sinks approximately 385 hectares. Dye traces were performed to elucidate subsurface flowpaths in these basins. Using rainfall data, discharge data in BMB, and stage recorders in ES and other locations, we were able to define a number of characteristics of the BMB/ES - TTS drainage system.

About 34% of the BMB/ES watershed is impervious surface and much of the natural channel of BMB has been converted into a concrete canal, resulting in rapid runoff into ES. Extrapolation of our data yields a peak discharge of about 100 m^3/s during the 100-year storm event, whereas drainage rates from ES are calculated to be an order of magnitude less when flooded to a depth of about 10 m. This disparity between input and drainage rates results in frequent flooding of ES, which may hold up to 123,350 m^3 of water during the 100-year event. During our study period, flooding in ES damaged homes, submerged streets, and inundated recreational facilities in the Ensor Sink Natural Area.

Rapid flooding at ES suggests a chokepoint in the underground conduit near the swallet. However, stage-discharge relationships for ES, for the swallet in the adjacent portion of the composite sink, and for flooding in the entrance chamber to TTS imply more complex controls on flow through the cave between ES and TTS. The breakdown plug at the collapse entrance to TTS is a known constriction in the conduit. Rapid, total flooding of a portion of the cave occurs upstream from this breakdown pile. Peak stage in ES occurs 30 minutes to two hours before peak stage in TTS, showing that at the time of this study the breakdown plug in TTS was not the cause of flooding in ES. This is expected to change as the interstices of the breakdown "filter" become increasingly plugged by debris, a process observed during our study. If the influx of urban debris at ES remains uncontrolled, Cookeville will lose the services of an important natural storm sewer.

1. Introduction

On April 25, 1994, ceiling failure in a cantilever dome produced a collapse sink 31 m long, 13 m wide and approximately 10 m deep. The collapse broke through at least 2.5 m of bedrock to give entrance to a hitherto unknown active stream cave developed in the Warsaw Fm. (Mississippian) beneath the city of Cookeville, TN. Albeit a virgin cave, exploration and mapping of the 630 m long cave revealed it to contain urban debris in prodigious quantity and variety: Cans, cigarette butts, a plastic milk crate, automobile parts, toys, a baseball bat, one full beer, a pot, shoes, a lawnmower (?) wheel, commercial truck cargo seals, a shopping cart basket, 5-gallon buckets, lumber, motorcycle tires and over 30 automobile tires (one still on its rim!). The plethora of tires (Fig. 1) inspired the name Tires-to-Spare Cave (TTS).

Figure 1: Four of over 30 tires in Tires-to-Spare Cave, accumulating at the base of the breakdown collapse.

Prior to the entrance collapse, the cave stream transported some large debris items (tires, buckets) through the cantilever dome room and on downstream. After the collapse, access to the upstream 380 m of passage was very nearly blocked. The breakdown pile now acts as a strainer removing all large and much small debris from cave floodwaters.

A shopping cart (Fig. 2) and plastic truck cargo seals of known provenance indicated the input point for the debris to be Ensor Sink (ES), 1220 m straight-line distance from TTS, but access to most of the underground conduit between the two is blocked by permanent sumps in the upstream section of TTS and 10 m inside the ES swallet. The hydrologic connection between ES and TTS was reconfirmed by a rhodamine-WT dye trace on April 8, 1995, with positive results.

Figure 2: Basket of Rose's shopping cart, first indication of the connection from Tires-to-Spare Cave to Ensor Sink.

ES is the sinkpoint for Breedings Mill Branch (BMB), which drains approx. 325 hectares (800 acres) of Cookeville. The BMB drainage basin includes both residential and commercial areas. At the time of this study, about one third of the basin was covered by impervious surface. In 1984, the city of Cookeville spent over $600,000 to improve stormwater drainage in the BMB basin, hiring an engineering firm to (a) clean out the debris-choked ES swallet, (b) line 225 m of the stream channel in the sinkhole with riprap, and (c) convert 850 m of BMB into a concrete-lined canal.

Today, due to the combination of widespread impervious cover and the canalization of BMB, stormwater runoff into ES is very "flashy" and the sinkhole is subject to rapid flooding several times a year. Flooding is generally harmlessly confined to the sinkhole area proper, but upon occasion has overtopped two city streets and damaged one or two houses. In addition to damage and inconvenience, floods in ES and BMB pose a safety hazard to children in the area, who find the BMB canal an attractive play area.

A second sinkhole, Walmart Sink (WMS), draining approximately 60 hectares (150 acres), lies adjacent to ES. The sinkholes are currently separated by a divide, but when ES floods to a depth of approx.10 m, there is overflow via a surface paleochannel from ES into WMS.

The primary purpose of this study was to better characterize the flooding and drainage of ES and provide the city of Cookeville with recommendations for preserving this natural storm drainage so essential to the city's welfare.

2. Drainage Basin Characterization

Most of the city of Cookeville is drained through sinkholes. Previous work in the area had established connections between a number of sink points and 6.6 km long Capshaw Cave, which resurges at a spring at the head of a short karst window stream known as "The Canal." The Canal stream, which was thought to also be the resurgence point for ES, disappears underground to pass through Ament Cave before resurging for a final time as the principal source for Pigeon Roost Creek, a tributary to the Caney Fork River.

Tracing performed in 1995 established that drainage from ES passes through TTS. The Canal stream sinks to join the downstream end of the TTS cave stream and the combined waters flow through Ament Cave. A second dye trace showed that drainage from WMS also joins the TTS cave stream. A final dye trace from a third sink lying between WMS and TTS indicated that water sinking here connects into both the TTS cave stream and into the spring at the head of The Canal.

The BMB and WMS drainage basins were delineated using a topographic map with a 2-ft contour interval. Drainage boundaries in these basins may not correspond exactly with topographic divides due to extensive stormwater drains and karstic flowpaths in the subsurface, but tracing results in adjacent basins indicate that such errors are minimal.

Rainfall within the BMB basin was estimated using a Rain Wise recording rain gauge deployed near the center of the basin, augmented at times by additional rain gauge measurements at other points in the drainage area. The recording rain gauge provided a record of rainfall amount and intensity at intervals of five minutes, at least for the center of the 325-hectare BMB watershed.

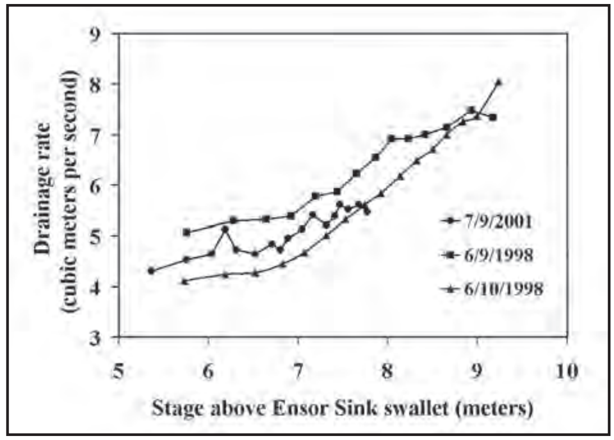
Flood stages in the BMB canal, ES, WMS, and the TTS entrance chamber were recorded through time with *in-situ* model 4000 and 8000 transducer/data loggers (Trolls). To guard against vandalism the Trolls were hidden or camouflaged. Additional measurements were made by tape and clinometer surveys to high water levels observed and marked. Discharge downstream of the stage recorder in the BMB canal was measured at low flow and at ten different flood stages with discharges ranging from about 1 cubic meter per second (cms) to over ten cms to develop a stage – discharge relationship for the canal. A stage-volume relationship for the composite Ensor-Walmart Sink was computed using the two-foot contour interval topographic map of the area.

Stage measurements in the sinkholes and discharge rates from BMB canal were used with the sinkhole stage-volume relationships to compute average sinkhole drainage rates in ES over five-minute intervals for various water depths (Fig. 3). We note that the drainage rates for the three largest floods for which we had complete data do not show the dependence on stage anticipated for a simple orifice constriction at the Ensor Sink swallet.

Using calculated drainage rates and the watershed characteristics, flood levels for storms not recorded during this study (e.g., the 100-year storm) were predicted.

3. Characterisitics of Flooding at Ensor Sink and Walmart Sink

Due to urbanization of the watershed and modification of the BMB channel, storm water runoff in the BMB basin is routed quickly to ES. The lag time between maximum rainfall intensity and peak discharge into ES measured during this study was typically between 15 and 30 minutes.



3: Drainage rates at Ensor Sink as a function of stage.

The BMB canal design allows brimfull discharge of approximately 28 cms (1000 cfs) near its terminus at ES. Hydrologic models incorporating our data indicate a peak discharge between 70 and 115 cms (about 2500 to 4000 cfs) during the 100-yr storm event, during which ES may hold up to about 125,000 m^3 (100 acre/feet) of water in temporary storage. In contrast, drainage rates from ES, as a function of stage, were calculated to be an order of magnitude less than the input: approximately 4.2–4.5 cms when flooded to a depth of 6.1 m (20 ft), and approximately 7.4 – 7.9 cms (260-280 cfs) when flooded to a depth of 9.1 m (30 ft).

This disparity between input and drainage rates accounts for the frequent local flooding of ES. After this study was initiated, the city of Cookeville took several steps to mitigate the impacts of flooding in ES. One road was raised and a bridge was rebuilt. Two homes subject to flooding were purchased and removed, and much of the area around the ES swallet was designated a natural area and made into a small public park.

During the time period spanned by this study, 1998–2001, 18 ES flood events with water depth >6.1 m (20 ft) were recorded (max recorded depth = 11.6 m). At least two events produced a merger of the ES and WMS flood ponds inundating recreational facilities in the Ensor Sink Natural Area, in addition to damaging homes and overtopping one bridge.

4. Causes of Flooding at Ensor Sink

The rapidity with which ES floods suggests a chokepoint in the cave conduit not far downstream from the ES swallet.

However, estimates of ES drainage rate do not display the functional dependence on stage (one-half power) anticipated for a single orifice constriction. Simultaneous stage peaks in ES and adjacent WMS, recorded during a June 1998 flood event (which did not produce merger of the two sinkhole flood ponds), suggest that at least one flow restriction lies downstream from the WMS input, causing simultaneous backup in both sinks.

During another flood event, which caused pond merger, prominent surface flow was observed from ES to WMS, suggesting that the flow restriction at the ES swallet and/or additional constrictions between the two sinks create sufficient gradient to cause overland flow to WMS.

In contrast to the June 1998 flood event, during a December 1998 event stage synchronicity was less perfect, with ES remaining flooded to higher levels for a longer time. There are at least two possible explanations for the disparity: (1) Rainfall intensity variations in the two drainage areas (we had no rain gauge in the WMS drainage basin); the WMS basin may have received lower intensity rainfall. (2) As previously suggested, flow constriction in the underground conduit between ES and WMS may result in some difference between sinkhole water levels for less intense storms. Some increase in this suggested partial blockage (possibly due to the continued influx of trash items into the ES swallet) might cause ES to flood higher and drain more slowly. More data are needed to resolve this question.

Another apparent restriction in the underground conduit occurs at the upstream sump in TTS where the cave passage size abruptly diminishes from walking passage to a low water-filled tube.

The fourth and best known constriction in the subterranean drainage is formed by the breakdown plug at the collapse entrance to TTS. Rapid, total flooding of a portion of the cave upstream from this breakdown pile is known to occur.

Does blockage in TTS cause flooding in ES? Not at the time of this study. Peak stage in ES occurs 30 min to two hours before peak stage in TTS, showing that the breakdown plug in TTS was not the principal cause of flooding in ES.

This, however, might be expected to change as the interstices of the breakdown "filter" become increasingly plugged by debris (Fig. 4). During the course of this study an increase in ponding on the upstream side of the breakdown was observed, hinting at growing blockage in the lower levels of the breakdown pile. Additionally, an apparent increase in the degree of in-filling by trash of the interstices higher up in the breakdown "filter" was noted. If steps are not taken to control the influx of urban debris at ES, Cookeville may lose the services of an important natural storm sewer.

Figure 4: Tire on rim, cans, sticks, sediment, and other debris filling the interstices of breakdown "filter" in TTS Cave.

5. Conclusions and Recommendations

Based on the results of our study, the following recommendations were made to the Cookeville City Council (which funded this study):

- That ES be thoroughly cleaned out: removal of some of the rip-rap that has washed into the swallet, and removal of all the trash currently in ES.
- Installation of a "trash rack" or strainer structure near the end of the BMB canal, at a point accessible for service. The structure would strain out trash from floodwaters entering ES and thereby reduce the influx of solid trash into the underground conduit, lessening the probability that this conduit will become totally blocked.
- Regular inspection and maintenance of the trash rack: removal of the collected debris after floods, to keep the trash rack functioning properly, and to insure that it does not itself become a cause of ponding and flooding.
- Installation of one or more smaller, subsidiary trash racks elsewhere in the BMB drainage to strain out some of the debris before it reaches the main trash rack at ES.
- Installation of fencing along the upstream sections of the BMB canal, to reduce the amount of urban debris being washed into BMB, while simultaneously enhancing the safety of children living near the canal.

Total plugging of the ES-TTS conduit at any of the several known and suspected conduit restrictions (or other undetected choke points) would necessitate construction of a 1.2 m (4 ft) diameter storm sewer at least 1220 m (4000 ft) long, blasted through bedrock, at great cost to the city of Cookeville. Fourteen years after this problem was first reported and five years after the results of this study were presented to the city, none of the above recommendations have been implemented. The city of Cookeville is considering the construction of a sump basin to extract bedload trash out of storm water runoff entering ES, combined with a floating screen to remove floating trash. However, to date these plans remain tentative, with no final design determined. The only concrete steps taken to reduce the amount of urban debris entering the ES-TTS conduit have been several trash clean-ups of ES performed by a local environmental activist group.

THE IMPORTANCE OF KARST AQUIFERS TO PUBLIC AND DOMESTIC WATER SUPPLIES IN THE UNITED STATES.

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The purpose of this paper is to demonstrate the relative importance of karst aquifers to the supply of fresh water in the continental United States. The distinction between ground and surface waters is often somewhat blurred in karst regions, with surface streams sinking to become ground water and ground water flowing from large springs to become surface water. There are many problems with quantifying the amount of water used from a particular aquifer type. The available records usually breakdown water usage by surface or ground water and classify by public supply, domestic, irrigation, aquaculture, industrial, mining, and thermoelectric. Total ground water usage figures are available for each state, but no breakdown by aquifers or regions within the states is readily available. Water supplies from the Edwards aquifer in Texas and virtually all fresh waters in Florida are from karst aquifers, but rough guesses must be made for most of the country. Using a state-by-state estimate of the area of karst aquifers and the total utilization of ground water for public and domestic water supplies, karst aquifers account for roughly 30 per cent of this total. Population densities are not uniform across the states, so some karst aquifers are relatively under utilized due to low demand.

1. Introduction

Karst rocks, including evaporites, are exposed over about 20% of the earth's dry ice-free land (Ford and Williams, 2007), but limestones and dolomites alone cover about 11%, increasing to around 14% if subsurface rocks involved in carbonate karst groundwater circulation are also included (Williams 2008). Karst landforms in the continental United States cover about 40% of the eastern half of the country. A brochure published by the Karst Waters Institute in 2001 had the statement that 40% of the drinking water supplied from ground water in the United States came from karst aquifers. This statement was unquantifed and based on the following assumptions: (1) karst aquifers are typically highly productive with hydraulic conductivity values several orders of magnitude greater than other consolidated bedrock aquifers; (2) the relative demand for ground water for potable water supplies was fairly uniform across the country and regions with 40% karst would supply at least 40% of the ground water; (3) in some cases, such as Florida, karst aquifers also sustain most of the surface streams and therefore represent a "drinking water supply" not usually listed under the heading of ground water withdrawals. The term "drinking water" was used to exclude the large pumpage from western aquifers for irrigation and agricultural uses.

The utilization of water from karst aquifers is represented by withdrawals from both ground and surface water sources. This is due to the rapid interchange of water within karst aquifers and the storage characteristics of these aquifers. The flow duration curves for surface streams draining karst terrains are typically flatter than for non carbonate terrains and show the role of karst aquifers in sustaining surface streams under base flow conditions. As an example, runoff from karst aquifers in the Shenandoah Valley help maintain flows in the Potomac River and the water supply for the Washington DC area.

There are many problems with quantifying the amount of water used from a particular aquifer type. The available records usually breakdown water usage by surface or ground water and classify by public supply, domestic, irrigation, aquaculture, industrial, mining, thermoelectric (Hutson et al, 2004). Figures are available for each state, but no breakdown by aquifer types is readily available. Water supplies from the Edwards aquifer in Texas and virtually all fresh waters in Florida are from karst aquifers, but rough guesses must be made for most of the country.

For this study, the public and domestic categories will be used for "drinking water supply". In practice, less than two percent of the water used by a typical household is used for drinking (van der Leeden et al, 1990). All carbonate and evaporite aquifers are assumed to be karst aquifers and may be unconfined or artesian. For most regions without specific data, the percentage of ground water from karst is assumed to be proportional to the amount of karst coverage per state or region. This may overestimate the karst water usage in a couple of the eastern states such as Virginia where large population centers on the coast result in high ground water withdrawals from non-carbonate sources.

2. Ground Water Use in the United States

Ground water supplies about half of the drinking water of the United States and about 40 per cent of public water systems (Reilly et al, 2008). A few numbers from the USGS (Hutson et al, 2004) showing ground water use in the US for 2000 serve as a starting point. Ground water withdrawals for the entire United States averaged 315 million cubic meters per day (Mm^3/d). About 67 percent of this total is used for irrigation. The most heavily exploited aquifer is the high plains aquifer in the west-central United States drawing about 64 Mm^3/d from ancient stream gravels. Ninety-seven per cent of this water is used for irrigation and about two per cent is used for public supply. Compare this to the carbonate Edwards aquifer of Texas where average withdrawals are 2.8 Mm^3/d with 38 per cent used for irrigation and 56 per cent used for public supply.

A study by Maupin and Barber (2005) presented figures for ground water withdrawals from thirty principal aquifers, but the classification of these aquifers was regional rather than by rock type or stratigraphic units. It is impossible to separate the carbonate aquifers from the regional groups and examine them individually. The study by Hutson et al (2004) presents ground-water withdrawals for 2000 by state grouped by the use categories of public supply, domestic, irrigation, aquaculture, industrial, mining, and thermoelectric power. Public and domestic withdrawals by state are presented in Table 1. A rough estimate of the per cent of outcrop area of soluble rocks (carbonates and gypsum) by state from karst maps by Davies et al (1977) and Veni et al (2001) is used in Table 1. The per cent of soluble rock aquifers times the ground water withdrawals for public and domestic supply gives an estimate of the amount of ground water from karst aquifers used for public and domestic water supply.

	Thousand m^3/d		Thousand m^3/d	
State	Public & Domestic	Karst Area	Total Karst Water	% GW from Karst
Alabama	1362.2215	0.3	408.88239	30
Arizona	1884.5515	0.15	282.832095	15
Arkansas	607.4925	0.15	91.172025	15
California	11570.745	0.01	115.76859	1
Colorado	456.0925	0.1	45.63335	10
Connecticut	462.527	0.01	4.627714	1
Delaware	220.6655	0.01	2.207821	1
Florida	9080.215	1	9085.013	100
Georgia	1468.58	0.5	734.678	50
Idaho	1151.397	0.2	230.40108	20
Illinois	1847.08	0.2	369.6112	20
Indiana	1767.595	0.5	884.2645	50
Iowa	1272.517	0.4	509.27576	40
Kansas	732.776	0.2	146.63264	20
Kentucky	342.5425	0.4	137.0894	40
Louisiana	1476.907	0.05	73.88437	5
Maine	247.1605	0.1	24.72911	10
Maryland	612.0345	0.2	122.47158	20
Massachusetts	905.372	0.05	45.29252	5
Michigan	1839.51	0.05	92.0241	5
Minnesota	1551.093	0.05	77.59563	5
Mississippi	1469.7155	0.1	147.04921	10
Missouri	1410.291	0.6	846.62172	60
Montana	277.819	0.05	13.89829	5

Nebraska	1190.004	0.05	59.53164	5
Nevada	656.319	0.15	98.49987	15
New Hampshire	279.7115	0.01	2.798593	1
New Jersey	1815.6645	0.05	90.831195	5
New Mexico	1110.519	0.3	333.33174	30
New York	2744.125	0.1	274.5575	10
North Carolina	1343.675	0.05	67.21925	5
North Dakota	167.6755	0.01	1.677641	1
Ohio	2392.12	0.3	718.0152	30
Oklahoma	524.2225	0.2	104.8999	20
Oregon	705.1455	0.01	7.055181	1
Pennsylvania	1302.04	0.2	260.5456	20
Rhode Island	97.99365	0	0	0
South Carolina	637.7725	0.4	255.2438	40
South Dakota	241.1802	0.15	36.196146	15
Tennessee	1338.376	0.5	669.5416	50
Texas	5264.935	0.7	3687.4019	70
Utah	1438.6785	0.15	215.915805	15
Vermont	152.157	0.2	30.44748	20
Virginia	771.0045	0.3	231.42357	30
Washington	2229.365	0.05	111.52715	5
West Virginia	307.342	0.2	61.50088	20
Wisconsin	1613.5455	0.3	484.31943	30
Wyoming	241.36945	0.1	24.149699	10
Totals	**72581.8413**		**22318.28687**	**31**

Table 1: Estimated use of karst water for public and domestic supply in the continental United States in 2000. Data on ground water withdrawals from Hutson et al (2004), page 9, table 4.

The calculation of thirty-one per cent of the drinking water supply (public plus domestic) of the United States derived from ground water is very much an estimate and does not try to account for population distribution relative to the location of the karst aquifers. This overestimates the percentage of ground water from karst aquifers in some eastern states such as Virginia where large population densities along the east coast create high demand and withdrawals from the North Atlantic coastal plain aquifer. Karst aquifers probably are of little importance in water supplies for the coastal northeastern states, but most of this area relies primarily on surface water. The combining of ground water and surface water withdrawals for Florida may inflate the numbers for this state, but there is some justification. Karst aquifers help sustain base flow for many surface water supplies and this is only reflected in this study by the data for Florida.

3. Conclusions

If half of the drinking water in the United States comes from ground water and thirty per cent of this is from karst aquifers, then fifteen per cent of the drinking water comes from karst aquifers. This is at best a somewhat crude estimate based on the available data and was made to illustrate the importance of karst aquifers in the national situation in the continental United States. Ideally data should be collected by aquifer type for each public and domestic water system in the country, but this type of information is not currently available. The next step in refining the estimates presented in this paper should be to obtain more precise numbers for the exposure area of karst aquifers and incorporate an adjustment for population densities in the karst regions.

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SOME EVIDENCE OF HYDROTHERMAL SPELEOGENESIS IN THE AKKA LIMESTONE, NORTHERN KITAKAMI MASSIF, JAPAN

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As is well known, many caves in the Trias-Jurassic Akka limestone were dissolved by the groundwater in contemporary drainage basins. However, the Akka limestone has been extensively subjected to contact-metamorphism by Early Cretaceous(120-110 Ma) granites. In this paper, the writers provide the following evidence that suggests hydrothermal activity -existence of a simple network of white calcite veins;-reconstructed to alternating and mixed black and white layers;-existence of hydrothermal crackle breccias;-identification of hydrothermal cave mineral (sepiolite)-occurrence of small skarn deposit; and-S and S(H_2S type) springs are sporadically distributed.

Auszug : Viele Höhlen im Trias-Jura Akka Kalkstein wurden durch Grundwasser in der zeitgenössischen Entwässerungbassins aufgelöst. Jedoch wurde der Akka Kalkstein weitgehend In Verbindung tretenmetamorphismus durch frühe kreidige (120-110 Ma) Granite unterworfen.□In diesem Papier schlägt der folgende Beweis hydrothermale Tätigkeit vor: Bestehen Adern eines der einzelnen Netzes des weißen Kalzit, Kalkstein, der die weißen und schwarzen Schichten wegen des Metasomatismus, Bestehen der hydrothermalen crackle breccias enthält, Vorhandensein des hydrothermalen Höhleminerals (sepiolite), des Vorkommems der kleinen skarn Ablagerung und des spärlich verteilten Schwefellagers und des Sulfidlagers entspringt.

1. Introduction

It has been common knowledge that the limestone dissolution is being chemically due by the reaction kinetics of the CO_2-H_2O-$CaCO_3$ system in a lot of karst areas distributed in Japanese Island. On the other hand, active hydrothermal Pirika limestone Cave (containing hot water) was the first discovered in the Pirika karst area, Imakane-cho, Hokkaido, Northern Japan (Kusaka et al., 1966). In addition, Lu (1999) points out with a large possibility that the compound thermal karstification has affected the Akiyoshi-dai (plateau) karst, Yamaguchi Prefecture, Southwest Japan. Recently, hydrothermal quartz crystals, calcite veins and silicified rocks due to paleo-geothermal activity (Early Cretaceous) were found in the Akiyoshi limestone (Akiyoshi-dai) (Taguchi et al., 2005).

The purpose of this work was to investigate the evidence of the hydrothermal speleogenesis and the discovery of the hydrothermal cave in the Akka limestone, the Kitakami Massif, Northeast Japan. The hydrothermal cave cannot be found yet, to keep investigating in the future.

The purpose of this work was to investigating evidence of the hydrothermal speleogenesis and the discovery of the hydrothermal cave in the Akka limestone, the Kitakami Massif, Northeast Japan. The hydrothermal cave cannot be found yet, to keep investigating in the future.

2. Geological Setting

The Northern Kitakami massif occupies the Pacific coast region of Northeast Japan. This region belongs to the North Kitakami Belt which the northeastern side of the Hayachine Tectonic Belt trending northwest is divided into two Subbelts, the Kuzumaki-Kamaishi Subbelt to the west side and the Akka-Tanohata Subbelt to the east side by the Iwaizumi Tectonic Line. These two Subbelts are composed Jurassic accretionary complexes and commonly characterized by the steeply dipping structures with NE-SW or NNW-SSE trends (Sugimoto, 1974; Kitamura, 1990; Okami, 1999; Ehiro, et al., 2008) (Fig.1).

The Akka limestone belongs in the Akka-Tanohata Subbelt, which is exposed in two lines of east and west in about 5km maximum-wide and approximately 60 km long, about 700 m in total thickness, and contains more than 200 caves. There are activities of granites in the Early Cretaceous (120-110 Ma) and a big and small granite bogies were intrusive in the North Kitakami Belt, and the Akka limestone have been contact metamorphosed to the recrystallized limestone (Kobayashi , 1974).

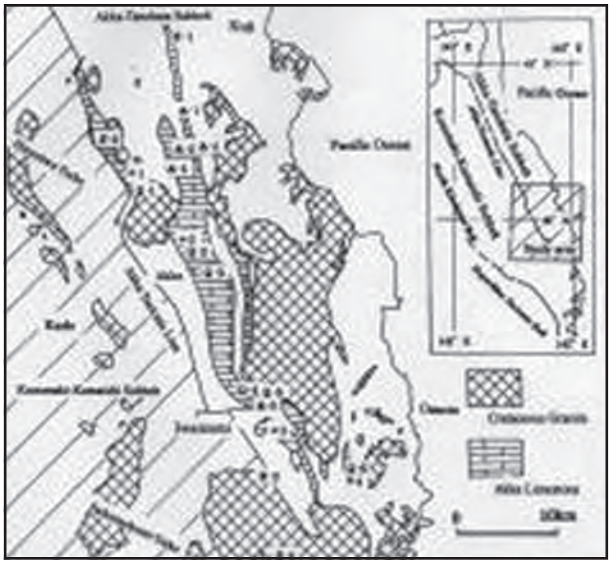

Figure1: Simplified geological map of study area, showing the approximate location of the Caves (Ω: 1. Uchimagi-do Cave, 2. Shigawatari-do Cave, 3. Akka-do Cave, 4. Ryusen-do Cave, 5. Ryusen-shindo Cave, 6. Oana Cave), Springs (1. Kawamata Spring, 2. Shinyamane Spring, 3. Shitatoku-sari Spring, 4. Momonokidaira Spring & 5.Sawamawari Sprig), Skarn Deposits (1. Okawame Deposit, 2. Kakukake-toge Deposit, 3. Torikaino Deposit & 4. Yamaguchi Deposit) and Outcrop points (1.Usaka-Toge, 2.Matsubayashi, 3.Shirando & 4. Sodeyama).

3. MajorEevidence of Hydrothermal Speleogenesis

3.1. Existence of white calcite vein

White calcite veins are found in a simple network pattern of the Akka limestone all over the investigated area. Two examples of the white calcite veins are shown Figure 2. The white calcite veins in recrystallized limestone are carbonate precipitation along the rising hydrothermal fluid paths.

Figure 2: Examples of white calcite veins in recrystallized limestone. (left) Usaka-toge, near Uchimagi-do Cave, Kuji City, (right) Akka-gawa river side, near Shigawatari-do Cave, Iwaizumi Town.

3.2. Existence of white and black layers

The recrystalized limestone composed of the disturbed white and black layers as a flow-banded texture and layer texture due to metazomatism. Thin section studies indicate that white layer consists of pure calcite and black layer, a minute opaque black minerals are arranged. Figure 3 shows examples of the outcrops for white and black layers as a flow-banded texture(left) and layer texture(right).

Figure 3: Examples of white and black textures in recrystallized limestone, (left) layer texture of the wall an evacuation tunnel in Ryusenn-do Cave, (right) road cutting wall at Shirando, Iwaizumi Town

3.3. Existence of hydrothermal crackle breccias

Exposures of crackle breccias are confined to a small area on cave entrance of Oana Cave, Sodeyama, Iwaizumi Town. The outcrop shown Figure 4, as easily visualized from the figure, the crackle breccia consists of brecciated wall-recrystallized limestone fragments and cemented by calcite.

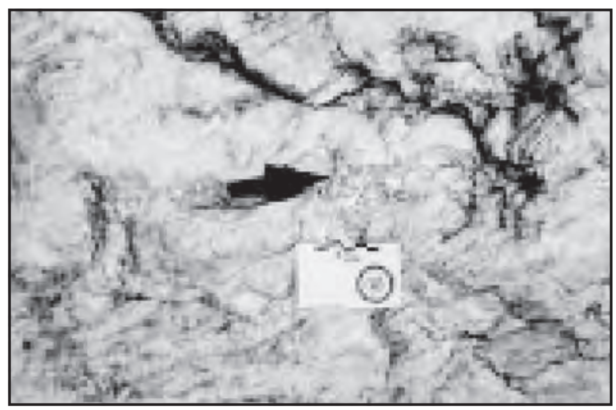

Figure 4: Close-up photograph of the crackle breccia, near entrance of Oana Cave, Sodeyama, Iwaizumi Town.

3.4. Presence of hydrothermal cave minerals

The hydrothermal cave minerals such as calcite, quartz, barite and sepiolite are described in Japanese Caves. Sepiolite ($Mg_4Si_6O_{15}(OH)_2 \bullet 6H_2O$) is common found as cave mineral from Uchimagi-do Cave, Kuji City and rarely found from Ryusen-shindo Cave, Iwaizumi Town. In Uchimagi-do Cave, sepiolite forms white, flexible sheets resembling leather hang down from open cracks in the recrystalized limestone result in corrosion of the bed rock (Kizaki, 2002). Sepiolite in Ryusen-shindo Cave showing vein-like occurrence in recrystalized limestone and resulted in condensation by the segregation from Mg and Si elements bearing bed rock (Honda, 1972).

3.5. Occurrence of small skarn deposit

Some skarn deposits are found in small bodies sporadically scattered in the Akka-Tanahata Subbelt. In the North area, Okawame molybdenum deposit and Kakukake-toge garnet skarn deposit in Kuji City formed in slate and recrystalized limestone (Yoshida, et al., 1987). In the South area, Yamaguchi deposit (Cu and W) and Makaino deposit (pyrrhotite, pyrite, hedenbergite, garnet) are distributed in Iwaizumi Town (Shimazu, et al., 1970). These deposits were formed by the skarnization due to hydrothermal metazomatism. The skarn deposits in the studied area are now not mined entirely.

3.6. Sparsely distributed sulfur-bearing and sulfide bearing springs

The chemical composition of spring waters in the Akka-Tanohata Subbelt classified to $NaHCO_3$, $NaSO_4$ - NaCl and intermediate types using a Trilinear diagram. The $NaHCO_3$ type springs and hydrogen sulfide (H_2S)-containing springs are closely associated with the Akka limestone. Many of the springs in this area are non-thermal (cold water), these original paleo(fossil)-spring waters probably derived from granitic magma .

4. Conclusions

The study has resulted in the identification of hydrothermal speleogenesis heretofore undiscribed for the Akka-Tanohata Subbelt, the North Kitakami Belt region. Most of the above evidences were suggested and wide cited as being characteristic of hydrothermal speleogenesis. One of the research objectives, the hydrothermal cave has not been recognized yet in this area. Investigations in the future are planned.

Acknowledgements

We wish to express our thanks for the supply of a Grant in Aid for Speleological Research Institute of Japan (Iwaizumi). We also thank the 15th ICS Science Committee reviewers, whose useful comments helped to clarify the paper.

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EVOLUTION OF THE BIŚ NIK CAVE ENVIRONMENT (KRAKOW-WIELUN UPLAND, SOUTHERN POLAND)

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Biśnik Cave is considered to be one of the best investigated caves in Poland due to results of absolute dating of the sediments and thorough research of its evolutionary background. It is one of the oldest archeological sites in Poland and one of very few places in Europe where a profile of sediments formed during climatic phases starting with the Odra glaciation through the Holocene has been preserved. The data obtained af

ter examining the sediments from the cave and their thorough analysis enable an attempt to reconstruct the evolution of the cave environment since its formation until today. An evolutionary model of Biśnik Cave has been presented. The cave environment is treated as a geocomplex of related elements (karstified rock, morphology, cave water, microclimate, vegetation, fauna and man) developing under the influence of external factors (climatic changes, geomorphological processes, seismic and tectonic events etc.) and internal factors (speleogenesis, formation of cave sediments etc.). The main stages and events of the cave development since its formation through today have been marked on a geological time axis. The reconstruction is based on a detailed dataset and multi-aspect investigation of the cave sediments.

1. Introduction

Biśnik Cave is one of the numerous (non-active) relic caves in Krakow-Wielun limestone Upland, Southern Poland (Fig. 1). It is located near Strzegowa village, close to Smolen (the Wolbrom commune). The cave entrance is placed on the left slope of Wodaca Valley, in the West wall of Bisnik Rock (approx. 405 m asl 50 25.3'N, 19 40.0'E). The three entrances, directed NW and NE, are situated 6–8m above the bottom of the valley.

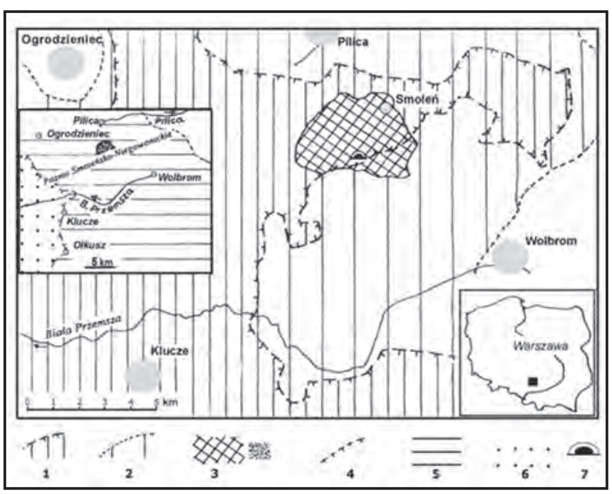

Figure 1: Location of the research area: 1 – the area of the Landscape Park „Orlich Gniazd"; 2 – surrounding reserves of the park; 3 – the area of Wodąca Valley; 4 – Upper Jurassic cuesta; 5 – Kraków-Wieluń Upland; 6 – Silesian Upland; 7 – Biśnik Cave.

Biśnik is a small cave, currently formed at three levels (approx 80 m long). Its system is tectonically predisposed by fissures, and consists of few horizontally developed passages and chambers (Fig. 2).

The cave is considered to be one of the best-investigated caves in Poland, due to the fact that its evolutionary background has been thoroughly investigated and absolute dating of sediments has been carried out. Besides, it is considered to be one of the oldest archaeological sites in Poland and one of the very few ones in Europe where the profile of sediments formed during climatic phases from the period preceding the Odra glaciation till Holocene has been preserved (CYREK, 2002; MADEYSKA AND CYREK, 2002).

Detailed and multi-aspect research on the sediments in the cave, their thorough analysis and interpretation, combined with the application of a special type of research methodology allow an attempt to reconstruct the evolution of its environment (treated as a geocomplex) since the its formation.

2. Research Concept

The evolution of caves is the result of the development of karst processes (tectonic movements, climatic changes, geomorphological processes, influence of human activities and others) and interactions between the formation of underground voids and their geological environment.

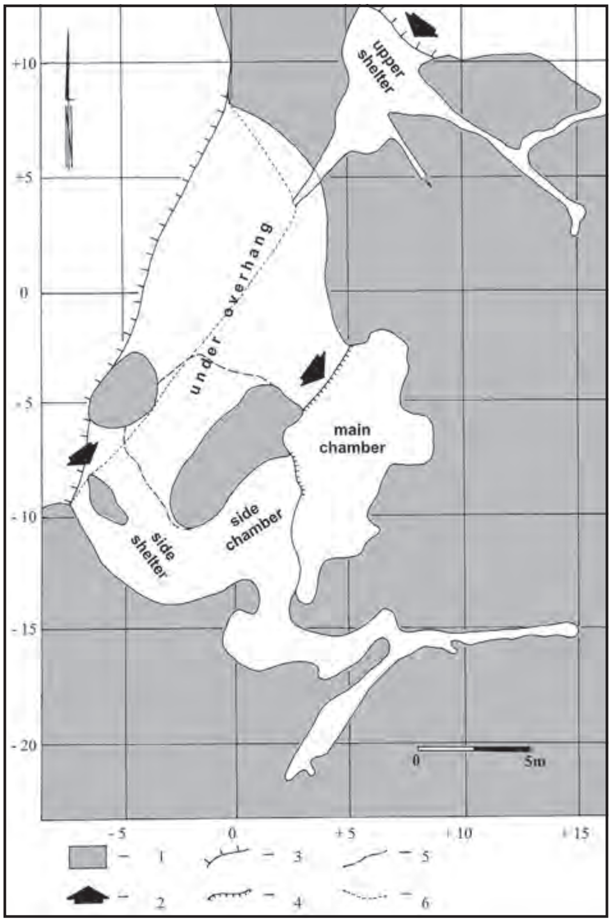

Figure 2: Plan of Biśnik Cave (after A. Polonius, 1991): 1 – rock; 2 – entrance; 3 – the edge of the terrace in front of the cave; 4 – vertical rock sill; 5 – the range of the hood; 6 – the border of the area covered by the rock overhang.

Generally, two main periods can be distinguished: speleogenetic (when the initial fissures are widened to bigger channels and passages) and speleoenvironmental (the period when these voids containing water, air, sediments, living organisms, etc., are forming the specific cave environment); the boundary between these periods is not well defined.

The cave environment can be considered as a geocomplex; a set or system of connected elements (geocomponents), occurring in the rock void – the cave. The geocomponents are: karstifying rock (L), morphology of caves (M), sediments (O), cave waters (H), underground atmosphere (A), vegetation (R), fauna (F), and sometimes a human being (C). Due to their nature the geocomponents can be grouped into: abiotic – not alive, biotic - alive and anthropic- a human being (Fig. 3).

Elements of the cave environment as a geocomplex are linked by numerous connections: spatial, genetic, material-energy, functional etc., creating a specific system. Various processes occurring in cave environment are nothing else but interactions of geocomponents.

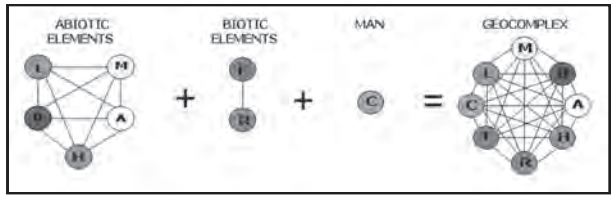

Figure 3: The structure of the cave geocomplex and its building elements (explanation in the text).

The formation of "stage" structures is due to interactions among elements of the cave environment. Their investigation allows reconstructing environmental conditions in the cave in different stages of its development. Multi-aspect investigation of cave sediments is especially important.

3. Methods of the Cave Environment Reconstruction

Geological (sedimentological), geomorphological, paleozoological and archaeological methods are the most important among the methods applied to reconstruct the Bisnik Cave environment. Physico-chemical methods, especially uranium-thorium disequilibrium (U-Th), electron spin resonance (ESR), and thermoluminescence dating have been the most important in determination of the age of the sediments. The archaeological investigations and dating of the cave sediments were carried on by PIELISIAK (1993-1994), CYREK (2002, 2006), HERCMAN AND GORKA (2002), MADEYSKA (2002), MIROSŁAW-GRABOWSKA (2001, 2002a, 2002b), WISZNIOWSKA *et al.* (2002) and others.

The cave has an almost complete and strongly differentiated stratigraphical-chronological sediment cross-section, over 7m thick. Eighteen layers and 3 series of sediments (Fig. 4) have been identified in the open profile in front of the main entrance to the cave. They probably formed during the Pliocene through the Wolstonian Stage, the Eemian interglacial, and the Vistulian through the Holocene period respectively (MIROSŁAW-GRABOWSKA, 2002a, b). Particular parts differ from each other by their background, lithological formation, manner of sediment accumulation, their continuity (or the lack thereof), and their incorporation of different palaeontological specimens and artefacts.

4. Reconstruction of the Environment Evolution in Bisnik Cave

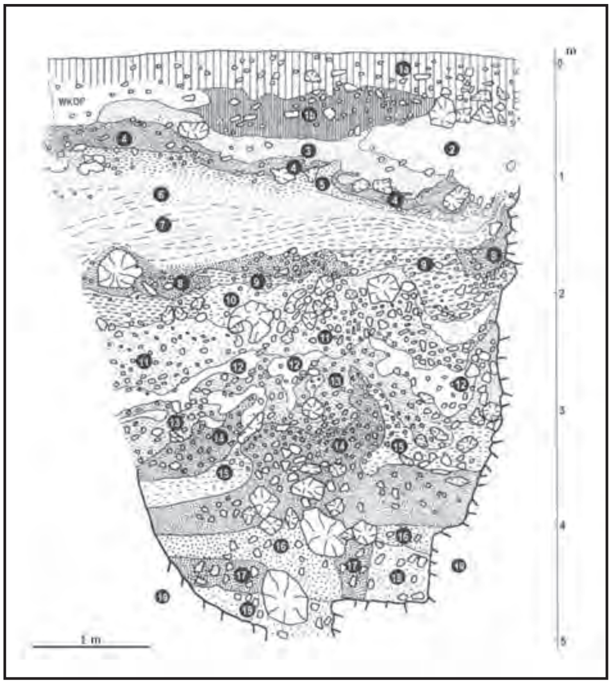

Figure 4: Cross-section of sediments after the field drawing by T. Madeyska (description of sediments after J. Mirosław-Grabowska, 2002 a): 1 – dark grey clay (a) and beige – grey dust clay (b) with sharp-edged limestone debris; 2 – light beige dust clay with single pieces of limestone; 3 – beige mid-grained sand ; 4 – beige-grey san clay and clay sand; 5 – red-yellow, fine grained and laminated sand; 6, 7 – dark yellow and yellow, fine grained sand with single pieces of limestone debris; 8 – yellow-brown sand dust with excess of limestone debris; 9 – grey-brown clay; 10-11 – brown and dark brown sand clay with limestone debris; 11 – sand clay; 12 – beige-green san clay and clay sand in the form of lenses; 13 – light brown and yellow-brown sand clay with debris; 14 – grey-yellow dust clay; 15 – yellow-brown, locally red-brown dust clay; 16-17 – green-brown and green-grey dust clay with limestone debris; 18 –red and red-brown residual loam.

An attempt to reconstruct the environment (geocomplex) of Biśnik Cave from its formation until today has been made based on lithological, palaeozoological and archaeological data (Fig. 5). Reconstruction of the cave geocomplex has been correlated with palaeogeographic data and the processes that have taken place in the cave (corrosion, gravitation, sedimentation processes, activity of living organisms etc.), leaving material and morphological traces of their appearance.

Two periods have been distinguished in the history of development of the cave geocomplex: speleogenetic (initial-karst – Neogene) and cave-environmental (Pliocene/Pleistocene – Holocene) ones, and among them three

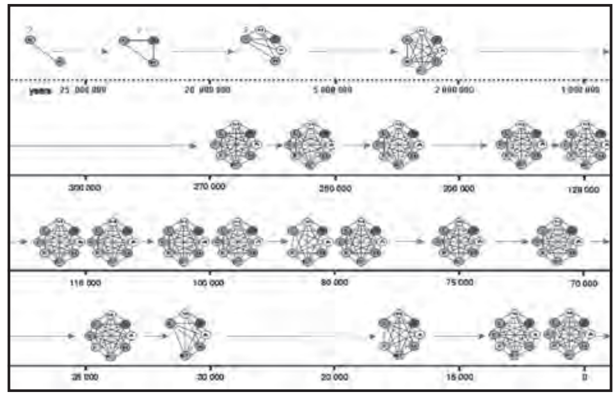

Figure 5: Evolution of the environment (geocomplex) of Biśnik Cave. Elements of the cave environment: L – karstifying rock; M – morphology; O – sediments; H – water; A – underground atmosphere; R – vegetation; F – fauna; C – man.

stages: abiotic (karst), biotic and anthropogenic. The cave- environmental period was completely recorded in the cave sediments (layers 18÷1 a). Based on cave sediment analysis, the character of the cave environment has been reconstructed at different stages of its formation as well as the factors (external and internal ones) influencing the processes (corrosion processes, frost disintegration, cryoturbation, climate oscillations, transgressions and regressions of land ice, activity of living organisms and humans etc.).

Evolution of the cave environment has been characterised by the increase in the complexity of the geocomplex due to the formation of new environmental elements and the growing number of connections among them. The share of factors influencing formation of the cave environment has been changing together with its development: the role of external factors has been decreasing, while the role of internal ones has been increasing (self-development).

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MORPHOGENETIC CLASSIFICATION OF TALUS CAVES BASED ON GEOMETRY OF CLASTS AND SEQUENTIAL DEVELOPMENT

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Abstract

Talus caves, also known as rockfall caves or boulder caves, consist of openings within an accumulation of broken or disaggregated rock (scree) on a steep mountainside, at the base of a cliff, or along the floor of a valley. Particles (clasts or grains) within a talus deposit vary in size, sorting, and shape. Interstices are created among clasts during the processes of mass wasting and slope failure. These caves are a subtype of pseudokarst that includes depositional, accidental, tectonic, and rift caves.

Clasts that compose talus may be (1) boulders: rounded or angular ranging from high to low sphericity, (2) blocks: generally angular and having a wide range of sphericity, and (3) slabs: angular and generally low in sphericity. The size and extent of the openings (caves) among the clasts depends on the texture of the talus accumulation, namely size, shape, and sorting of the particles, much in the same way as these parameters determine the degree of porosity in a traditional finer grained sediment.

Talus caves have three stages in development. (1) In the primary stage, the host rock is fractured, creating blocks bounded by joints. The nature of fracturing, including extent, density (spacing), and orientation of fractures will determine the size, shape, and sorting of the clasts. (2) In the secondary stage, rock fragments become dislocated and moved, creating enterable openings (caves). Processes in this step include movement under the force of gravity (rock falls, rock slides, toppling, creep, and other mechanisms), fluid transport of clasts by fluvial or glacial action, and packing of clasts into their final orientation. (3) In the tertiary stage, diagenetic changes occur within the talus deposit, including physical and chemical weathering of clasts and changes in sizes of interstices through infilling of interstices with finer grained particles or removal of fill by erosion. Superlative talus caves (long, deep, or voluminous openings) occur where talus deposits are sufficiently thick, clast size is maximized, sorting of clasts is high, interstitial matrix of fill is initially minimal or has been erosionally removed, and openings remain large over time.

THE SINKHOLES OF LAYLA LAKES; SAUDI ARABIA AND THEIR SINGULAR SUB-LACUSTRINE GYPSUM TUFA

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The uplifted basement of the Arabian Plate is overlain by east-dipping Mesozoic sediments. The more resistant of these strata form escarpments that curve throughout Saudi Arabia north to south. Level areas occur between these escarpments, one formed by the upper Jurassic Heeth Formation composed of about 150 m thick anhydrite. This formation is locally punctured by hypogene karst sinkholes. The most prominent sinkholes are the former Layla Lakes at 22.17°N 46.70°E. The lakes (17 formerly), that originally provided water for a sustainable agriculture in the area, have been drained in the late 1980s, revealing 19 sinkholes, some of them composites of several subsidence centers. The largest sinkhole is 1.1 km long, 0.4 km wide and about 40 m deep. Others are less than 10 m across and rather recent. The bottom of the former lakes and the flats around them are composed of thick layers of fine-grained lake chalks ("Layla Formation").

The most striking feature of these sinkholes is the several meter thick tufa covering the vertical walls of the sinkholes. It formed sub-aqueous and is entirely composed of large gypsum crystals. Morphologically, the tufa displays thick bulbous forms at the bottom of the walls changing to inverted conical forms at middle depth, and to gour-, gutter-, or shovel-like forms near to the former lake surface. The mineralogy and morphology of this tufa appear to be singular worldwide. Their growth apparently was caused by gypsum saturated water that formed by excessive evaporation in the shallow shore waters around the sinkholes. These dense water layers then cascaded underwater down the walls of the sinkholes, triggering the growth of centimeter-sized crystals along the walls. The Layla Lake area should be protected by a natural reserve to prevent further dumping of refuse into them.

1. Introduction

The Arabian plate is composed of crystalline basement in the west and of eastward dipping Phanerozoic strata in the east. In the center of the Kingdom of Saudi Arabia (KSA), a band of Jurassic and Cretaceous sediments crop out running nearly north-south throughout the entire country. Prominent escarpments are formed by middle Jurassic and lower Cretaceous limestones. The plain in between the escarpments is partly formed by the upper Jurassic Heeth (or Hith) Formation, which is composed of a >150 m thick sequence of laminated and autobrecciated anhydrite. This band of anhydrite can be followed on satellite images, such as those provided by Google Earth, as a string of bright, almost white areas. Ground inspection showed that these areas are marked by gypsum caliche, presumably formed by ascending waters that left gypsum upon evaporation. The Heeth Formation is locally punctured by hypogene karst sinkholes, which include the deepest cave in Saudi Arabia, Ain Heeth, about 40 km south of Riyadh, and the former Layla Lakes, a series of sinkholes about 300 km south of Riyadh.

The Heeth Formation is an aquitard, below which fossil groundwater is trapped that is extensively used for agricultural purposes. Consequently, the groundwater level has dropped in many areas by >100 m in the last decades. This is illustrated by the history of the Ain Heeth cave. The cave formed by upward solution of the groundwater body in a hypogene setting *sensu* KLIMCHOUK (2007), its walls show the typical morphology of a convective cave formation in a phreatic setting in gypsum (e.g., KEMPE, 2008). In the 1950s, the groundwater body reached the surface, forming a spring lake. Nowadays, the groundwater level is 160 m below surface, revealing the cave. The drop of the groundwater level following agricultural activities is also the reason for the dry-up of the Layla Lakes.

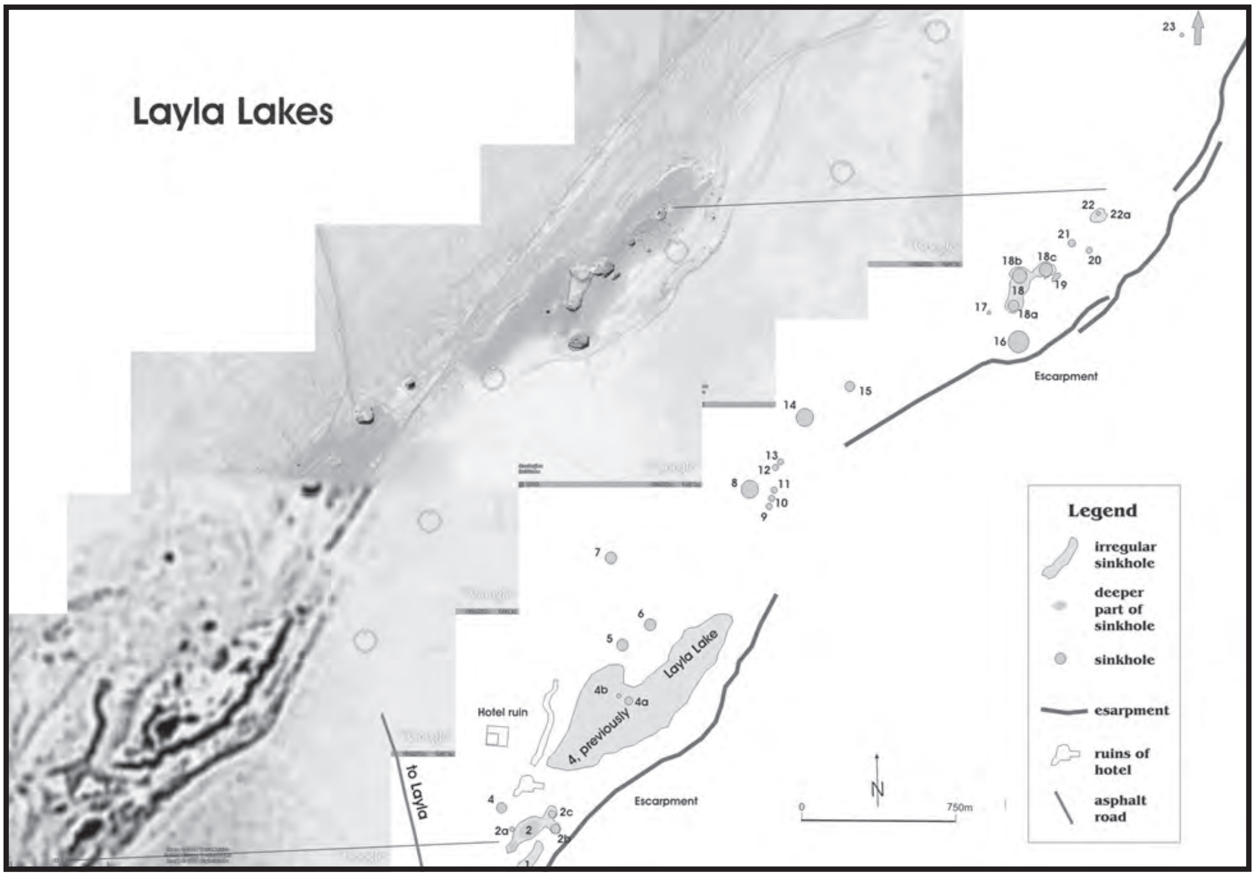

Figure 1: Google Earth view of the Layla Lakes area and annotated map of sinkholes.

2. Layla Lakes Sinkholes

In the early 1990s, the lakes dried up, revealing a series of textbook sinkholes. Before, the lakes were used as touristic spots for swimming and water sports. Google Earth provides a high resolution view of the northern sinkholes, while those in the south are barely perceptible once the ground situation is known (Fig. 1). All in all 23 sinkholes can be listed (Table 1), of which some have several subsidence centers (Numbers 2, 4, 18, and 22). We were able to visit most of the sinkholes on February 21 and 25, 2008, in order to inspect them for tufa occurrence (KEMPE & DIRKS, 2008). The largest sinkhole is No. 4 with an north-south axis of 1.1 km, a width of 0.4 km, and a depth of up to 40 m. The smallest ones have openings of less than 10 m across, but are bellowing out below, forming real sinkhole caves. Two of the sinkholes (18 and 19) are connected by a natural bridge. For a few sinkholes, we were not able to estimate the depth because the bottom was not visible. In general, the small overhanging sinkholes are extremely dangerous because their margins are composed of loose material (lake marls). Many appear to have opened rather recently because they lack signs of tufa. All in all, 19 of the structures (including the sub-sinkholes) have tufa, i.e., they are older and had standing water in them (Fig. 2). However, how many lakes these represented is not recorded. Apparently most of the sinkholes were originally covered by water and, thus, not known at all. The Water Atlas of Saudi Arabia lists 17 lakes (MINISTRY OF AGRICULTURE AND WATER, 1984). The publication also lists electrical conductivities of the lake waters. These ranged from 2510 to 8600 µS/cm, i.e., the values are higher than to be expected in carbonate saturated waters. Some values appear to be even much higher than gypsum (or anhydrite) saturated waters. This may be due to ongoing evaporative concentration in the shallow lakes. Thus, the lake water most probably was high in sulfate as well as carbonate. This may explain why we only found two species of gastropods, quite a small number of mollusk species for a freshwater habitat. The shells of one of the species are ubiquitous while the second one, a cerithiid species, was found only in one place (half-way down in Sinkhole 2). The shallow lake bottoms (around the sinkholes) was occupied by reeds, the roots of which are still noticed everywhere.

The bottoms of those sinkholes that contained lakes as well as the flats around the sinkholes are composed of very fine-grained marls or lake chalk (seekreide). Since the draining of the lakes, these deposits have dried out and shrunk. Numerous meter-deep shrinkage cracks crisscross

No	North°	East°	Size (m)	Depth (m)	Type	Remarks (T = Tufa)	Qanat
1	22.1689	46.7166	200*50	Ca. 3-10	elongated	T, fresh circular cracks	No
2	22.1626	46.7034	400*100	Ca. 5-30	elongated	T, fresh cracks; pit caves	No
2a	22.1628	46.7024	10*10	>20	narrow pit	T	No
2b	22.1626	46.7045	50*50	ca. 10	circular	T	No
2c	22.1632	46.4043	30*30	ca. 10	circular	T, fresh cracks	no
3	22.1634	46.7019	60*60	ca. 15	circular	Post-lake	no
4	22.1681	46.7087	1100*400	ca. 30	elongated	T, former main lake, fresh cracks, terraces	channel
4a	22.1682	46.7077	50*50	ca. 10	circular	T, sand dune	no
4b	22.1686	46.7073	15*15	ca. 10	circular	T, sand dune at bottom	No
5	22.1706	46.7087	50*40	>20	circular	T ?, bottom not visible	no
6	22.1715	46.7087	60*60	ca. 30	circular	T, undercut, caves?	no
7	22.1744	46.7068	60*60	?	circular	not visited	no
8	22.1774	46.7133	70*70	ca. 40	circular	T	no
9	22.1771	46.7140	9*8	ca. 10	circular	overhanging, with sand pile	no
10	22.1769	46.7139	15*13	6	circular	overhanging, with sand pile	no
11	22.1776	46.7142	7*10	>25	circular	overhanging	
12	22.1785	46.7143	15*15	5	circular	half filled by dunes	no
13	22.1786	46.7146	16*14	6	circular	half filled by dunes	no
14	22.1807	46.7157	105*90	ca.40	irregular	T, sand dunes	yes
15	22.1820	46.7178	50*50	ca.50	circular	T	yes
16	22.1840	46.7256	100*110	35	irregular	T, collapse blocks	yes to 15 (80m)
17	22.1853	46.7241	15*15	30	circular	overhanging	no
18	22.1865	46.7257	315*110	Up to 25	elongated	T, composite of 3 sinkholes	channel to 17 (130m)
18a	22.1857	46.7254	95*70	ca. 15	elongated	T, terraces	“
18b	22.1870	46.7257	112*85	ca. 15	irregular	T, terraces	“
18c	22.1872	46.7268	95*80	ca. 25	irregular	T, collapse blocks	“
19	22.1869	46.7273	51*25	ca. 20	elongated	T, natural bridge with 15c	yes
20	22.1884	46.7280	38*38	ca. 20	irregular	T, pit	channel to 19 (160m)
21	22.1880	46.7287	26*22	?	elongated	not visited	yes
22	22.1897	46.7294	60*35	?	elongated	not visited	channel
22a	22.1897	46.7292	20*18	?	circular	not visited	“
23	22.2097	46.7345	48*38	?	circular	not visited, half filled by dunes	yes (?)

Table 1: List of sinkholes near Layla. Sizes according to Google Earth and own field inspection.

the lake bottoms and surround the sinkholes. They can not be differentiated from cracks caused by ongoing subsidence. The shrinkage of the lake bottom sediments has caused their subsidence. In places, shrinkage amounted to more than a meter (Fig. 3) and opened over 10 m deep “shrinkage caves” between the sediment and the solid tufa (for example, at the southern end of Sinkhole 2).

Figure 2: Layla Lakes in the early 1980s.

Figure 3: Shrinkage of lake-bottom chalk deposits.

Field observation and Google Earth images also revealed that the lakes served as natural outlets of the deeper aquifer. A series of parallel channels and qanats (Arabic for subterraneous water channels) conducted water over about 5 km from the lakes to farms in the north. This usage of the lake water was sustainable, since the qanats did only allow for gravitational outflow, thus only water that naturally flowed out of the aquifer was consumed.

3. Layla Lakes Gypsum Tufa
3.1 Observations

The most important discovery made in Layla Lakes is the magnificent tufa that covers the vertical walls of the lake sinkholes (Fig. 4). Tufa here is understood as a sublacustrine low-temperature mineral deposit. Repeated test with 2N-HCl, fingernail scratching and macroscopic inspection showed that the tufa is entirely composed of gypsum. In it, numerous gastropod shells can be found immured at places. Even though the tufa surface is covered with fine-grained, cream-colored calcareous dust, the tufa itself is a sparitic selenite or a massive, fine-grained gypsum. Since so far no such site has – to our knowledge – been described in the literature, the term "tufa" is used even though it has so far exclusively been used for calcareous deposits (compare FORD & PEDLEY, 1996). The term "travertine" is avoided because it is more commonly used for hydrothermal and high pCO_2 sources of calcareous deposits. The expectation to find calcareous tufa or stromatolitic microbialites, as is common in $CaCO_3$-supersaturated lakes such as Plitvice (KEMPE & EMEIS, 1985) or Mono Lake, Pyramid Lake, Walker Lake, and Searles Lake in the western USA (compare KEMPE & KAZMIERCZAK, 2008), Lake Van in eastern Anatolia (KEMPE et al., 1991), or in crater lakes such as Vai Lahi on Niuafo'ou (KAZMIERCZAK & KEMPE, 2006), was not met. An overview over calcareous tufa deposition in low temperature environments was given by FORD & PEDLEY (1996).

Apart from the singular mineralogy, the morphology of the tufa is the most striking feature: The 20 to 30 m high walls of the sinkholes are covered with a several meter thick crust of tufa. There is a distinct morphological change from bottom to top (example Sinkhole 2, eastern wall; Fig. 4): At the bottom, the crust forms a solid, overhanging panel with only shallow vertical groves. Above, the crust is more segmented into meter-sized bulbous, inverted cones (left on Fig. 4), and further up the tufa forms protruding, upward-oriented, shovel-like bowls or cups (Fig. 5). Some of the cups are more delicate than in other places and can form large shell-like basins. The rims are often less than 10 cm thick and the cups are partially filled with loose sediment.

Figure 4: Panorama view of the eastern wall of Sinkhole 2.

In a sense, they resemble speleothem gours. In places where the sinkhole does not display vertical walls, such as in the center of Sinkhole 4, we find rather regular rows of cup-like structures forming steps. A specifically regular tufa display was found at the northern wall of Sinkhole 4b. Overall, this triple division of the gross morphology of the tufa is found in all of the sinkholes.

Figure 5: Upward oriented, shovel-like cups of tufa (Sinkhole 2, western wall, size about 7 x 4 m).

3.2 Genetic considerations

It is clear that we will never be able to fully understand the genesis of this special form of tufa because the lakes and their physico-chemical environment in which they grew are gone forever. We, thus, can only speculate on these conditions, based on the few data that are available. The observation that the conductivities were high, i.e., in or even above the range of gypsum-saturation, and from the fact that these tufa forms exist, we must conclude, that the Layla Lakes were saturated with respect to gypsum. In contrast to calcite, gypsum cannot be highly supersaturated but precipitates at saturation. Apart from evaporation, two more processes govern gypsum saturation, best explained by WIGLEY (1973) and exemplified for a gypsum karst setting by BRANDT et al. (1976). These processes are: co-dissolution or co-precipitation of calcite and temperature alteration. Thus, several processes can be discussed that may have caused the gypsum precipitation along the walls of the lakes:

- Concentration by evaporation. It is conceivable that on the wide flats that surrounded the deeper sinkholes, evaporation would concentrate the water much faster than over the deep sinkhole sections of the lakes. Higher concentrated solutions may have run down along the floor and cascaded underwater over the lips of the walls of the sinkhole, bringing saturated solutions into contact with the crystals already growing on the walls (precipitation upon reaching nucleation sites).
- Calcite co-dissolution. Concentration on the flats by evaporation and degassing of CO_2 causes precipitation of $CaCO_3$ (calcite and/or aragonite). Downward cascading solutions bring the water into deeper water layers with a higher $p$$CO_2$. There, the co-transported fine-grained lake chalk is being dissolved, pushing (because of the common ion effect of the increasing calcium activity) the gypsum over the saturation limit and causing its crystallization along the walls.
- Temperature change. Ascending water from the deep aquifer, delivering gypsum saturated solutions warmer than the lake temperatures, cools in the lake and gypsum crystallizes along the walls.

In any case, the continued delivery from the underlying aquifer of nearly gypsum saturated water is the key condition. These solutions may either have risen slowly through the sediments of the lake bottoms or through distinct vents. One of such vents may have been adjacent to Sinkhole 2. Another vent may have been located at the northwest-end of Sinkhole 4 and in the western wall of Sinkhole 20.

4. Conclusions

The situation seen today is the product of a long geologic history. At this point, one can only guess what its history. One of the clues is the fact that all of the sinkholes seem to occur in unconsolidated lake chalks, the "Layla Lake Formation". Thus, the outflow of deep aquifer water over long periods refills any subsidence holes with chalk. During times of wetter climate, the groundwater is recharged and the lakes expand. During dry climate periods, the groundwater flows out only sparingly and the lakes retreat to the immediate vicinity of the sinkholes. Where the gypsum tufa has collapsed from sinkhole walls, we find over 10 m high profiles of laminated or layered lacustrine chalks. These offer the possibility to do paleoclimate research, an aim we will pursue next.

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GEOMICROBIOLOGY AND HYDROLOGY OF POOL PRECIPATES IN THE GUADALUPE MOUNTAINS, NEW MEXICO, USA

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The Guadalupe Mountains of southeastern New Mexico (USA) are home to hundreds of caves hosting a variety of speleothems. These arid-land caves, as semi-closed systems stripped of the influence of surface weathering, provide a particularly valuable window into the world of carbonate-precipitating microorganisms and the interaction of meteoric waters mixing with deep waters.

The cave pool precipitates, many of which are biogenic, record microbial influences, surface climate, and ecosystem changes. The cave pool precipitates researched in this study are pool fingers. Pool fingers are subaqueous pendant, finger-like speleothems. Previous work in Hidden and Cottonwood caves has shown microbial fossils associated with pool finger precipitates. This work expands on those observations by presenting data on biomarkers extracted from pool fingers. Preliminary analysis indicates that plant waxes (imported into the cave environment) dominate the organic residue in abiologic carbonates (pool spar), while evidence of hopenoids coupled with an absence of plant residues is found in carbonate deposits associated with biogenically-active environments ('moonmilk').

The connection between microbial communities and their chemical environment is especially strong in 'extreme' environments (extreme pH, salinity, temperature, presence/absence of light, low nutrient conditions, etc.). Modern bacterial communities are known to utilize chemical species that are present in the cave environments for metabolic processes. Through the use of available water data from the literature and calculations of Gibbs free energy available from equilibrium considerations we identify energetically-favored metabolic pathways. Study of the 'fossil' biomarkers combined with modern environments will lead to a better understanding of subsurface carbon cycling, characterization of microbial communities, and the input of deeply circulating waters.

1. Introduction

Fundamental questions remain regarding formation of secondary calcite and the possible role of microbial precipitation. An interdisciplinary approach to field and laboratory studies allows us to address some of these major geomicrobiological issues. Subsurface carbonate systems constitute a major arena of interaction between microorganisms, minerals, and water (Barton and Northup, 2007). The bio- and geochemical signatures identified in carbonates may be generalized to other biogenic carbonate occurrences such as travertine mounds (Crossey et al., 2006) and deep sea hydrothermal vents, and have potential use in identifying the presence of life on other planets.

This research focuses on a less well-studied speleothem that forms in subaqueous cave environments: pool fingers. In the Guadalupe Mountain (Fig. 1) cave pools host a wide variety of speolothems such as pool fingers, webulites, U-loops, and pool meringue (Davis et al. 1990; Hill & Forti 1997; Queen & Melim, 2006). Pool fingers are finger-like speleothems that hang down in cave pools. Pool fingers form entirely underwater and lack a central drip canal. The majority of pool fingers are 1-2 cm in diameter and 5-15 cm long (Davis et al. 1990). The giant pool fingers of Hidden Cave, NM are an exception at nearly 10 cm in diameter and well over 1 m in length. The internal layering of pool fingers indicates downward growth with lesser outward growth (Fig. 2). The current hypothesis is that microbial filaments, hanging down from submerged surfaces, act as nuclei for the growth pool fingers. A previous study of fossil pool fingers in Hidden Cave found evidence of alternating microbial and abiotic layers (Melim et al. 2001). Further work in other caves has found a number of potentially biogenic carbonate precipitates (Queen & Melim, 2006). These published studies suggest biogenic processes contributed to the formation of these cave paleo-pool carbonate deposits, and thus pool fingers provide a record of paleo-hydrology and paleomicrobiology.

Figure 1: Regional and local map of the study area.

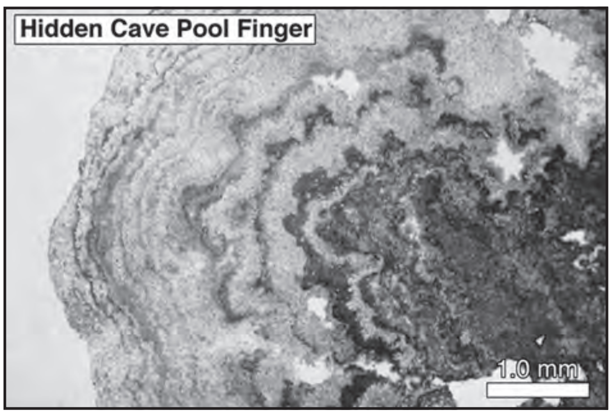

Figure 2: Cross section of pool finger from Hidden Cave. Photo by Dr. Leslie Melim.

Biomarker analysis is an important tool for understanding biogenic carbonates. Past and present bacterial communities utilize chemical species present in the cave environments for metabolic processes and may directly or indirectly contribute to carbonate production. The lithified communities leave behind fingerprints in the form of biomarkers. Biomarkers can include fossilized microbes, mineral fabrics, mineralogy, and preserved lipids. Lipid biomarkers left behind by microbes in the calcite can have a unique signature that can be used to identify different types of microorganisms. Several studies (Blyth et al., 2006, 2008) have shown that bacteria and plant biomarkers can be extracted from cave stalagmites.

Earlier studies (Thraikill 1971; Forbes 2000; Turin & Plummer 2000, Palmer and Palmer, 2001) have examined the chemistry of pool waters or compared the chemistry to pool precipitates, but none have considered the role of microbes in modifying either the pool chemistry, pool speleothems, or linked the geochemistry, mineralogy, and microbiology of the cave pools. Bacterial communities utilize chemical species present in the cave environments for metabolic processes. Using available water data from the literature and calculations of Gibbs free energy available from equilibrium considerations, we identified the energetically favored metabolic pathways. Most metabolically important reactions involve oxidation-reduction reactions among chemical (gas, aqueous and mineral) forms of hydrogen, nitrogen, carbon, sulfur, iron and manganese. The combination of thermodynamic analysis and field observations (minerals forming in cave environments and identified microbial communities) further refine the list of potential metabolic reactions. These predictions guide further investigation into the ways in which microbial species participate in the formation of cave precipitates.

2. Methods

Samples were collected from Hidden Cave and Carlsbad Cavern. A pool finger from Hidden Cave and pool spar were processed for lipid biomarker analysis. The biomarkers were extracted using a series of solvent washes in a Soxhlet Extractor; the products of each wash were analyzed using gas chromatography followed by gas chromatography/mass spectroscopy. Detecting other types of biomakers requires using various microscopy techniques. We used a on a JEOL 5800 scanning electron microscope (SEM) equipped with an Oxford (Link) Isis energy dispersive x-ray analyzer (EDX) to identify mineral fabrics and fossilized microbes; x-ray mapping provided mineral composition and on occasion identification of mineral via crystal habits, distribution of elements, and targets for the microprobe; back-scattered emission (BSE) supported the identification of chemical layering; cathode luminescence gave information about different trace element variations among layers. Analysis on a JEOL 8200 electron microprobe provided quantitative elemental composition, and x-ray diffraction (XRD) was used for confirmation of mineral phases.

Cave pool water samples were collected and analyzed using inductively-coupled plasma optical emission spectroscopy (Perkin Elmer Optima 5300 DV ICP-OES) and anion chromatography (Dionex 500x) to provide major ion chemistry for the active hydrologic system. Alkalinity was performed by standard titration methods using sulfuric acid. Analyses were performed in accordance with standard quality assurance – quality control protocol. These data provided information for hydrochemical mixing models, microbial metabolism models, and evaluation of stability of several important minerals (including gypsum and

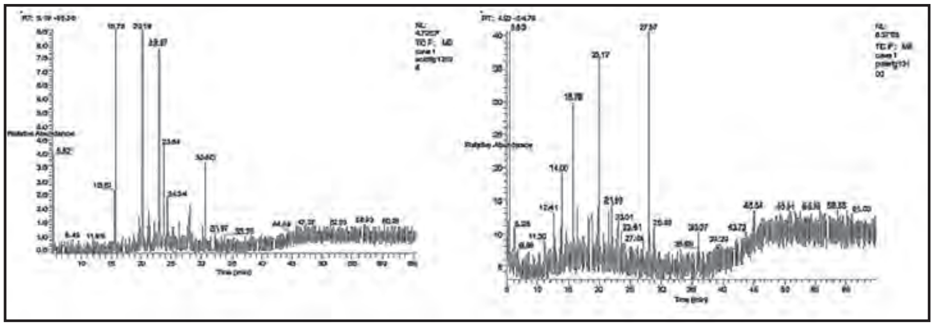

Figure 3: Preliminary biomarker data from moonmilk portion of a pool finger.

carbonate). To understand trends in hydrochemistry, regional aquifer data were compiled from the literature and Piper diagrams were constructed to identify geologic units with chemically similar water and to define the evolution in water chemistry along potential flow paths. Chloride/bromide plots were constructed to determine salt sources, and external carbon was computed (Chiodini et al., 2000) to identify the presence of carbon sources above that due strictly from carbonate dissolution. To provide reference points for active speleothem formation, we incorporated data from two cave systems, caves in Alaska (Cataract Cave and Thrush Cave) with active moonmilk formation and unnamed caves in La Madera, NM with active pool fingers, were examined as well. Several water analyses were selected for further thermodynamic modeling. The initial modeling looked at five pools from Lechuguilla Cave: Lake of the Blue Giant, Sulfur Shores, Lake of the White Roses, Lake Chandelier, and Briny Pool. Waters that represent active biogenic formations as well as inactive waters were plotted and modeled to determine likely microbial metabolic pathways. The thermodynamic models were compared to each other to discuss differences/similarities in potential pathways.

3. Results and Discussion

Biomarker analysis was done on a pool finger from Hidden Cave (Fig. 3) and a piece of pool spar from Carlsbad Cavern. The moonmilk portion of the large pool finger from Hidden Cave contained several short-chained fatty acids (C16-C22). The C16-C22 are considered generic lipid biomarkers. In the polar fraction unknown hopanes were detected. The presence of a hopanes with the short-chained fatty acids confirms the presence of bacterial biomarkers in the moonmilk portion of the pool finger. The pool spar sample (assumed to be abiotic) produced a different mass spectra pattern for the acid fraction and polar fraction. The acid fraction contains short chain fatty acids (C16-22), but there are no hopanes present in the other fractions. The polar fraction for the polar spar is dominated by plant biomarkers producing the "rainbow" spectra of C22 and higher chains. The initial x-ray map of one section of a pool finger showed spheres of magnesium carbonates (confirmed by EDS) (Fig. 4), but this is not conclusive evidence for microbial involvement and bears further investigation. The cathodoluminescence (CL) images of the pool finger showed very faint CL in the cores of two samples and plumes of brighter areas rimward (Fig. 5). The results from the CL imaging might be due to changes in trace elements or from re-precipitation (biotic or abiotic) of the calcite. Further investigation using high resolution imaging and microprobe data is planned.

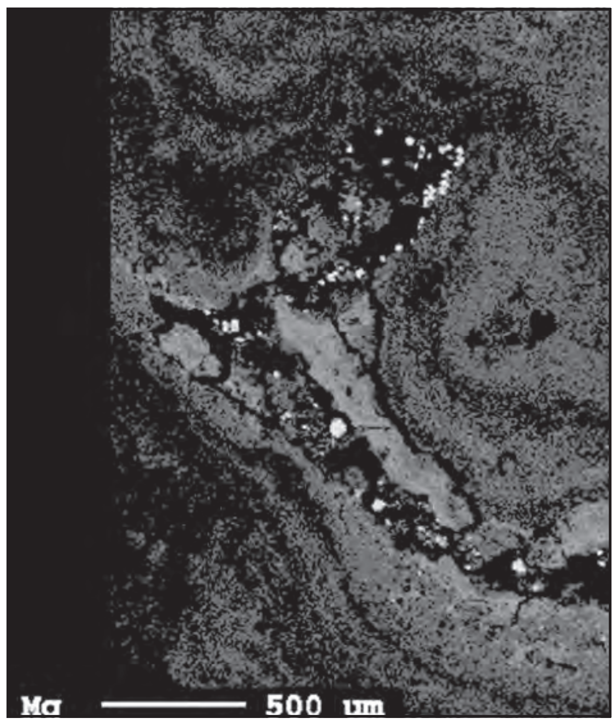

Figure 4: Microprobe x-ray map of magnesium in pool finger. The light grey spheres are a magnesium carbonate.

Fig. 5

Geochemical analysis was done on waters from three different cave systems: the caves in Alaska (in the Tongass National Forest); the La Madera waters (travertine mounds with caves); and finally, the cave pools in the Guadalupe Mountains The Piper Diagram shows a clear trend for the different cave systems (Fig. 6). The Alaskan caves, which have actively precipitating moonmilk, are clustered in the lower-left corner. The La Madera waters, which originate

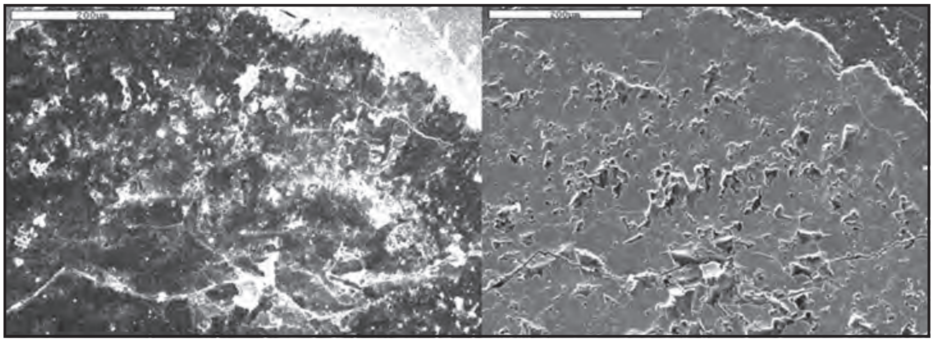

Figure 5: CL (left) and BSE (right) image of outer portion of pool finger.

from CO_2 springs with other deeply sourced gases (Newell et al.,), plot roughly in the center, whereas the Guadalupe Mountain cave pool waters trend to the far left side. The sulfate + bicarbonate plotted against calcium + magnesium shows a clear trend of the Guadalupe Mountain waters trending on the 1:1 line with the Alaskan and La Madera waters are off to the right of the line. There are a few exceptions for the Guadalupe Waters that do not follow the 1:1 line. The 1:1 line represents carbon sources from water-rock, soil, and atmosphere input (Crossey et. al., in press). The waters that plot off this line have a higher then expected carbon signal. The chloride/bromide plot shows that most of the salt present in the cave waters is from water-rock interactions. The preliminary thermodynamic modeling (using reaction quotient computations from activities calculated by the speciation program PHREEQc (Parkhurst, 1995) and methods of Meyer-Dombard et al., 2005 for five cave pools from Lechuguilla Cave showed that microbial communities would potentially use oxygen as the primary electron acceptor, followed by nitrate, goethite, hematite, and sulfur. One pool, Sulfur Shores, was predicted to have communities that utilize goethite and hematite before elemental sulfur.

4. Conclusions

The initial lipid biomarker analysis shows potential bacterial biomarkers in the outer portion of the pool finger from Hidden Cave. The spar sample (assumed to be abiotic) does not have bacterial lipid biomarkers, but instead there are preserved plant biomarkers, potentially confirming its abiogenic nature. These results suggest a bacterial role in precipitation of the outer portion of the pool finger. The x-ray maps from the microprobe and the CL images from the SEM showed areas on the pool finger sample that will be targeted for analysis.

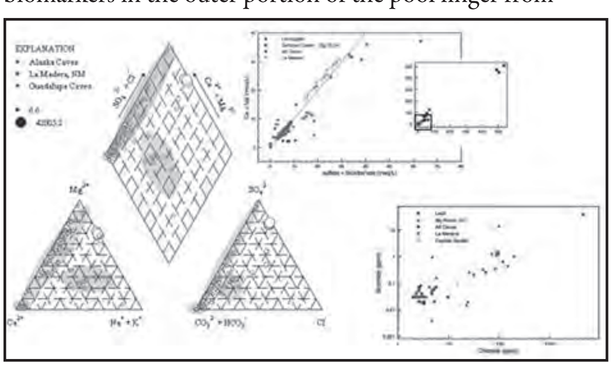

Figure 6: Geochemical analysis including Piper Diagram, Chloride/Bromide Plot, and External Carbon Plot.

The geochemical analysis shows that most of the cave pool water chemistry in the Guadalupe Mountains is derived from water-rock interactions. The Alaskan caves and La Madera waters are a combination of water-rock interactions and other processes. There are several (nine pools) exceptions in the Guadalupe Mountains. The nine pools in the Guadalupe Mountains, along with the Alaskan and La Madera have an external source of carbon above what would be expected from water-rock, soil, and atmosphere interaction (Crossey et. al., 2003, 2006). Usually, this signal is accompanied by other gases such as H_2 or H_2S. In the case of La Madera, these gases are from deep sources (Newell et al., 2005). In the Guadalupe waters this might arise from active microbial communities. We will target these nine pools for further study. The thermodynamic profiles predict that the five pools that were modeled would have bacterial communities that use similar metabolic pathways except for Sulfur Shores. The thermodynamic profiles are not complete until fieldwork has been done to confirm mineral phases and microbial communities that may be present.

The pool finger communities in the Guadalupe Mountains do not appear to be currently active based on the water chemistry and field observations. However there are nine pools in the Guadalupe Mountains that need to be investigated based on their geochemistry to determine if there are active pool finger communities. The Alaskan caves and La Madera provide a speculative glance at what geochemical conditions would support a microbial role in pool finger formation. Evidence from previous studies by Melim et. al. (2001) and current work with lipid biomarkers provides increasing evidence of a biogenic origin for pool fingers.

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CONDUIT FLOW PROCESS (CFP) FOR MODFLOW-2005

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A Conduit Flow Process (CFP) for MODFLOW-2005 is now available from the U.S. Geological Survey at (http://water.usgs.gov/software/ground_water.html). The CFP is designed to simulate karst aquifers by: (1) coupling the traditional ground-water flow equation with a discrete network of cylindrical pipes (CFPM1 is an update of Carbonate Aquifer Void Evolution code); (2) inserting a high-conductivity layer that can switch from laminar to turbulent flow (CFPM2); or (3) simultaneously coupling a discrete-pipe network while inserting a high-conductivity layer that can switch from laminar to turbulent flow (CFPM3). The pipe network (1) represents secondary conduit porosity under laminar or turbulent flow conditions. Preferential flow layers (2) may represent either: a single secondary porosity subsurface feature, such as a well-defined laterally extensive underground cave; or a horizontal preferential flow layer consisting of many interconnected tubes, such as the burrowed limestone with interconnected vugs greater than 10 millimeter diameter of the Biscayne aquifer, Florida. Data preparation is more complex for CFPM1 than for CFPM2. For CFPM1, pipe locations, lengths, diameters, tortuosity, internal roughness, critical Reynolds numbers, and exchange permeability are required. CFPM1 solves the pipe network equations in a matrix independent of the porous media equation matrix, which may avoid numerical instability for some problems. Large pipe networks, however can result in systems of equations that are either slow to converge to solution or will not converge. Water is exchanged between the rock matrix and the conduits via head-dependent flux terms. For both CFPM1 and CFPM2, the Reynolds number is calculated to determine if flow is laminar or turbulent. With CFPM1, the Hagen-Poiseuille equation is used when flow is laminar, and the Darcy-Weisbach equation is used when flow is turbulent. With CFPM2, energy losses due to turbulent flow are approximated by lowering the laminar hydraulic conductivity once the critical Reynolds number is exceeded.

1. Introduction

Rapid laminar or turbulent ground-water flow can occur in dual porosity aquifers through relatively large interconnected voids. Within these large voids, frictional and surface-tension forces between the fluid and rock are less significant because the conduit diameters are so large that wall roughness only restricts flow moving close to the conduit wall. The term "hydraulic radius" is defined as the channel cross-sectional area divided by the perimeter of the channel cross-sectional area that is wet. As the radius of a pore increases, the hydraulic radius also increases and greater flow will occur under the same energy forces due to reduced resistance to flow from the pore walls. When flow becomes turbulent in both porous media and conduits, some of the energy that drives the flow is lost to water eddies, and specific discharge no longer increases as rapidly as the head gradient increases.

The CFP was designed to be flexible enough for use in locations with limited or abundant field data. In some geologic environments, such as Mammoth Cave, Kentucky, detailed information is available (or could be derived) on the location, diameter, tortuosity, and roughness of the subsurface caverns. CFP Mode 1 (CFPM1) was designed with these locations in mind. In other locations, such as the Biscayne aquifer of southern Florida, void connections and distributions are so complicated within preferential flow layers that a complete characterization as a pipe network is not possible. CFP Mode 2 (CFPM2) was designed with these locations in mind; specifically, laminar and turbulent flow through complicated void connections is represented with a limited number of "effective" or "bulk" layer parameters.

The CFP is an outgrowth of long-term research into speleogenesis in karst systems, including the Conduit Aquifer Void Evolution (CAVE) code developed by Clemens (1998) and Hückinghaus (1998). Subroutines of a version of the CAVE code described in Bauer (2002) and Birk (2002) were extracted and modified to work with MODFLOW-2005 to partially create the CFP. The CFP expanded upon the CAVE work by: (1) integrating new equations that handle partially saturated pipe flow; (2) working with traditional MODFLOW units other than meters and seconds; (3) including user-defined, rather than constant values, for critical Reynolds numbers (N_{Re}) that transition ground-water flow from laminar to turbulent; and (4) specifying model layers (CFPM2) that can transition between laminar and turbulent flow conditions, while requiring less input data than conduit flow pipes (layer may represent vuggy stratiform bed or bedding plane flow zones). A final advancement is the creation of CFP Mode 3 (CFPM3), which simultaneously simulates conduit flow pipes (CFPM1) and preferential flow layers (CFPM2). A complete description of the model code equations and parameter guidance can be found in Shoemaker et al. (2008 a,b), Kuniansky et al. (2008), and Bauer et al (2003).

2. Reynolds Numbers

Laminar and turbulent conditions in porous media are differentiated by the value of the Reynolds number (*Re*) (Darcy, 1856; Schneebeli, 1955). The Reynolds number represents the ratio of fluid inertial to viscous forces and is a function of mean velocity, pore diameter, and fluid density and viscosity. Typically, flow in porous media is laminar under natural gradients due to small (less than 0.01 m) pore diameters . In porous media flow there is controversy over the dominant micro-scale forces, processes and even equations for transitioning between fully laminar flow to fully turbulent flow. Laminar flow is a flow regime in which water moves along parallel streamlines or layers, and shear stresses within the water are overcome by the viscous forces of the water. Turbulent flow is characterized by streamlines that are no longer parallel but flow in random complex patterns (eddies) with large variations in flow velocity from the mean flow velocity. When flow becomes turbulent, specific discharge no longer increases as rapidly as the head gradient increases (non-linear relationship). Huang and Ayoub (2006) provided an excellent review and discussion of the theory and research about flow in the fully laminar, transitional, and fully turbulent regimes. Barr (2001) presented much data in dimensionless graphical forms for examination of the transition from laminar to turbulent flow. Nivens (2003) provided additional discussion of the paper by Barr (2001).

The critical Reynolds number (N_{Re}) defines the threshold where laminar flow ceases and turbulent flow begins. The term turbulent flow for CFPM2 includes transitional non-Darcian flow because the relation between hydraulic gradient and specific velocity are non-linear. Typically, N_{Re} ranges between 1 and 60 in porous media (Bear, 1979; Freeze and Cherry, 1979; Darcy, 1856; Schneebeli, 1955). The N_{Re} for samples of different aquifer or experimental material can be determined through laboratory experiments from the mean velocity at the point where the hydraulic gradient and specific velocity cease to be proportional (Darcy, 1856; Schneebeli, 1955; Kuniansky et. al. 2008).

Reynolds numbers (*Re*) for pipes are also used to differentiate between laminar and turbulent flow. However, the diameter used in the calculation is the pipe diameter and upper and lower critical Reynolds numbers are required to fully describe when flow is laminar or turbulent. Due to conservation of momentum, flow in a laminar state tends to stay laminar and flow in a turbulent state tends to stay turbulent. Therefore, an upper N_{Re} needs to be assigned when a CFPM1 pipe and/or CFPM2 layer with laminar flow transitions to turbulent flow, and a lower N_{Re} needs to be assigned when a CFMP1 pipe and/or CFPM2 layer with turbulent flow transitions to laminar flow. During a transient simulation, for example, with lower and upper N_{Re} equal to 2000 and 3000, laminar flow in a hypothetical conduit pipe or layer would transition to turbulent when the Re equals or exceeds 3000, respectively, and remain turbulent until the *Re* is less than or equal to 2000. Conversely, turbulent flow in the hypothetical conduit pipe or layer would transition to laminar when the Re is less than or equal to 2000, and remain laminar until the *Re* is again equal to or exceeds 3000. In the pipe experiments of Reynolds and numerous similar experiments in hydraulics laboratories, this phenomenon was repeatedly observed. For porous media, upper and lower N_{Re} have not been observed; therefore upper and lower N_{Re} for CFP simulations of porous media can be set approximately equal, for example 11 and 10, respectively. Additionally, it has been observed that between the upper and lower N_{Re}, the discharge in pipes is a function of mean velocity to the power of greater than 1 but less than 2 (Vennard and Street 1975, chap. 7) and this is sometimes referred to as the transitional flow regime. For smooth pipes the lower N_{Re} ranges from 2,000 to 4,000 and the upper N_{Re} ranges from 12,000 to 14,000 (Vennard and Street 1975, chap. 7).

3. Coupling a Discrete Pipe Network with a Laminar Flow Model (CFPM1)

The main objective of CFPM1 is to couple a porous media flow model (MODFLOW-2005) with a discrete pipe network to approximate the dual porosity nature of many flow systems. The porous media flow model code (MODFLOW) is well documented in McDonald and Harbaugh (1988), Harbaugh and McDonald (1996), Harbaugh and others (2000), and Harbaugh (2005). Laminar and turbulent flow within fully and partially saturated pipes and open channels is discussed in more detail in Vennard and Street (1975), and Chin (2000).

The pipe network consists of many pipes, each having two ends called nodes. A node of a pipe is the location where up to six individual pipes can connect. Each node is located at the center of a finite-difference cell, and there can be only one node within a finite-difference cell. Finite-difference cells can have equal or different row and column lengths. Model layers composed of finite-difference cells also can have constant or variable thicknesses. Pipes can connect diagonally between two finite-difference cells within and between adjacent model layers. Note that the resolution of the model grid should be fine enough for the conduit features to span multiple grid cells. A pipe network, for example, cannot be designed within a single finite-difference cell.

The CFPM1 was designed to simulate laminar and turbulent flow in fully saturated pipes. Additionally, an approximation was incorporated for partially saturated pipes, but should be limited to partially saturated pipes of minimal slope as the approximation is not valid for steeply sloping pipes. Laminar pipe flow can be approximated with the Hagen-Poiseuille equation (Vennard and Street, 1975, p. 390-391). The functional relation between the friction factor (*f*) and *Re* used for turbulent flow in CFPM1 is the empirical Colebrook-White formula (Colebrook and White, 1937; Dreybrodt, 1988).

The exchange of ground water between a MODFLOW cell and pipes, at the pipe node, is accomplished with a linear head-dependent flux term, where the flow resistance between the MODFLOW cell and the pipe node is defined by a pipe conductance term. The pipe conductance is a resistance term that limits ground-water exchange between the pipes and porous media (similar to the conductance terms used in the other head-dependent flow packages of MODFLOW). The CFP assumes ground-water exchange occurs along the entire pipe, and is not turbulent.

Computations of pipe flows, storage changes, and matrix exchanges depend on heads at pipe nodes; however, node heads are unknown. Newton-Raphson iterations are used to solve for node heads in the system of equations for the pipe network. These heads are then used to calculate the head-dependent flux between the pipe network and the MODFLOW cell and the new flux is sent back to the pipe network and MODFLOW cell. This procedure repeats itself until convergence of the solution for head in both models is achieved or until the maximum number of iterations is reached. Note that changes in pipe storage are only computed when the water level in the pipe drops below the top of the pipe. An assumption is made that the node head applies along the length of the pipe in the encompassing MODFLOW cell, so that volumetric storage changes are computed.

4. Computations of Turbulent Flow in Preferential Flow Layers (CFPM2)

Halford (2000) showed that turbulent and laminar flow in well bores can be solved in terms of the Darcy equation if hydraulic conductivity is made a non-linear function of the laminar and turbulent friction factors for pipes, which requires only minor modifications to MODFLOW. The approach for simulation of laminar and turbulent flow in preferential flow layers for CFPM2 is similar to the approach taken in Halford (2000).

Turbulent flow is simulated in CFPM2 by computing a turbulent hydraulic conductivity (K_{TURB}) as a non-linear function of the *Re*, when *Re* is greater than N_{Re}. Turbulent loss is defined with Reynolds number because differences in mean pore diameter also affect specific velocity. The equation relating K_{TURB} and *Re* is

$$K_{TURB} = K_{LAM}\sqrt{\frac{N_{Re}}{Re}},\ Re > N_{Re} \qquad (1)$$

Where K_{TURB} is the reduced laminar hydraulic conductivity (K_{LAM}). The K_{TURB} equals K_{LAM} when *Re* is less than or equal to N_{Re} (Shoemaker et. al, 2008a,b; Kuniansky et al., 2008).

The power function in CFPM2 (equation 1) must be solved iteratively because *Re* is a function of specific velocity. Specific velocity, heads, K_{TURB}, and *Re* will converge in CFPM2 if an iterative solver such as the strongly implicit procedure (SIP) or pre-conditioned conjugate gradient (PCG) is used. Turbulent head loss computations are triggered in CFPM2 when head differences between cells exceed critical thresholds rather than explicitly calculating *Re* and comparing to N_{Re}. The simple empirical power function in equation 1 applied in CFPM2 was verified with laboratory data from permeameter tests conducted with carbonate rock samples with touching-vug porosity and pore diameters of 0.01 m and at fairly low Reynolds numbers (data from DiFrenna et al, 2007; Kuniansky et al. 2008).

5. Examples of the Use of CFP for MODFLOW-2005

Hill et al. (2008) evaluated two methods for simulating spring discharge and matrix-conduit water levels in a dual-porosity karst aquifer in west-central Florida; including (1) a equivalent continuum model (ECM MODFLOW-2005) with only laminar flow and (2) a dual-continuum model, also called dual-porosity model (DCM MODFLOW-2005 CFP mode 1), with laminar and turbulent pipe flow driven by exchanges of groundwater with the porous media model. The DCM models of the two spring systems better simulated transient spring discharges as compared to ECM models; improving the match between simulated and observed discharges by an average of 12% at Weeki Wachee Spring and 40% at Twin D's Spring (Fig 1). Hill (2008) also concludes that when possible, in karst terrain where known underlying conduit networks exit, "it is increasingly difficult to defend the continued application of laminar, equivalent-continuum models for karst aquifers."

Shoemaker et al. (2008b) used CFP Mode 2 to simulate preferential flow layers within the Biscayne aquifer in southern Florida. Turbulent flow was spatially extensive (Fig 2) in the preferential groundwater flow layers with mean void diameters equal to about 3.5 centimeters and critical Reynolds numbers less than 400 (temperature of 25 degrees Centigrade was use to calculate density and viscosity). Turbulence either increased or decreased simulated heads from laminar altitudes. Specifically, head differences from laminar elevations ranged from about -18 to +27 cm and were explained by the magnitude of net

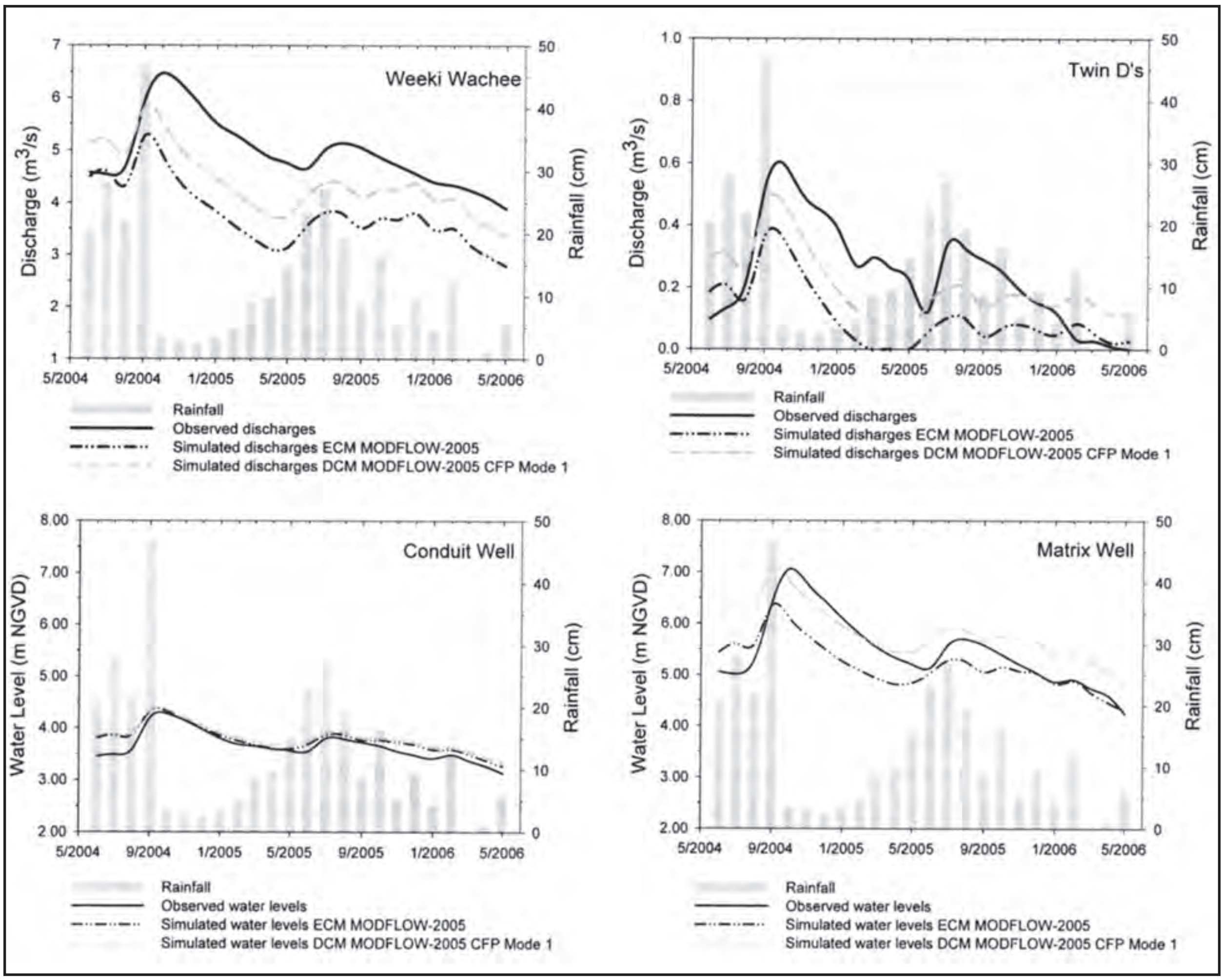

Figure 1: Plots of observed and simulated discharges at Weeki Wachee and Twin D's Springs for the laminar equivalent continuum model (ECM) using MODFLOW-2005 and the laminar/turbulent dual-conductivity model (DCM) using MODFLOW-2005 CFP Mode 1. Average monthly rainfall quantities are for a 132 km2 area. Rainfall estimates provided by OneRain, Inc. and consist of Doppler radar distributions coupled with rainfall quantities calibrated using rainfall gauges (Hoblit and Curtis, 2005). Note the increase in discharge and water levels during September 2004 with passage of Tropical Storms Frances and Jeanne and the cessation of discharge in May 2006 at Twin D's Spring. Caliper or video logs were used to determine if wells monitor the matrix or conduit networks. The conduit well intercepts an underwater cave with a height of approximately 8 m (from Hill et al., 2008, figure 3).

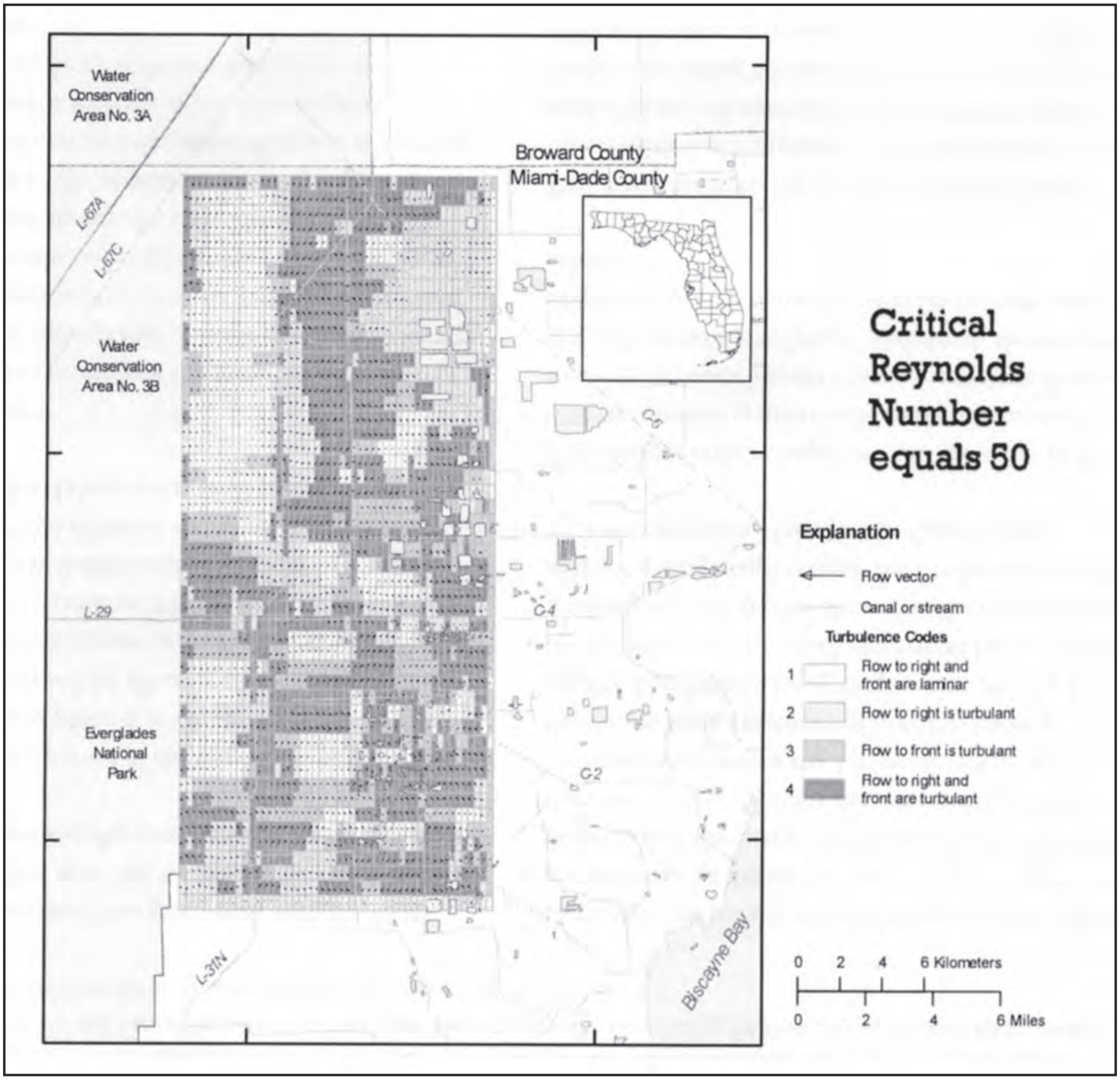

Figure 2: Extent of turbulence in preferential ground-water flow layer (from Shoemaker et al., 2008b).

flow to the finite-difference model cell. Turbulence also affected the sensitivities of model parameters. Specifically, the composite-scaled sensitivities of horizontal hydraulic conductivities decreased by as much as 70% when turbulence was essentially removed. These hydraulic head and sensitivity differences due to turbulent groundwater flow highlighted potential errors in equivalent porous media models without the ability to simulate both laminar and turbulent flow.

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ANTHROPOGENIC SINKHOLES IN THE DELAWARE BASIN REGION OF WEST TEXAS AND SOUTHEASTERN NEW MEXICO, USA

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A significant minority of sinkholes formed in gypsum bedrock in the Delaware Basin of west Texas and southeastern New Mexico are of human origin. These anthropogenic sinkholes are often associated with improperly cased abandoned oil wells, or with solution mining of salt beds in the shallow subsurface. In July, 2008 a sinkhole formed abruptly at the site of a brine well in Eddy Co., New Mexico. The well operator had been injecting fresh water into salt beds of the Permian Salado Formation and pumping out the resulting brine for use as oil field drilling fluid. Borehole problems had prevented the operator from conducting required downhole sonar surveys to assess the dimensions of subsurface void space. The resulting sinkhole formed in just a few hours by catastrophic collapse of overlying mudstone and gypsum, and in less than one month reached a diameter of 111 m and a depth of ~64 m. The event has prompted the New Mexico Oil Conservation Division to review its regulations regarding brine well operations in the southeastern New Mexico oil fields. Fortuitously, a seismograph had been deployed ~13 km southeast of the brine well a few months earlier, and precursor events were captured on the seismograph record a few hours before the subsurface cavity breached the surface. This may be the first documented seismologic record of catastrophic sinkhole formation.

1. Introduction

Sinkholes and karst fissures formed in gypsum bedrock are common features of the lower Pecos region of west Texas and southeastern New Mexico. New sinkholes form almost annually, often associated with upward artesian flow of groundwater from karstic aquifers of regional extent that underlie evaporitic rocks at the surface (e.g., Martinez et al., 1998; Land, 2003a). A significant minority of these sinkholes are of anthropogenic origin, including the well-known Wink Sinks in Winkler Co., Texas (Fig. 1). These features probably formed by dissolution of salt beds in the upper Permian Salado Formation (Fig. 2), in association with an improperly-cased abandoned oil well (Johnson et al., 2003). Powers (2003) reports that a sinkhole that formed near Jal, New Mexico, was probably the result of Salado dissolution related to an improperly-cased water well. Both sinkholes overlie the middle Permian Capitan Reef aquifer. In the case of the Wink sinks, Johnson et al. (2003) observe that hydraulic head of water in the Capitan Reef is locally above the elevation of the Salado Formation. Undersaturated water rising along the borehole by artesian pressure may have contributed to subsurface dissolution and collapse of the Wink sinkholes.

Sinkholes in the greater Permian Basin region have also resulted from solution mining of Permian salt beds in the shallow subsurface. The Borger sinkholes, in Hutchinson Co., Texas, are associated with brine mining operations conducted to extract brine from the upper Permian Flowerpot salt beds. Surface subsidence was first observed in 1964, and sonar surveys subsequently revealed that the solution mining had produced a cavern 180 m below ground level with dimensions of ~120 by 380 m. The survey also showed that the cavern roof had migrated to within 137 m of the surface. Within the next 14 years two sinkholes ~15 m deep and 50 m in diameter formed above the cavern (Johnson et al., 2003).

2. Geologic Setting

The lower Pecos region includes the city of Carlsbad in Eddy County, New Mexico (Fig. 3). Evaporitic rocks, primarily gypsum, are widely distributed in the Carlsbad area both at the surface and in the subsurface (Bachman, 1984; Hill, 1996). Carlsbad is located on the Northwest Shelf of the Delaware Basin, a large hydrocarbon-producing sedimentary basin containing >7300 m of Paleozoic rock and occupying over 44,000 km^2 in west Texas and southeastern New Mexico (Land, 2003b). The uppermost part of the Delaware Basin section is comprised of ~1700 m of redbeds and evaporites of upper Permian (Lopingian) age (Lucas, 2006a; 2006b). This section includes the Salado Formation (Fig. 2), which in the subsurface of the Delaware Basin consists of ~710 m of bedded halite and argillaceous halite, with lesser amounts of anhydrite and polyhalite. Rare amounts of potassium salts (sylvite and langbeinite) occur in the

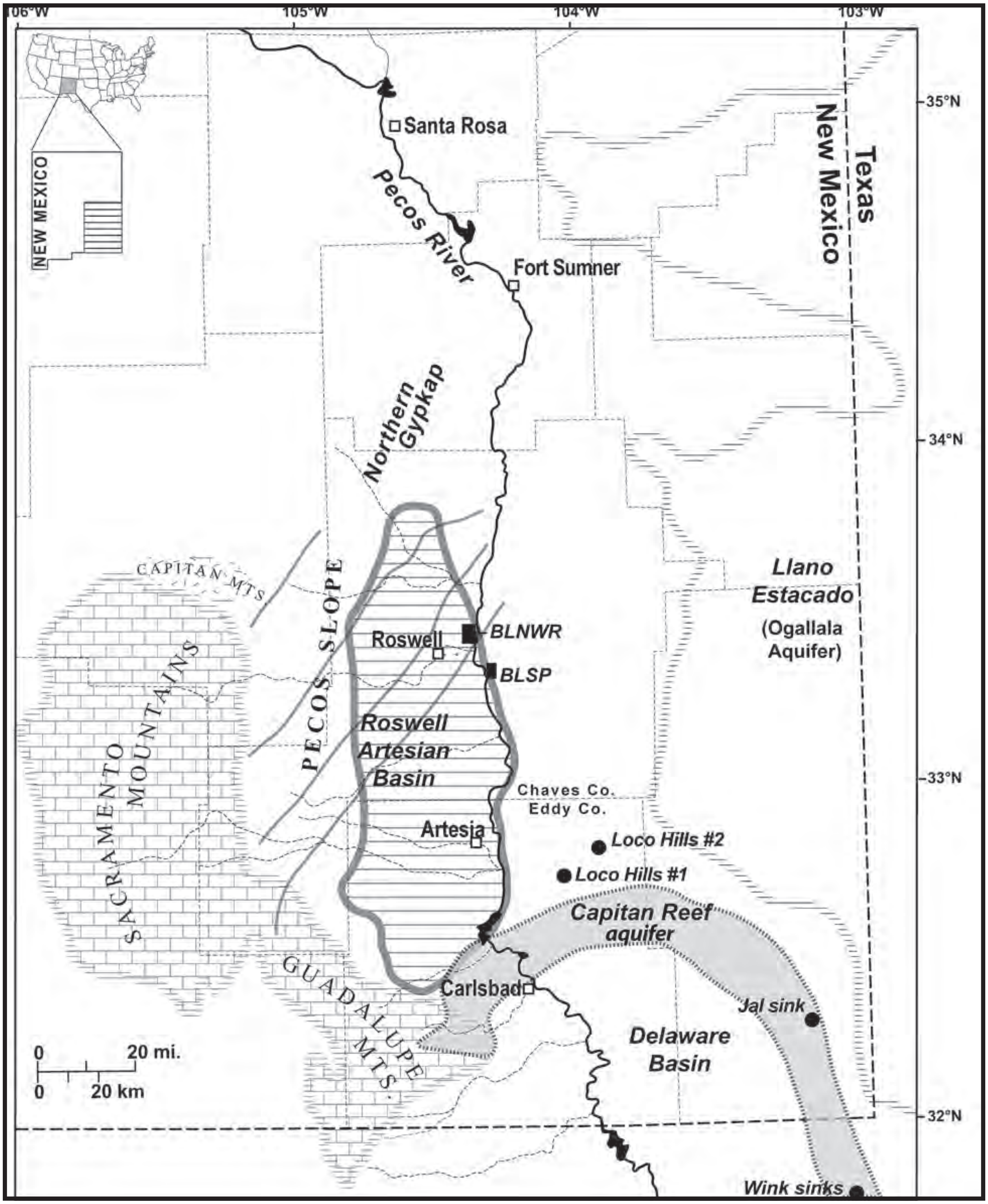

Figure 1: Regional map of southeastern New Mexico and adjoining areas of west Texas, showing location of sinkholes discussed in text, and their position with respect to the Capitan Reef.

McNutt potash zone near the center of the formation (Cheeseman, 1978). Clastic material makes up less than 4% of the Salado (Kelley, 1971). Potash ore is mined from the McNutt Potash Zone in underground mines a few kilometers east of Carlsbad. The formation is also the host rock for the Waste Isolation Pilot Plant (WIPP), a repository for transuranic radioactive waste in eastern Eddy County (Fig. 2).

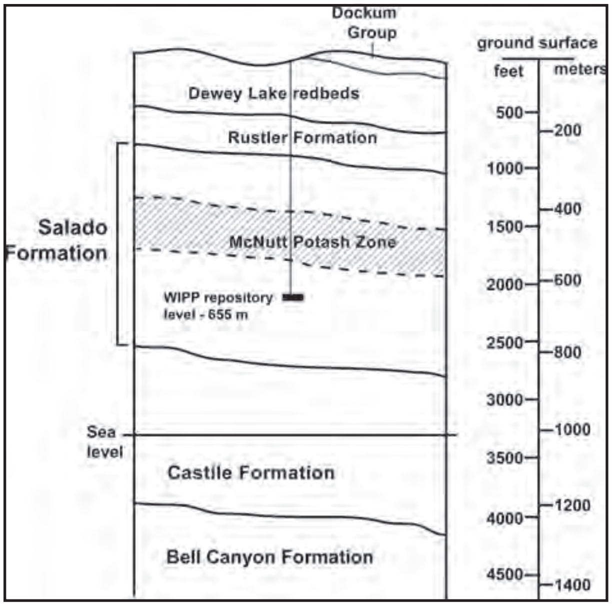

Figure 2: Upper Permian stratigraphy in the northern Delaware Basin, southeastern New Mexico.

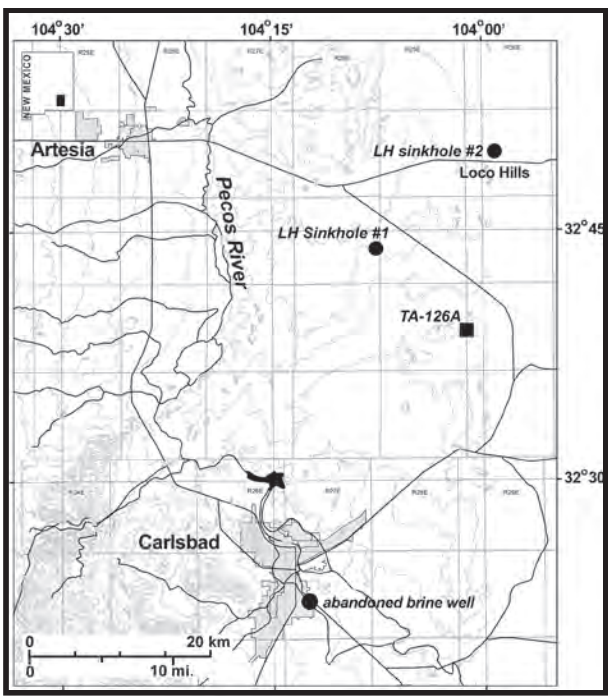

Figure 3: Map of study area in Eddy Co., New Mexico, showing locations of the two Loco Hills sinkholes with respect to the Transportable Array seismograph TA126. Southernmost dot shows the location of an abandoned brine well within city limits of Carlsbad.

The Salado Formation thins to the north and west by erosion, halite dissolution, and onlap onto the Northwest Shelf of the basin. Because of the soluble nature of Salado rocks, the unit is very poorly exposed in an outcrop belt ~5 km east of the Pecos River valley (Fig. 4). In that area the Salado is represented by 10 to 30 m of insoluble residue consisting of reddish-brown siltstone, occasional gypsum, and greenish and reddish clay in chaotic outcrops. In most areas the Salado outcrop is covered by a few meters to tens of meters of pediment gravels and windblown sand (Kelley, 1971; McCraw and Land, 2008).

3. Observations

Around 8:15 on the morning of July 16th, 2008, a driver for a local water service company was inspecting a brine well located on state trust land ~ 35 km northeast of Carlsbad. While on location the driver noticed a rumbling noise and quickly vacated the site. Minutes later, a large sinkhole abruptly formed, engulfing the brine well and associated structures. The well operator had been solution mining the Salado Formation by injecting fresh water and circulating it through the 86 m thick section of halite until the water reached saturation. The resulting brine was then sold as oil field drilling fluid. The brine well was being operated under permit from the New Mexico Oil Conservation Division (NMOCD).

This sinkhole, referred to as Loco Hills Sinkhole #1 because of proximity to the nearby community of Loco Hills (Fig. 3), was originally several tens of meters in diameter and filled with water to a depth of ~12 m below land surface. Large concentric fractures developed around the perimeter of the sink, threatening the integrity of County Road 217, 100 m to the south. By July 24 the originally vertical walls of the sinkhole had begun to collapse, and the sink continued to grow in diameter over the course of the next two weeks. By July 28, the walls of the sink had developed an angle of about 45° to within ~30 m below ground level, above which the sides of the sink were vertical, and the water originally present had subsided into the subsurface. There are no significant sources of groundwater at shallow depths in the immediate vicinity of the sink, so the water was solution mining fluid that had presumably been forced up the debris chimney in the initial stages of collapse, and was now stored in pore space in the resulting collapse breccia in the subsurface cavern. By this time the sinkhole had attained a diameter of ~111 m, based on air photo interpretation. Representatives of the State Land Office used a range finder to estimate a maximum depth of 64 m.

4. Solution Mining

During solution mining operations a subsurface cavern is excavated. Most cavern excavation occurs at the top of the void space, since the injected fresh water floats on top of the denser brine. Thus, caverns produced by solution mining tend to approximate the shape of an inverted cone.

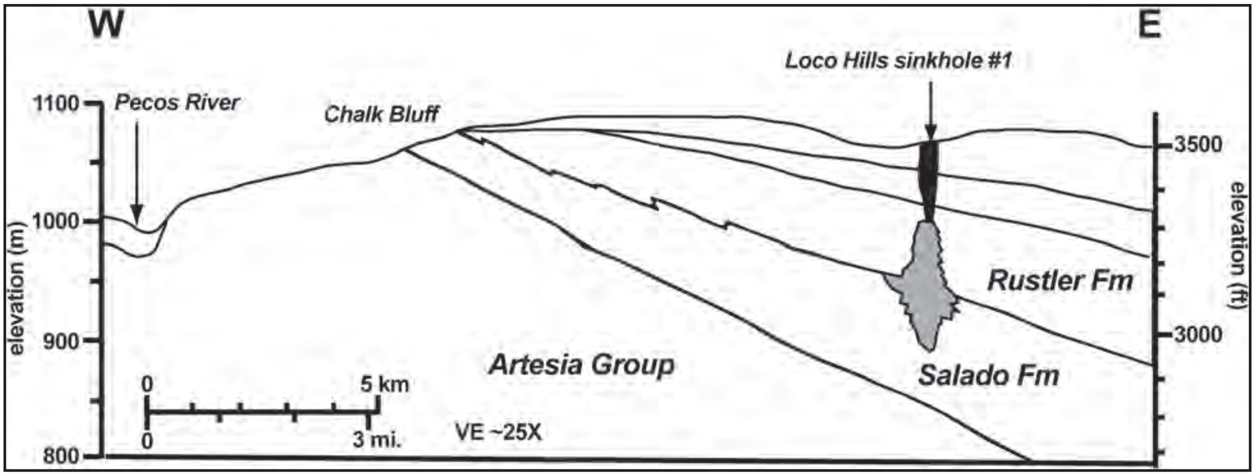

Figure 4: West-east cross-section showing stratigraphic section penetrated by Loco Hills sinkhole #1.

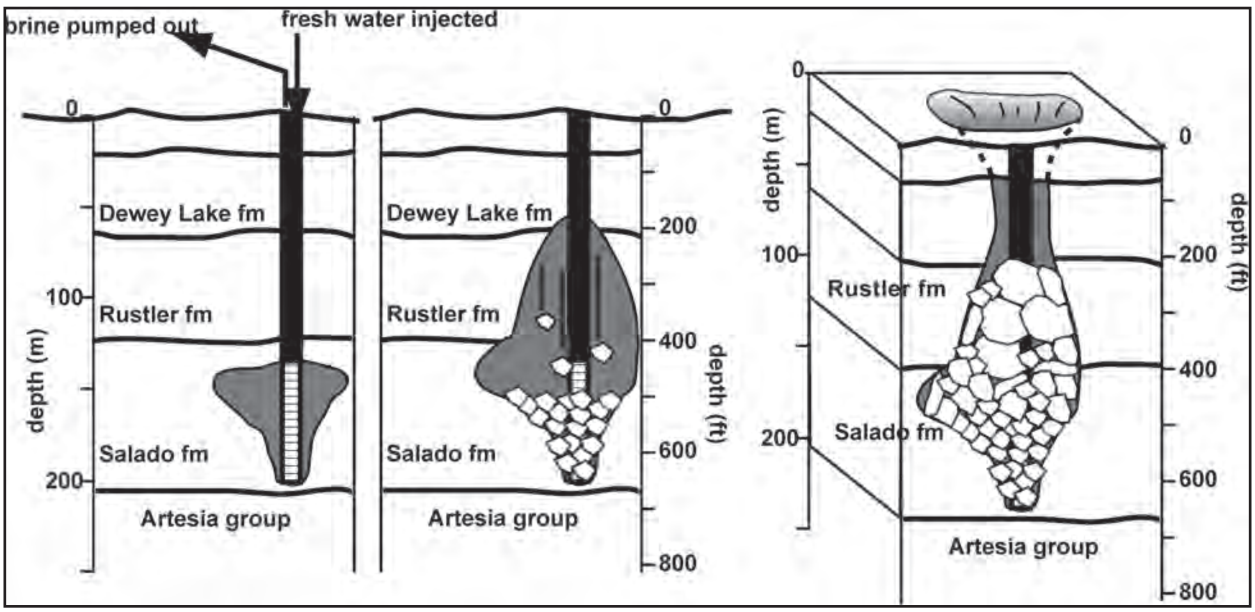

Figure 5: Sequence of events associated with solution mining that led to development of Loco Hills Sinkhole #1. Unnamed uppermost section consists of ~20 m of Quaternary sand, gravel and calcrete.

Typically, a cushion of crude oil or diesel fuel is injected into the void to protect the cavern roof and ensure that cavern excavation occurs outward rather than upward. To prevent surface subsidence and collapse, brine well operators in New Mexico are required to conduct annual pressure tests and downhole sonar surveys to assess the size and proportions of the cavern being excavated. However, borehole problems prevented the operator from conducting these surveys, and the resulting collapse was unanticipated.

In the absence of precise borehole geophysical surveys, a rough estimate can be made of the volume of the subsurface void beneath the Loco Hills Sinkhole based on volume of fluid injected. Brine well operations were approved by NMOCD in 1982, with a production rate of 900 barrels of 10 pound brine per day. Over a 25 year period, this production rate would yield ~5.8 million barrels of brine. Each seven barrels of brine produced dissolves approximately one "barrel" of cavern space (Hickerson, 1991, unpublished report), indicating a cavern volume of ~133,000 m^3 (1 barrel = 5.61 ft^3 = 0.16 m^3), corresponding to an equivalent spherical radius of about 32 m, consistent with the observed sinkhole radius.

The top of the Salado Formation is 121 m below ground level and the formation is 86 m thick at the site of Loco Hills Sinkhole #1 (Fig. 5). The brine well operator had set casing 6 m below the top of salt and suspended tubing for open-hole fresh water injection down to the base of the salt section. Assuming the resulting cavern was 80 m in vertical dimension and originally shaped like an inverted cone, simple volumetric calculations indicate a roof diameter of 80 m. This figure is consistent with the ~111 m diameter of the sinkhole that later formed above the cavern. Apparently, the mechanical strength of the mudstone and gypsum in the overlying Rustler and Dewey Lake Formations was insufficient to prevent upward stoping of the cavern roof, causing eventual catastrophic surface collapse (Fig. 5).

5. Seismic Record

On March 15, 2008, an EarthScope Transportable Array three-component broadband seismograph TA126 was installed near the Intrepid potash mine ~13 km southeast of Loco Hills sinkhole #1 (Fig. 3). This transportable seismograph is a component of the National Science Foundation's EarthScope USArray continental seismic investigation program that is presently imaging the North American continent at a mean station spacing of approximately 75 km. About 6 hours before surface disruption at the site of the brine well, TA126 began recording high frequency (>5 Hz) seismic signals, with vertical ground motion velocity amplitudes of ~5 microns/s (Fig. 6). These seismic events probably reflect subsurface spalling during upward stoping of the cavern roof, with seismic energy resulting from the fall of material into the solution cavity. Another transportable array seismograph 50 km west of the site showed no obvious record of the sinkhole formation, indicating that these high-frequency seismic waves do not travel very far due to the shallow source of the seismic event and high near-surface attenuation (Land and Aster, 2009).

6. Subsequent events

In the aftermath of formation of Loco Hills Sinkhole #1, another water supply company voluntarily abandoned an injection brine well located within the city limits of Carlsbad (Fig. 3). NMOCD ordered a review of regulations covering all brine wells across the state. Then, on November 3, 2008, a new sinkhole formed ~17 km northeast of Loco Hills Sinkhole #1 (Fig. 3). This sinkhole, referred to as Loco Hills Sinkhole #2, is also associated with a brine well that was shut in 3 months earlier after it failed a mechanical integrity test as part of the statewide review. At the time of this writing, nearby structures and a large water storage tank have fallen into the hole and large concentric fractures are threatening an adjacent county road. Aerial observations of Loco Hills sinkhole #2 indicate that it is presently ~80 m in diameter. Downhole surveys conducted in 2001 showed three stacked voids. The uppermost cavern was ~150 m below land surface, the deepest cavern was ~180 m in diameter, and the upper two caverns about one-third that size. The New Mexico cabinet secretary for Energy, Minerals and Natural Resources has ordered NMOCD to impose a 6 month moratorium on new brine well applications located in geologically sensitive areas. The closest EarthScope Transportable Array seismic station to Loco Hills sinkhole #2 was again TA126A (20.5 km), and no obvious precursor candidates have been detected to date.

7. Conclusions

Seismic recordings have been used in the past in a forensic capacity to analyze catastrophic events in southeastern New Mexico, such as pipeline exposions (e.g., Koper et al., 2000). However, this may be the first documented seismologic record of catastrophic sinkhole formation, and suggests that precursory seismic activity related to collapse events of this size may be detectable at ranges up to approximately 10 km.

Johnson (2002) observed that "most solution-mining collapses result from cavities formed 50-100 years ago,

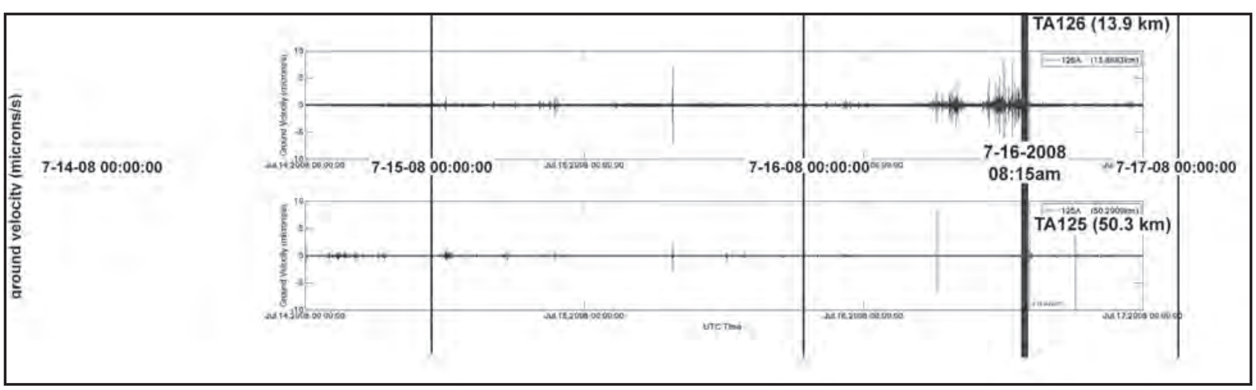

Figure 6: Transportable array seismograph TA126-A 3-day high-pass (filtered above 5 Hz) record of vertical ground velocity (top), located 13.9 km southeast of Loco Hills Sinkhole #1, showing more than 6 hours of apparent precursor ground motion associated with sinkhole formation. Estimated time of surface breaching (8:15am) indicated by heavy vertical line. Seismograph TA125 (lower plot), located 50.3 km from the site, showed no obvious candidate precursor signals.

before modern-day engineering safeguards were developed. Proper, modern design has virtually eliminated this problem in new facilities." It would appear that developing engineering safeguards for solution mining is still an evolving science.

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CARBONATE DISSOLUTION IN COLD WATER: *IN SITU* EXPERIMENTS AND THE CONSEQUENCES FOR SUBGLACIAL KARSTIFICATION.

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Abstract

Subglacial speleogenesis (i.e., formation of caves by ice-contact underneath or along glaciers) is an important speleogenetic modus that have taken place in many previously glaciated areas. It is, however, controversial how efficient this process is when compared to speleogenesis under non-glacial conditions. Can caves be formed from "scratch" – from a pristine, microscopic fracture (*speleogenesis sensu stricto*) - or is this process more intensive under non-glacial conditions, so that ice-contact water can only widen pre-existing conduits (*speleogenesis sensu lato*)? Subglacial waters are low in CO_2 and close to 0°C. Apart from the initial aperture and length of the percolation paths through the rock mass, two factors are important: the concentration of glacial rock flour and its ability to interfere with the carbonate chemistry. A series of thermostated dissolution experiments using marble and various additions of authentic glacier silt and crushed metamorphic rocks demonstrate and support theoretical considerations that subglacial speleogenesis in low CO_2 waters is slower than first anticipated. The *sensu stricto* mechanism is also severely hampered by the clogging effect of glacial silt, whilst the *sensu lato* mechanism is sluggish because corrosion of the large specific area of silt particles consumes aggressiveness thus slowing first-order rates when the water comes in contact with the karst surface.

FRACTURE CONTROL OF CAVES IN MARBLE: EARTHQUAKE MEDIATED? EXAMPLES FROM SCANDINAVIA

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Abstract

Metamorphosis of limestone to marble quenches all primary porosity, yielding a crystalline rock that is practically impermeable to water. Endokarst development is, then, entirely dependent of later fracturing. The formation of fractures, therefore, predates speleogenesis and provides an upper time constraint. In central Scandinavia, Caledonian orogenesis provided regional and contact (intrusive) metamorphosis. Opening of the Atlantic rift and Neogene uplift resulted in a fracture-controlled marble karst situated on a passive continental margin. Fracturing can be related to various stages of plate and uplift movements as well as erosionally and glacially mediated unloading. Present-day seismicity is weak and epicenter distribution is concentrated along the outer coastline and at the continental margin. The pattern suggests a combination of tectonic stresses and, perhaps, deglacial and paraglacial effects. It is, therefore, interesting to test whether endokarst distribution and intensity can be related to historic and pre-historic earthquake events. The Norwegian cave database was combined with a carbonate database and tested against a quality-screened set of all recorded earthquakes in the region, using only events that are completely defined (magnitude, position, and depth). Almost all recorded events are of small magnitude ($< M4$) and released at a depth between 10 and 15 km. At this depth, only earthquakes of $M > 5.7$ cause liquefaction at the land surface. Moreover, earthquake epicenters and cave locations are not correlated; the longest and deepest caves are concentrated where there is almost no activity, which also holds true for pre-historic, large magnitude ($M \leq 7$) events, which are believed to be related to deglaciation. Such large events were extremely rare onshore and the likelihood for one of them to actually hit a marble band is extremely low. However, cave concentration and depth correlate better with the amount of Neogene uplift, suggesting that the guiding fractures originated pre-glacially and that cave inception commenced sometime after that. On a smaller scale, caves are guided both by regional (tectonic) fractures and by exfoliation joints. Speleogenesis and related fracture movements in central Scandinavia are most likely mediated by aseismic creep on pre-existing lineaments.

NATURAL HISTORY OF CLAY CAVE, NAPA COUNTY, CALIFORNIA

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Abstract

Clay Cave is located in grass and oak woodland of the California wine country adjacent to the northern margin of San Francisco Bay, California. Known since the 1870s, the cave has developed in the Miocene Sonoma Volcanics,

a continental packet of rhyolitic to andesitic volcanoclastic sediments and tephras. The cave consists of 229 m of linear passage with several small rooms floored with a seasonal stream. It appears that this soil pipe cave initiated along root casts in the bedded volcanic sediments that are mostly altered to smectite clay locally stained with iron oxides. Subsequent invasion by seasonal streams has integrated the initial fist-sized soil pipes into vadose canyon passages. A limited biota is present consisting of some unusual terrestrial invertebrates.

UNUSUAL TALUS-FISSURE CAVES IN TUOLUMNE COUNTY, CALIFORNIA

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Abstract

A series of talus caves have developed on the west side of Tuolumne Table Mountain in Tuolumne County, California in grass and oak woodland at an elevation of 460 m. The caves are located along the western flank of Pliocene age Table Mountain that has been exhumed to form inverted topography over the last 9 Ma. Several large landslides have been shed off the sides of the nearly vertical walled Table Mountain to form unexpectedly deep caves of partly talus and partly fissure origin. The caves range up to 30m deep and 50m long. Drapery and micro-gour speleothems made of the uncommon mineral silhydrite are present. The shattered blocks containing the caves have formed as the enclosing Tertiary continental sedimentary rocks were stripped away by entrenching of the adjacent Stanislaus River. Subsequently, the margin of Table Mountain slid away on the underlying clay-rich, continental sedimentary rocks. While most of the caves have formed in talus, some appear to be fissure caves formed in partly intact blocks of columnar latite. A limited biota is present, and consists of mosses, lichens, and terrestrial invertebrates.

For many years, cavers were visiting one of these caves, which had been discovered in the late 1970s during a wildlife study. Recently, a different group of cavers visited a different cave, thinking it was the one cave that was usually visited. When it was discovered that there were, in fact, two different caves, exploration started in earnest, with many more caves having been discovered and explored. Several of these have been surveyed and mapped. Exploration is continuing.

CONTAMINANT TRANSPORT IN TWO CENTRAL MISSOURI KARST RECHARGE AREAS

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Karst watersheds with significant losing streams represent a particularly vulnerable setting for ground water contamination because of the direct connection to surface water. Because of the existing agricultural land-use and future threat of heavy urbanization, two losing stream karst basins were chosen for intensive monitoring in Boone County, MO: Hunters Cave (HC) and Devils Icebox Cave (DI). Both caves were formed in Burlington Limestone and have similar sized recharge areas (33-34 km^2) and land uses. However, the DI recharge area has more row crop and less grassland areas than the HC recharge area. Year-round monitoring was initiated in April 1999 and completed in April 2002 with the objective of characterizing the water quality status of the main cave streams relative to herbicide, nutrient, and sediment contamination. Water sampling for contaminants entailed grab samples at regular intervals, and runoff event samples collected using automated sampling equipment. Herbicides or their metabolites were detected in almost 100% of the samples from both cave streams. Total nitrogen and phosphorus concentrations and loads were consistently higher in Devils Icebox watershed. Greater mass flux of nutrients and herbicides in the DI recharge area compared to HC was a result of both greater stream discharge and the occurrence of most cropped fields on high runoff potential soils. Prevailing land management has significantly degraded the water quality in both watersheds.

1. Introduction

The vulnerability of groundwater contamination in karst recharge areas has been well established over the last 20 years (e.g., VESPER et al., 2003; BOYER, 2005). A wide variety of agricultural, industrial, and wastewater contaminants in karst aquifers has been documented (BOYER and PASQUARELL, 1994; LERCH et al., 2001; VESPER et al., 2003). These contaminants may be harmful to humans exposed through drinking water obtained from karst aquifers and through recreational activities in caves. The establishment of maximum contaminant levels for drinking water and whole-body contact standards for fecal coliforms reflects the health concerns associated with exposure to these contaminants. In addition, cave-adapted organisms may also be harmed by the presence of these contaminants in cave streams and drip waters, leading to disruption of karst ecosystems (Elliott, 2000).

It is now well accepted that surface land uses directly impact the water quality of karst aquifers, especially those with discrete or allogenic recharge mechanisms (Ruhe et al., 1980; BOYER and PASQUARELL, 1994; LERCH et al., 2005). Agricultural land uses generally have a negative effect on water quality while urban land uses typically impact both the quantity and quality of water in karst aquifers. The negative hydrologic impacts associated with urban land uses have led to the development of strategies for urban growth management to protect karst water resources (BUTLER, 1987; FRUEH et al., 2008).

Within central Missouri, the karst recharge area of the Devils Icebox Cave (DI) has been extensively studied (HALIHAN et al., 1998; WICKS, 1997; LERCH et al., 2005; DOGWILER et al., 2007), but the recharge area of nearby Hunters Cave (HC) was only recently documented (LERCH et al., 2005). The two recharge areas are located within the Bonne Femme watershed located due south of Columbia, Missouri, USA (Fig. 1). The DI recharge area is approximately 34.0 km^2, and it is comprised of an allogenic recharge area corresponding to upper Bonne Femme Creek, and a discrete recharge area encompassing the Pierpont sinkhole plain (Fig. 1) (LERCH et al., 2005). The majority of the stream discharge in DI derives from the allogenic portion of the recharge area (DOGWILER et al., 2007). The HC recharge area encompasses approximately 33.3 km^2, and its recharge is also predominantly allogenic. Both cave streams show characteristics typical of surface streams, with relatively rapid response to precipitation and broad variations in resurgence discharge (HALIHAN et al., 1998; LERCH et al., 2005). The HC discharge characteristics showed that the areal extent and size of sub-surface conduits are apparently very limited in this recharge area. In contrast, discharge at the DI resurgence is characterized by a sub-surface conduit system that is both greater in volume and

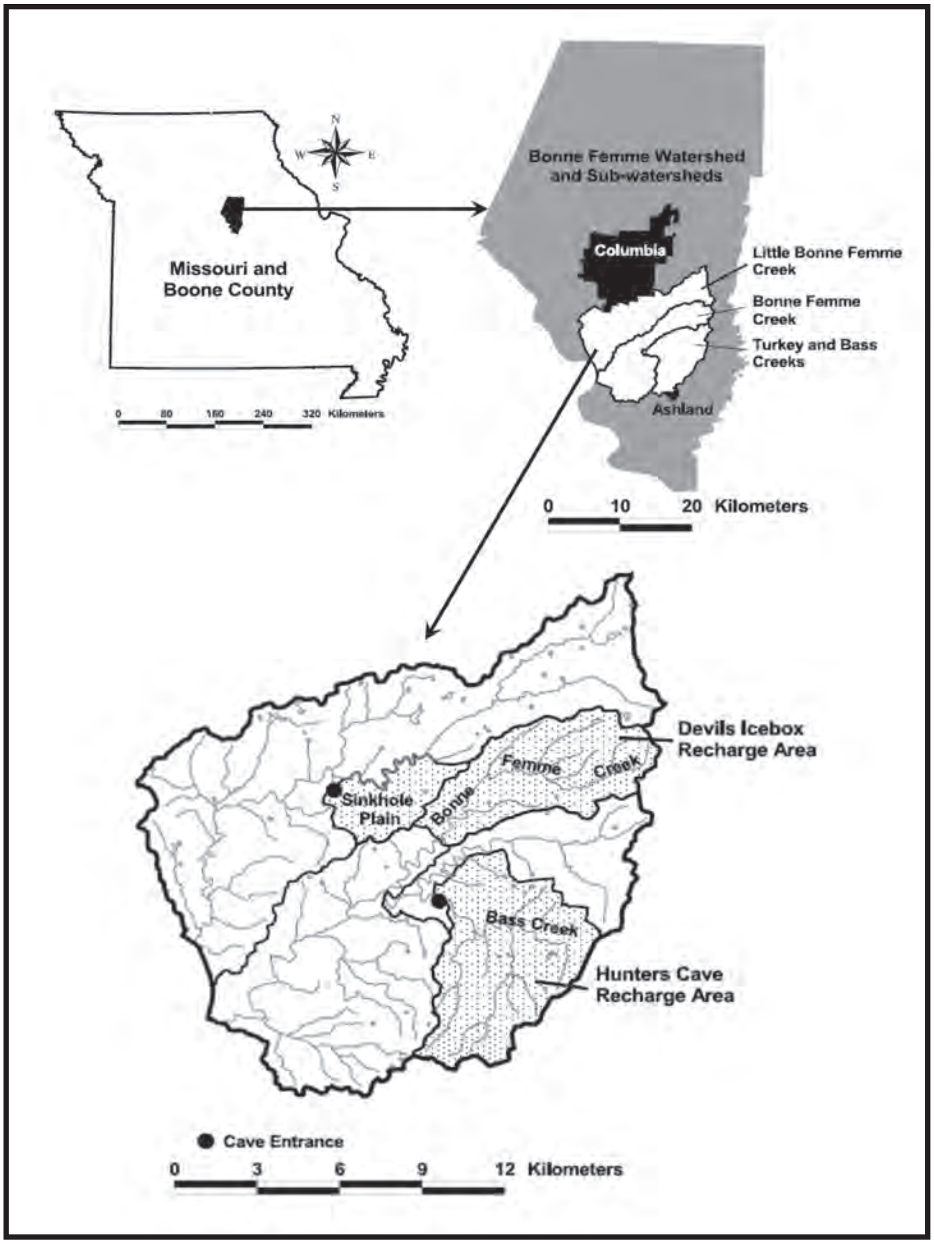

Figure 1: Location and drainage basin map.

areal extent than HC (LERCH et al., 2005).

Few studies to date have intensively monitored karst aquifers for both water quantity and quality over multiple years. The study presented here was conducted to assess the transport of agricultural contaminants within the HC and DI recharge areas. The Bonne Femme watershed at present is predominantly agricultural, but it is rapidly urbanizing. This study was initiated before significant changes in urban development and impervious surface have occurred so that the effect of changing land use on the quality and quantity of water in these two karst recharge areas could be evaluated. Agricultural contaminants were chosen for study because of the current predominance of agricultural land uses within the recharge areas. The objectives of this study were to characterize the concentrations and determine the loads of sediment, nutrients, and commonly used soil-applied herbicides in the HC and DI recharge areas via intensive monitoring at the resurgence of both caves.

2. Materials and Methods

2.1 Site descriptions and land use

The caves were formed in the Burlington Limestone (WICKS, 1997). The upper (eastern) portions of both cave recharge areas are covered by clay-rich Pleistocene age glacial and loess deposits (WICKS, 1997). These low permeability, fertile soils are generally in the Mexico-Putnam or Mexico-Leonard soil associations, and much of the row crop production within both recharge areas occurs on these soils. They are classified as hydrologic group D soils, the highest runoff potential category. Both caves exhibit rudimentary branching patterns, with smaller side passages that are tributaries to the primary cave streams (Fig. 2). These cave patterns are indicative of flood water recharge aquifers. The main trunk passage in the DI cave is the primary stream conduit, and it extends for approximately 6.4 km before reaching a sump. The cave system's downstream terminus is a spring that forms a tributary to Little Bonne Femme Creek, creating an interbasin transfer between Bonne Femme and Little Bonne Femme watersheds (Fig. 1). The main passage in HC is also the primary stream conduit, and its flow path extends for approximately 1.25 km before reaching a sump. The cave terminates at a spring resurgence discharging directly into

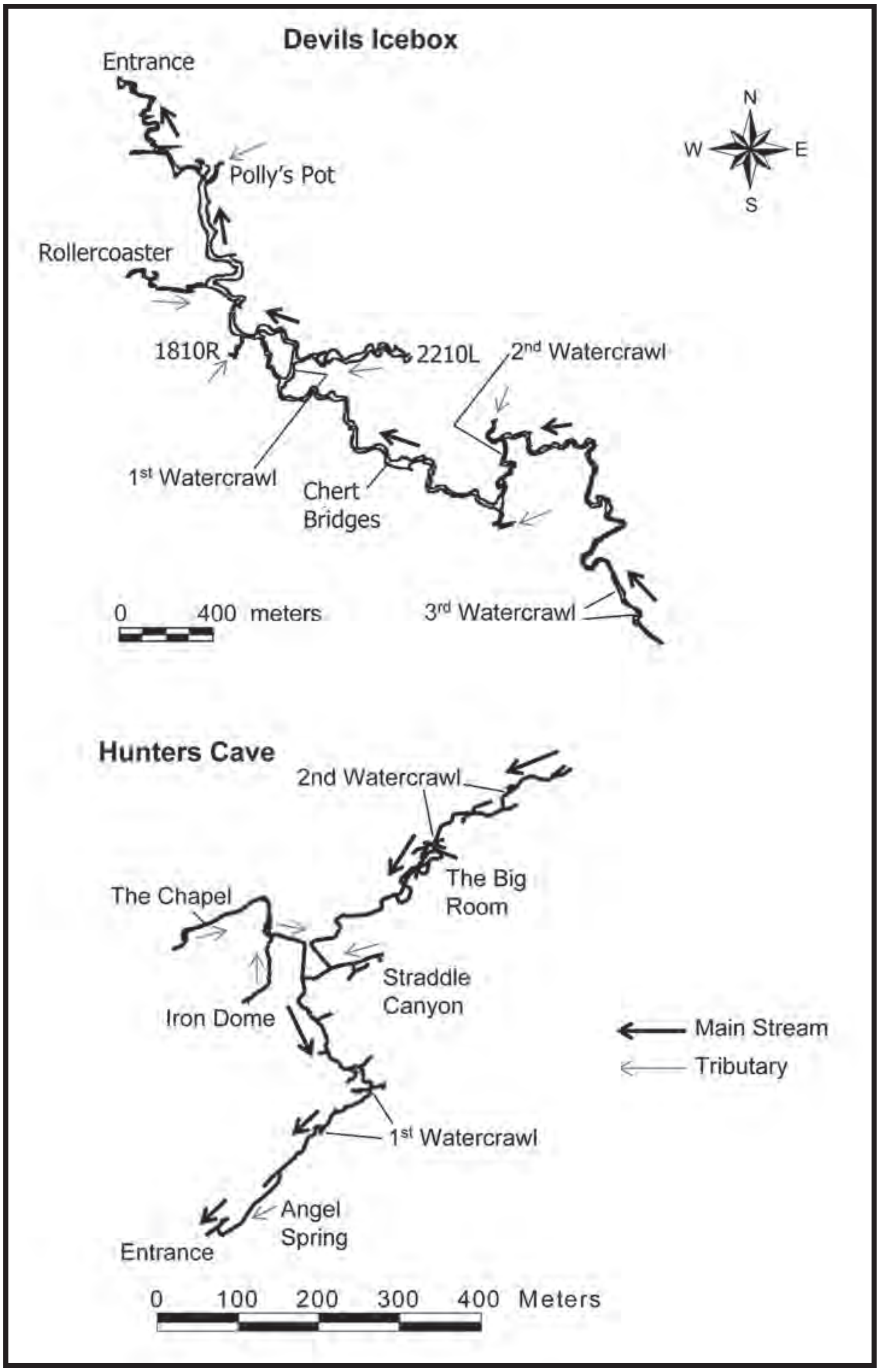

Figure 2: Generalized maps for Hunters Cave and Devils Icebox.

their close proximity and similarities in geology and soils, both recharge areas had similar land use/land cover (Fig. 3). However, the HC recharge area has a higher proportion of grasslands and a lower proportion of row crops than DI. Row crop areas within the DI recharge area were mainly concentrated within the upper Bonne Femme watershed while row crop areas within the HC recharge area were more evenly distributed (Figs. 1 and 3). To express herbicide losses on a treated area basis, the areas of corn, soybean, and sorghum within each recharge area were estimated for 1999 to 2001 growing seasons using Boone County, MO crop data from the USDA-National Agricultural Statistics Service (NASS) (USDA-NASS, 2000-2002). The herbicides monitored in this study were limited to use on these three crops. Herbicide use estimates were obtained from the USDA-National Agricultural Statistics Service (NASS) annual crop reports (USDA-NASS, 2000-2002). By combining the crop area and herbicide use data, estimates of the treated areas and total input mass for each herbicide were calculated.

Bass Creek. Additional details about these sites can be found in Lerch et al. (2005).

Land use information for the major land cover classes was obtained from 30 m resolution Landsat imagery data collected from 2000 to 2004 (http://www.msdis.missouri.edu/ data/lulc/lulc05.htm, accessed 8/11/08). Because of

2.2 Monitoring procedures

Hydrologic, chemical, and physical monitoring of the water was conducted near the resurgence of each cave from April 1999 to March 2002. Hydrologic monitoring consisted of measuring stage height at 5-minute intervals with submerged pressure transducer probes. Stage height

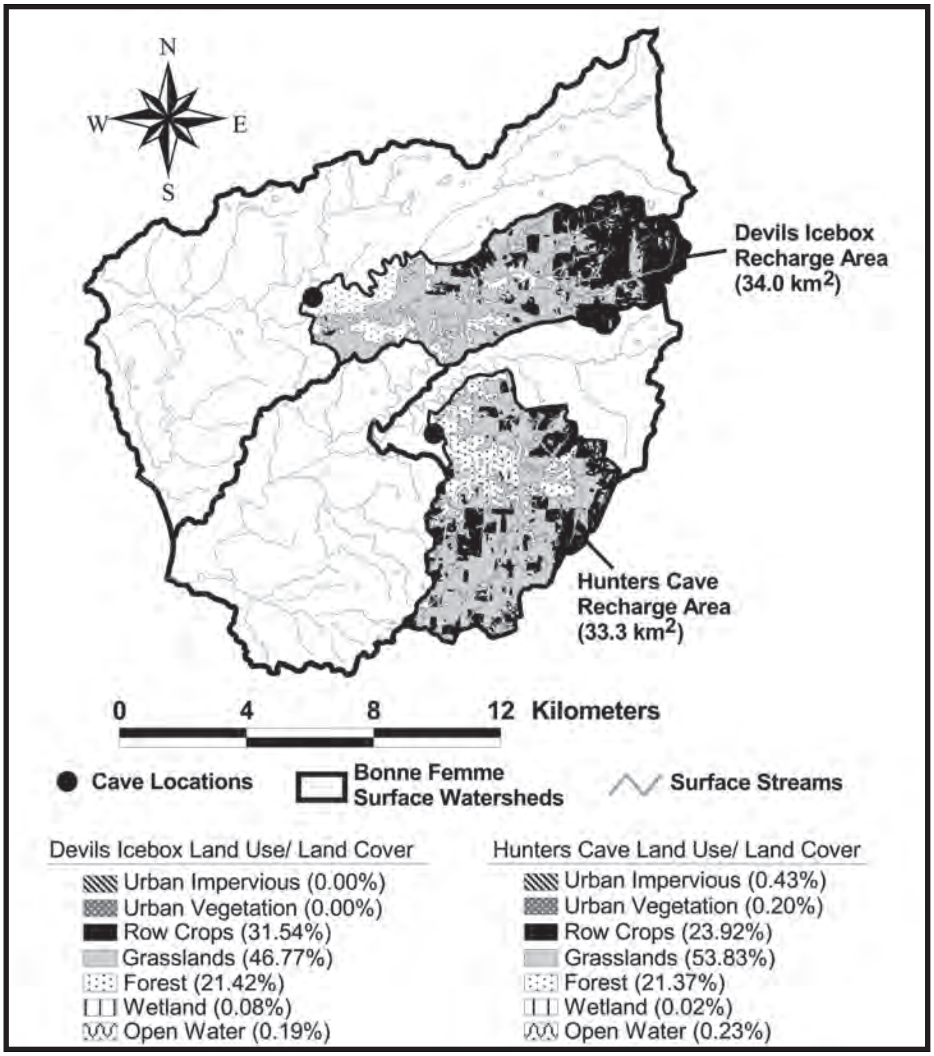

Figure 3: Land use and land cover maps for Hunters Cave and Devils Icebox drainage basins.

was then used to compute stream discharge, as detailed in LERCH et al. (2005). Turbidity, expressed as nephelometric turbidity units (NTU), was measured at 15-minute intervals.

Water samples were collected under baseflow and runoff conditions for determination of nutrient, herbicide, and sediment (runoff samples only) concentrations. Grab samples were collected at regular intervals under baseflow conditions, and storm runoff samples were collected with automatic samplers. The total number of samples collected at each site over the study for herbicide and nutrient analyses were 1031 at HC and 765 at DI. The higher number of samples at HC resulted from the greater number of runoff events at this site over the course of the study.

2.3 Analytical procedures

All samples were analyzed for nutrients and herbicides, and suspended sediment (SS) analyses were also conducted for selected runoff events at both sites from 1999 to 2001. Herbicide and dissolved nutrient samples were filtered within 48-72 hours of collection. Nutrient analyses included total and dissolved nitrogen (N) and phosphorus (P) species determined by standard colorimetric methods using a flow injection system. Total N and P were determined by autoclave digestion with potassium persulfate. Organic N and P were computed by the difference between the total and the inorganic concentrations for each sample. Method detection limits were 0.10 mg/L for total N and NO_3-N, 0.020 mg/L for NH_4-N, and 0.005 mg/L for total P and PO_4-P. Herbicide analyses included atrazine, alachlor, acetochlor, metolachlor, and metribuzin, and the stable atrazine metabolites, deethylatrazine (DEA) and deisopropylatrazine (DIA). Herbicide analyses were conducted using C_{18} solid-phase extraction followed by gas chromatography/mass spectrometry (LERCH and BLANCHARD, 2003). Method detection limits were (in µg/L): atrazine, 0.003; alachlor, 0.003; acetochlor, 0.006; metolachlor, 0.002; metribuzin , 0.008; DEA, 0.004; and deisopropylatrazine, 0.008. SS analyses were performed by the evaporation method. Regression analysis was used to correlate the SS data to the turbidity data, and SS concentrations were then estimated from the 15-minute turbidity data, providing the equivalent of about 105,000 SS estimations per site over the study.

2.4 Load computations and statistical analyses

Contaminant loads were computed using concentration data from grab and automated samples and from the computed SS concentrations combined with the 5-minute discharge data. Linear interpolation was used to estimate concentrations for any un-sampled period, and loads were calculated at 5-minute intervals. The load data were then aggregated to a quarterly or annual basis. Nutrient and SS areal loss rates were based on the entire recharge area and herbicide loss rates were expressed on a treated area basis. Statistical differences in concentrations and load between sites were determined using a two-tailed t-test. For the concentration data, the *a priori* level of significance was chosen to be " = 0.05 because of the large number of observations for each contaminant (df > 800). For the areal loss data, the *a priori* level of significance was chosen to be " = 0.10 because comparisons between sites were only performed on the annual data (df = 3).

3. Results and Discussion

3.1 Nutrient and herbicide concentrations

Nitrogen concentration data showed that DI had significantly greater concentrations than HC for total N and NO_3-N (Fig. 4). The rank in concentration of the N analytes was also different between sites, with the order reversed for NO_3-N and organic-N. Total N concentrations showed a similar range between sites, but DI had 68% greater mean and 54% greater median concentrations than HC, respectively. At both sites, total N concentrations showed a very narrow range between the 10^{th} and 90^{th} percentiles (2.07 mg/L at HC and 2.52 mg/L at DI), indicating consistent total N contamination over time. Among the N analytes, NO_3-N showed the highest relative difference between sites, with mean concentrations that were 2.69 times greater at DI (0 = 1.52 mg/L) than HC (0 = 0.57 mg/L). Organic-N concentrations showed nearly equal distributions, and the mean concentration at both sites was 0.80 mg/L. Concentrations of NH_4-N were generally very low at both sites, and it had the lowest overall concentrations of any nutrient analyte. The consistently low NH_4-N concentrations were not expected given the near certainty of ammonia-based fertilizer inputs from row crop areas, and the high fecal coliform levels observed at both sites (LERCH et al., 2001), indicating significant wastewater inputs as well. Dissolved O_2 concentrations at both sites were generally at or slightly above saturation throughout this study (LERCH et al., 2005), and the NH_4^+ may have been oxidized to NO_3^- during transport or lost from solution by sorption to clay sediments.

Concentrations of all three P analytes were significantly greater at DI than HC (Fig. 4). The range in 10^{th} to 90^{th} percentile concentrations was very similar between sites for all three analytes, demonstrating similar variation in P concentrations, but DI was consistently greater in mean and median P concentrations. For example, average DI concentrations were 1.53 times greater for total P, 1.40 times greater for organic-P, and 1.82 times greater for PO_4-P than HC. Only NO_3-N had a greater relative difference between sites than PO_4-P. Since PO_4-P is quite insoluble at the alkaline pH observed under typical baseflow conditions for the cave streams (pH 7.5 to 7.8; LERCH et al., 2005), it was expected that PO_4-P concentrations at DI would be lower than HC given the greater possibility for PO_4^{3-} precipitation

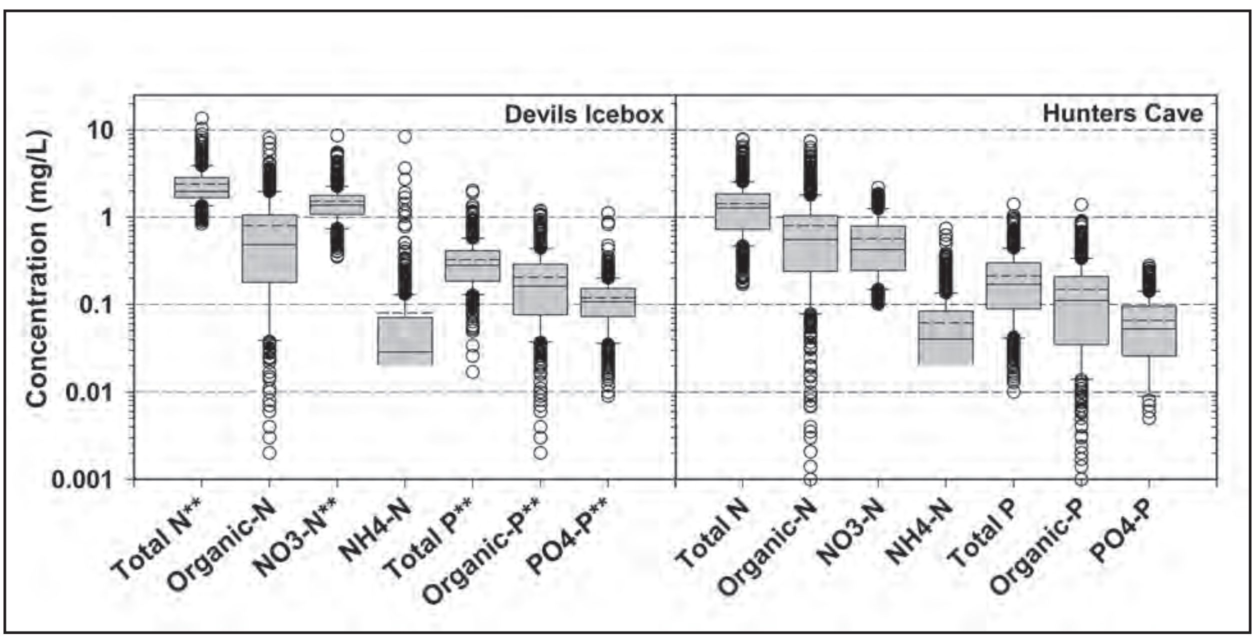

Figure 4: Concentrations of nitrogenous, phosphate, and organic contaminants.

to occur along its much longer flow path (LERCH et al., 2005). Apparently, the DI recharge area was either more vulnerable to P transport and/or had much greater P inputs to its recharge area (see below).

Land use within the HC recharge area did not result in elevated concentrations of N and P except under high flow conditions. Nutrient concentrations in DI indicate a more significant and negative impact of land management on water quality within this recharge area as nutrient concentrations were consistently high, even under baseflow conditions. However, the greatest nutrient concentrations at both sites were always associated with runoff events. Total N and P closely corresponded with each other and were related to stream flow (see below). A previous unpublished study at DI from 1982-84 showed average NO_3-N (total N was not determined) of 2.10 mg/L and average total P of 0.10 mg/L. In the current study, nitrate accounted for 63.8% of the total N. Assuming this same proportion for the 1982-84 study, estimated average total N would have been 3.30 mg/L compared to the average in this study of 2.40 mg/L. Thus, average total N at DI has decreased 27% since 1982-84. Conversely, total P levels have increased more than 3 fold over this same time period.

Herbicides were frequently detected at both sites (Table 1). Overall, 95.6% of DI samples and 84.8% of HC samples had a detection of at least one herbicide or metabolite compound. At the both sites, atrazine and its DEA metabolite were most commonly detected, but the frequency was much greater for both compounds at DI. The DIA metabolite was detected much less often than atrazine and DEA at both sites. The frequency of alachlor and metribuzin detections was similar between sites, but acetochlor and metolachlor were more often detected at DI. Despite the frequent detections, herbicide concentrations were quite low overall, with median concentrations that were generally below the detection limits and none greater than 0.100 μg/L. Herbicide concentrations showed a typical seasonal trend, with the greatest concentrations occurring in spring followed by an exponential decrease to very low levels (e.g., <0.100 μg/L) by late summer. In general, herbicide detection frequency and median concentrations of these two karst aquifers were considerably less than those in surface streams of the Midwestern U.S. (THURMAN et al., 1992; LERCH and BLANCHARD, 2003).

3.2 Contaminant loads

Nutrient, SS, and atrazine loads showed different seasonal patterns of transport, but transport of all three categories of contaminants was greatest in the 2^{nd} quarter (Fig. 5). Total N and P loads by quarter of the year were nearly identical and strongly tied to seasonal discharge. In the 2^{nd} quarter, 45% of the year's discharge occurred along with 49% of the total N load and 48% of the total P load. For SS, 50% of the annual load occurred in the 2^{nd} quarter, but it differed from the total N, total P, and discharge distributions in the other quarters. For atrazine, 95% of its annual load occurred in the 2^{nd} quarter, showing the extreme seasonality typical of herbicide transport (THURMAN et al., 1992; LERCH and BLANCHARD, 2003). Apparently, a significant amount of the annual N and P transport in DI occurred as soluble organic and inorganic species under baseflow conditions. Otherwise, their seasonal distribution would have been more similar to that of SS. The seasonal dependence of atrazine transport occurs because farmers apply herbicides during a relatively narrow window in April and May combined with their limited mass inputs and short persistence in the environment.

To facilitate comparisons between sites, annual contaminant loads were computed on an areal loss basis (Fig. 6). Based

	Hunters Cave			Devils Icebox		
Herbicide	Detection Frequency	Concentration Range	Median	Detection Frequency	Concentration Range	Median
	%	μg/L		%	μg/L	
Atrazine	77.4	<0.003 – 75.6	0.036	94.9	<0.003 – 36.9	0.058
DIA	41.0	<0.008 – 0.703	<0.008	36.3	<0.008 – 4.42	<0.008
DEA	67.8	<0.004 – 1.02	0.028	88.2	<0.004 – 6.18	0.086
Metribuzin	40.3	<0.008 – 0.356	<0.008	37.6	<0.008 – 0.280	<0.008
Acetochlor	9.0	<0.006 – 2.58	<0.006	18.7	<0.006 – 5.82	<0.006
Alachlor	48.4	<0.003 – 5.17	<0.003	45.2	<0.003 – 0.400	<0.003
Metolachlor	24.1	<0.002 – 0.206	<0.002	57.0	<0.002 – 4.06	0.005

Table 1: Herbicide detections and concentrations for Hunters Cave and Devils Icebox recharge areas.

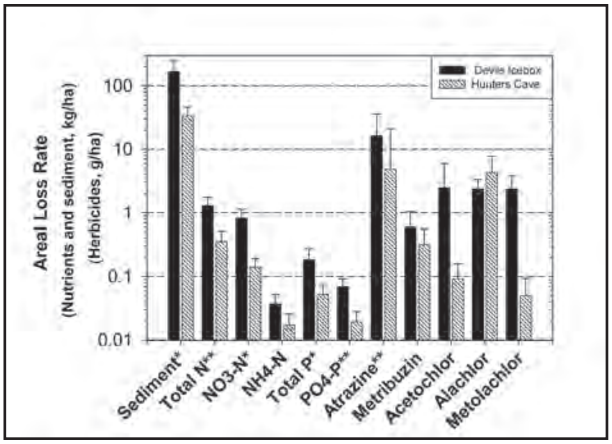

Figure 5: Loss rates of contaminants.

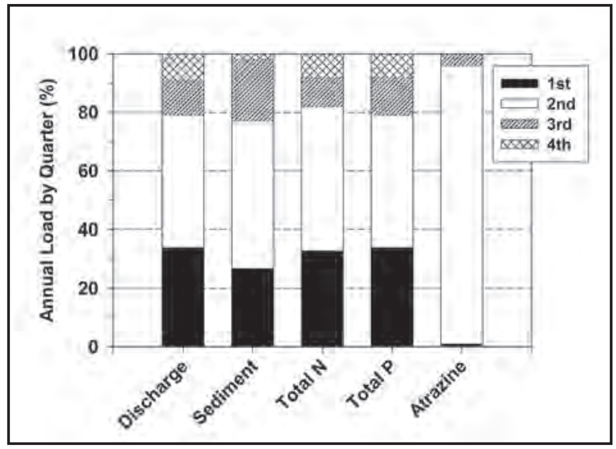

Figure 6: Annual loads of various contaminants.

on the large annual mass transport of SS (>100,000 kg) and nutrients (>100 kg P and >1000 kg N) at each site, it was assumed that the monitored contaminants were derived primarily from allochthonous sources distributed throughout the recharge areas. SS, N, and P transport were all significantly greater at DI compared to HC. Only NH_4-N loss rates were not significantly different between sites. Areal loss rates of NO_3-N and sediment at DI were more than five times greater than HC. In addition, total N and P and PO_4-P loss rates were all more than three times greater at DI than HC. The herbicide transport data showed that only atrazine loss rates were significantly greater at DI compared to HC (Fig. 6), but metolachlor and acetochlor losses were also much greater at DI while alachlor losses were greater at HC. SS and herbicide loss rates were generally much lower than measured for surface watersheds of the Midwestern U.S. (LARSON et al., 1983; LERCH and BLANCHARD, 2003). Atrazine and metolachlor loss rates were 7 to nearly 1300 times lower in the karst recharge areas than a nearby non-karst watershed, Goodwater Creek (SADLER et al., 2006), for the same time period as this study. Areal loss rates of nutrients in DI were similar or greater than Goodwater Creek while HC nutrient losses were consistently lower (BAFFAUT et al., 2008). Given that Goodwater Creek has about 6 times greater relative discharge (i.e., discharge as a percent of precipitation) than DI and 10 times the relative discharge of HC, these findings showed the high degree of vulnerability to contaminant transport of these two karst recharge areas, particularly for DI.

The higher areal loss rates of DI compared to HC were related to its consistently greater discharge and contaminant concentrations. While greater discharge was a function of the recharge area characteristics, the greater observed concentrations at DI were related to the occurrence of row crops on high runoff potential soils. Within the DI recharge area, 94% of the row crop areas occurred on hydrologic group D soils compared to only 57% of the row crop areas within HC. Nearly all the row crops on group D soils within the DI recharge area lie above the losing reach of Bonne Femme Creek, and therefore, contaminant transport from these fields directly impacts its water quality. These high runoff potential claypan soils are known to be especially problematic with respect to surface transport of sediment, nutrients, and herbicides (LERCH and BLANCHARD, 2003; LERCH et al., 2008). In both recharge areas, prevailing land management has significantly degraded water quality. Therefore, funding was obtained to develop a stakeholder-led watershed plan for the Bonne Femme watershed (Frueh et al., 2008), with the primary goal of improving water quality. The plan has a number of detailed recommendations for karst protection, including limiting stormwater runoff to pre-development levels in karst recharge areas, use of economic incentives to reduce urban development on karst (e.g., transfer of development rights or conservation easements), new zoning regulations to provide special protections to karst recharge areas (e.g., require no-discharge on-site sewer systems), and adoption of a stream buffer ordinance that limits construction within the 100 year flood plain of all stream channels in the watershed. With the data collected from this study, the impact of implementing these management practices and changes in land use can be documented.

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RECORDING A FLOOD EVENT INSIDE THE WATER SINKS CAVE

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A nearly two kilometer long sinkhole receives drainage for much of the Burnsville Cove, which is a significant karst area, with large cave systems in Bath County, Virginia, USA. Prior to September 2008, a small cave, Water Sinks Cave, was known to exist in the downstream terminus of the sinkhole. In September a flood washed open a narrow fissure just inside the entrance. There a good draft of air was detected flowing into the fissure. When the fissure was widened to allow entry, it was found that an extensive cave exists below the "old" cave.

To date, 3.6 km have been surveyed to reveal a complex multi-level maze. At the lowest level, a large stream up-wells from a deep sump and flows 70 m before entering another sump. This is a major stream of the sub-surface Burnsville Cove drainage. Nearly all of the cave's lower passages are washed clean from fast flowing flood waters. Leaves stuck to the ceiling near the entrance demonstrate the depth of flooding (50 m).

Video cameras have been placed in the cave and are remotely controlled from the surface. A video recording has been accomplished that shows a flood event as it occurs inside the cave. The first camera is attached to the cliff face above the entrance (a vertical culvert pipe) to the new section of the cave. The surface creek is seen first starting to flow, and then overflowing its banks against the cliff reaching a depth of over 5 m. Finally the flood level rises above the camera. The second camera is positioned at the bottom of the 6 m entrance drop. The video shows the flood water starting to cascade down the drop as a small waterfall and becoming a raging torrent 12 m wide. A third camera records a view of a rocky floor with the flood coming in a series of rapids around the rocks. A forth camera position shows the level of the deep sump rapidly rising with a water fall appearing around the camera.

1. Introduction

The Burnsville Cove is a significant karst area in Virginia and contains more than 101 km of cave passages. All surface streams flowing off non-carbonic rocks from the slope of Jack Mountain into this karst area are captured at various sinkholes and swallets. The Water Sinks is a large sinkhole nearly 2 km long and up to 600 m wide. None of the Burnsville Cove cave systems have entrances in sinkhole insurgencies and nothing was known about any cave extending below the bottom of the Water Sinks Sinkhole prior to 2007.

Digging through a sediment and debris choke in the bottom of a large sinkhole is a dubious enterprise, especially when heavy rains bring more and more sediments with every flood. Prior to 1987 the bottom of the Water Sinks Sinkhole was a huge mass of logs and flood debris that had accumulated over the centuries. When flowing, a (losing) stream would end its surface journey in the debris pile. Since 1987 the flood debris pile has been removed as it accumulates and inspections made after flood events to determine if a new collapse opening would allow entry into a cave.

One side of the sinkhole is a limestone escarpment (cliff) that contains a maze cave with a number of entrances (Fig. 1). This cave, called Water Sinks Cave, is higher in elevation than the bottom of the sinkhole. Its passages are canyons and tubes generally about 2 m wide and 3 m high. It is a maze cave having more than 640 m of passages but none extending below the bottom of the sinkhole. Flooding fills the bottom of the sinkhole with a temporary lake 260

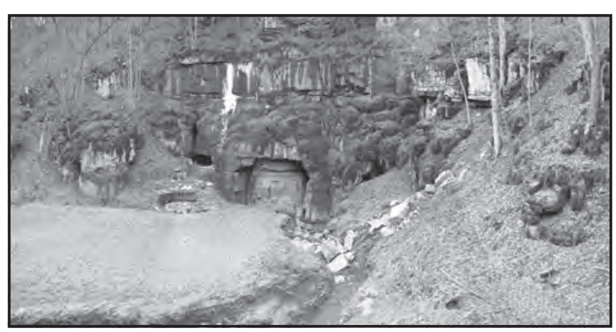

Figure 1: The wet weather stream sinks at the base of the cliff. This is the downstream terminus of the Water Sinks Sinkhole where a limestone escarpment is exposed having the entrances to the Water Sinks Cave.

Figure 2: A view of the Water Sinks Sinkhole before flooding. Notice the footbridge crossing over the dry streambed.

Figure 3: The Water Sinks Sinkhole during a flood. Notice the cave entrances are now covered.

meters long. Severe flooding can reach a depth of 10 meters, filling much of the Water Sinks Cave (Figs 2, 3).

During one such event (witnessed by the author), the debris laden surface of a flood water lake suddenly began flowing toward the sinkhole's cliff face and within a few minutes the lake completely drained into a new collapse filling it with logs and tree limbs. The disappearance of such a large volume of water suggested that a cave passage or several passages had to exist to accommodate the flow. All such collapses had been carefully examined since 1987 and none had revealed any openings that might lead to a cave – until fall of 2007. That September an unremarkable flood once again covered the floor of the Water Sinks Sinkhole. This time, however, a new collapse had exposed a small crack about 12 cm wide against the cliff. The crack had a current of air. The subsequent enlargement of this fissure opened an entry to a cave of unsuspected size and character. It was recognized that flooding would quickly seal the new "entrance" unless some action was taken to prevent logs from jamming into the fissure. Accordingly a 4.2 m culvert pipe was set on top of the fissure and chained to the cliff

Figure 4: A culvert pipe was placed over the newly opened fissure to prevent large flood debris from sealing the entrance.

face. Originally the pipe extended well above floor of this new collapse and was accessed by standing on top of a large rock against one side. The closure was complete with a lid fastened to the top of the pipe (see Fig. 4).

2. Description

Subsequent surveys of the new discovery and cave system show 3.6 km of cave passages. The cave is developed into distinct levels. The previously known Water Sinks Cave is the uppermost level. The only connection between it and the lower cave, called the Subway, is at the entrance. The newly opened fissure leading down to the Subway is within the drip line of the cliff face entrance. The enlarged entrance fissure descends vertically for 9 m into a large passage that extends below the cliff face beneath the hill to the south (Fig. 5).

Figure 5: A large passage extends away from below the entrance pipe. Leaves and twigs are seen on the ceiling.

It carries no permanent stream but is a flood water flow route. There is remarkably little flood debris in this passage which has a washed rock-strewn floor with only scattered leaves and an occasional limb to demonstrate flooding. There are, however, leaves wrapped around the ends of stalactites and sticks stuck to the ceiling. This certainly means that much of the cave becomes submerged during times of heavy flooding. The lack of large flood debris in the cave is probably due to a large collapse (in the geologic past) of a section of the cliff face into the entrance. This created a plug that acts as strainer that prevents large objects from entering the cave during flooding.

The passage continues beneath the hill for about 182 m averaging 15 m wide and 8 m high. At this point fast flowing streams (only present during times of flooding) follow a prominent northeast trending joint in a narrower canyon for 200 m and reaching a depth 38 m below the entrance before entering a lift tube. Beyond the tube is an area of breakdown, called the Scary Breakdown Room. Although this room receives flooding from three different passages, no way through this collapse has been discovered.

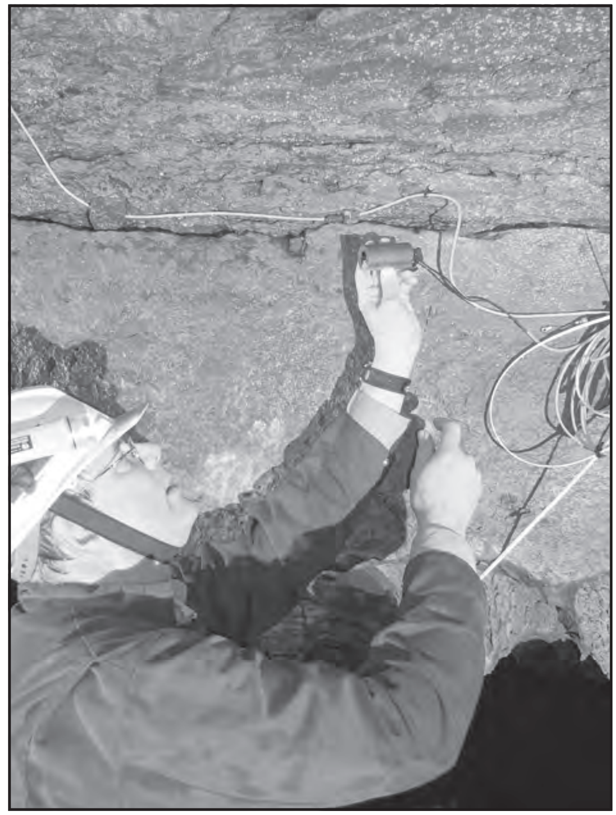

Figure 6: One of the video cameras that will record the flood event is being adjusted.

Another passage 82 m from the entrance leads to narrow descending fissure for 18 m that reaches the top of a 12 m drop. Below, at the base of a slope of breakdown, is a large deep pool, called the Emerald Pool. Upwelling from this pool is a large stream that flows 70 m down a large passage to another sump. This sump has been penetrated for 11 m only to reach yet another sump. This is the present extent of exploration.

3. Video

All the passages described have evidence of rapidly flowing flood water. It was wondered what it might be like inside the cave during a flood event. To satisfy this curiosity a number of video cameras (waterproof) and lights were placed at the entrance and various points inside the cave (Fig. 6). The farthest camera position is overlooking the Emerald Pool (Fig. 7).

A control cable connecting these cameras and lights was routed out of the cave to the author's home on the hilltop on the north side of the sink. The lights and camera are turned off and on remotely from this control cable. The lights are battery operated and recharged via a trickle charge from the control cable. Some lights are not recharged.

Figure 7. A large stream resurges from the Emerald Pool, and flows down a large passage for 70 m to another sump. A camera was placed at this position to record a flood event.

Thus far there have been two flood events since the installation of the video cameras. Although these were not large floods successful recordings of the events were accomplished. Judging by the video it was perhaps fortunate that they were not big floods as the cable and cameras may have been damaged otherwise. The camera at the entrance was in a position 2 m above the top of the pipe. With the onset of heavy rains the video shows a stream beginning to flow down a normally dry creek bed (Fig. 8). Rapidly it becomes a torrent and then a flood. Quickly the flood swirls around the entrance pipe becoming deeper and deeper until the lid is covered. The flooding continues until finally the camera becomes submerged. Inside the cave there is a camera directed towards the bottom of the entrance fissure and a rebar rung ladder. The flooding becomes a trickle and then a torrent. Eventually the entire area becomes a large waterfall as the water under pressure finds its way through the jumble of rocks choking the entrance. Deeper in the cave the large passage floor becomes a wide rushing creek. The camera at the Emerald Pool shows the somewhat tranquil pool become larger and larger and more agitated. The pool level rises higher and soon the camera becomes enclosed by a waterfall from above. The scene fades into mists and foggy lens.

Figure 8. Heavy rains begin flooding that will soon cover the entrance pipe to a depth of 2 meters.

4. Conclusion

This would not be a good place to be during a flood.

STRATIGRAPHIC AND STRUCTURAL CONTROL OF CAVE DEVELOPMENT IN SINKHOLE FLAT, EDDY COUNTY, NEW MEXICO, USA

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Stratigraphy and passage trends of caves in Sinkhole Flat, Eddy County, New Mexico, were studied to determine their role in the development of the caves. Stratigraphic sections were measured in each cave. The stratigraphy between caves was compared. Lineation rosettes showing the total length of cave passages in 10-degree intervals were developed for each of the caves studied. Plots of this data show dominant passage trends. The rosettes were placed on a surface map at their appropriate cave location to compare passage trends throughout the basin. It was observed that there are no basin wide trends along which passages are developed. There are no common stratigraphic layers controlling development of the caves in Sinkhole Flat area.

1. Introduction

Sinkhole Flat is located northeast of Carlsbad, NM in Marathon Basin (Fig. 1). Five caves located there were used in this study; Batman Cave, Whirlpool Cave, Berry Tree Cave, Gourd Cave, and Oasis Cave. Biology studied in this area was done by Cokendolpher et al.,(1996). Sinkhole Flat was a prime place to study stratigraphy because this area has alternating layers of gypsum, sandstone, and dolomite. These layers were created in the back reef area of the Permian age Capitan Reef. The study area was a shallow bay area where climate, water level and water composition changed to result in different layers.

2. Methods

The two main methods used in this study are stratigraphy and jointing analysis using rosettes. Stratigraphy is mapping and correlating rock layers. In this study, the stratigraphy was mapped using the following technique:

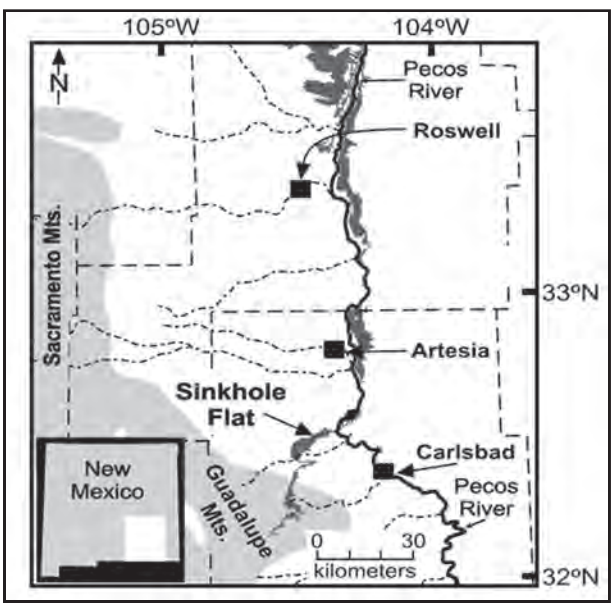

Figure 1: Location map.

1. The deepest strata layer in each cave was located.
2. The boundaries of each rock layer were determined; the thickness was measured, rock type, color and other features described (Swanson 1981). Photos taken of the layers for future analysis.
3. Drafted vertical stratigraphic columns.
4. Surface survey was done to pinpoint the exact location of each cave entrance.
5. Stratigraphic columns were aligned by elevation for comparison.
6. Layers were correlated between caves.

The second procedure was to determine if there was joint control in the basin.

1. Mapped caves or obtained previous survey data for each cave studied.
2. Compiled the azimuth of cave passages in sections of 10 degrees and their lengths taken from survey data.
3. Plotted this data on rosette graphs for each cave.
4. Evaluated rosettes to determine passage trends in each of the caves (Appendix 1 Table 1).
5. Place rosettes on a surfaces survey by cave to see if there were dominate passage trends within the basin. These trends would indicate dominant joint sets.

3. Results

Stratigraphic correlation showed some strata are found

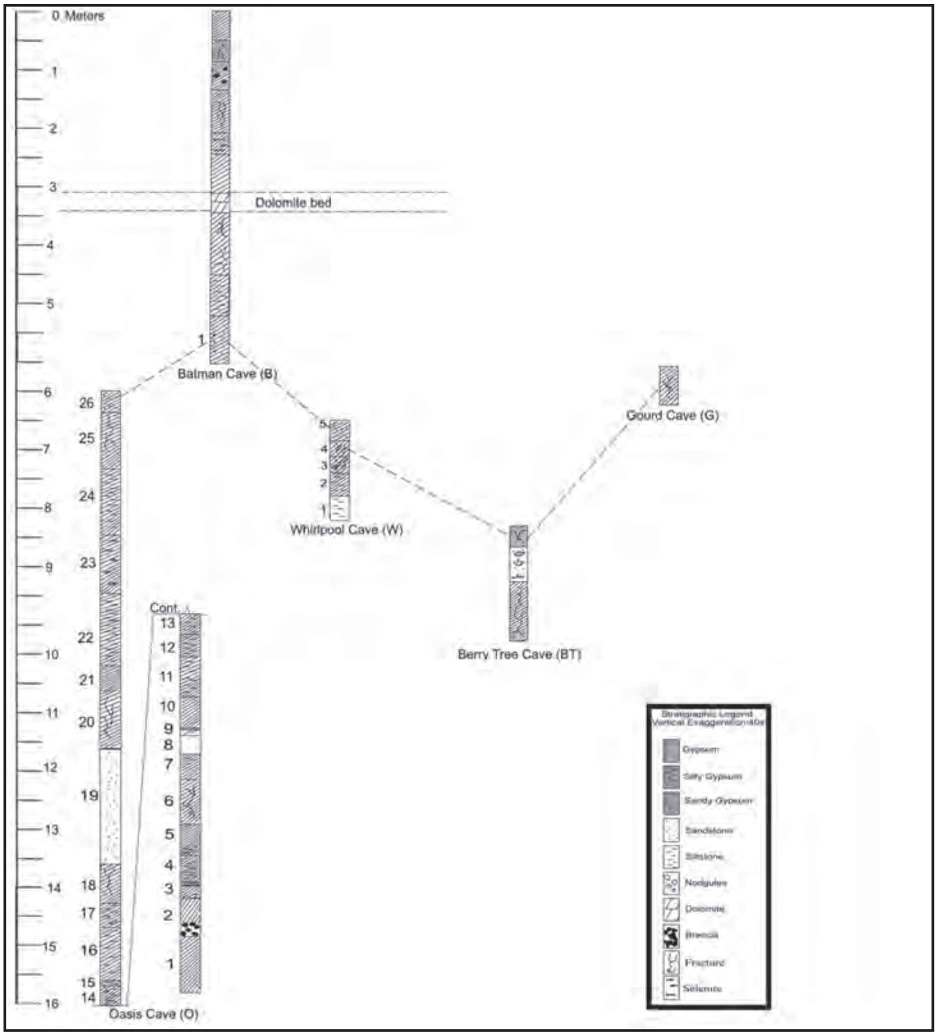

Figure 2: Stratigraphic correlations.

in more than one cave (Fig. 2). A key marker bed was determined to be a dolomite layer that was measured in Batman Cave and seen above the Oasis and Whirlpool entrances. Another marker layer was an orange gypsiferous sandstone layer measured in Oasis and Batman Cave. This layer is layer number 26 in Oasis Cave, layer number 1 in Batman Cave and layer number 5 in Whirlpool Cave (Fig. 2). There is also a reddish silty gypsum layer measured in Berry Tree, Gourd, and Whirlpool caves.

The evaluation of the rosette graphs (Fig. 3) indicated there was no basin wide joint pattern in Sinkhole Flat. However, the rosettes did indicate that the development of individual caves was joint controlled. The dominant direction of jointing in Berry Tree and Gourd Cave is 190-200 degrees (Table 1). The dominant directions for Batman and Whirlpool Cave are 90(270)-80(260) and secondary direction is 100 (280) - 110 (290) degrees. In the north side of the basin the dominate trends were 70(250) - 80(260), 290(110) - 300(120), 30(210) - 40(220) and 250(170) - 360(180) degrees.

4. Conclusions

The hypothesis about jointing was partially wrong. There were no dominant joints found throughout the basin, meaning there was not basin wide joint control on the development of the caves. However, every cave was developed individually along a dominant set of joints. Berry Tree Cave and Gourd Cave seemed to follow the same joint set. Caves on the south side of the basin seemed to be formed along a different joint orientation than those on the north side. None of the stratigraphic layers seemed to control development of the caves in Sinkhole Flat, proving the stratigraphic hypothesis wrong. I did not see a specific stratigraphic layer that affect the development of the caves.

Future plans are to go back to Sinkhole Flat to measure the dolomite layer above Whirlpool Cave and look for same layer in, or near, Berry Tree and Gourd Caves. Also more field observations will be made of stratigraphic columns to see if any other correlation can be made between caves. If possible, nearby caves in the area not evaluated in this study, will be visited.

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Degrees	90-100	100-110	110-120	120-130	130-140	140-150	150-160	160-170	170-180
or	270-280	280-290	290-300	300-310	310-320	320-330	330-340	340-350	350-360
Caves									
Oasis	2.9	13.1	22.9	9.6	12.8	10.2	7.3	9.1	16.7
Batman	7.6	6	5.1	7.1	8.6	2.4	2.8	3	4.1
Whirlpool	8.2	20.4	11	4.9	0	5	2	0	0
Berry Tree	0	0	0	0	0	0	0	17.6	9.2
Gourd	0	0	0	1.8	6.2	14.6	2.8	0	18.6
Degrees	180-190	190-200	200-210	210-220	220-230	230-240	240-250	250-260	260-270
or	360-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90
Caves									
Oasis	8	7.2	6.6	21.5	8.8	0	4.74	27.9	4.8
Batman	0	3.8	5.1	6.1	4.7	7.2	4	4.7	0
Whirlpool	4.1	2	0	0	0	0	0	0	0
Berry Tree	15.2	22.6	0	0	0	0	0	0	0
Gourd	4.1	22.3	0	13.3	10.4	2.6	0	0	0

Table 1: The azimuth of the passages of each cave.

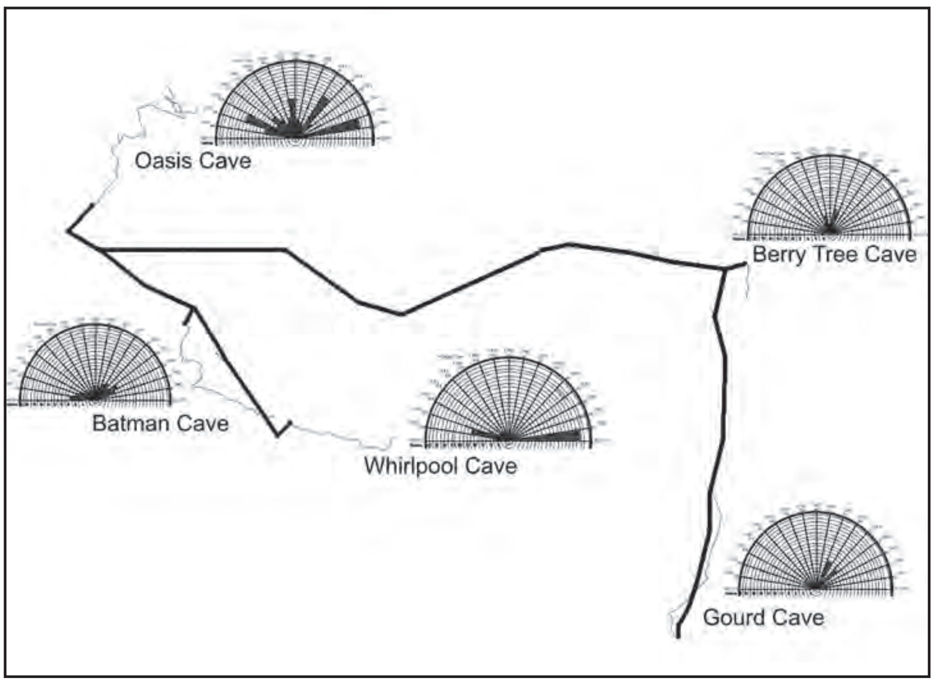

Figure 3: Rosettes for caves.

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COLLAPSE DOLINES OF THE DIVAČA KARST, KRAS PLATEAU, SLOVENIA

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Besides solution dolines, which are the most common relief feature, there are numerous large dolines of collapse origin found on the Kras plateau and through the whole Dinaric karst. Usually they are connected with main underground water courses, and are more abundant in leveled surfaces near sinks or springs of the rivers. The evolution of large chambers by collapsing and collapsed dolines is a result of combination of several factors and not just simple collapsing because of rock failure in the cave ceiling. It can not be treated as decay of caves only, but as a distinct speleologenetic and geomorphic process.

A large group of collapse dolines formed close to sinking of Reka river in Škocjanske jame cave in the area of Divaški kras. We can follow the underground course of Reka trough 18 km of cave passages through Škocjanske jame and Kačna jama. Large passages and large chambers about 180 – 270 m below the surface are characteristic for both caves. Most of the cave passages are more than 10 m wide and high. There are several large chambers, the biggest one with volume of 2,100,000 m^3.

On the surface above, there are 16 large collapse dolines, 5 of them are above the accessible cave passages. The collapse dolines represent important element of the karst surface, regarding the portion of the surface and volume of the rock removed. We studied the distribution and properties of collapse dolines, dolines and large passages and chambers of the caves that lie below.

The collapse dolines that formed above the caves have volumes that are much greater than the known chambers or galleries. The deepest is 160 m deep Velika Dolina and the largest is Radvanj with volume of 9,000,000 m^3. Most of them are about 100 m deep and have several 100 m in diameter.

Observations showed the collapses in cave chambers or collapse dolines developed in fracture zones through which the water was penetrating, corroding the rock, make it loose and prone to collapsing. The same conditions were necessary for the chamber or collapse doline formation. The collapsed rocks were dissolved on place or transported away as particles by the underground river.

Some collapse chambers developed in phreatic conditions and continue to developed in epiphreatic conditions where flood waters are oscillating for 130 m in the karst. If abandoned by the river and left above the oscillating karst water, the collapsing stopped or was slowed down, especially if the fractured zones were cemented by flowstone.

1. Introduction

In Dinaric karst, large dolines of collapse origin, often several hundreds m in diameter, with steep or vertical walls and volumes of to several million cubic meters are common relief feature. Usually there are more abundant on leveled surfaces close to sinks or springs of large rivers or between the karst poljes. These features are much larger than normal solution dolines. Local people clearly distinguish among usual dolines from the large collapse ones which were named with terms kukava, koliševka, or dol.

Collapse dolines were clearly described from that genetic point of view in the early days of the karst geomorphology. Some authors attributed the collapse origin to all dolines and included the collapsing within the cyclic theory of karst or cave evolution and as diagnostic process of the old age of the karst. In practice, it is often difficult to distinguish collapse dolines from other types of the karst depressions, especially older collapse features, which have been modified by the corrosion and other surface processes and where primary hydrological conditions have been substantially changed.

Collapse dolines are important morphological element because of their abundance and obvious connection with the evolution of the large river cave systems. Collapse dolines have been studied from a theoretical point of view (Šušteršič, 1973), tectonic predisposition (Šebela & Čar, 1991), later transformations of dolines, or their connection to the evolution of certain cave systems or parts of the karst as a whole (Gams, 1983; Habič, 1982; Gospodarič, 1983; Mihevc, 2001; Stepišnik, 2004). Less was done on the study of the conditions and mechanisms that are responsible for the occurrence of the large chambers, evolution into collapse dolines and later evolution till disappearing with the karst erosion (Mihevc, 1999; Stepišnik; 2006).

The purpose of this paper is to show the importance of large collapse dolines in the relief of Divaški kras and possible mechanisms and conditions necessary for their formation, evolution, and disappearance from the relief.

2. Field Observation

The study area, the Divaški kras (45° 40' 50''N, 13° 57' 50''E,) is in the southeastern part of a larger, 40 km long and 15 km wide plateau Kras (Fig. 1). Most of the area study area of 31 km^2 is build of thick-bedded Cretaceous limestone, with only the northeast part from Paleogene limestone. The surface is without any running water since all precipitations penetrate into the karst immediately. Karstification of the terrain started after the Oligocene, when the entire plateau was uplifted, and exposed to the present day. On the southeast part of Divaški kras river Reka sinks into Škocjanske jame at an elevation of 317 m a.s.l., then it flows underground 35 km to distant springs at the coast (Fig. 2).

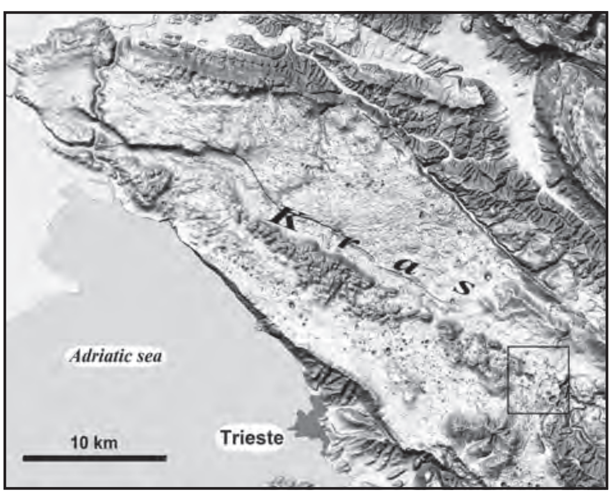

Figure 1: Location of the study area Divaški kras.

The surface of the Divaški kras is between 400 and 450 m a.s.l. The main morphological element of the landscape is a nearly flat surface that inclines less than 10°. This type of surface represents about 88% of the total area and tells us

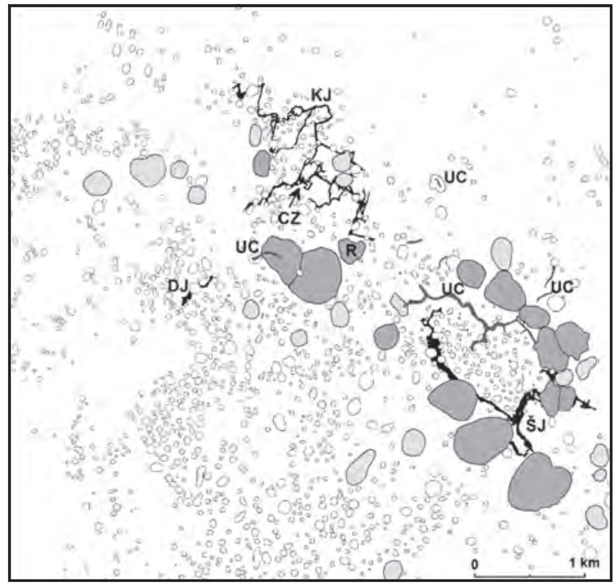

Figure 2: Relief features of Divaški kras. Marked are perimeters of dolines. Empty circles are solution dolines. Old collapse dolines are light grey. Recent collapse dolines are marked dark grey. Outlines of caves are marked black: ŠJ is Škocjanske jame cave, KJ is Kačna jama, DJ is Divaška jama. Unroofed caves are maked with light grey and leters UC. Collapse doline Dol Risnik is marked with letter R and zone of collapsing in Kačna jama cave described in text with CZ.

that in present conditions, leveling is the main geomorphic process.

The most abundant morphologic features on the leveled surface are dolines. There are 776 dolines and they comprise about 12% of the surface area. The dolines have different genetic origins; they evolved as solution dolines, collapse dolines (Fig. 3), or dolines that formed by denudation of the rock above the caves. It is difficult to distinguish among these types, however we divide them according to size, sediments, and some clear morphologic signs like elongated shapes, vertical walls, position above collapsing zones. We measured the surface of all dolines, estimated the volume for smaller dolines and calculate volume of large collapse dolines.

If we compare the dimension of the dolines we can see, that most of them (740) are small. Their diameters are about 50 m and they are about 8 -10 m deep. We presume that they are solution dolines. They cover about 5% of the area and their total volume is estimated to 6-10 Mm^3 (Mihevc, 2001).

There is another group of dolines, which are clearly of collapse origin. This is evident from morphology, sediments,

Figure 3: Collapse doline Dol Risnik. See the fractured zone in the massive limestone.

position above the active caves and recent debris flow or collapsing. The largest are more than 500 m across, and the deepest are more than 150 m deep. The largest collapse doline is the 122 m deep Dol Sekelak, with the volume of 8.5 Mm^3. Dol Globočak is smaller, 90 m deep, and has the volume of 4.8 Mm^3. Dol Risnik is 86 m deep, and has the volume of 1.4 Mm^3. This group of the largest 15 collapse dolines covers only 4% of the area, but their total volume is about 38 Mm^3 (Fig. 4).

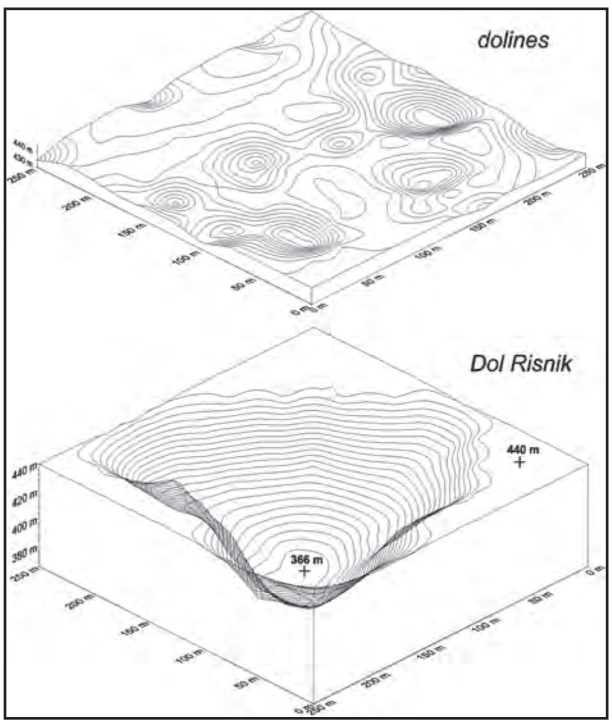

Figure 4: Comparison between the volume of the solution dolines and collapse doline.

In leveled surface of Divaški kras there are several large unroofed caves, which were the first time described as important elements of karst surface morphology by Mihevc (1996). They are expressed as rows of elongated trench like depressions or elongated dolines with allogene fluvial sediments and exposed flowstone. The unroofed caves represent small part, only about 0.16% of the entire surface, but they are important, because they tell us that the karst evolution in the area is going on for a long time since caves, similar to the active river caves that are today 250 - 300 m deep, are now exposed on the surface.

Important unroofed caves are exposed on the slopes of collapse doline Radvanj at the altitude of 390 - 415 m a.s.l. It is a remnant of a large cave passage, which is entirely filled with cave sediments. Similar sediments can be seen in the Divaška jama cave. This is a 600 m long cave, whose continuation towards the unroofed cave is completely filled. Divaška jama is inactive and high above recent water flow. The cave was also filled, but sediment was later washed from it by seepage water. Here we can connect the unroofed cave with existing cave.

The longest roofless "cave" is a 1800 m long remnant of cave passages about 20 m wide that was shaped by an underground river similar to the recent river Reka in respect of size and sediments. The cave was filled with fluvial sediments and massive speleothems. It is located above the Škocjanske jame, where the actual river in the cave flows 250 m below the unroofed cave.

The age of the unroofed caves can be established by comparative methods according the denudation rate of the surface. If we presume that the rate is about 50 m/Ma (Gams 1963) and there was between 100 m - 200 m of rock removed from above the caves, the caves would be at least 2 – 5 Ma old (Bosak et al. 2004; Horaček et al. 2007; Mihevc, 2007). Similar time frames 3.8 to 5 Ma were given also by paleomagnetic dates from clastic sediments (Zupan Hajna et al. 2008). The age of the roofless cave can also be illustrated as the time it took the water table in caves, some of them are now unroofed, to lower 290 m, from about 450 m to 160 m a.s.l.

A group of about 20 larger depressions covers about 3% of the study area, a larger area than covered by solution dolines. They are more rounded in ground plan, have gentler slopes and transition to surface and show no recent collapsing or connection with active caves. No clear explanation of their genesis is understood. Most likely, they are an old collapse dolines that were already much affected by the denudation of the relief and transformation of their slopes. Their age is not clear, but the unroofed caves in the same surface indicate their great age. In such case they are product of "normal" evolution of the collapse dolines when the main process of collapsing and washing of the particles underground by concentrated flow diminished.

We can follow the underground river Reka through 5800 m long and 250 m deep Škocjanske jame and 13,250 m long and 275 m deep Kačna jama. The mean annual discharge of Reka river is 8.26 m^3/s^{-1}; high discharge is estimated to over 300 m^3/s^{-1}. High waters are causing the rise of water level in caves, 134 m in Škocjanske jame and about 124 in Kačna jama.

Škocjanske jame is a relatively simple cave with a large main channel between the ponor and terminal sump. After about 900 m, Reka emerges in Kačna jama, which consist of several smaller passages at different altitudes. At low water, Reka flows southwest through the cave towards the terminal sump at 156 m a.s.l. With higher discharge, water reaches the elevation of about 280 m, flooding about 10 km of passages. In such conditions, the cave is not accessible, but driftwood and garbage show that the river bifurcates towards south, southwest, and northwest (Mihevc, 1984).

In both caves and above them, we can observe the collapse processes and formation of large chambers and collapse dolines. The largest cave chamber is the Martel Chamber in Škocjanske jame cave, with volume of 2.1 Mm^3. The chamber is 123 m wide and 146 m high, the thickness of the roof is about 100 m (Mihevc A. 1994). In the chamber, the water table oscillates for 134 m. In Kačna jama there are several points where the cave is under the collapse doline or where within the cave large chambers are forming (Fig. 5). In all cases we can observe that most intense collapsing occurs in the tectonically fractured zones in thick bedded limestone within the height of the flood level. Here large caverns were formed or maze of smaller passages, which by time joined as the remaining walls in between collapsed. Such a case is evident in Kačna jama where a passage crosses a fractured zone (Fig. 6) and a large chamber, Kalvarija, developed. About 50 m below, the passage Spodnji rov crosses the same zone. In the zone, a maze of passages and the collapse chamber Hojherjeva dvorana formed. The lower passage is active several times per a year, the upper several times in a century.

Figure 5: Collapse chamber in Kačna jama at Kalvarija.

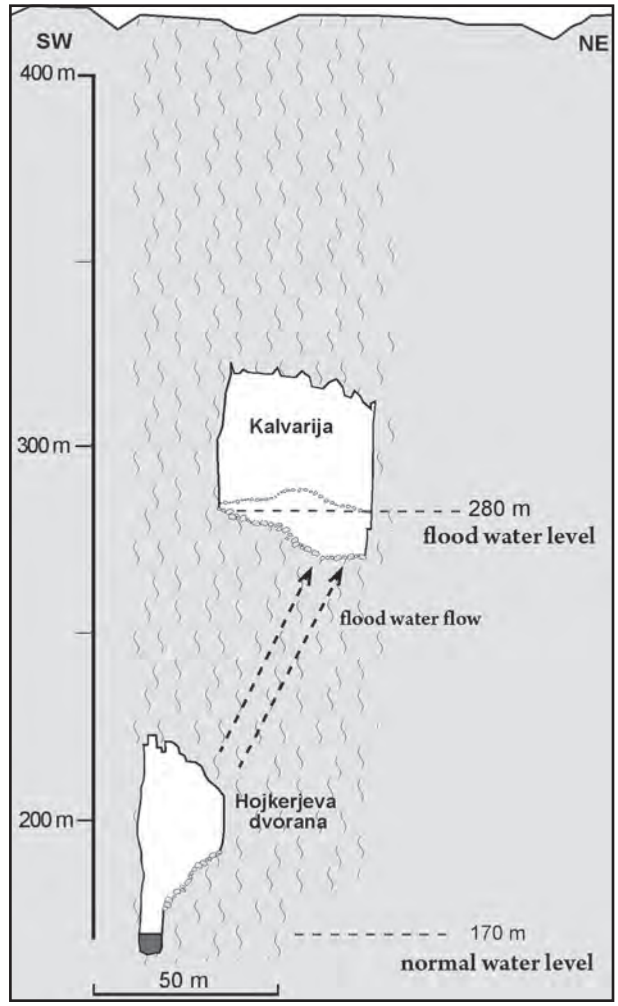

Figure 6: Section across two passages in Kačna jama. In fractured zone two large collapses formed.

In both chambers we can observe collapsing of walls controlled by loosening along tectonic joints and with traces of dissolution. This means that the collapsing is not a simple failure of fractured rock, but active speleological processes and is such more connected with a "young" stage of cave evolution. The water is not only removing the collapse material, but its oscillations enable corrosion in the fractured zones, creating wider chambers. The collapsing of the ceiling of Hojkerjeva dvorana is less active because it depends only on smaller quantity on the vadose seepage water, which is also depositing flowstone.

3. Discussion

Collapse dolines are important morphologic and diagnostic elements of the Divaški kras. Detailed morphological and speleological analysis show two generations of collapse dolines. The active one shows steep morphology, collapsing, and movement of debris. The older ones have much gentler topography but their size excludes them consideration as solution dolines. We can compare or date them with the unroofed caves that show the great age of the karst evolution of the area.

The term collapse doline presumes the formation of a doline by collapse of a karst void. The volume of the newly formed feature, collapse doline, should be smaller, since the collapse rock occupies a larger volume than the solid rock. It is evident that their number and dimensions are mainly the result of the removing of the disintegrated collapse rock at depth, by solution of important underground rivers. But rivers also have another role. The formation of big voids cause locally enhanced dissolution of limestone, which occur in our case where flood water is oscillating in fractured zones. Collapsing begins in early stages of cave genesis. By the general lowering of the karst water level these most favorable conditions move downwards. Later collapses occur when aggressive vadose water corrodes and destabilize the ceiling of the cave or when denudation lowers a surface nearly to a cavity below and thins its ceiling.

At this point, we can distinguish between unroofed caves, which were formed by denudation of the surface and collapse dolines that were formed by speleogenetic processes.

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BELLHOLES AND BELLBASINS: BIOGENIC (BAT) CAVE FEATURES OF PUERTO RICO AND THE NEOTROPICS

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Data from the survey of 63 solutional caves were used to outline the associations of bellholes and bellbasins in Puerto Rico. These features are restricted to tropical caves, and in more than 100 km of mapped cave in the Neotropics these are paired solution phenomena. Bellholes are vertically symmetrical and circular (commonly 60 cm height and 30 cm width), slightly tapering cavities (sometimes exceeding 1 m high) in ceilings of limestone caves; bellbasins are shallow depressions in floors, located vertically beneath a bellhole in solid substrate such as rock or speleothem. They are rarely influenced by joints or bedding. Sampled densities in caves show they contain tens of thousands of bellholes, found dominantly in dark areas, in association with bats, primarily the species *Artibeus jamaicensis* (Jamaican Fruit Bat).

Four mapped caves in Puerto Rico, with adjacent passage segments in diverse hydrologic situations, illustrate the vadose origins of bellholes and a causative association with bats. In three caves, entrance passages contain hundreds of bellholes and thousands of bats until physical obstacles are reached: after 150 m Cueva Murciélago reaches a sump that has been dived and surveyed for 200 m but has no bellholes. Cueva Escalera has more than 1500 m of air-filled inter-sump passages that have no bellholes. Cueva Perro has an interior section of free air and water flow (bounded by an airspace of 5 cm over a pool, and distal narrow rock rifts), which has no bellholes. In Cueva Represa bellhole densities (a total of ~ 4000) and bats decrease with distance from the single entrance to 1020 m inside, and bellhole-bellbasin pairs are found in speleothem and in ceilings above post-formational collapse blocks. Circular, increasingly indented ceiling cavities demonstrate a sequence of bellhole development. The numbers of bellholes and bellbasins suggest they may be an important post-formational erosional process in tropical caves: 4.8 cm of rock has been removed from the ceilings of the first 600 m of Cueva Represa. Small (23 cm diameter, 9 cm high), circular, streaked cavities in a limestone drainage tunnel constructed in 1927 in Puerto Rico could indicate an age less than 900 years.

Bats of the species *A. jamaicensis* are frequently found in the bellholes, whose walls and exits are commonly stained with thin dark brown streaks. In Cueva Represa x-ray-diffraction analysis of the bellhole streaks revealed apatite minerals associated with bat guano-limestone reactions; unstained surfaces showed only carbonate minerals. Bellbasins directly beneath the ceiling cavities contained fresh or indurated bat guano, and walls of altered rock rinds of apatite and hydroxyapatite. *A. jamaicensis* roosts singly or in harem groups of 2-14 that commonly cluster in the bellholes. It is hypothesized that the social habits of this species focus corrosion resulting from the transfer of feces to rock (producing altered rock removed by claws) to create discrete upward-growing cavities. Fossil evidence from Jamaica supports an arrival to Jamaica in the past 12,000 years, suggesting bellholes and bellbasins are geologically recent features in the Neotropics. Bellhole locations could provide clues to paleoclimate information related to past activity of specific bat species, their diets, and the hydrologic and meteorologic history within a cave.

1. Introduction

Those who spend much time in the dark zones of Neotropic caves comment on the large numbers of symmetrical cavities in the roofs, where ceilings are almost completely pitted with bellholes. Mature *bellholes* are vertical, symmetrical, bullet-shaped cavities common in the ceilings of cave interiors; the senior author has observed them in Central America, the Caribbean, and South America. Their shapes and dimensions have been described with regularity as having circular diameters of 20-50 cm, depth (cavity height) that may exceed two meters, and usually in solid rock without obvious control by dip, bedding, joints, lithology or ceiling morphology. In Puerto Rico alone they may number more than a hundred thousand. Their sides are often are streaked brown and black, with a relatively clean top.

Bellholes were possibly first reported from Jamaica in 1953 by V.A. Zans (White, 1962) who referred to them as "ceiling pockets," dissolved by bat urine. "Bell-shaped cavities" in Trinidad in soft coral-reef limestone, were postulated as "... excavated by the claws of generations of roosting bats," whose guano was found beneath each cavity (King-Webster and Kenny, 1958). Wilford (1966) used "bell hole" for features in Sarawak caves. He noted the absence of typical geologic controls (dip, bedding, joints, or lithology) and suggested their formation by turbulent "...eddies in fast flowing water," but acknowledged problems with the physics of that process. His photographs show birds in the bellholes, and he made no reference to bats. Medway (1971) however, did trap the bat *Miniopterus australis* in bellhole roosts in Sarawak, which he preferred to call "cupolas" after a usage in caves in Tanzania. In this manuscript the contraction *bellhole* is used, as per the geomorphic *pothole*, to reduce confusion with the existing engineering term "bell hole."

The first published cave map showing labeled "bellholes" appears to have been by Miller (1979) who described them as "...cylindrical ceiling holes half a metre in diameter, punched one or two metres upward into the rock... ubiquitous in most large Belizean caves..." Later, based on observations and photographs recorded during 42 km of surveyed passage data in caves of Belize, and after viewing thousands of bellholes, Miller (1981, p.77-79) added other maps of bellhole caves, also citing their dimensions and typical morphology. He stated that at least some bellholes were vadose, being "... found above relatively recent collapse in old phreatic chambers, where it is obvious they postdate the phreatic activity." He regarded bats as involved in bellhole formation, declaring he found no group of bellholes located where there was no presence of bats, and noting the presence of bat guano in bedrock depressions beneath the bellholes. Miller did not advocate any particular process of formation, though his focus on bats, combined with speculation about "... films of aggressive water as suggested by the re-solution of some nearby stalagmites," was an early version of condensation corrosion hypotheses.

Subsequent to mapping an additional 61 km of cave in Belize, Guatemala and Mexico (which included cave-dives), Miller (1990, 1996) introduced the term *bellbasins* to draw attention to the common presence of hundreds of these shallow, roughly circular depressions in rock floors, always located vertically beneath a bellhole. They usually contained bat guano, but no scallops nor stones and did not occur in unconsolidated or alluvial strata beneath bellholes; Miller attributed bellbasins to formation by reaction of guano with limestone. In noting that bellholes were not scalloped, were sometimes found in speleothem, and had not been observed in submerged conduits, Miller established that they were *vadose* features. He described shallow roof "saucers" and deeper ceiling cavities as progressive stages in the evolution of a bellhole. Miller noted the near-ubiquitous association of bats with bellholes, absence of bellholes in extensive vadose passages beyond sumps, and the common presence of brown streaks in/from most bellholes, to hypothesize that acids associated with bat wastes could also be a causative factor in their development. In 2006, he reported analyses of the dark streaks and stains in Puerto Rican bellholes/ bellbasins that showed the presence of apatite and hydroxyapatite minerals (reaction products of guano with limestone). He posited a mechanism of "social habits" of bats, e.g. *Artibeus jamaicensis* (Jamaican Fruit Bat) that would focus erosion at discrete points on cave ceilings. Recently Osborne (2007) reported bellholes and "solution pans" in Australia associated with phosphates, and attributed to bat guano corrosion.

Others (e.g. Tarhule-Lips and Ford, 1998) considered bellholes as infrequent or even rare, suggesting a condensation corrosion mechanism to explain the formation of bellholes in the interiors of shallow Caribbean caves and entrances. They did not explain how the mechanism could focus on specific sites in the cave roofs, and viewed bats as simply opportunistic users. Recently, Lundberg and McFarlane (in press) have modeled bat metabolism products (water vapor and CO_2) as central to condensation corrosion and enlargement of large bellholes.

2. Objectives and Methods

Given their numbers, widespread distribution, and the volumes of removed rock they represent in caves, understanding the genesis of bellholes and bellbasins would be useful. The initial speculations of association between bats and bellholes have been strengthened by Miller's map data and observations, summarized in the aphorism:

"Where there are bellholes, there are almost always bats, and where there are no bats, there are very rarely bellholes."

If bats are causal, a genetic mechanism should be able to

- distinguish whether bats are opportunists simply colonizing pre-existing ceiling cavities, and
- suggest an erosion mechanism for the removal of hard rock in cave ceilings.

For testing, suitable caves were culled from 63 large bellhole caves examined in Puerto Rico, and four were selected that each had hundreds of bellholes:

a. If only hydrologic parameters or air circulation are involved in their formation, bellholes should form irrespective of bat activity. Bellhole caves are common in Puerto Rico; examples were sought where bellhole segments were adjacent to passage segments with similar hydrologic/meteoric environments, but with physical barriers that excluded or restricted bats. The first three caves tested the hypothesis of opportunistic bat association, and the fourth was examined and mapped for bellhole association and sampling. These caves were in limestone of Miocene to Oligocene age (Renken et al., 2002), but numerous bellhole caves have also been mapped in Cretaceous rocks in Puerto Rico (Miller, 2004).

b. Bellholes were counted to estimate densities in Cueva Represa, a cave with accessible bellholes and bellbasins. Samples of the dark interior staining and/or rinds of bellholes and bellbasins were collected and prepared with standard methods (grind to powder, oven heating to eliminate carbon or biological residue) for analysis with a Siemens XRD Diffraktometer D5000. Stains of three individual bellholes and a group were sampled with a wire brush, and the altered "rinds" of four bellbasins were collected by removing guano and loose material inside, then chipping or brushing the walls for a sample. Dimensions of interior depth and width were measured by stretching a nylon measuring tape across the diameter, or for bellholes, raising a measuring tape on a pole inside the dome and/or measuring with a Leica Disto-D3 laser meter (± 1.5mm precision at 30 m).

c. Photographs were taken of bats occupying bellholes to identify the species involved, e.g. Kunz et al. (1983) had censused the bat *A. jamaicensis* in a portion of Aguas Buenas Cave, Puerto Rico with 287 ceiling "solution cavities.", and recorded its harem roosting behavior in them. Other bats have been reported in the same caves (Gannon et al., 2005)

3. Results

3.1 Bellhole caves In varying hydrologic environments

- Water was a natural barrier that excluded bats, yet allowed human access: Cueva Murciélago is an example of a bellhole cave with open entrance galleries and interior flooded phreas. It is colonized by thousands of bats, and 150 m inside the cave enters water-filled, phreatic-loop passages. Cave-dived, and mapped for 200 m to 14 m depth, no bellholes or bellbasins were observed.
- Cueva Escalera is a bellhole cave with a large air-filled passage (10-15 m high/wide) located between sumps. Entry is via a wide pit bisecting its conduit and stream. The conduit leads upstream 180 m through an area of bellholes and bat colonies to a short sump, beyond which is 1500 m of large conduit ending at another sump. There are no bats, bellholes or bellbasins in this section between sumps.
- Lastly, Cueva Perro has a vadose section barred to bats, but without sumps. Surface water and air are able to freely enter a section of cave conduit where the entry of bats is restricted, first by a small column in a crawlway (that also prevented human entry), and secondly by an airspace above water too small (2-5 cm) for a bat's flight to negotiate. There are no bats or bellholes in the restricted area, but downstream past these obstacles are numerous bellholes and bellbasins and thousands of bats in a large stream passage that leads to another entrance.

3.2 Sampling of surficial deposits in bellholes and bellbasins

Cueva Represa, a site with easy access to bellholes, was mapped. Numerous bats are found throughout the first 260 meters of passage, where 2136 bellholes were counted. The passage maintains regular dimensions of 5 m high and 5-6 m wide, although bellhole density and size decrease with distance into the single-entrance cave. At 550 m, 88 were counted in the 30 m prior to a sharp, short reduction in passage height (to one-meter of airspace, 5 m wide); only 11 bellholes were located in the following 45 m, and only 5 more from there to a total distance of 1020 m from the entrance. Using a density of 5.5 bellholes per linear meter of passage (intermediate between the 8/m of the entrance area, and the final 3/m before the constriction) 3940 bellholes are estimated for the first 580 m of the cave, of which 82 are in the dim entrance area, and fewer than 300 in view of twilight.

Cueva Represa is representative of many bellhole caves in that bellhole-bellbasin pairs are common (some occurring in speleothem, with bellholes that occur in ceilings above post-formational collapse, and without bellholes on the underside of the collapse blocks. The hundreds of bellbasins are all located vertically beneath bellholes, but only in solid soluble substrate such as rock or speleothem. Deep bellbasins did not always have deep bellholes above; some bellholes were found at the inflection between ceiling and wall, or steep changes of slope on the roof. Numerous smaller circular ceiling indentations < 20 cm width with dark stains (some with bats) were noted: interior depths of up to 20 cm varied symmetrically with the widths.

Bellbasins almost always contain bat guano, which was analyzed in numerous Puerto Rican caves by Gile and Carrero (1918). Their 247 samples often found phosphoric acid (H_3PO_4) concentrations above 20%, with lower concentrations of sulfur and nitrogen. In Cueva Represa, dark streaks and staining on ceilings are virtually restricted to bellholes, though not all bellholes contained them. At the sides of the room and passage, the ceiling was low enough to collect samples of the brown streaks that run down the interior of the bellholes and out onto the nearby ceiling. These deposits were thin veneers, or patinas that at times could be pried loose with a fingernail. Dark brown streaks on rock in all four bellhole samples were greatly enriched in phosphorus, and XRD analysis revealed hydroxyapatite and apatite [$Ca_5(PO_4)_3(OH)$] in two. These minerals were found on the brown material taken from the altered limestone rinds of all four of the bellbasins. Hill and Forti (1997, p.169) comment that "Hydroxylapatite is probably the most common phosphate mineral in caves because it is the direct reaction product of bat guano and limestone." This reaction is $3H_3PO_4 + 5CaCO_3 \rightarrow Ca_5(PO_4)_3(OH) + 5\,CO_2 + 4H_2O$. Only calcite was found in samples from unstained ceiling surfaces (Figueroa-Mulet, 2006).

3.3 *Artibeus jamaicensis* in bellholes

King-Webster and Kenny (1958) noted that certain bats "...tend to sleep...crowded close together...," some of the "social habits" of specific bats that Miller (2006) suggested could focus bellhole erosion on cave ceilings. The mostly widely distributed bat in Puerto Rico and the Neotropics is *A. jamaicensis* (Gannon et al., 2005 and Genoways et al., 2005), which biologists commonly report roosting in "solution cavities" (identifiable in their photographs as bellholes) in caves in Puerto Rico and elsewhere. In Cuevas Aguas Buenas (Puerto Rico) *A. jamaicensis* roosts singly or in harem groups of 4-16 that commonly cluster in the bellholes (Kunz et al., 1983), with bellhole walls and exits frequently stained with thin dark brown streaks. Not every bellhole is always occupied: e.g. Kunz et al. recorded only 13% occupancy at Cuevas Aguas Buenas. *A. jamaicensis* is one of only 13 bat species reported from Puerto Rico and its large "nose-leaf", size, roosting habits, color, and pointed ears make it relatively easy for non-biologists to identify: this is the only species yet identified by the authors in bellholes in Puerto Rico.

4. Discussion

4.1. Genesis

It is clear from the absence of bellholes in submerged phreatic passages, and their presence in speleothem and above post-formational collapse, that they are vadose features. The association of all bellbasins with bellholes also indicates that the former are vadose as well. Given the near-universal presence of bat guano in bellbasins, the demonstrated presence of guano-limestone reaction minerals, and the absence of scallops or abrasive stones, it is difficult to suggest a likely genetic mechanism for the bellbasins other than dissolution by bat feces and urea. Assertions that convective currents and condensation-corrosion alone could produce bellholes are not supported: the examples of barriers in Cueva Escalera and Cueva Perro with internal, and external air circulation, demonstrate that a solutional process that ignores bats is not likely.

Bellholes must start on pre-existing cave surfaces, guided initially by those relict shapes, and then follow a standard sequence of development. As noted in Cueva Represa and elsewhere, increasingly-indented ceiling hollows, often with the dark streaks characteristic of mature bellholes, can be found in areas with bellholes. Some of these larger "inverted saucers" are demonstrably bellholes (as shown by bellbasins beneath), which resemble the tops of the larger bellholes. Given the demonstrated association with bats, the widespread examples of considerable corrosion of cave floors and walls by bat feces, and the evidence of alteration of soluble bedrock in bellholes by reaction with them, an obvious starting point is to link bat excreta with behavior that would focus and maintain corrosion of bats for a long period in one location.

It is hypothesized that the social habits of *A. jamaicensis* both transfer feces and focus corrosion. The clustering of bats into harems of small size provides a limiting focus for bellhole development, while excretion transfers feces and urine to sides of the bellholes. *A. jamaicensis* climbs upside down, facing the rock, into its roost. This (and possibly grooming behavior) could transport feces via fur and claws to higher walls and ceiling, and then produce altered minerals later removed by claws and physical contact of these same activities. Gravity would control both the removal of excreta and limit the manner in which the bat exits and enters the dome, to create discrete upward-growing cavities.

As noted, Lundberg and McFarlane (in press) reformulated in detail the bat-related "films of aggressive water... and re-solution..." posited by Miller (1981). Based on rock-surface temperatures measured in bellholes in Runaway Bay Cave, Jamaica, they hypothesize that thermal gradients induced by metabolism products of bats could possibly generate condensation corrosion at 25.4 C sufficient to produce a 1-meter-high bellhole within 50,000 years. Although no additional physical evidence was produced, this argument is intriguing, even though Kunz et al. (1983) had been unable to discern microclimate differences within colder bellholes in Puerto Rico: the latter used a thermistor probe within, and outside of 287 occupied and unoccupied bellholes used by *A. jamaicensis* in Aguas Buenas Cave, but 'invariably' found the (air) temperature to be 21°C. The modeled process rate also seems slow (see below), but perhaps the main problem is with initiation and subsequent evolution of the bellhole: Lundberg and McFarlane comment that "…wider, shallower holes…do not retain the [bats'] heat…" They suggested that bellholes deeper than the average measured would best allow an optimum bat population and geometry to contain the water vapor and CO_2 they produced. Clearly, until mature bellholes develop, initial saucer shapes would not retain either the bats' heat or respiration, although once a bellhole had achieved an optimum size, the corrosion process could play a progressively larger role. The reaction of phosphoric acid with limestone also releases CO_2 and H_2O that could boost corrosion in the bellhole.

4.2. Growth and age

A maximum age for bellholes can be established from the ages of caves, or the rock in which caves and bellholes have formed, e.g. Walker et al. (2008) found that caves of Abaco Island in the Bahamas formed at 125 ka before present, so bellholes inside are younger features. In Puerto Rico, bellholes are found in a large Atlantic littoral cave (Cueva del Indio) formed in calcarenite/ aeolianite that is an undetermined age younger than an underlying radiometrically-dated marine terrace of 120-130 ka (Taggart, 1992). Fossil evidence may provide a more recent limit to bellhole growth: Genoways et al. (2005:85) assert that *A. jamaicensis* only arrived in Jamaica from Central America 12,000 years ago, approximate to arrival in Puerto Rico. If the hypothesized association of bellholes with *A. jamaicensis* is correct, it implies that bellholes could be very recent, Holocene features of the cave environment of the Caribbean.

4.3. Volume removed / rates

Irrigation tunnels (to 2 m diameter) constructed in 1927 in Puerto Rican mogotes have small, circular, black/brown streaked cavities in their limestone roofs. Seven in one tunnel were found with mean dimensions of 23.2 cm diameter, 9.4 cm high (volume 0.004 m^3). Assuming they are juvenile bellholes that commenced development since 1927, a typical bellhole in Cueva Represa- of 60 cm height and base diameter of 30 cm (volume 0.042 m^3)- could form in 860 years. As noted, bellhole occupancy is episodic, which would retard development. The estimated 4000 bellholes of Cueva Represa represent a total removal of 168 m^3 for the first 580 m. At the 6 m widths usual in Cueva Represa, a mean 4.8 cm of passage ceiling has been removed in perhaps as little as 860 years. This figure does not include the amount dissolved in bellbasins, and suggests that *A. jamaicensis* alone could be a significant post-formational erosion factor in some of the larger caves of Puerto Rico. Even if all assumptions of Lundberg and McFarlane (op cit.) are eventually supported by physical data, condensation corrosion rates as much as 50-60 times slower could prove insignificant in bellhole development.

4.4. Distribution

Bellholes are found widely in the Neotropics, in a range that broadly- perhaps identically- corresponds with that of *A. jamaicensis*. They are known to elevations of at least 500 m asl in Central America, but may be limited by the distribution of *A. jamaicensis*, which is not commonly found above 1000 m asl in Jamaica. No other Neotropic bat species occurs everywhere there are bellholes. Other bats are associated with *A. jamaicensis*, e.g. *Monophyllus redmani*, although bats may be reported to share the same roost simply by being in the same cave chamber (e.g. Rodriguez-Duran, 1998; Lundberg and McFarlane, in press). *M. redmani* and another species *Erophylla sezekorni* (and possibly *Brachyphylla cavernarum*) that have been noted in bellholes (pers. comm., Armando Rodriguez-Duran), are normally found in large colonial clusters of thousands, with much smaller densities in nearby areas. Given the frequency of caves in Puerto Rico with bellholes, these incidences are likely opportunistic occupancy; certainly by far the dominant bellhole bat in Puerto Rico is *A. jamaicensis* (pers. comm., Armando Rodriguez-Duran). Finally, *A. jamaicensis* is the only bat that overlaps all locations where Neotropic bellholes are found, and is the only bat yet identified in published photographs of bellholes. Although bellholes are also associated with fruit (and insectivorous) bats of harem behavior in Asia (e.g. Sarawak, Medway, 1971) -supporting the idea that this behavior (and diet?) is causative- an urge to rename them harem-oids should be resisted! Studies and literature of Asian bellholes are less common than in the Neotropics.

5. Summary

Bellholes are vadose features, clearly associated with bats. They are common, frequent features of Neotropic caves, dominantly in the dark zones. Development of bellholes is hypothesized as a chemical alteration of carbonate bedrock by bat feces and urine, and then physical removal by claws and bodily contact. The uniformity of size as they develop from initial ceiling saucers to mature bellholes is probably constrained by social habits limiting roosting *A. jamaicensis* to harems of generally fewer than 20 individuals. Bellholes may possibly develop in fewer than 900 years, which could make them significant erosional factors of ceilings in some caves, where they represent nearly 5 linear cm of roof removal for large areas. Bellholes may also be geologically recent features, due to the migration of *A. jamaicensis* throughout the Caribbean within the past 12,000 years.

Bellbasins are always located beneath a bellhole, and form in solid substrates such as rock or speleothem. Their walls and floors usually contain bat guano, and are corroded by these acids to produce phosphate minerals such as apatite and hydroxy-apatite. They are vadose features, as shown by their association with bellholes, which are also vadose. The ubiquity and numbers of bellholes (4000 in a single Puerto Rican cave) and bellbasins suggest they may be an important post-formational erosional process in tropical caves, and their presence may also provide clues to past bat activity and paleo-climate, and the internal hydrologic and meteorologic history of passages in a cave.

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MORPHOLOGY OF SOLUTION-DOMINATED VS. CLASTIC-DOMINATED CAVE PASSAGES IN THE CAVES BRANCH KARST, BELIZE

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Abstract

The Caves Branch Cave System has a primary conduit that exceeds 15 km in length and parallels a large polje to its east. The local lithology is Cretaceous limestone distinguished by an extreme degree of angular brecciation with rare bedding. The majority of exposures show 2 - 15 cm limestone clasts cemented in a very pure red calcite matrix. Structurally, limestone bedding is insignificant, and joints are common, with faults of indeterminate offset in similar-appearing limestone. A series of hydraulically-restricted cave channels pirate allogenic river water from the polje into the master conduit, where it mixes with high discharge from the overlying holokarst from the west. The pirate river channels and holokarst inputs thus join from opposite sides of the same conduit at similar elevations, yet have distinctive morphologies.

The holokarst waters are instantly recognizable by their noticeable coolness (relative to the conduit), averaging ~23.7–24.5 °C., with high-solute and saturated with respect to calcite. Other than occasional clay, they contain few clastics (none of allogenic origin), and travertine deposition is common where they join the conduit. Their channels are scalloped, irregularly pocketed, joint-guided, occasionally anastomosing and frequently tubular in plan, and lack graded profiles; most can be followed no more than 50–100 m before they sump or shrink to non-explorable dimensions. They most frequently enter 2–3 m above the main conduit, and evidence suggests they are older than the pirating tributaries. Unenterable in wet season flow, they are phreatic with mostly flooded segments (sumps) with intervening air-filled sections in the dry season, and full inundation as runoff pulses through in the wet season. Like the holokarst channels, the pirating conduits are joint-guided, with phreatic features, and they rapidly lead to sumps. But in contrast, they also convey mud and larger clastic sediments derived from the Maya Mountains, they are always located on the river valley side, and their floors enter flush with the valley bottom. Unlike the karst channels, their dimensions remain constant (2–3 m wide and high) and do not diminish with distance from the main conduit. They do not deposit travertine at their conduit confluences, but may have speleothems along their ceilings. Their waters are low in hardness, unsaturated with respect to calcite, and instantly recognizable by their relative warmth (24.5–26.4°C) with respect to the main conduit. They appear to have developed after the main conduit, following an episode of aggradations that partly blocked the main channel to outside river flow and contributed to initiation of the pirate channels.

The two passage types enter on opposite sides of the same conduit in identical brecciated bedrock, at similar levels, with comparable flows, yet the holokarst pathways have more complex morphology and deeper phreatic loops than the more recent pirate channels in the same rock. The relative proportions of clastic sediment load material differ far more than the differences in chemistry and corrosion capacity, and in the absence of bedding, may best explain these dramatic differences.

AIRFLOW AND CO_2 IN ROBBER BARON CAVE

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Robber Baron Cave, located in San Antonio, Texas, is known for bouts of "bad air", which indicates intermittent high levels of carbon dioxide (CO_2). Visitors to the cave have reported a wide range of conditions, even during the same week. The cave has also been observed to have substantial airflow at various times in one particular passage that leads to a lower level, which only has a small known extent. A custom, low-cost airflow data logger based on an iButton was developed, which uses the hot-wire anemometer principle, in an attempt to better understand the meteorology of the cave. Several other iButton loggers were used to monitor temperatures in various locations. Later a Pasco data logger was acquired that measures CO_2 as well as airflow and barometric pressure.

Results from the iButton-based airflow logger show that the amplitude of the airflow is very closely correlated with changing barometric pressure. Sustained velocities are commonly above 0.5 m/s during normal daily cycles and above 1 m/s during high-pressure fronts. Measurements of CO_2 indicate that the CO_2 levels also correlate closely with barometric pressure changes and airflow. Since there is typically a daily cycle to airflow changes, this would explain the varying anecdotal reports of air quality. It appears that the CO_2 is forced back into unknown parts of the cave during periods of rising pressure and is drawn out into the main portion of the cave when pressure falls. Based on the airflow data, the lower limit to the volume of cave beyond the lower level crawl was computed to be 75 times the mapped portion.

1. Introduction

Robber Baron Cave is one of the most significant caves in the San Antonio area, being the longest cave in the county, with a large sinkhole entrance, a complex two-dimensional maze of passages, and a long, colorful history. The cave is also visited frequently and visitors have noted frequent episodes of "bad air", meaning that it becomes difficult to catch ones breath. Anecdotal reports have shown that the cave tends to have more "bad air" during the summer months, but that breathing conditions can vary widely from day to day. Visitors have used hand held lighters to determine if there was a decrease in oxygen levels, and presumed that this meant an increase in carbon dioxide. Certain passages also appear to have occasional airflow, most notably from one particular passage, which is a small crawlway that connects to the lower level of the cave. The lower level has not been fully explored due to the extreme challenge of maneuvering through a body-sized 5-meter deep pit and the observed increase of "bad air" as one descends.

The passages of the currently mapped cave are thought to be only a portion of the cave that was known in the past. In the 1920's and 30's Robber Baron operated as a commercial cave (VENI, 1988). Historical notes from the period tell us that the cave manager blasted shut some passages leading out of the current maze for fear of people getting lost. First-hand accounts describe trips taken by local youth who traveled through extensive cave to underground streams and encountered well pipes that tied into windmills nearly a kilometer from the cave entrance.

Previous work has examined airflow in caves and its relationship to barometric pressure changes on various time scales (LEWIS, 1991) and has shown that the volume of a cave can be approximated based on the airflow (CONN, 1966). Carbon dioxide research has been pursued in caves for many reasons, most notably for the purpose of linking speleothem growth to carbon dioxide concentration (BANNER ET AL, 2007). This research has shown that levels of carbon dioxide tend to change seasonally, and that there is some correlation to barometric pressures, but does not comment on daily cycles that can be seen within the cave. Due to the fact that the "bad air" in Robber Baron seems to be more prominent at different times of the day, understanding the daily cycles of the cave was also an important area of investigation.

This work examines two specific questions about the cave: 1) what does the amount of airflow tell about the volume of the unknown portions of the cave, and 2) how does the "bad air" phenomenon relate to the airflow experienced in the cave? Since airflow monitoring equipment is expensive and can be bulky, a small inexpensive alternative was needed. This paper also reports on the development of a compact, low-cost airflow data logger used to perform some of these measurements.

2. Geologic Description

Robber Baron Cave is a maze style cave formed in the 16-m thick geologic formation known as the Austin Chalk. The Austin Chalk is a carbonate layer that is made up of 83% calcium carbonate with silica, ferrous oxides and magnesium making up the rest of the material (HILL, 1901). The Austin Chalk overlies the Edwards Formation, a Cretaceous limestone that contains the Edwards aquifer. The section that the main level of the cave has formed in seems to have three distinct layers, with the uppermost layer containing abundant fossil remains. Many passages have been formed crossing all three layers, and creating a set of passages with interesting shapes. Because the layers have different dissolution rates, the taller passages often have a narrow fissure shape at the bottom, while the upper portion of the passage bells outward. At some points where the joint between two layers is exposed in a larger passage, a 15-cm gap in the wall has developed off the main passage. There is also a series of keyhole features in the cave where the joint between layers resists dissolution, and the bottom and top of the feature have dissolved out more.

The mechanism that formed Robber Baron Cave is currently under debate, with recent study by KLIMCHOUK (2007) and others proposing that formation of the passages is due to hypogene processes when water moved up from the underlying Edwards formation. This is in contrast to PALMER's (1975) description of maze cave formation, where water would have to move through the overlying Pecan Gap Chalk. Major passages in the cave are typically 2 m wide and 2.5 m high, crawlways are 0.75 m wide and 0.3 m high, and intersections are as large as 3 m in diameter and 3.5 m high. Passageways in the northern and eastern portions of the cave tend to run either on a general East-West trend or Northeast-Southwest trend, with some passages at the southwest part of the cave running in a Northwest-Southeast trend.

3. Methods

Initial airflow measurements were made using a custom-made airflow logger based on an iButton temperature logger. Additional iButtons were used to record temperatures in other parts of the cave. Later, a Pasco Explorer GLX Data logger was acquired that records barometric pressure, temperature, humidity, and carbon dioxide levels.

To facilitate the airflow measurement, a custom, low-cost data logger was developed to permit airflow studies without requiring expensive, easily damaged equipment. The logger, shown in Figure 1, is based on a Maxim iButton thermochron (DS1921H-F5) and uses the hot-wire anemometer principle. A thermal source heats the iButton, and as air moves across it, convection cools the sensor to a temperature that is inversely related to the airflow velocity. A 100-ohm resistor was selected as the heat source to achieve a high initial temperature, resulting in more sensitivity. The iButton and resistor are mounted on a plastic strip and the resistor leads bent such that the resistor is pressed firmly against the top iButton surface. Several wrappings of foil surround the resistor to improve the thermal conduction to the iButton. To keep the resistor temperature uniform, a 5V regulator (LM340TS) is used. Power is provided by 6 D-cells, which are sufficient for 10 days of use before the resistor voltage begins to drop. This logger is designed to measure airflow regardless of direction, so it is intended to be mounted parallel to the airflow direction.

Figure 1: Low-cost airflow data logger based on the hot-wire anemometer principle that uses a resistor thermally coupled to an iButton.

To calibrate the sensor, a wind tunnel was built with a DC-powered fan at one end and the measurement point in the middle of the tunnel. A Fluke 975 AirMeter was used to determine the actual airflow velocity with respect to fan drive voltage. Then, the temperature response of the iButton airflow sensor was recorded at several fan drive voltages while the ambient temperature was recorded with an unmodified reference iButton. A calibration function was determined by first subtracting the airflow iButton temperatures from those measured with the reference iButton (ΔT) to remove any small ambient temperature variations and then performing a curve fit to the data. An inverse logarithmic function was found to provide the best relationship between the calibrated airflow velocity and ΔT. The response of the iButton sensor does differs somewhat depending on the ambient temperature, so for a complete calibration, the response should be measured at a range of ambient temperatures. For a given cave, this is not a limitation as the ambient temperature does not vary significantly (at locations distant from an entrance) compared to the sensor's zero-airflow temperature of 38°C. For the purposes of this experiment, the ambient calibration temperature was set to the same as the average temperature in Robber Baron (about 21°C).

This custom airflow data logger does have some limitations and areas for improvement. The sensor does not provide any directional information. However, a reference iButton, placed just inside the cave entrance clearly distinguishes periods of inflowing air when the outside temperature is different from the cave's temperature. The directional limitation can also be solved by using two airflow loggers back to back, facing perpendicular to the airflow direction. Another issue is the 10-day power limit. A higher value resistor can be used, although this will reduce sensitivity. A thermal paste between the resistor and iButton might compensate by improving thermal conductivity. Use of a resistor in a flat, surface-mount package that increases the contact area is another option. The other limitation is non-linear sensitivity. The logger has been found to be very sensitive to small airflow values (<0.5 m/s) while having much reduced sensitivity to airflow velocities over 1 m/s. This is in contrast to most traditional air velocity meters, which have a lower limit to their measurement range of 0.25-0.5 m/s. Sensitivity to higher velocity airflow can be improved with a hotter resistor, but would involve a larger power source.

The primary measurement location used in this study was a crawlway that leads to a lower level of Robber Baron. Due to the significant airflow at this location, it is thought to be the primary connection to the unknown portions of the cave. This crawlway is about 85 m from the nearest entrance and is a fairly uniform sized passage (about 0.9 m by 0.4 m) that extends about 7 m before dropping into a small diameter pit to the lower level. The custom airflow logger was hung by wire from the ceiling parallel to the passage wall at about the midpoint of the passage. At the entrance to the crawlway, an additional iButton was hung to monitor the ambient temperature to calculate ΔT. A third iButton was placed about 5 m inside one of the two entrances to the cave to monitor temperature changes near the entrance. A fourth temperature logger was occasionally placed at other locations in the cave. Data was typically recorded in 10-minute intervals. The loggers were initially placed in the cave in June 2008 and then about once a month afterwards through the beginning of January 2009, allowing for a range of seasonal conditions to be examined. To correlate to external conditions, barometric pressure and temperature data was utilized from a National Weather Service station located at the San Antonio International Airport, about 3 km from the cave.

In work done at Wind and Jewel Caves, equations were derived to estimate the volume of a cave based on its airflow characteristics (CONN, 1966). Assuming a large chamber with an opening to the outside that is very small compared to the chamber, the volume flow rate in m^3/s under a changing barometric pressure is given as:

$$Q = \frac{V}{P_{atm}} \frac{dp}{dt}, \quad [1]$$

where V is the volume of the chamber in m^3, P_{atm} is the atmospheric pressure in Pa, and dp/dt is the rate of pressure change in Pa/s. The volume flow rate is related to the actual airflow velocity by:

$$Q = vA \quad , \quad [2]$$

where v is the measured air flow velocity in m/s and A is the cross sectional area of the passage in m^2 at the location of the flow measurement.

4. Results and Discussion

Data collected with the airflow iButton is shown in Figure 2 for typical summer conditions, while Figure 3 shows data during the arrival of a winter high pressure front. A direct correlation is seen between the rate of change of barometric pressure and airflow velocity. There was no measurable lag between the pressure changes and the onset of increased airflow. Whereas the pressure changes appear fairly smooth and continuous, the airflow data is very noisy, indicating gusty conditions. This pattern was also observed in person with periodic puffs of air at times and sudden increases and decreases in flow over a period of minutes. Even during times of little pressure change, there still appears to be a small amount of airflow. This low level "noise" was only observed when the airflow sensor was in the cave and not in the calibration wind tunnel, indicating that these are likely real airflow effects. LEWIS (1991) indicated that caves can act as highly sensitive barometers where otherwise undetectable small pressure variations can produce short, rapid shifts in cave airflow.

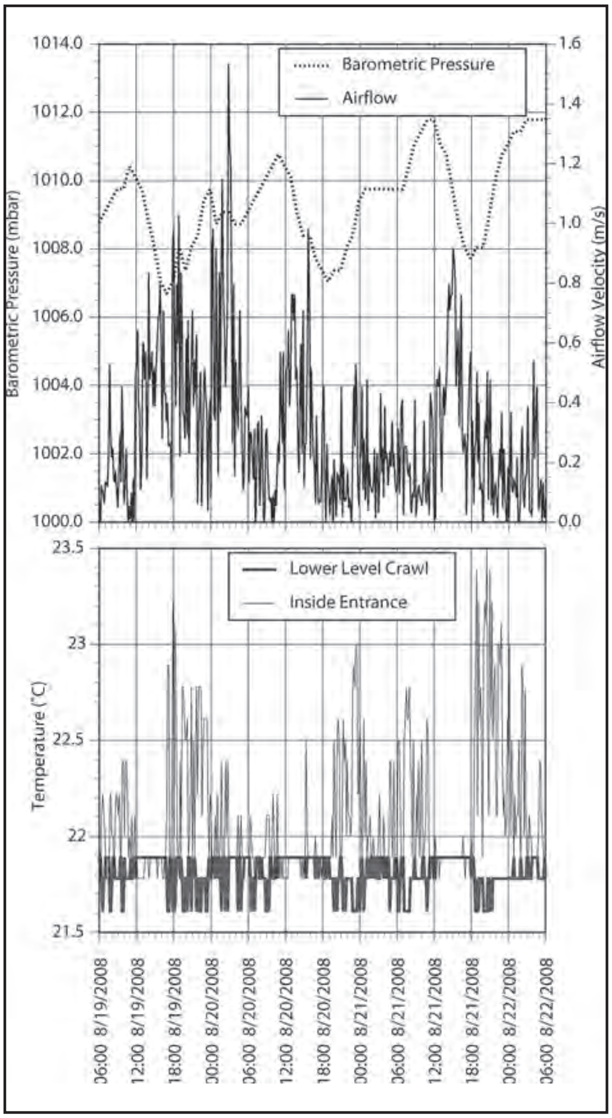

Figure 2: Daily cycle of airflow and temperature data during typical summer conditions. At top, barometric pressure is compared to the custom airflow logger. At bottom, temperature data is shown from near the cave entrance and at a point deep inside the cave showing the temperature inversion effect during inflow cycles.

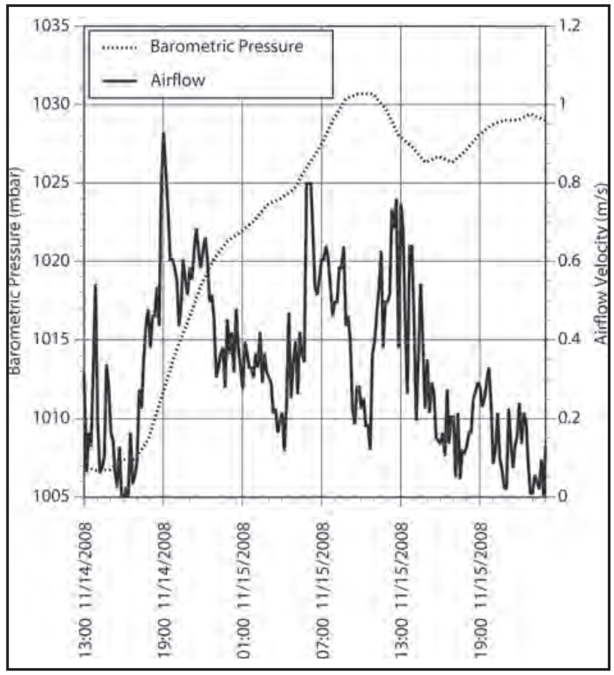

Figure 3: Airflow and barometric pressure data during a typical winter cold front.

The reference iButton temperature data was also analyzed. The magnitude and direction of the airflow could be inferred, although the variations were near the temperature resolution limit. The temperature of the sensor near the entrance was flat when pressure was falling, but increased when pressure was rising (Fig. 2). The data shows that the outside air, which was always warmer than the cave's temperature during summer months, was blowing inward during rising pressure. Cooler air with a uniform temperature from deeper in the cave flowed outward during falling pressure. This effect can also be seen on other iButtons placed deep in the cave, but the polarity of the temperature was unexpectedly reversed with inflowing air being cooler. In fact, the temperature inversion of was observed at all locations more than 15 m from the entrance. This effect is might be due to condensation forming on the sensors from the drier inflowing air that cools them in an evaporative manner.

As seen in Figure 2, during summer months the airflow exhibits a daily cycle with two major and two minor cycles. The major cycle occurs in the late afternoon when the flow is outward until about mid-evening, when the flow reverses, blowing inward until after midnight. There is a similar, but smaller amplitude cycle in the early morning hours. The amplitude of daily pressure variations is small, on the order of about 5 mbar. During winter, the airflow is dominated by regular cold fronts that move over south Texas, bringing large high-pressure systems with pressure changes of as much as 30 mbar. As shown in Figure 3, these typically have a major period of inflow when the front first arrives that may last for more than half a day, with the pressure gradually dropping over many days until the next front arrives. During the periods between fronts, the daily cycle may sometimes be observed, although the times are offset to earlier in the day in the winter.

In December, the Pasco data logger was acquired and also placed in the crawlway to the lower level with data recorded in 10-minute intervals. Although the Pasco does not respond to airflow velocities of less than 0.3 m/s, at times of greater airflow it showed the same trend of average velocity corresponding to the rate of change in barometric pressure. It also showed the same gusty wind effect, with velocities changing from below measurement threshold to over 1 m/s and back within a 20-minute interval. When compared to the custom iButton airflow logger, (Fig. 4) the Pasco gave similar average velocity results, but the peaks were generally higher. This is because the iButton airflow sensor acts as a low-pass filter since the resistor temperature takes a couple of minutes to fully respond to changes in airflow. This averages out the sharp peaks and valleys but retains the average value.

The Pasco unit also provided other measurements including barometric pressure, temperature, and humidity. The barometric pressure data was corrected for elevation and overlaid on the airport data and found to be an exact match indicating that use of the airport data is legitimate and that there is no significant pressure variation between the surface and the measurement location in the cave. Temperature data was found to be nearly identical to that measured by the reference iButton. The humidity data was not useful since it continually read a value of 100%, which may be due to limitations in operating this particular sensor in a very high humidity environment.

A CO_2 sensor was also acquired for the Pasco data logger and used in conjunction with the other sensors. As seen in Figure 4, the data revealed an obvious link between changes of barometric pressure and changes in CO_2 concentration

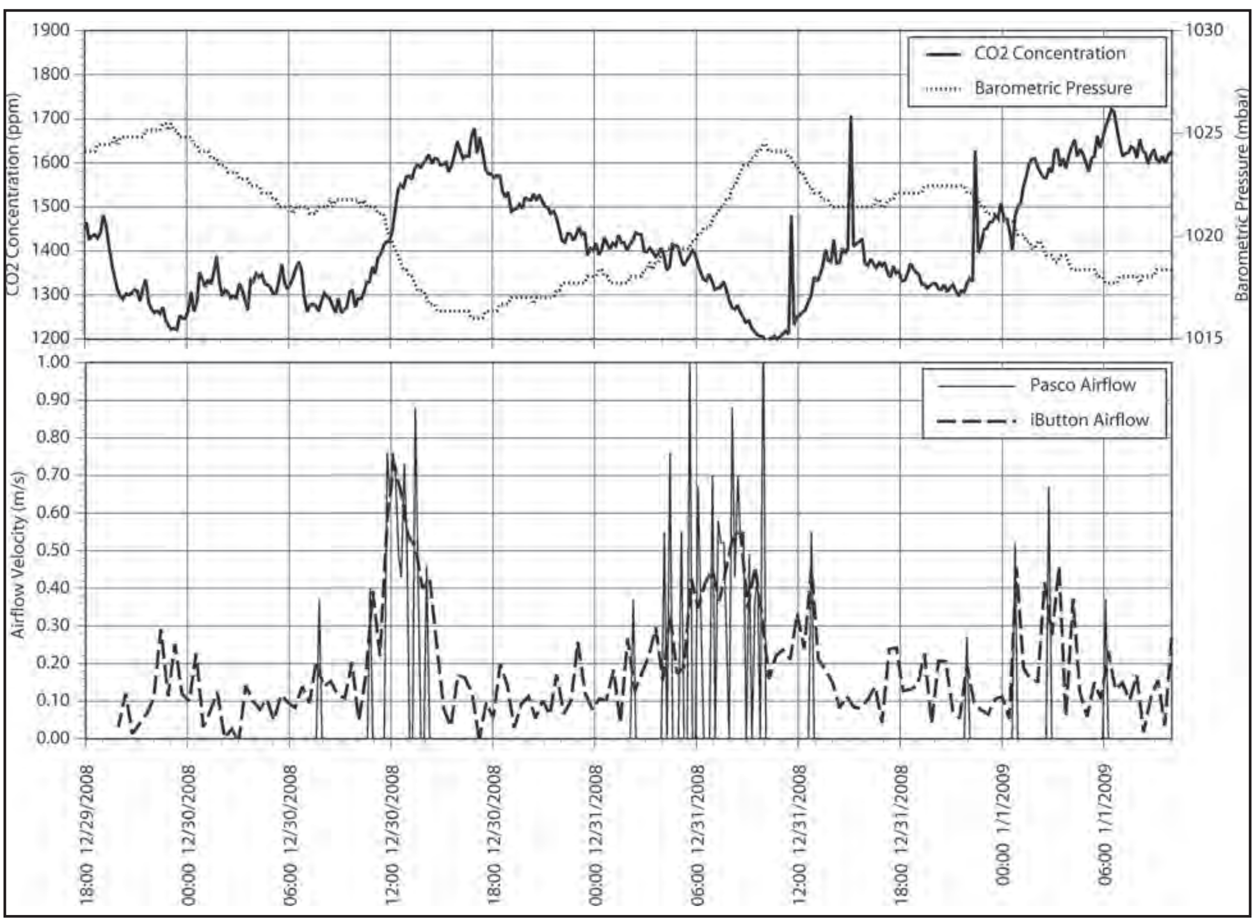

Figure 4: At top, barometric pressure is compared to CO2 showing that CO2 concentration has an inverse relationship to the pressure. At bottom, airflow data from both the Pasco and the custom iButton-based airflow loggers are compared.

in the cave. Multiple changes in barometric pressure over a 3-day period resulted in inverse changes in the level of CO_2. A decrease in barometric pressure from 1022 mbar to 1016 mbar, correlated to a carbon dioxide increase of 300 ppm. In the same figure, an increase in barometric pressure of 5 mbar correlated with a decrease in CO_2 levels by 200 ppm. Airflow data taken at the time confirms that when large changes in pressure occur, air flows either into or out of the cave, and likely provides the mechanism for moving the CO_2. Typical values seen in this plot were around 2000 ppm, which is not greatly above that found in most buildings. Although data for summer months does not yet exist, a CO_2 concentration of 11,000 ppm was measured during a logging session in mid-December (Fig. 5), indicating that CO_2 levels can be much higher. At this level, which is two times the OSHA eight-hour time-weighted-average exposure limit, significant physiological effects begin to occur such as difficulty catching one's breath even while resting (OSHA, 2006).

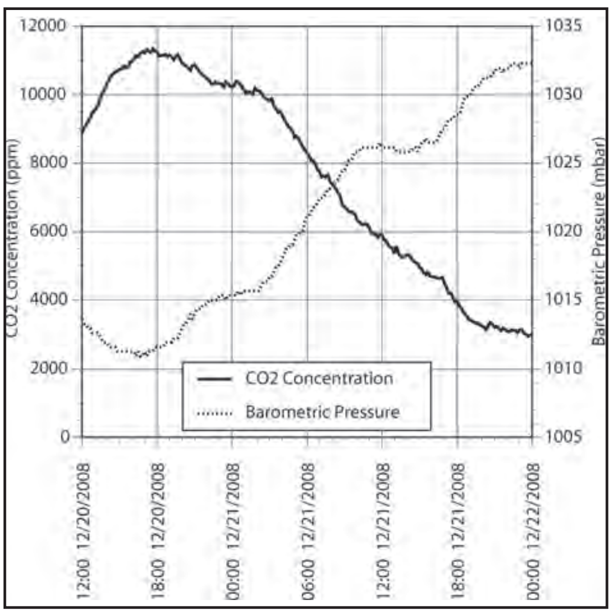

Figure 5: Pressure and CO2 concentration from the Pasco data logger showing that a strong high-pressure cold front can have an immediate and major effect on the CO2 levels.

Figure 4 also shows a daily cycle in CO_2 levels, linked to the daily airflow cycles, where the concentration is lowest at mid-morning. Increasing pressure and inflowing outside air corresponds to decreases in CO_2 concentrations, apparently forcing the CO_2 to the lower levels of the cave, while outflowing air draws carbon dioxide upward into the main portion of the cave. If the CO_2 was being simply being flushed out of the cave instead of forced deeper, we would expect to see to CO_2 concentration fall during outflow cycles. Additionally, if the source of the CO_2 was from decaying organics on the surface, instead of a deep source, we would expect the concentration to increase during inflow cycles. BANNER (ET AL, 2007) attributes low winter CO_2 levels to a temperature-density driven mechanism, but has based this claim on sparse data taken bimonthly through out the year. In contrast at Robber Baron, barometric pressure changes are seen to be the driving force in controlling CO_2 levels. Although there are seasonal average variations in concentration, significant daily fluctuations also occur that can mask the seasonal effects if only single point in time is considered.

On December 21, 2008, a large high-pressure front moved over Robber Baron producing about 10 hours of linearly rising barometric pressure (seen in Figure 5) with an average airflow velocity of about 0.5 m/s. From this data, a computation of cave volume beyond the sensor location was performed. The passage in which the measurement was taken is about 0.4 m x 0.9 m in cross section, giving a volume flow rate of 0.2 m^3/s. During the 10-hour period, the change in pressure was 16 mbar (1600 Pa). Solving equation [1] for the volume, we get a value of $4.5x10^5$ m^3. A rough estimate of the cave's known volume is 6000 m^3, so the unknown part of the cave is a minimum of 75 times the size of the known cave. Note that this is a lower limit value. More complex geometries add additional terms to equation [1], which act to reduce the flow rate for a given volume. Thus, for a certain flow rate, the volume would be larger.

5. Conclusions

This study has demonstrated a novel low-cost, compact data logger for airflow measurement in caves, which was used in Robber Baron Cave to correlate airflow with barometric pressure changes. The logger provided data showing hourly changes and daily cycles of cave airflow as well as seasonal variations. A Pasco data logger was acquired and used to confirm the measurements, and furthermore, the iButton airflow logger was found to be able to detect much lower airflow velocities than the Pasco. Additional data collected on barometric pressure, carbon dioxide, and temperature confirmed anecdotal information about changes in the cave's meteorology, and allowed the authors to determine that cyclic changes in airflow correlated with daily pressure cycles. Carbon dioxide was confirmed to be the cause of the "bad air" experienced by visitors to the cave and the daily airflow cycle explains the reported differences in air quality, as the visits may have occurred at different times of the day. Daily inflow and outflow patterns suggest that CO_2 likely originates from a deeper portion of the cave, and that concentrations are regulated by barometric pressure changes.

The apparent decrease in "bad air" in the winter is likely due to the frequent passage of high-pressure systems, which push significant volumes of fresh outside air into the cave and then maintain the higher-pressure level for some time thereafter. In the summer, the pressure changes are much smaller and cyclic, so the CO_2 is cycled in and out of the lower levels diurnally.

Using the airflow recorded in the passage to the lower level and Equation [1], the potential volume of the cave was computed. The results indicate that a significant volume of the cave may be yet undiscovered, as least 75 times the volume of the mapped portion. While this number seems to be fantastic, stories discussing the passages that had been blasted shut may account for a portion of this undiscovered volume.

Although much research still needs to be performed to understand the full dynamics of the atmospheric conditions of Robber Baron Cave, the documentation of daily cycles is a significant finding. The measurements from this study have provided a better understanding of the cave's meteorology, the sources and occurrences of "bad air", and the potential extent of the cave.

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MONITORING DRIPWATER CHEMISTRY IN EL REFUGIO CAVE (SOUTHERN SPAIN) AS A CONTRIBUTION TO UNDERSTANDING INFILTRATION AND SPELEOGENETIC PROCESSES IN KARST AQUIFERS

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Caves provide exceptional, strategic sites for the investigation and monitoring of hydrokarstic processes. Environmental conditions and the hydrochemistry of dripwater within a cave can provide information about infiltration and flow path patterns through the unsaturated zone, speleothem precipitation processes and speleogenesis. Since 2003, studies have been carried out in the cave known as El Refugio, located in Sierra Mijas, to the west of the city of Málaga (southern Spain). The cave is developed within highly fissured Triassic dolomitic marbles, with a low degree of karstification. The cave is situated in the unsaturated zone of the Sierra Mijas aquifer, overlain by five metres of marble and a thin layer of soil. Two environmental parameters were monitored in the cave: CO_2 and air temperature. The CO_2 content is higher and the air temperature lower in summer, while in winter, CO_2 levels decrease and the air temperature rises. Several hydrochemical components - Cl^-, NO_3^-, Ca^{2+}, Mg^{2+}, alkalinity and total organic carbon (TOC) – were monitored at five dripwater points inside the cave. The data recorded show there are two dripwater groups with different chemical compositions. The first group consists of three dripwater points and is mainly characterized by a high Mg content, linked to relatively slow flows. The second group consists of two points and displays a lower Mg content. The temporal evolution of the hydrochemical parameters and TOC at each dripwater point shows there is a seasonal variation during the hydrological year. In the autumn, electrical conductivity decreases with alkalinity, Ca^{2+} and Mg^{+2}, while the Mg^{+2}/Ca^{2+} ratio increases. This hydrochemical evolution during the period of low CO_2 content inside the cave promotes the precipitation and growth of calcite speleothems in this period. During the rest of the year, electrical conductivity, alkalinity, Ca^{2+} and Mg^{+2} present higher values. NO_3^- and TOC concentrations increase only by recharge following the first rainfall after the summer, which indicates that rapid infiltration reaches the cave prior to the slow infiltration that drips into the cave during the rest of the year.

1. Introduction

Karstic caves are sites of exceptional scientific interest, being the only route for exploration within aquifers, mainly in the unsaturated zone. This fact has led to such caves becoming strategic points for controlling and monitoring different environmental and hydrokarstic processes, which provide invaluable information on the functioning of karstic aquifers.

The concentration of CO_2 within karstic caves influences the development of various speleogenetic processes and particularly the precipitation and dissolution of carbonates (White, 1988, 1997; Dreybrodt, 1988; Dreybrodt et al., 1997). The temporal study of CO_2 concentration and air temperature provides information on the cave, its atmosphere and the environment for the formation of speleothems (Spötl et al., 2005). This information is complemented by hydrochemical data on the dripwater, thus enabling us to characterize infiltration processes and the precipitation of calcium carbonate in the form of speleothems, which are formed in the unsaturated zone of karstic aquifers.

Previous studies have shown that the hydrochemical monitoring of dripwater from speleothems within a cave can reveal the types of infiltration within the unsaturated zone of karstic aquifers (Bakalowicz, 1995; Perrin et al., 2003b; Fairchild et al., 2006; Tooh and Fairchild, 2003). One of these types corresponds to the rapid circulation of water through karstic conducts to the saturated zone, with a relatively high flow volume. Another type is that of water flowing more slowly through the bedrock and through rock fractures, with lower flow volumes. Finally there is seepage flow through matrix or minor fractures. On the basis of this information, it is possible to characterize the passage of water towards the aquifer, its involvement in karstification processes and the types of water flows produced towards the saturated zone (Mudry et al., 2008). Various authors

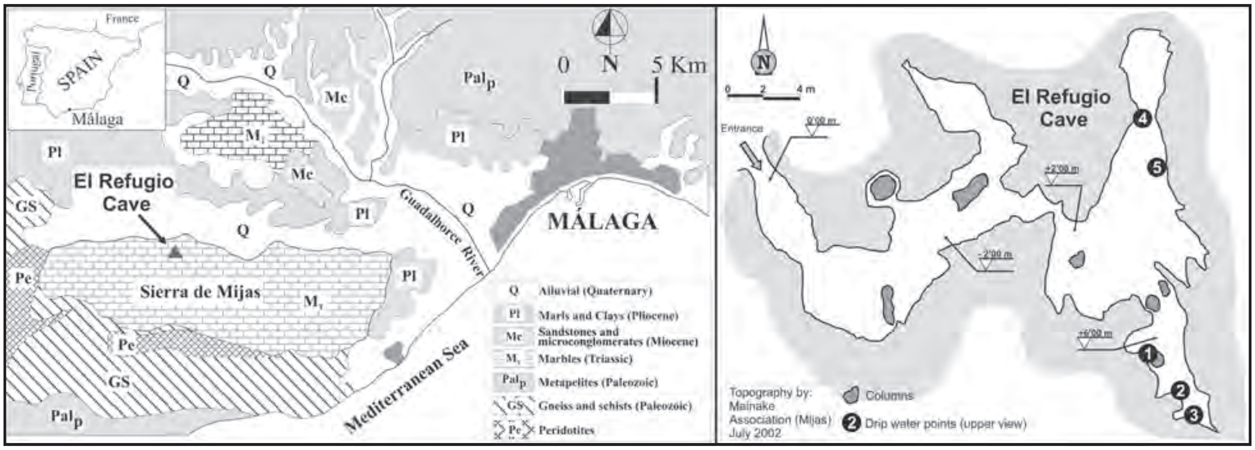

Figure 1: Location and geological setting of El Refugio cave (left). Cave framework and dripwater points sampled (right).

consider that the hydrogeological functioning of dripwater points from speleothems within caves depends on the total volume of water infiltrated into the aquifer (Baker et al., 1997, Liñan et al., 1999). Genty and Deflandre (1998) showed that changes in atmospheric pressure also affect the flow rate from a dripwater point.

The aim of the present study is to characterize processes of infiltration and speleogenesis by means of investigations carried out at a cave in southern Spain.

2. Characteristics of the Study Zone

The cave called El Refugio lies in the province of Málaga, in southern Spain (Fig. 1, left). Its entrance is at an altitude of 690 m a.s.l., in the Sierra Mijas range. The climate in the area is Mediterranean-type: mild, with an annual mean precipitation of 600 mm and an average temperature of 18°C. The cave is situated within Triassic dolomitic marbles. The geological structure of this range is characterized by the existence of isoclinal folds lying ESE-WNW, which in a subsequent tectonic stage were affected by fracturing. In the vicinity of the cave, dolomitic marbles are only slightly karstified, but intensely fractured, mainly in the directions N045°E and N135°E, which has favoured the development of the cave.

The cavity is a small one, formed at a depth of 5 metres beneath the land surface and measuring 100 m in length. It is basically divided into two main chambers, one near the entrance and the other more distant, separated by a narrow passage (Fig. 1, right). It has a high degree of speleogenetic development, with abundant stalactites and stalagmites.

3. Methodology

Although various methodologies may be applied to study the unsaturated zone of a karstic aquifer, research within cavities is not possible without applying hydrogeological techniques to characterize the fractured medium and the environmental conditions under which speleothems are formed. Hydrodynamics provides an approximate idea of the volumes of water circulating and which may drain towards the cave. Moreover, hydrochemistry helps us understand the infiltration processes that take place within the unsaturated zone, through a hydrogeological interpretation of the chemical characteristics of the water in speleothems. This is the aim of the present study.

For a sampling period of almost five years, we monitored the principal hydrochemical parameters of the dripwater at five points (Fig. 1, right) and environmental parameters (CO_2, air temperature and relative air humidity) relevant to studies of caves.

Since 2005, a continuous record was kept of the partial pressure of CO_2 and of the air temperature within the cave, as well as point measurements outside it. Samples were taken and point measures obtained within the cave approximately twice monthly, although less frequently during rainy periods. CO_2 and air temperature within the cave were measured using two continuous-record sensors (Vaisala, models MI70 and HM70, respectively), with an inter-measurement interval of three hours.

At the same time, measures were obtained, in situ, of electrical conductivity, temperature and pH, and we recorded the principal chemical components dissolved in the water. Of these, we selected for particular study the contents of the following ions: Ca^{2+}, Mg^{2+}, Cl^- and NO_3^-, as well as total alkalinity (TAK). Table 1 summarises the mean values of these parameters at one of the sampling points. Both the chemical analyses of the major components, performed by ion chromatography, and the TOC analyses (performed using a carbon analyzer) were carried out at

Table. 1. Mean values of the dripwater chemical data

Dripwater point (ref.)	Number of samples	E.C. µS/cm	T ºC	TAK mg/L	Ca^{2+} mg/L	Mg^{2+} mg/L	NO_3^- mg/L	Cl^- mg/L	TOC mg/L
1	35	495	16.8	312.5	83.1	17	0.9	10.1	0.50
2	7	487	15.9	312.7	70.9	16.4	0.4	8.2	0.64
3	20	470	16.8	314.7	92.4	16	0.3	9.8	0.57
4	20	436	16.6	298.5	84.4	10.5	0.4	16.6	0.55
5	7	396	16.0	246.7	74.3	9.5	0.2	11.4	0.62

the Hydrogeology Centre laboratory at the University of Málaga.

Analysis of the hydrochemical data provides an approximate hydrogeological interpretation of the functioning of the unsaturated zone of the cave. There are different numbers of samples from different dripwater points because all except point 1 dry up during part of the year. Therefore, we decided to represent the temporal evolution of the hydrochemical parameters of the dripwater from stalactite 1 (Fig. 2), which presents a longer-lasting drip. From this analysis, we may determine, approximately, the response time of the system, from the moment at which the input signal (rainfall) enters the cave until it drains out as dripwater, the output signal. The variations in the concentration of the different chemical components, for a single recharge event, provide an initial approximation of the flow types and processes taking place over the cave. The binary dispersion diagrams (e.g. the ratio of TOC vs. Mg^{2+}) made for all the samples enabled us to characterize the various dripwaters. The representation of the TOC content, which is indicative of rapid flows from the land surface, with respect to the concentration of Mg^{2+}, representative of the residence time of the water within the aquifer (water-rock interaction) (Batiot et al., 2003a), informs us of the different types of flow that characterize each of the different dripwaters. A statistical analysis of the principal components (PCA) completed the hydrochemical study. This method allowed us to take into account, simultaneously, the variations in all the chemical variables considered and their

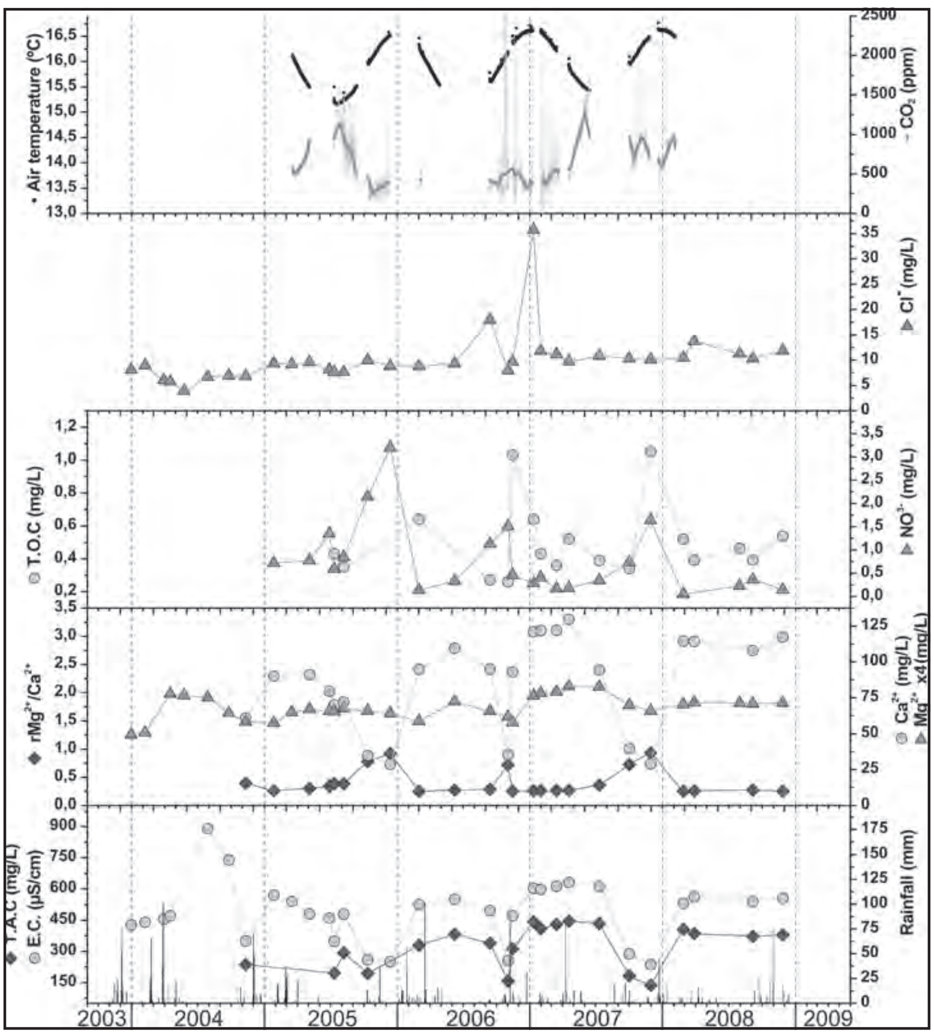

Figure 2: Time series of hydrochemical and environmental parameters sampled at dripwater point 1.

relations of interdependence.

4. Results

Figure 2 shows the temporal evolution of the most significant hydrochemical parameters of the dripwater at point 1, together with the rainfall recorded in the zone and the variations in temperature and CO_2 concentration in the cave atmosphere. The electrical conductivity, the content of the Ca^{2+} ion and the total alkalinity of the water at this drip point evolve almost in parallel, such that the minimum values are recorded in early autumn, coinciding with the first rains of the hydrologic year. The content of the Mg^{2+} ion evolved similarly, albeit with less marked variations. As with the three previous parameters, the Mg^{+2} ion presented minimum values during the autumn-winter and slightly higher ones in spring-summer. As a result of this differing pattern of the Ca^{+2} and Mg^{+2} cations, there were slight increases in the Mg^{2+}/Ca^{2+} ratio during the autumn months of 2005, 2006 and 2007. The sharp increase in the Mg^{2+}/Ca^{2+} ratio observed in the summer of 2008 (3.01) was caused by an exceptionally dry period, in which, after seven months without significant rainfall, dripwater point 1 became exhausted.

The concentrations of the NO_3^- ion and of TOC evolved in a similar way over time. They presented seasonal variations that were different from those of the Ca^{2+} species and of total alkalinity, being almost the inverse of the latter, with higher contents during the final months of the year and the early months of the new year. The maximum concentrations were recorded during periods of intense rainfall, mainly the first rains of the autumn. The content of the Cl^- ion increased gradually, from values of 8 mg/L at the outset of the sampling programme in early 2004, to 12 mg/L by the end of 2008. This trend only varied during periods of rainfall, when fresh recharge of water to the system was made.

Regarding the control of environmental parameters, the atmosphere in the cave was saturated with water vapour during most of the measurement period. The CO_2 content varied from less than 500 ppm during the autumn-winter to 1500 ppm during the summer months. The air temperature within the cave ranged between 15ºC and 17ºC, approximately, throughout the year. The seasonal increases and decreases in the internal temperature of the cave presented a lag of approximately six months with respect to the outside temperature; within the cave, maximum air temperatures were recorded at the beginning of winter (while outside, this took place in July). In the same way, and as shown in Fig. 2, the maximum concentrations of CO_2 in the air inside the cave coincided with the minimum temperatures there, and vice versa, when temperatures were highest, the concentration of atmospheric CO_2 was lowest.

The process of supersaturation in calcite is shown in Figure 3. The cluster of points reveals a prior calcite precipitation trend at the dripwater points. The dripwater points that present a Mg^{2+}/Ca^{2+} ratio of around 0.25 are characterized as producing dripwater that is in a state of equilibrium or slightly saturated in calcite. However, the six dripwater points with higher such values (0.6 to 1), which correspond to drips 1 and 2, have a low content of the Ca^{2+} ion and a high concentration of Mg^{2+} with respect to the former. These results correspond to part of the samples taken during from October to December.

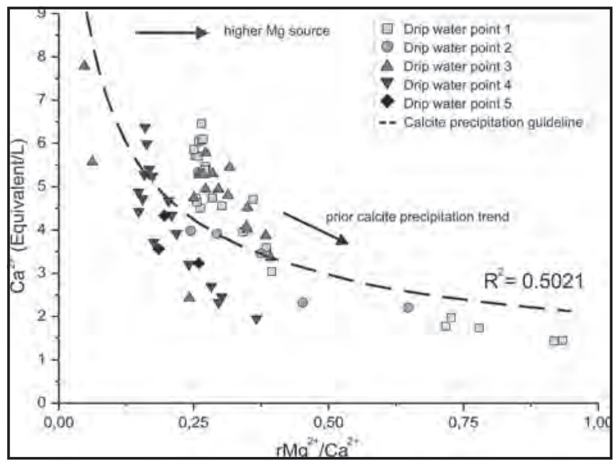

Figure 3: Plot Ca2+ versus rMg2+/Ca2+ showing hydrochemical variations of dripwaters and calcite precipitation paths.

The bidimensional ratios Alkalinity vs. Mg^{2+} and TOC vs. Mg^{2+} (Fig. 4) allow us to distinguish two groups of dripwaters that are clearly differentiated. Figure 4A shows one group comprised of dripwater points 4 and 5, with a lower concentration of Mg^{2+} (between 7.5 and 13.5 mg/L) and a level of alkalinity ranging from 100-400 mg/L. A second group is then observed, at dripwater points 1, 2 and 3, characterized by higher levels of Mg^{2+} (13.5-21 mg/L) and maximum alkalinity values close to 450 mg/L. The value for TOC concentration (Fig. 4B) are similar in the two groups, and increase to a similar degree during periods of recharge.

A multivariate statistical analysis was carried out of the principal components (PCA) for the whole set of variables (Fig. 5A) and for individual cases (Fig. 5B). The three most important factors account for almost 79% of the variance, although only two factors – accounting for 66% of the total

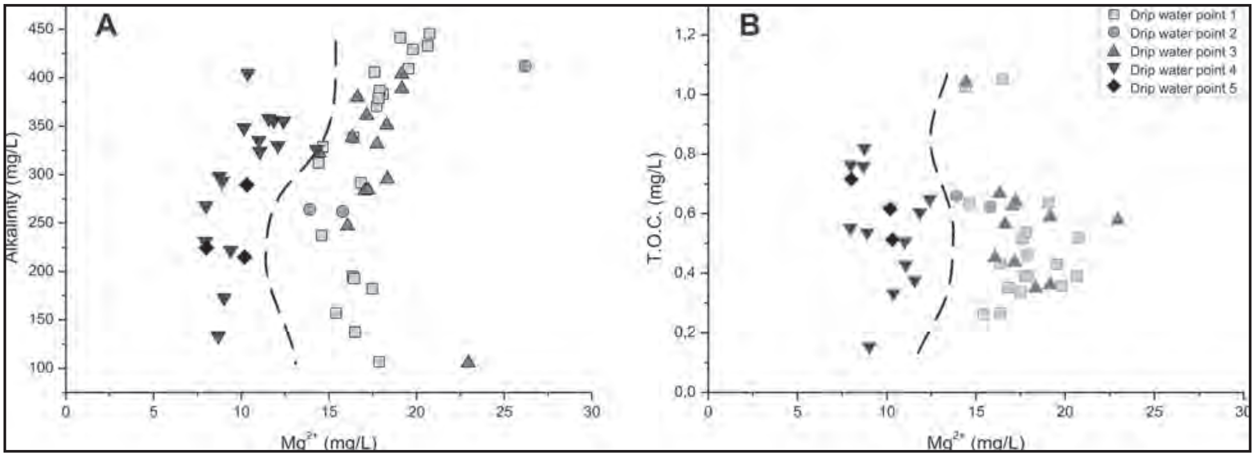

Figure 4: HCO3- vs. Mg2+ (A) and T.O.C vs. Mg2+ (B) ionic relationships.

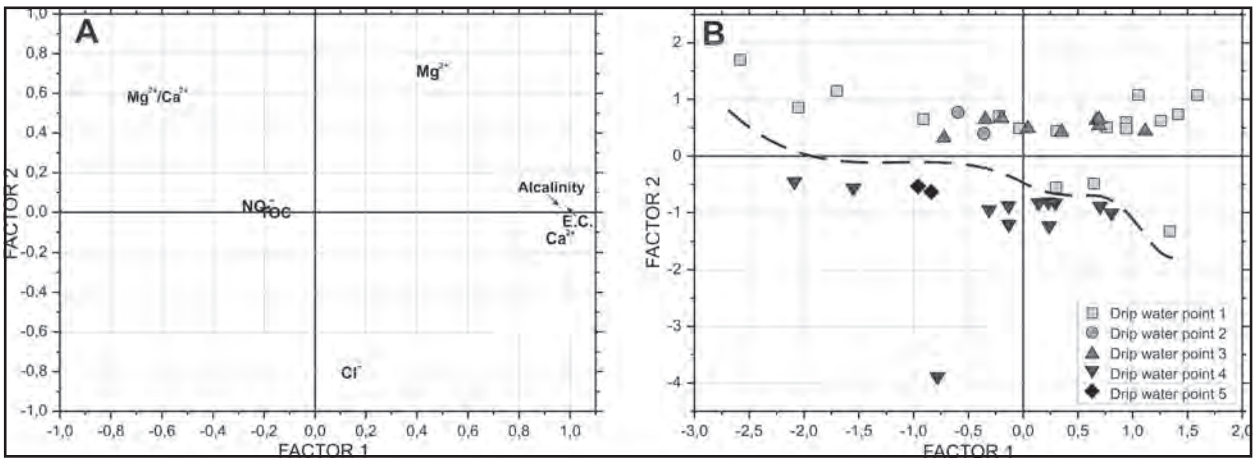

Figure 5: Principal components analysis (PCA) of all dripwater data collected in El Refugio cave: (A) PCA considering variable spaces and (B) PCA for sample spaces.

information supplied by the variables – were utilized in their explanation. In Fig. 5A, factor 1 reveals the existence of two groups of variables. Electrical conductivity, Ca^{2+} and alkalinity are located on the positive part of the axis, while TOC and NO_3- are grouped on the negative part of factor 1, although with less statistical weight. The Cl^- variable is accounted for exclusively by the negative part of factor 2. Mg^{2+} and the Mg^{2+}/Ca^{2+} ratio are located on the positive part of axis 2, although the former lies on the positive part of axis 1, while the latter is on the negative part of the same axis.

The PCA for the individual cases (Fig. 5B) shows there is a differentiation in the cluster of points for the two groups of waters. This distinction is produced by the factor 2 values presented by the samples and, to a lesser extent, by the positive or negative value of factor 1. Thus, the samples from dripwater points 4 and 5 are located on the negative part of factor 2, while those from dripwater points 1, 2 and 3 are mostly found on the positive part of this axis, with the exception of only three samples.

5. Discussion and Conclusions

Speleothem production and infiltration processes are influenced by the hydrochemistry of the dripwater and by the environmental conditions of the El Refugio cave. Important dilutions of electrical conductivity are caused by the significant fall in the concentration of the Ca^{2+} ion and in alkalinity. The Mg^{2+}/Ca^{2+} ratio reflects the dilution taking place in the water stored for dripwater point 1, where the flow rate is constant in time. This favours the precipitation of $CaCO_3$ that takes place over the cave, as the atmosphere with a low concentration of CO_2 during this period produces the degasification of the dripwater, and thus a supersaturation in calcite. When this occurs – mainly from October to December – speleothems are formed. The 6-month lag between internal and external temperatures is caused by a degree of disconnection between the cave entrance and the chambers where the sensors and the dripwater points are located.

The dissolution kinetics of the Mg^{2+} are slow, which reveals the slow circulation of recharge water through the non-saturated zone. The water stored is enriched in Mg^{2+}, the product of the interaction with the dolomitic marbles that constitute the cave structure. Only under conditions of significant recharge do these concentrations decrease. TOC and NO_3^- and, to a lesser degree, Cl^-, characterize the rapid circulation of water, as variations in these parameters, in response to rainfall events, take place quite rapidly. These increases present maximum values in early autumn, after the first rains of the hydrologic year.

The hydrochemical variations in the dripwaters from the five points selected enabled us to distinguish two groups of waters: one consisted of points 1, 2 and 3, where Ca^{2+} and alkalinity was high, and where under exceptional conditions significant $CaCO_3$ was precipitated (this happened in the autumn of 2005, 2006 and 2007), and where the Mg^{2+} content was around 15-20 mg/L. The second group, constituted of points 4 and 5, presented lower concentrations of Mg^{2+} and lower alkalinity. In general, two patterns of water infiltration into the cave can be distinguished. The maximum TOC values presented by various samples belonging, especially, to the dripwater points of group 1 confirmed the existence of a relatively speedy water flow through the non-saturated zone, although the predominant infiltration pattern corresponded to slow flows, caused by the concentrations of $Mg^{2+}$and Ca^{2+} , and by the levels of alkalinity.

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A MAJOR UNMAPPED FAULT IN GANTER CAVE, AND POSSIBLE GEOMORPHOLOGICAL EFFECTS ON TURNHOLE BEND OF GREEN RIVER, MAMMOTH CAVE NATIONAL PARK

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In the Mammoth Cave area, subtle structural contours exert primary control of cave passage orientation, with little influence from vertical joint fractures or faults. As with any general rule, there are exceptions, and passages in both Ganter and Bat caves in the Turnhole Bend vicinity of Mammoth Cave National Park serve as excellent examples. None of the faults discussed in this paper have been fully mapped or previously reported on.

In the mid-nineties, an exposure of slickensides was observed in Ganter Cave. Unable to match beds on either side of the fault in passage about 8 m high, we concluded that there was significant displacement. Geologists Art and Peg Palmer lent their expertise in June 2001, and they agreed that the displacement along the fault was greater than the height of the beds exposed in the walls. By happenstance on our way out of the cave, we found a complete exposure of the fault in the walls of Dinosaur Dome, which is approximately 35 m high. Displacement was estimated to be greater than 9 m. In August 2007, the displacement was measured with helium balloons at 13 m. However, uncertainties about the precision of this measurement due to the angle of view led to a reevaluation in January 2009 with a laser rangefinder and clinometer. By this technique, the fault has a displacement of 11.5 m. Previous to this find, the largest known fault in the park had a displacement of about 6 m, so the Ganter Cave fault is significant in our region.

If the trend of a major passage controlling fracture in Ganter Cave is projected to the southwest at 15°, then it crosses the peninsula, including two aligned sinkholes on Turnhole Bend, and then Turnhole Spring on the south shore. We have been unable to determine whether this fracture exhibits displacement. With over 60 m of exposed limestone, the narrow isthmus of Turnhole Bend appears to have been a perfect opportunity for development of a subterranean meander loop cutoff cave such as those in Mansfield Bend on Green River. However, none have been found. This may be due to multiple high angle mineral filled fractures that impeded flow down dip along bedding planes, which would otherwise be expected. In addition to possibly preventing a meander loop cutoff, the location of Turnhole Spring may also have been influenced by the Ganter Cave fracture.

Bat Cave is located across the base of the Turnhole Bend peninsula from Ganter Cave, and has two major fault controlled passages heading toward Ganter Cave. An upper level in Ganter has been interpreted as being part of a ancient meander loop cut off, with the other part being the entrance passage in Bat Cave. However, there is an elevation difference of about 30 m, which does not support this idea.

1. Introduction

Ganter Cave is located just east of Turnhole Bend, and 3.5 kilometers have been mapped to date (Klausner 2002). Bat Cave is on the west side of the bend, and has a total survey of 1.7 kilometers (Barton 2008). Both caves and Turnhole Bend are shown in Figure 1. In the Mammoth Cave area, passage orientations are generally guided by subtle structural variations in bedrock dip and strike (Palmer 1981). Often cave passages cut across faults or fractures without any significant effect on passage morphology or direction. However, in Bat and Ganter caves, passages are highly concordant with faults and fractures. Perhaps if direction of water flow is roughly aligned with the axis of a fault or fracture, then it can influence passage orientation and shape to a greater degree.

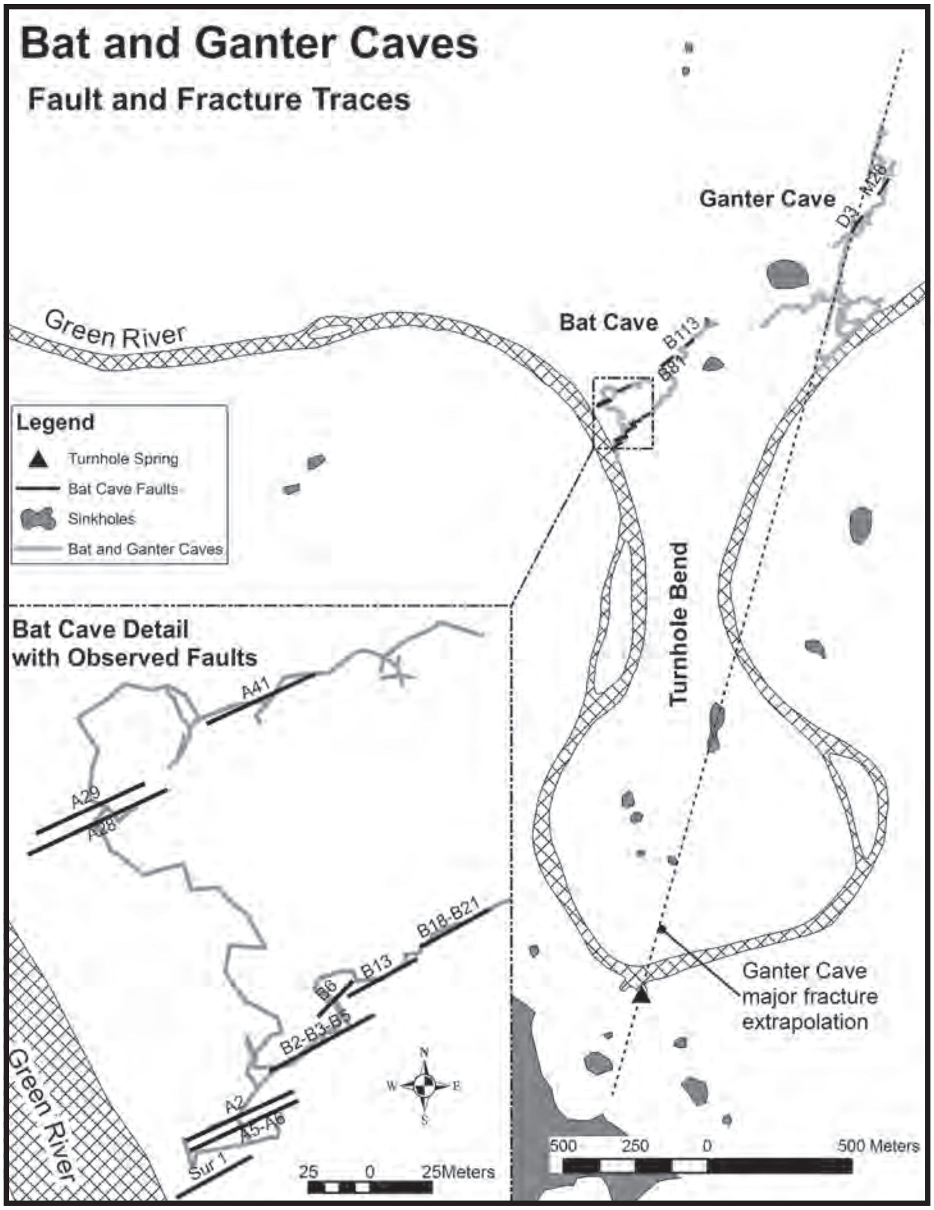

Figure 1: Map of the Turnhole Bend area showing fault and fracture traces found in Ganter and Bat caves. The dashed line crossing Turnhole Spring is an extrapolation of a major fracture in Ganter Cave, which possibly may have affected the location of the spring.

In the mid-nineties, Rick Olson went with Dr. Horton Hobbs to Ganter Cave to look for cave crayfish. They did not find any crayfish, but did notice an exposure of slickensides in the ceiling of the main passage at survey station M28. Slickensides are formed as bedrock masses slide past each other. We looked at the walls on either side of the fault to see if the amount of displacement could be determined (Fig. 2), but could not find corresponding beds on either side of the fault within the passage dimensions.

Geologists Art and Peg Palmer accompanied a group on a trip to Ganter Cave in June, 2001. We determined that the normal fault at M28 had a strike of 37 degrees and a dip of 65 degrees to the northwest. They agreed that the displacement along the fault was greater than the 8 meter (25ft) height of the beds exposed in the walls. On our way out of the cave, we stopped at Dinosaur Dome, which is a shaft about 35 meters (120ft) high, While there, we noticed a rock layer in the wall of the dome near survey station D3 that appeared to be distorted. Borrowing Colleen Olson's extremely bright Mammoth Cave Guide flashlight, it became apparent that the bedrock layers were offset along a high angle fracture. Fortunately, there was a distinctive shaly bed at our level that was truncated, and we found its continuation at least 9 meters (30ft) up the wall on the other side of the fault. The exposed feature was a normal fault with a strike of 35 degrees and a dip of 75 degrees to the northwest. Because of its location and similar orientation to the fault at M28, we concluded that it was probably the same fault. Locations of both fault exposures are shown in Figure 1.

Bat Cave also shows evidence of fault controlled passage development. In June of 1996, while conducting a resource inventory of Bat Cave, we found several fault fractures in the B survey. At stations B2, B3, and B5, the passage was aligned along a normal fault with a strike of 60 degrees, a dip of 75 degrees to the northwest, and a displacement of 15 centimeters (6 in). At B6 there was a fracture with a strike of 45 degrees, and a dip of 75 degrees to the northwest, but no visible displacement. At B13 we found a fracture with a strike of 60 degrees, and a dip of 70 degrees to the northwest, that also had no visible displacement. From B18 to B21 the passage is developed in the same or a parallel

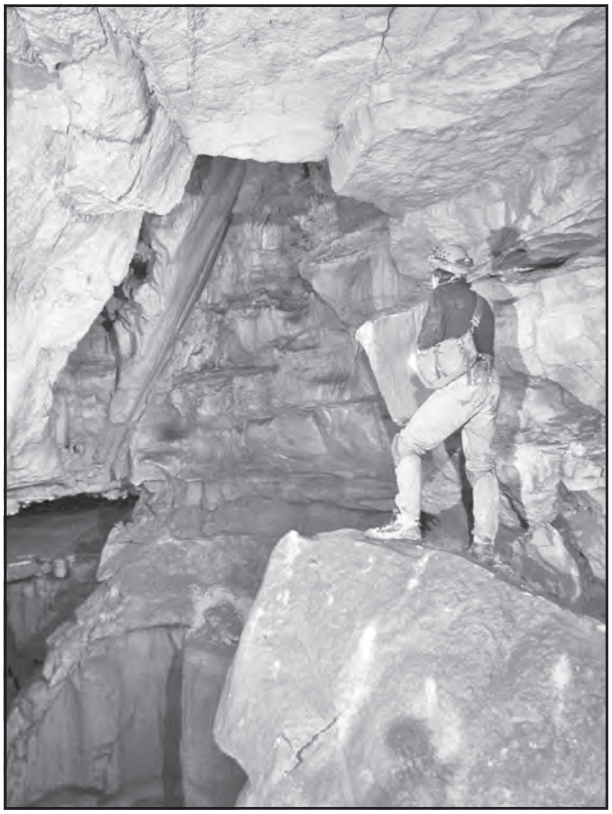

Figure 2: Rick Toomey examines a major fault and passage walls exposed at M28. The fault is visible as a diagonal slash in the upper left portion of the photo.

fracture with the same strike as before, but with a dip of 80 degrees to the northwest and no discernable displacement. Finally, for the B survey at least, at B81 and B113, Rick Toomey noted that the passage is developed in a fracture. Locations of these faults and fractures are shown in Figure 1.

During a paleontology inventory trip to Bat Cave in July of 2001, at the entrance on the left side at station A2, we noticed a normal fault with a strike of 63 degrees, a dip of 65 degrees to the northwest, and a displacement of 2.5 meters (8ft). Just southeast of the entrance was another fault exposed in the cliff face with a strike of 60 degrees, essentially no dip, and displacement of about 2 meters (7ft) down to the southeast. Inside the cave, we found a normal fault between survey stations A5 and A6 with a strike of 63 degrees, a dip of 75 degrees to the northwest, and a displacement of 2 meters (7ft) in 3 steps. At station A28 there was another with a strike of 70 degrees, a dip of 65 degrees to the northwest, and a displacement of 2 meters (7ft). Nearby, at A29 we found another normal fault a strike of 64 degrees, a dip of 50 degrees to the northwest, and a displacement of 15 centimeters (6 in). Finally, at A41 there was a normal fault with a strike of 64 degrees, a dip of 80 degrees to the northwest, and a displacement of 1.5 meters (5ft). Locations of these faults are shown in Figure 1.

2. Field Measurements

On August 7 of 2007, we returned to Ganter Cave with a crew of National Speleological Society (NSS) cavers involved in restoration work. We brought helium balloons tethered with fishing line to measure the vertical displacement along the fault (Fig. 3). With the base of the shale bed as our point of reference, Eric Buckelew allowed the balloons to rise while I watched from further up the slope to judge when they had reached the base of the shale above. At that point, Eric tied a knot in the fishing line so that the distance could be measured, and this turned out to be 13 meters (42ft). Because of our poor viewing angle, the potential for error was considered to be high. Therefore in January of 2009 Rick Toomey led a team equipped with a Leica Disto A3 laser rangefinder and Suunto inclinometer. By this much more precise method, the fault displacement was determined to be 11.5 meters (38ft).

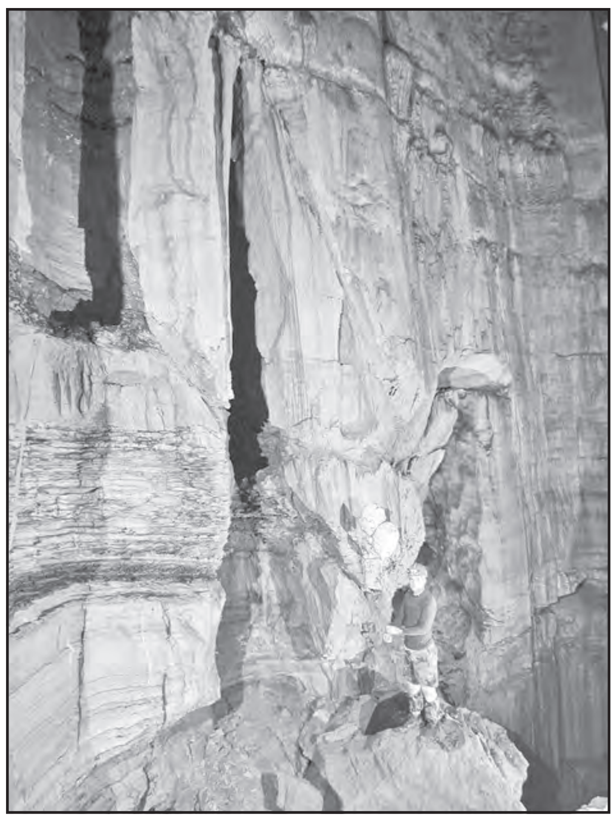

Figure 3: Eric Buckelew with helium balloons held even with the base of the shale layer, which he is facing in Dinosaur Dome near station D3.

Surveys of Bat and Ganter caves are being conducted by the Cave Research Foundation using Suunto compasses and clinometers plus fiberglass tapes for distance. Surface surveys from the entrances of Ganter and Bat Caves to the

Green River were run on January 1, 2009, using Suunto instruments and the Leica laser rangefinder. These surface surveys allowed elevations of passages in Ganter and Bat caves to be compared. A gradient value of .09 meters per kilometer was used for Green River, and with 5.1 kilometers of river between the two entrances, the elevation difference of the water surface was determined to be 0.46 meters (1.5ft).

3. Significance of the Fault and Fracture Sets

The largest fault mapped on the geologic quads for the park is the Cub Run fault, which has a displacement of about 6 meters (20ft), so for our region the Ganter Cave fault, with its 11.5 meters (38ft) displacement, is a large structural feature. Much of the main passage in Ganter Cave is aligned with a major fracture zone oriented approximately 15 degrees, and much of the B survey in Bat Cave appears also to be aligned with the faults oriented roughly at 60 degrees. Dinosaur Dome in Ganter Cave is much taller than most domes in the cave, and the extent of its development could have been enhanced by the fault or related fractures.

If the trend of the major fracture in Ganter Cave is projected to the southwest, then the line runs sub-parallel to the gooseneck of Turnhole Bend, in line with two sinks on top of the ridge, and across the Green River to Turnhole Spring (see Fig. 1). This fracture needs further study to see if faulting has occurred and whether it extends across Green River. An "unmapped fault west of Cedar Sink with a throw of more than 40 feet" was reported in a paper by Will White and others (1970). None of the author's still living recall anything about this fault, so likely this information came from Dr. E.R. Pohl, who worked for many years as the park geologist. Permission was obtained to search for the fault on private property west of Cedar Sink, but no indication of it was found. The reported fault may still be found by someone who is a better observer, or perhaps remote sensing may reveal its location. In any case, the structural contours on the geologic quad map about 900 meters (3000ft) west of Cedar Sink indicate a change of 12 meters (40ft) over a distance of about 300 meters (1000ft), which is pretty steep for this region.

4. A Meander Loop Cutoff Through Turnhole Bend?

The gooseneck of Turnhole Bend appears to be an ideal situation for the development of a subterranean meander loop cutoff. Despite careful searching on land and trolling the Green River with temperature and conductivity probes, no cutoff has been found (Tom Brucker pers. comm.). Such cutoffs form where river water can take a shortcut through soluble rock (Frank and Jennings 1979, Mylroie and Mylroie 1990, Fabel et al 1996, Palmer 2007). Even today with Lock and Dam #6 in place, there is a hydraulic gradient between the upstream and downstream halves of Turnhole Bend due to the Sand Cave Island gravel bar that creates a riffle. The contact elevation between the Big Clifty Sandstone and the Girkin Limestone on the gooseneck is at 190 meters (620ft), which leaves about 60 meters (200ft) of limestone exposed, and the dip of the rock is to the northwest, which would favor flow through to the downstream half of the meander loop. The overall entrenchment rate of Green River is approximately 30 meters (100ft) per million years (Granger et al 2001), so the river has had roughly two million years to develop a subterranean meander loop cutoff, which is plenty of time. Regarding Turnhole Bend, George (1989) said: "It is a classic example of an intrenched meander: its name being derived from a karst vortex (whirlpool) situated upstream and east of the meander bend in Green River (Wilson, 1967)." However, Wilson says "Almost midway between the eastern and western ends of the park is Turnhole Bend, where Green River forms a great loop. Turnhole, locally, means a whirlpool and names the one that formerly was so obvious in Green River, down at the tip of the bend. At this place an underground river enters the larger stream." So these two versions are at odds. According to local historian Norman Warnell, Wilson's account of the name origin is correct (Warnell, pers. comm.).

So, in spite of an apparently appropriate configuration, and the fact that a subterranean meander loop cutoff has been postulated for the area, there is no solid evidence for the development of such a feature. George (1989) interpreted the Moondust Passage in Ganter Cave as being part of a paleo meander loop cut off, with the other part being the entrance passage in Bat Cave. However, there is an elevation

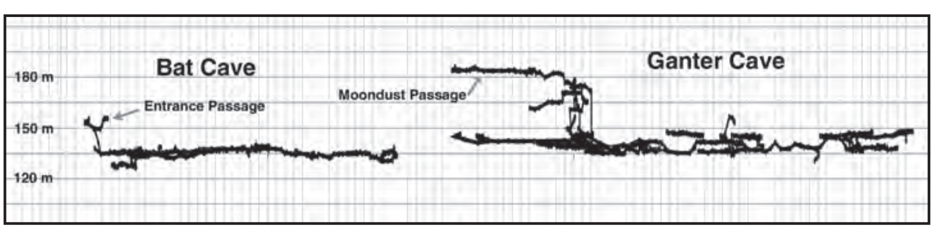

Figure 4: Cross section through Turnhole Bend showing Bat and Ganter caves in profile view. Note that the entrance passage of Bat cave is at about 150 meters (500ft) elevation, and that the Moondust Passage is at about 180 meters (600ft), which is an elevation difference of 30 meters (100ft). Cartography by Cave Research Foundation.

difference of about 30 meters (100 feet), which does not support this hypothesis (Fig. 4).

One possible reason that a major subterranean meander loop cutoff failed to develop might be the presence of vertical fractures filled with a dense crystalline mineral. Peg Palmer analyzed samples from M9 and M10 in Ganter Cave, and determined that the fracture fill at that location consisted of saddle dolomite, calcite, and slivers of bedrock (Palmer, pers. comm.). Such filled fractures are easily seen in Ganter Cave (Fig. 5), associated with the faulting. These vertical filled fractures may act like dams blocking flow along bedding planes, as would typically occur, and this could have inhibited the development of a subterranean meander loop cutoff. Otherwise, the conditions for a cutoff at Turnhole Bend appear to be ideal in that the isthmus of the loop is narrow, and the bedrock dip is toward the downstream side. A similar situation exists at Mansfield Bend upstream of the park on Green River where both an active and ancient meander loop cutoff have been documented (Hess 1970).

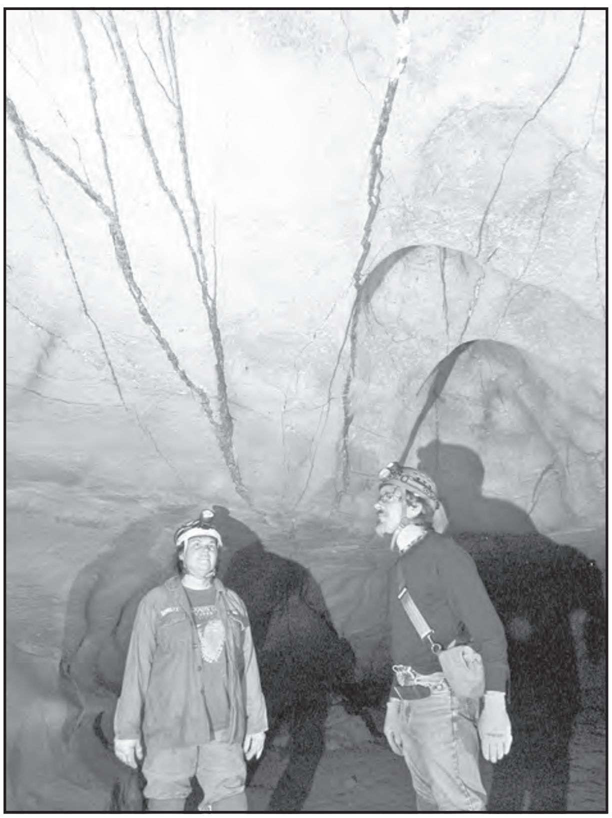

Figure 5: Geologists Julie Angel and Rick Toomey examine mineral filled fractures in Ganter Cave.

The B survey in Bat Cave appears to be well situated to function as part of a subterranean meander loop cutoff because it heads generally toward Ganter Cave across the base of the gooseneck of Turnhole Bend, and has a canyon that reaches to base level. However, if there were any significant flow of Green River water through, then we would expect to see some fog in Bat Cave during summer months like we do in River Styx in Mammoth Cave during back flooding events. However, fog has never been observed and temperature/conductivity probe surveys in Green River detected no indication of a cutoff. As exploration continues in both Ganter and Bat caves, perhaps more light will be shed on this question.

5. Conclusions

The development of Bat and Ganter Caves was greatly influenced, potentially controlled, by significant faulting and fracturing in the Turnhole Bend area. This pattern is unusual in the Mammoth Cave area, where subtler structure, such as small variations in strikes and dips in the generally flat-lying limestones, generally controls cave development. The influence we have indicated in this paper is only the currently verified influence. For example, the fault and fracture sets in Bat Cave with a strike of approximately 60 degrees may have extended over into Ganter Cave, and influenced passage development there. The western end of the Moondust Passage appears to be a candidate for such influence, and this needs to be investigated.

Although the long narrow Turnhole Bend peninsula would seem to be an ideal candidate for the development of a subterranean meander loop cutoff, evidence indicates that one did not form in this location. High-angle faults and fractures, in at least some cases filled with dolomite and calcite, may have prevented the development of such a cutoff.

The Turnhole Bend area in Mammoth Cave National Park has very complicated geologic structure. Several differents sets of faults and fractures are evident with at least two dominant orientations. The fault found at M28 and D3 in Ganter Cave has by far the greatest displacement of any fault that has been identified in the park.

This complex structure has probably led to the development of additional geohydrological novelties yet to be discovered. For example, Hess (1974) reported a cryptic spring in Green River on the west side of the bend. This spring needs to be further studied, because it may lie along the trace of some of the faults identified in Bat and Ganter Caves.

Acknowledgements

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JEWEL CAVE AND WIND CAVE VS. ONE BLACK HILLS CAVE SYSTEM

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Jewel and Wind Caves are two big cave systems in South Dakota, USA. Compared to smaller caves with air flow due to thermal effects, Wind and Jewel Caves are so-called barometric caves. The air flow of caves of this type results from atmospheric air pressure changes. Each cave system shows a characteristic air flow pattern that depends on the size of the cave and the cave structure in addition to the weather situation. The more similar the air flow pattern of two caves is, the higher is the possibility that these belong to the same system.

Since the discovery of Wind and Jewel Caves, the extent of the cave system has remained unknown. There are weekly survey-trips by the national park, cave clubs and interested people, to discover, measure and map the caves' extent. Climatological measurements and volume analysis based on the theory of Conn have shown that at present only 10 to 20% of the total volume of the caves is known.

The entrances of Jewel and Wind Cave are roughly 50 km apart, yet the question remains as to whether these are two separate cave systems or form a single cave system. The most recent examinations are showing that close-by smaller (a few kilometers long) cave systems (Jasper Cave, S & G Cave, Coyote Cave, and Reeds Cave) have the typical features of barometric caves, too. Those caves are far too small to show typical feature of a barometric cave system, which leads to the speculation that the several smaller caves are attached to the two big caves, which maybe form one massive cave system.

The full size of both caves is one of the main aspects of a research project from the working group cave- and subway-climatology at the Ruhr-University of Bochum (Germany) in 2001. The measurements initially concentrated on both big caves systems, Jewel and Wind Caves, but the smaller neighboring caves have now been added to the project measurements. The presentation shows various examples and results of this research and will present climatological evidence that strongly suggests that both caves are much bigger than hitherto explored by survey trips and that most of the smaller neighboring caves and blowholes belong to one of the two systems

1. Introduction and Aims

Jewel and Wind Cave are two big cave systems in South Dakota, USA. Compared to most of the caves where air flow is caused by temperature differences between the outside atmosphere and the air inside the cave, Wind and Jewel Cave are so-called barometric caves. The air flow of caves of this type is a result of atmospheric air pressure changes.

Since the discovery of Wind and Jewel Cave the extent of the cave system has remained unknown. There are weekly survey-trips by the national park, cave clubs and interested people, to discover measure and map the cave's extent. Climatological measurements and volume analysis based on the theory of Conn (1966) have shown that at present only 10 to 20% of the total volume of the caves is known.

The entrances of Jewel and Cave are roughly 50 km apart from each other, yet the question remains as to whether these are two separate cave systems or whether they form a single cave system. The most recent examinations are showing that close by smaller (a few kilometres long) cave systems (Jasper Cave, S & G Cave, Coyote Cave & Reeds Cave) have the typical features of barometric caves (Fig. 1). Those caves (known parts) are far too small to show typical feature of a barometric cave system, which leads to the speculation that the several smaller caves are attached to the two big caves which maybe forms one massive cave system.

The question of the basic air flow mechanisms in barometric caves and the full size of both caves are the main aspects of a research project from the working group cave- and subway-climatology at the Ruhr-University of Bochum (Germany) (PFLITSCH et al., 2007-1 & PFLITSCH et al., 2007-2).

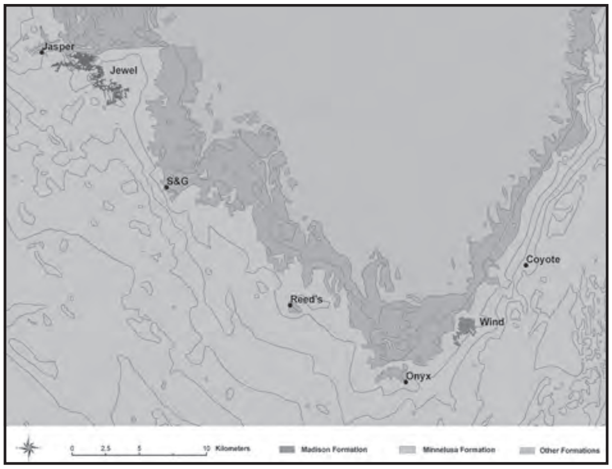

Figure 1: Overview of the location of Jewel Cave and Wind Cave, compared to different smaller caves showing the characteristic air flow pattern within the southern Black Hills, SD, USA (devel-oped by NPS of Jewel and Wind Cave).

2. Genesis of Air Flow in Barometric Caves

There are hardly any thermal mechanisms within barometric caves that lead to different air pressures or pressure balance. However, there are air currents within the cave that are the result of air pressure differences between the cave weather and the outside atmosphere (Fig. 2).

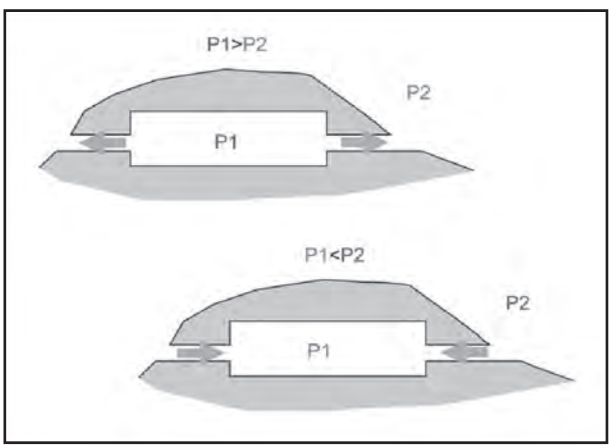

Figure 2: Schematic overview of the functioning of barometric caves (air pressure: inside the cave=p1, outside=p2).

Air pressure variations in the outer atmosphere usually enter the cave system quite quickly through its openings. Air pressure increase leads to a rising pressure inside the cave, falling air pressure outside to a decrease of pressure within the cave. Short-term air pressure differences between the outer atmosphere and cave and air pressure exchange are not or hardly measurable in most cave systems. This holds especially true for small and middle-sized cave systems which either have a high number of openings or caves with a few small openings where quick air exchange is not possible. Even big cave systems with big openings show a quick air pressure exchange, but the air flow is not measurable.

This is different for cave systems with an entrance that has a small cross section, compared to the size and volume of the cave behind the entrance. The air exchange is prevented and a quick air pressure exchange is not possible. This can be explained as follows:

Starting with an even air pressure between cave and outer atmosphere, there is no equilibrating air flow. If a high pressure system exists, the air pressure is rising outside the cave and an air pressure difference between cave and outer atmosphere arises. If the relation between the cave entrance and the cave volume is not favourable, a direct exchange of air pressure will be impossible and, as a result of this, a relative over-pressure occurs outside the cave. This pressure difference – with a relative under-pressure within the cave – leads to equilibrating air flow into the cave. This remains as long as an equilibrium situation is reached. If air pressure is still rising, the pressure difference rises too and the air flow increases as a consequence. If the air pressure outside the cave is falling again, the pressure difference between both systems decreases and the air flow speed decreases. In case these relations are even, air exchange stops. If the air pressure keeps falling, a higher pressure within the cave compared to that outside will result in the airflow being reversed from the cave to the outer atmosphere. This process operates as long as either enough air has flown out of the cave (i.e. an equilibrium situation has been reached) or until the air pressure outside raises again.

Passing and stationary pressure systems are macro-scale features with meso-scale variations and not micro-climatic phenomena. Therefore they influence a whole region and the whole cave system. The compensating air flow takes place at all cave openings at the same time. Rising air pressure outside means air flow into the cave, falling air pressure outside means air flow out of the cave. It is of no importance how many openings a cave has. The important factor is the relation of cave volume and the width of the cave openings. The more the disadvantage between these factors, the more the compensational effects are noticeable and measurable. Furthermore, the cave structure and the friction coefficient of the cave walls are responsible for the duration and strength of the air exchange. Especially with longer-lasting or very quick changes in air pressure the result is a rapidly-rising pressure difference between cave air and outer atmosphere. This leads to long-lasting and intense compensating air flow. If the cave structure represents one big unit, with wide corridors and halls, the compensating air flow can only be detected near the openings. If the cave structure is strongly jointed with several different parts, which are separated by narrow passage ways and tunnels, compensating air flows are detectable in many parts of the cave system. In general, the former explanation holds true for Wind Cave and the latter for Jewel Cave.

3. Thermal vs. Barometric Caves

The most important difference between thermal and barometric caves resulting from the character of the air flows are:

- **Strength of compensating air flow.** Even if there are reports about some caves with very strong chimney effects, the air flow in most caves of this type is rather poor (maxima < 0.5 m/s or just < 0.2 m/s). Within barometric caves air flow of several m/s can be measured, at least close to the openings and sometimes deeply within the cave.
- **Variability in time.** The compensating air flow within thermal caves mainly has a strong seasonal influence with clear differences between summer and winter and stronger oscillation of direction during spring and autumn. Barometric caves show small differences between summer and winter; this effect is due to the seasonal variability and stability of passing pressure systems. The typical change of direction is taking place throughout the whole year and they are showing different intervals of a few seconds up to several days.
- **Direction of air flow.** The most characteristic difference between both cave systems is the direction of air exchange. Within an ideal barometric type of cave, air exchange is taking place through all openings at the same time and into the same direction (into or out of the cave). In contrast to this, air flow into and out of the cave in thermal caves takes place usually at the same time (inflow in one outflow at another entrance), but through different openings. Caves with just one opening show a vertical difference in air exchange.

The above considerations are useful theoretical concepts, as, apart from showing the different processes at an ideal type of cave, thermal and barometric caves are clearly separated from each other. This clear separation does not exist in reality. Within each cave thermally and barometrically-generated processes exist side by side. Key factors that influence the most important effects are:

- Cave structure
- Size of the cave
- Relation between cave volume and width of the openings

Within a thermally distinct cave, the identification of barometric processes is relatively small (as far as they are detectable). The fast processes, occurring at all openings at the same time, air flow changes or modifications of the thermally-generated air flow can be easily and clearly identified. The identification of thermal processes in barometric caves is more difficult. Thermally-generated air flow is weaker, not very distinct and different at the different openings. Therefore, barometric events are overprinting or overlapping each other more or less intensely. Furthermore, the reasons for several different cause-and-effect connections are harder to put together as the barometric processes are based on atmospheric air pressure changes.

4. Details About Jewel and Wind Caves

The Wind and Jewel Cave are part of the Black Hills in South Dakota, USA. The Jewel Cave is with a up to today knowledge length of 230 km the second-longest cave of the world. The Wind Cave is at present estimated as being 200 km long and is the third-longest cave of the world (November 2008). Both caves have several openings and blow holes. Some of them have been discovered by the research projects listed below. The so called "Historic Entrance" of the Jewel Cave is located 1614 m above sea level. The caves' vertical expansion is 134 m. The so called "Natural Entrance" of the Wind Cave is located 1244 m above sea level and the vertical extent is 198 m (Jewel Cave 2007, Wind Cave 2007).

5. Recent Research at Jewel and Wind Cave and Neighbouring Caves

The last big measurement campaigns on climate system of barometric caves have been done by Herb and Jane Conn in the 1960s (CONN 1966). Despite their elementary work, the technical possibilities were very limited in those days. The self-constructed mechanic measurement equipment could only be used for basic measurements. Herb Conn was still able to define the basic mechanism very clearly. He also did different calculations that are important up to today.

During the last 40 years, electronic development has taken place very rapidly and today we are able to use instruments that are far more precise and sensitive. The use of highly precise ultra sonic anemometers (PFLITSCH & FLICK 2000) as well as long lasting, precise temperature sensors with robust data logger and long lasting batteries, enables us to take more exact and very sensitive long term measurements.

5.1 Current measurement programme

A widespread and long-term measurement programme has been installed in 2001 to fulfil several research aims. The measurements concentrated on the both big caves systems (Jewel & Wind Cave). The smaller neighbouring caves were added to the measurements during the course of the project as well. The measurements relevant for this report are those of air flow using ultra sonic anemometers at several measurement points within the cave and air pressure measurements at different points outside Jewel & Wind Cave, plus short-term measurements at the Jewel Cave. A detailed description of the measurement programme can be found in PFLITSCH et al. (2007).

5.2 Jewel and Wind Caves

Each cave system shows a characteristic air flow pattern that depends on the size of the cave and the cave structure in addition to the weather situation. The more similar the air flow pattern of two cave openings is, the higher is the possibility that these belong to the same system. Figure 3 shows the results of air flow measurements in the Wind Cave in comparison to the results of the Jewel Cave. It shows the air flow velocity in dm/s and the direction of air flow for each cave. The direction of air flow is visible from the direction of the graph in relation to the zero line. Numbers > 0 m/s means air flow is streaming out of the cave (outflow), numbers < 0 m/s relates to ingoing air flow (inflow). Each time the graph is passing zero again, indicates that the direction of air flow has changed. The distance of the graph from the zero line stands for the air flow velocity.

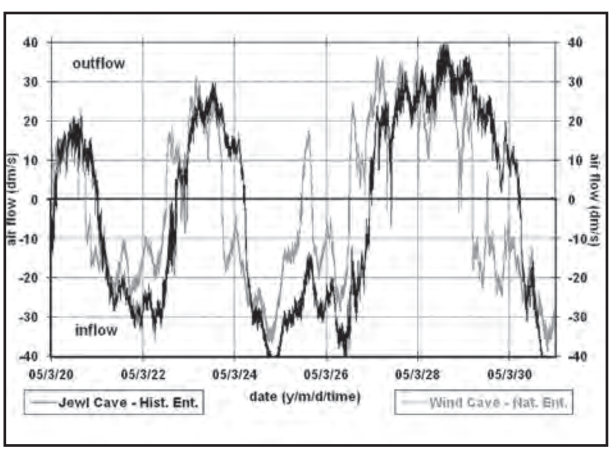

Figure 3: Comparison of direction of air flow and velocity at the entrances of Jewel and Wind Cave, SD, USA. Measured from the 20.03.-10.03.2005 with an ultra sonic anemometer (10 hz and averag-ing time of 10 seconds).

5.3 Connection to other caves and between the cave systems

We have used ultra sonic anemometers (PFLITSCH & PIASECKI 2003) to find out which of the smaller caves are connected to the large cave systems. Therefore we measured the air flow at each entrance. Figures 4 and 5 show results of air flow measurements at the S & G Cave – which is located pretty much in between Jewel and Wind Caves - in comparison to the results of Jewel and Wind Cave, now in m/s. Figure 4 shows a very strong relation between the structure of air flow change at the S & G Cave and Jewel Cave. However, the direction of air flow at the Wind Cave (Fig. 5) is clearly different from the ones at the S & G Cave. Those similarities and differences can be seen from the number of changes and the simultaneity of the air flow changes. In particular changes in direction for long-term and distinctive air flow situations correspond very well at Jewel and S & G Cave. Compared to that, Wind Cave and S & G Cave show large differences.

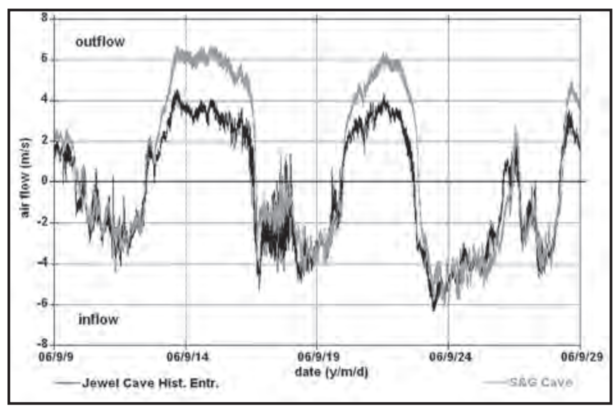

Figure 4: Comparison of direction of air flow and velocity at the entrances of Jewel and S & G Cave, SD, USA. Measured from the 06.-30.09.2006 with an ultra sonic anemometer (10 hz and av-eraging time of 15 seconds).

The small differences in air flow at S & G and Jewel Cave can be explained by the size and structure of the caves. The large similarities in air flow patterns of those two caves indicate very strongly that they belong to the same big cave system. The same correspondence has been found for Jewel and Jasper Cave. Measurements of the Coyote Cave show good or less good correspondence with the Wind Cave from time to time. It seems that the changing groundwater level masks the linkage of the caves. Some passages that connect both caves are sometimes water-filled and thus airtight.

6. Final Evaluation of the Measurement Results

The measurement campaigns of the different caves of the Black Hills, from which we have shown a very few selected

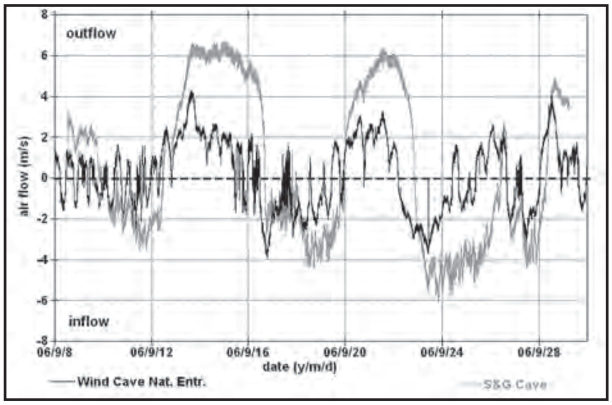

Figure 5: Comparison of direction of air flow and velocity at the entrances of Wind and S & G Cave, SD, USA. Measured from the 06.-30.09.2006 with an ultra sonic anemometer (10 hz and av-eraging time of 15 seconds).

number above, can be summarised as follows:

Extent of the cave systems:

- The Jewel Cave System extends from at least the Jasper Cave in the northeast to the S & G Cave and even Reeds Cave in the southeast. Therefore, the cave system is much bigger than the morphological unit known so far. These results are in good agreement with the volume calculations of at least 400 000 000 m^3.
- The Wind Cave system is also bigger than hitherto assumed. The surrounding blow holes can be assigned to this system. The Coyote Cave in the east – even if it is in another geological formation - seems to be part of the Wind Cave system too, albeit with less clear signals. From a climatic point of view the changing groundwater level seems to partly separate the two caves.
- A connection between Jewel and Wind Cave could not be demonstrated yet. The air flow patterns partly differ from each other indicating two separate cave systems. However, it might be possible that the distance between the two systems is too large and the connection too small to get a climatically-similar reaction.
- Further research will enable the real extent of both cave systems to be established.

Acknowledgements

We thank the DFG (German Research Association) for financial support. Without this a lot of the measurements would not have been possible. Furthermore, we are grateful to the management of the two national parks of Jewel and Wind Cave. They generously enabled us of an unrestricted measurement campaign and helped us with some constructional and technical changes of the infrastructure. Our personal thanks goes to Mike Wiles, Rod Horrocks as well as Mark and Rene Ohms, Jason Wall, Andy Armstrong and several students of the Department of Geography, Ruhr-University of Bochum. Without them this project would not have been possible.

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JEWEL CAVE AND WIND CAVE – DIFFERENCES AND COMMON FEATURES OF THE TWO LARGE CAVE SYSTEMS IN THE BLACK HILLS OF SOUTH DAKOTA

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Abstract

Jewel and Wind Caves are two big barometric cave systems in South Dakota. The entrances of Jewel and Wind Caves are roughly 50 km apart, and until now it is unknown as to whether their entrances belong to two separate caves or to one much larger cave system.

One possibility of testing these two competing hypotheses is to measure and analyze the climatic conditions in the vicinity of these entrances and within the caves, in detail. In this context, the thermal conditions and air currents are crucial. These, in turn, can be characterized by detecting the spatial and temporal patterns of the dynamics of air entering and leaving through the respective entrances. Even though these dynamics are coupled to atmospheric pressure fluctuations outside the caves, they differ for different cave systems and provide a “fingerprint” that has implications for the size and structure of individual cave systems. To give an example, the second and fourth-largest cave systems on Earth show some similarities, but many more noticeable differences regarding their climatological behavior despite their close proximity to each other.

The last big measurement campaigns on the climatic systems of the two barometric caves were carried out by Herb and Jan Conn in the 1960s. The technical possibilities were very limited in those days and the self-constructed mechanic equipment could only be used for basic measurements. Herb Conn was still able to clearly identify the basic mechanisms. He also carried out a number of different calculations that remain important to the present day.

During the last 40 years, rapid electronic development has enabled us to use instruments that are far more precise and sensitive. The use of highly precise, ultrasonic anemometers as well as long lasting, precise temperature sensors with robust data logger and long lasting batteries enables us to take more exact and very sensitive long term measurements. A widespread and long-term measurement program commenced in 2001 to fulfil several research aims and we are now in a position to decipher the different fingerprints much more reliably.

GEOLOGY AND TECTONICS OF POLOVRAGI CAVE - ROMANIA

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Polovragi Cave, with its 10,350 m of passages developed on three levels is located in the Southern section of the Paring and Capatinii Mountains, part of the Southern Carpathian Mountain Range. A limestone ridge/belt was formed in the Jurassic, and is crossed by several rivers. Oltet River penetrated the limestone ridge/belt, generating steep gorges 10 - 20 m wide at the base and three to four hundred meters high. A few hundreds of meters into the limestone, part of the waters of the Oltet River sink underground through an impenetrable swallet, generating the Polovragi cave. The cave is developed in the Eastern/left side of the river.

1. Introduction

Polovragi Cave is located in the Southern section of the Capatinii Mountains, which are part of the Southern Carpathian Mountain Range, Romania (Fig. 1). A limestone ridge was formed in the Jurassic, and is crossed by Oltet River, generating steep gorges 5 to 10 meters wide at the base and 300 m high (Fig. 2). Twenty five meters above the bottom, the gorges enlarged up to 40 m, where several cave entrances, including of Polovragi Cave may be found. A second erosional level at 75 m above the bottom of the gorge with several cave entrances is present. A few hundreds of meters into the limestone, part of the waters of the Oltet River sinks underground through an impenetrable swallow hole, generating the Polovragi Cave. The cave is developed on the left side of the river, by successive captures of the Oltet River along east–west fractures. The cave and gorge were formed in the same time.

Figure 1: Karst of Romania Map (after Bleahu, 1972) with location of Polovragi Cave.

Figure 2: Oltet Gorges.

The main entrance of the cave was known for a long time, as Cave of Pahomie from Polovragi. A brief description of the cave was made by Joanes in 1868, followed by another by Alexandru Vlahuta in "Romania Pitoreasca" (1901). The first data regarding the location of the cave were published in 1929 by P. Jeannel and E. G. Racovita. In 1951, Chappuis and Winkler published the first description of the cave itself (Bleahu et al., 1976). The first paper related to the cave, which includes a map of 961 m of passages was published in 1961 by Silvia Iancu. In 1974, "Focul Viu" Grotto, from Bucharest, Romania began an extensive study of the area, surveying the cave, and conducting geologic, geomorphologic, and tectonic observations. In 1976, a description of the cave was included in the book Pesteri din Romania (Caves of Romania) (Bleahu et al., 1976). In 2006, in the Field Trips in the Karst of Romania, edited by Silviu Constantin, a brief description of the Oltet River/Polovragi Cave is presented by Cristian Goran and others.

2. Regional Physiography and Geology

The hydrographic network in the area is dominated by the Oltet River, with a yield of 300 to 400 liters/second, forms a natural boundary between the Paring (West) and Capatinii Mountains (East), collecting the surface and underground waters in the area, including the spring of Polovragi Cave. During geologic times, the changes in the base level of the Oltet River controlled the development of the four known levels in the cave.

The geology of the area is complex; a relatively small area of sedimentary rocks, including limestone, overlies a granitic and crystalline basement. The crystalline rocks are part of the Oltet Thrust and have been penetrated by Susita granitoides and are overlain by Mesozoic deposits. The Mesozoic deposits are 100 to 500 m thick, depending on their position in the Oltet micrograben. Jurassic sandstones (Dogger - Middle Jurassic) outcrop at the entrance in the Oltet Gorges, on both sides of the river. These are calcareous in the upper part (10 – 120 m thick) and Dogger (Middle Jurassic) in age based on Belemnites findings (Nedelcu, 1978). These deposits are overlain by up to 400 m of Tithonian (Upper Jurassic) limestones. Measurements in the area indicate bedrock is dipping to the southeast between 17° and 23° (on Figure 3, bedrock is dipping about 410, due to 2x vertical exaggeration.). Microscopic analysis determined that this 400 m thick unit is formed from several limestone layers 50 to 80 m thick, separated by calcarenites. The limestones are strongly fissured and fractured, with breccia fragments 0.5 – 2 mm size identified along the fracture planes. The joints and fractures are part of two distinct systems: one north-south and the second one northwest–southeast (dips 800 to 900). The Jurassic limestones are overlain by Cretaceous Flysch represented by black calcareous marls and green clays with coal beds. A Neogene deposit south of the Oltet Gorges is represented by sedimentary rocks of the Getique Nappe and is characterized by an east–west fault system.

3. The Cave

The Polovragi Cave is located on the left side of the Oltet River and has six entrances, three are fossil and three active. The upstream entrance (dry - 2 x 3.5 m size) is at the northern end of the gorges, at about 15 m relative elevation (645 m elevation), and initially functioned as a sinking stream (Fig. 4). At the bottom of the gorge, in the same area the Oltet River is sinking partially underground through

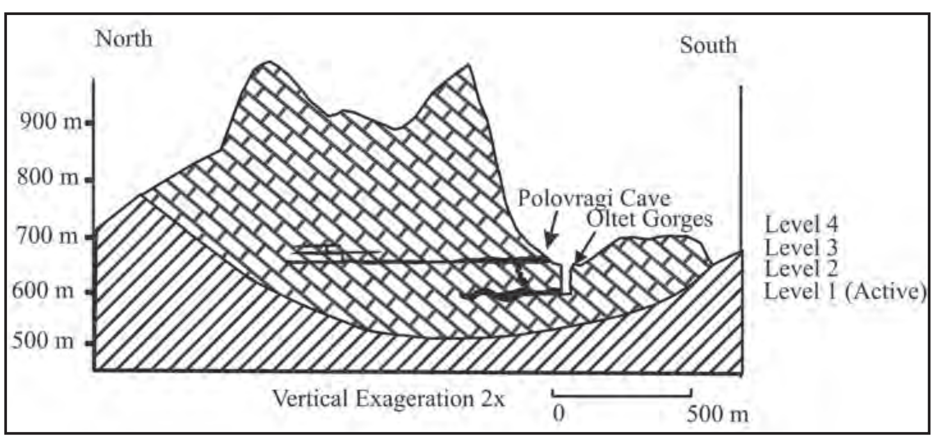

Figure 3: Stages of passages development in the Polovragi Cave.

a swallow hole (630 m elevation), generating Polovragi Cave's stream. In the upper section of the gorges a diffuse infiltration occurs through the bedrock fissures recharging the cave's stream. The next three entrances are 1.4 km downstream at the Oltet River elevation, (6 x 1 m, 4 x 1 m, 4 x 1 m, size – 605 m elevation). Through these entrances a karst spring is fed by the cave stream (one permanently and two temporally, during heavy rains or melting snow). About 25 m above, the main entrance of the cave is located (7 x 11 m size – 630 m elevation). Next to it is a smaller one, 1 x 0.4 m, both being fossil.

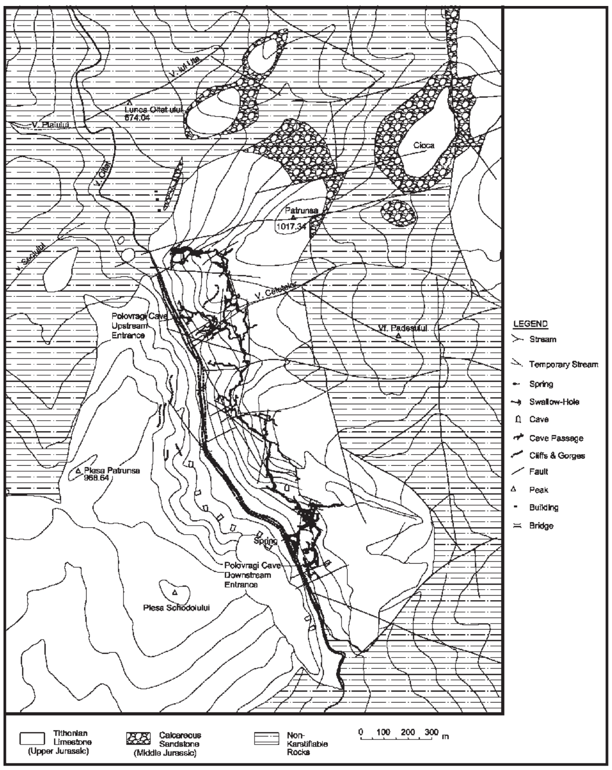

Figure 4: Geologic and Tectonic Map of Oltetului Gorges/ Polovragi Cave Karst Area.

Polovragi Cave with 10,350 m of passages and 87 meters vertical development (-62 m, +25 m) has a ramification coefficient of 6.81 and an extension of 1,520 m. It is a cave with a stream water table. For description purposes, the cave was divided in three sections: The Access Section, the Upstream Section and the Downstream Section (Fig. 5).

The Access Section, with 1,224 m of passages, is between the upstream entrance and The Wonder Chamber. Generally, the passages are small, formed along east-west, northeast-southwest oriented fractures, and developed on three different levels, most of them being formed by sinking streams. The passages in the Access Section have frequent changes in direction and an average height of 1 m. This area functioned for long period of time completely submerged (under phreatic level). This hypothesis is sustained by the cave morphology (horizontal ceiling, narrow passages), negative corrosion forms (ceiling pendants), and large argillaceous deposits. In two areas were the passages narrows, a strong air flow exists, and a group of eccentric stalactites were formed. In most of this section, those three cave levels are distinct, but in some areas they come together forming one large borehole, well decorated with stalagmites up to 4 m high and 2 m in diameter (The Dome). Large deposits of argillaceous materials and the existence of numerous ceiling collapses (breakdown), complete the description of this section. Upstream of The Dome, Passages 23 and 25 make the connection with the Upstream Section of the cave. The Access Section has a meander segment, well decorated with columns and rimstones, and at the end of an ascendant passage is an underground lake.

The Upstream Section is formed mainly by Passages 27, 23, and the Wonder Passage, with a total length of 2,880 m. The fractures in this area are oriented north-south and east-west. As in the Access Section, several passages formed by sinking streams generated a main borehole, Passage

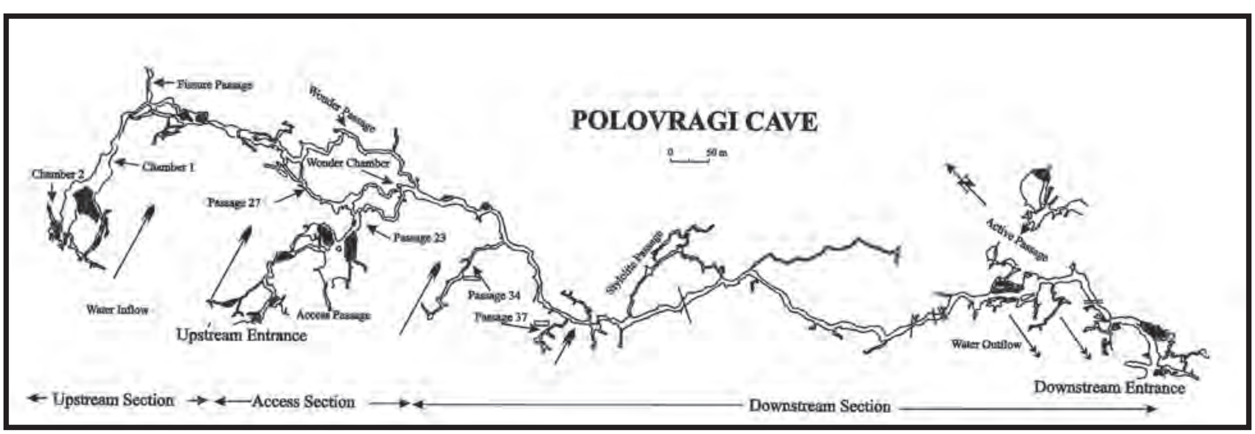

Figure 5: Polovragi Cave.

27, which has two upper level passages with chimneys recharged by sinking streams located on the side of the mountain. The passages which form the main borehole in this section originated near the limestone/noncalcareous rock interface and are developed on three levels, 13 m apart. Their morphology varies from conduit flow to well decorated sections, with calcite deposits occupying most of the passage. The place where the three levels join forms large rooms, Chamber I and Chamber II. These large rooms were developed at the intersection of the fractures systems mentioned earlier. A 15 m deep Fissure Passage was surveyed in this area. Downstream from Chamber I, Passage 27 is formed by combination of high and medium level passages. The difference in elevation between the two levels decreases downstream from 4 m to 1.5 to 2 m. The medium level continues downstream 110 m, ending in argillaceous deposits 5–10 m thick, which separate this segment from the Wonder Passage. The medium/main level passages are about 3 m height with some lower areas, and is connecting with Access Section through Passages 23, 25, and 27. The Downstream Section of the cave with 5,067 m is the longest one. The Main Passage is a result of the intersection of passages of the Access Section and Upstream Section. The main fault system which controlled the development of this area is oriented north–south, east-west, and northwest-southeast. Except the Active Passage, the entire section corresponds to the medium level of the previous two sections.

The passages mapped on the right/west side of the Main Passage were formed by partially sinking streams recharged by Oltet River, and those close to the main/downstream entrance represent hydrogeologic conduits to the main spring. Downstream of the Wonder Chamber, the main passage is oriented north - south, 3 to 4 m high, partially decorated, with sand and clay on the floor. The footprint of an old flow channel recharged by a temporary surface stream through a chimney was mapped. Beyond Passage 37, the main passage narrows to 1 x 1 m, with thick argillaceous deposits, gravel and boulders on the floor to the intersection of Stylolites Passages, which is a side meander of the main passage. Past the junction with the Stylolites Passages, the main passage becomes wider and higher (borehole type) up to the downstream entrance of the cave. In this area a narrow passage was identified which descends to the lower level of the cave (Active Passage). The waters are coming in through a sump, 12 m deep and 54 m long, followed by a second 30 m long sump, the end of it not being found yet. Between this sump and the sinking point on the Oltet River, the path of the stream is unknown. It is possible to be formed by inundated conduit, penetrable or not for the divers. The subterranean stream cross the Active Passage, sinking in a series of five downstream sumps, the water coming out in the Oltet Gorges through three entrances (one permanently active and two temporally, during heavy rains or melting snow), with a 50–100 l/s yield, and a temperature of 7.10 C. This temperature is constant year around. The fractures oriented northeast–southwest are controlling the development of the cave in this section. As in Figure 2, the caves passages generally follows the fractures, faults and joints identified at surface by geologic mapping. The cave map identified some of those features during the survey and illustrates the important roll of the tectonics in the genesis of the cave.

4. Conclusions

Polovragi Cave is a cave with a stream water table, developed on four levels (three fossils and one active). . In a multi-level cave, the largest passages are typically those that have been active for the longest period of time (Palmer, 2007), in our case being the Medium Level.

The rock in which the Polovragi Cave is developed has a $CaCO_3$ content close to 90%. Based on A Bulk compositional classification of carbonate rocks (Leighton and Pendexter, 1962), the rock is included in the limestone category. As a result, the passages developed in this limestones are well decorated, the water with CO_2 being capable to dissolve the limestone and to generate flowstones.

Numerous fractures, faults, and joints, identified during geologic mapping, proved afterwards to have a significant impact in the cave development. At the intersection of tectonic planes, the main chambers were formed. The majorities of the passages were developed along or parallel to these tectonic features. The changes in direction of the passages are also controlled by tectonics.

The noncalcareous rocks/limestone boundary combined with the tectonic structure, control the location of the sinking points along the Oltet River, or on the side of the mountains. Here, temporary streams develop occasionally, sinking underground through swallow holes and generating narrow passages, which are part of the Polovragi Cave System.

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INFLUENCE OF METEOROLOGY ON SPELEOTHEM DEPOSITION: EXAMPLE FROM KRIŽNA JAMA, SLOVENIA

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Križna jama is situated in the middle of triangle between three Dinaric karst poljes: Cerknica polje, Lož polje and Bloško polje. Together with its hydrologic and geomorphologic continuation as Križna jama 2 Križna jama forms more than 9688 m long horizontal epiphreatic cave system. Water enters Križna jama quite sparsely through many small sumps which gives together usually about 0.2 m^3/s of water. At high water levels discharge can be more than 2 m^3/s. Since the connection with sinking superficial streams at Bloke polje is very weak (tracing test in 2007/2008 proved this), primary infiltration in mentioned triangle is most probably the main source of water which is flowing through Križna jama. Downstream, water flows through Križna jama 2 toward Cerknica polje.

Križna jama is well known cave because of great biodiversity (45 defined troglobionts until 2000), rich findings of *Ursus spelaeus* bones (over 2,000) and more than 40 underground lakes. The latter were formed behind rimstone dams, most probably in Holocene, and still grow nowadays about 0.1 mm per year. Intensive study of corrosion and flowstone deposition rates with limestone tablets in the years 2005-2009 showed that corrosion rates are absent even at high water levels and that flowstone deposition rates at rimstone dams strongly depend on cave meteorology. Due to intensive winter ventilation the majority of flowstone deposition takes place within few winter days, when outside daily temperature does not exceed about -3 °C. This phenomenon is related to CO_2 concentration in Križna jama, which is strongly lowered in winter time (from 2500 to 360 ppm). Additional precise measurement with interval of 15 days, spatial measurements of flowstone deposition rates, morphology observations, cave meteorology measurements and periodical observations of water chemistry brought us also insight into flowstone deposition rates through the entire cave. We realized that flowstone deposition strongly increases from upstream confluences toward downstream confluences and that flowstone deposition rates are strongly influenced by tributaries and also CO_2 concentration within individual passages.

Križna jama 2 is because of its special beauty (thin and fragile flowstone coating in the water channel and sensitive rimstone dams) closed for visitors and cavers. Only special permission from Ministry of the Environment and Spatial Planning make us possible to measure flowstone deposition rates at several locations from the influx sump to terminal sump. Although the measurements were done on the continuation of water flow from Križna jama, flowstone deposition rates were up to 43-times smaller. Comparison of results with 30 day resolution showed that in Križna jama 2 we lack high flowstone deposition rates due to much weaker ventilation. Therefore, the meteorology appears to be a key factor which is controlling flowstone deposition rates. Due to significantly lower flowstone deposition rates, protection of Križna jama 2 is well-founded.

1. Introduction

Križna jama is, together with its hydrological and geomorphic continuation as Križna jama 2 (together abbreviated as KJ-KJ2 cave system; Fig. 1), one of the best examples of hydrologically active water-table cave in the area of Classical Karst, Slovenia. More than 9688 m long cave system is located in the centre of triangle between Bloško polje (~720 m a.s.l.), Cerknica polje (~550 m a.s.l.) and Lož polje (~570 m a.s.l.). KJ-KJ-2 cave system lies below typical high plateau karst with elongated conical hills and closed depressions without superficial streams. The majority of nearly horizontal water passages are developed within the elevations 577 m (the lowest siphon in Križna jama 2) and about 630 m (spring under the ending breakdown in Blata passage). Therefore, gradient is very low, being about 1 % in Križna jama and 3 % in Križna jama 2 (Prelovsek et al., 2008). Main trunk passages are usually more than 10 m wide and usually about 5 m high. Where they cross well fractured rock several collapse chambers developed in the past. Initiation of first channels took place at the

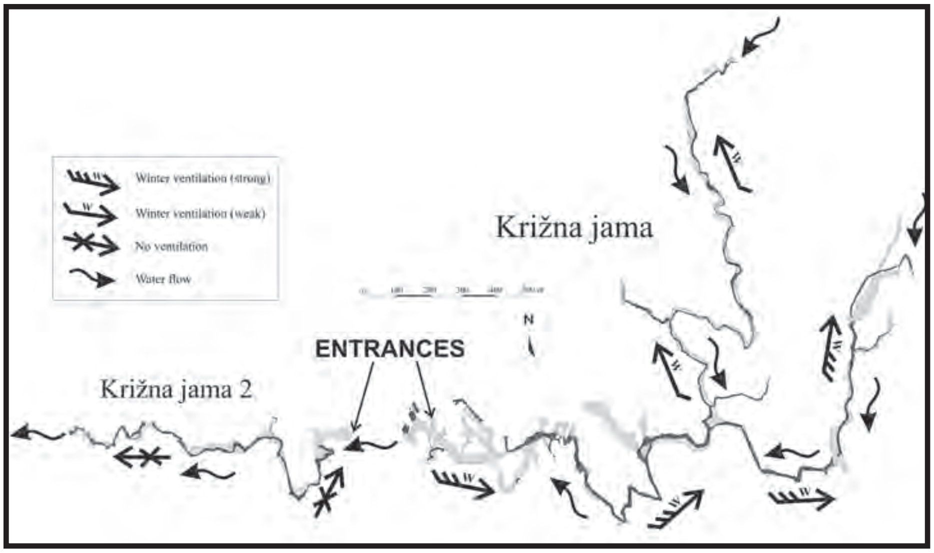

Figure 1: Map of KJ-KJ2 cave system with direction of main water course and winter air flow (summer ventilation is opposite to winter ventilation).

intersection between bedding planes and present-day water table or at the intersection between faults/joints and water-table. Paragenetical deformation of phreatic loops is less probable since the roof of passages is nearly parallel (horizontal) to rocky cave floor, subvertical or subhorizontal phreatic passages are very rare and paragenetically flattened roof is just slight modification of lower passages. It seems that from the beginning, preferential corrosional zone was exactly at the water-table. Time of formation of trunk passages is difficult and still opened question – the oldest dated sediments are from 146 ka B.P. (Ford & Gospodarič, 1989) but not more than 780 ka B.P. old (Zupan Hajna et al., 2008). In spite of these sparse datations, passages seem to be much older since all these allochtonous sediments were sedimented in well formed passages with similar diameter as today.

General discharge in cave system amounts from 0.1 m^3/s to 0.2 m^3/s. At very high water level discharge was estimated to be over 5 m^3/s. Origin of water, which flows through the KJ-KJ2 cave system, was always questionable. Due to location of KJ-KJ2 cave system between occasionally flooded Bloško polje with several ponors and Cerkniško polje with several springs, brook in the KJ-KJ2 cave system thought to be a connection stream between poljes. This was partially proved with allochtonous sediment (Gospodarič, 1974) and polystyrene findings in Pisani rov. Both are located only at Bloško polje, which has proved hydrological connection with Cerknica polje. This generally accepted idea of allogenous water flow through KJ-KJ2 cave system is in conflict with very stable annual temperature of water (8.4 ± 0.5 °C), high hardness of water (13.9 °N after Gams (2003, 73), usually oversaturated water ($SI_{Ca} \approx 0.7$) even at higher water levels and tracing test in 2007/2008 (Kogovšek et al., 2008). The latter showed very weak hydrological connection between ponor at Bloško polje and Križna jama since only 2 % of injected tracer was detected in Križna jama. Later measurements of water temperature in Križna jama, which showed that allogenous water pours over from unknown side channels into the Križna jama when discharge exceed 1.3 m^3/s, supported the theory of Kogovšek et al. (2008) that hydrological connection between Bloško polje and Križna jama becomes important only at high discharges ($Q \geq 1.3$ m^3/s) when southern part of Bloško polje becomes flooded. This happens on average only twice per year for several hours, while in much longer time KJ-KJ2 cave system transfer only percolation water infiltrated through 10-270 m thick roof composed of Lower Jurassic dolomite and Lower-Middle Jurassic limestone. Detailed hydrological network of KJ-KJ2 cave system is quite complicated since several visible and invisible (underwater) springs and ponors appear along main water course (Prelovsek et al., 2008).

In Križna jama, majority of passages are very well ventilated (Fig. 1). This is especially true for Glavni rov and Pisani rov, while Blata passage (northern branch in Fig. 1) is much less ventilated. Ventilation of cave is strongly related to outside temperatures: when they exceed 8 °C, air flows through the all cave toward main entrance. In winter time, when the temperature falls below 8 °C, cold air enters the cave through the main entrance and flows toward higher unknown entrances behind the cave endings (breakdown chokes). In Križna jama, CO_2 concentration is the highest through the summer (~2500 ppm) and the lowest through the winter time (~400 ppm). Križna jama 2 is almost unventilated due to only one known small entrance dug through in 1991. Therefore, CO_2 concentration is high (from 1540 to 3780 ppm) through all the year.

Very widely distributed geomorphic micro feature in the cave is scallop which points out on corrosion. Opposite process is flowstone deposition, which takes place in water channel, which is covered with water at low and middle water levels. The annual rate of flowstone deposition was measured by Mihevc (1997) and amounts on average 0.09 mm/a. In deep slow flowing water bodies, flowstone deposition forms flowstone coatings while at fast flowing water, flowstone deposition forms rimstone dams. Behind them, more than 50 underground lakes were formed. The lakes with rimstone dams are the main touristic attraction and also the most fragile part of Križna jama. Main questions, we are trying to answer from 2004, are:

- When the flowstone deposition takes place?
- Which are the most important factors that control flowstone deposition?
- How various are flowstone deposition rates in the KJ-KJ2 cave system?

2. Methods

Beside morphological observations, 3 major methods stand out: usage of limestone tablets, measurements of CO_2 concentrations and measurement of physical-chemical characteristics of water.

Usage of limestone tablets was very popular in 70-ies, when Ivan Gams under the patronage of Commission on Karst Denudation at UIS sent more than 1500 standard limestone tablets all over the world to observe chemical denudation in various climatic conditions (1985). Although methodology of limestone tablets is very simple and accurate, usage of limestone tablets in cave corrosion measurements is rare (Chevalier, 1953 after Gams, 1985; Gams, 1959; Rebek, 1964; Delannoy, 1982 after Gams, 1985; Gams, 1996). The biggest disadvantage is fixation of limestone tablets to cave walls, which was successfully solved by Prelovsek (Prelovsek et al., 2008). Central hole in limestone tablet with diameter of 8 mm pave the way for fixation of 3-5 mm thick limestone tablets with stainless steel screw and 2 nuts. Abrasion is prevented with 2 felted washers which make a soft contact between stainless steel parts and limestone tablet. This improvement together with high accuracy (average ±0.0001 mm and maximal ±0.0004 mm) makes possible very short reliable measurements of corrosion or flowstone deposition rates. Two limestone tablets were used for measurements at each measurement point – one was dried and later weighted in chemical laboratory at Karst Research Institute ZRC SAZU and the other was at the same time exposed in underground water course. After 15 or 30 days limestone tablets were replaced. Transformation from grams to millimeters bases on specific weight of used Cretaceous limestone (2688 kg/m^3) and individual exposed surface of limestone tablets. Therefore, final results is not an average of many individual reading, as this is the case in micrometer measurement (MEM) but an average corrosion or flowstone deposition over all exposed surface of limestone tablet.

CO_2 concentration was determined using Vaisala's hand-held carbon dioxide meter GM70, which consists of the indicator and GMP222 CO_2 probe. The latter had a resolution of 20 ppm and accuracy of ±1.5 % of range plus ±2 % of reading (Vaisala's Technical data, 2007). The range of the CO_2 probe was between 0 and 3000 ppm, while the worst accuracy was 105 ppm at 3000 ppm.

Gealog S was used to observe variation of water level, temperature and specific electrical conductivity (SEC) at 1st Lake in Križna jama (370 m from the entrance). Several discharge measurements at different discharges with salt dilution method (Käss, 1998) enable us to define stage-discharge curve, which offered us easy determination of discharge from water level. Spatial changes of physical and chemical characteristics of water were measured with WTW Multiline P4 with SEC and pH probe. SI_{Ca} was calculated with computer program WATEQ4F (BALL & NORDSTROM, 1991). Input parameters for SI_{Ca} were SEC, T, pH (defined in situ) and Ca^{2+}, Mg^{2+} and carbonate alkalinity (defined in chemical laboratory at Karst Research Institute ZRC SAZU).

3. Relation Between Discharge and Flowstone Deposition Rates

Widely accepted belief in speleology is that intensity of corrosion or flowstone deposition, away from the first contact of water with carbonates, strongly corresponds to discharge (Herrera et al., 2006; Palmer, 2007). In KJ-KJ2 cave system, water mainly percolates through the soil, epikarstic and vadose zone before it arrives through many small springs into the trunk channels. During fast percolation, dissolved load is thought to be lower due to shorter time for interaction between rock and water. Therefore, less saturated water is expected at water-table. If the water percolates slowly, much more time is available for interaction between water and carbonate rock and therefore high hardness of water is expected at water-table. Lower CO_2 concentration in majority of caves enhances degassing of CO_2 from the water which, if the water was saturated or nearly saturated, leads to less or more visible flowstone deposition. Weak interaction of percolation water with carbonate rock, slow dissolution rates when approaching equilibrium (Dreybrodt, 1988) and mixing of waters with different partial CO_2 pressure in unsaturated zone can lead to (low) corrosion rates also in phreatic or epiphreatic zone. Such behavior of primary infiltrated waters is common in karst and was expected also in KJ-KJ2 cave system.

Results of contemporary measurement of discharge, SEC as a good approximation for total hardness of these unpolluted waters (Ford & Williams, 2007, 63) and corrosion/flowstone deposition rates are represented in Figure 2. Surprisingly, no important correlation between discharge and corrosion/flowstone deposition was observed in KJ-KJ2 cave system. The highest flowstone deposition rates were measured at low and high discharges. It seems that short-term high discharges have no influence to corrosion or flowstone deposition rates and that only slightly low SEC in June and July reflected in lower flowstone deposition rates (if compared with higher deposition rates in March, April and May). In spite of this, values are quite close to error of measurement (±0.0001 mm). At such small flowstone deposition rates it is also clear that annual sum of such 15-day flowstone deposition rates is too small for annually measured flowstone deposition rate measured by Mihevc (0.09 mm/a; 1997). Therefore, high flowstone deposition

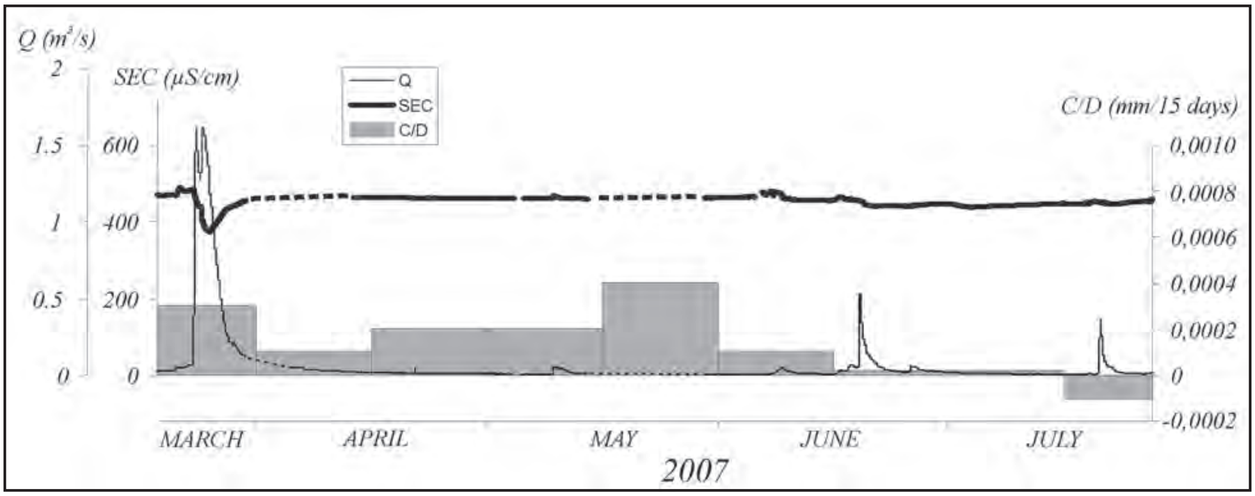

Figure 2: Relation between discharge (Q), SEC as approximation of total dissolved load and corrosion/flowstone deposition rates (C/D).

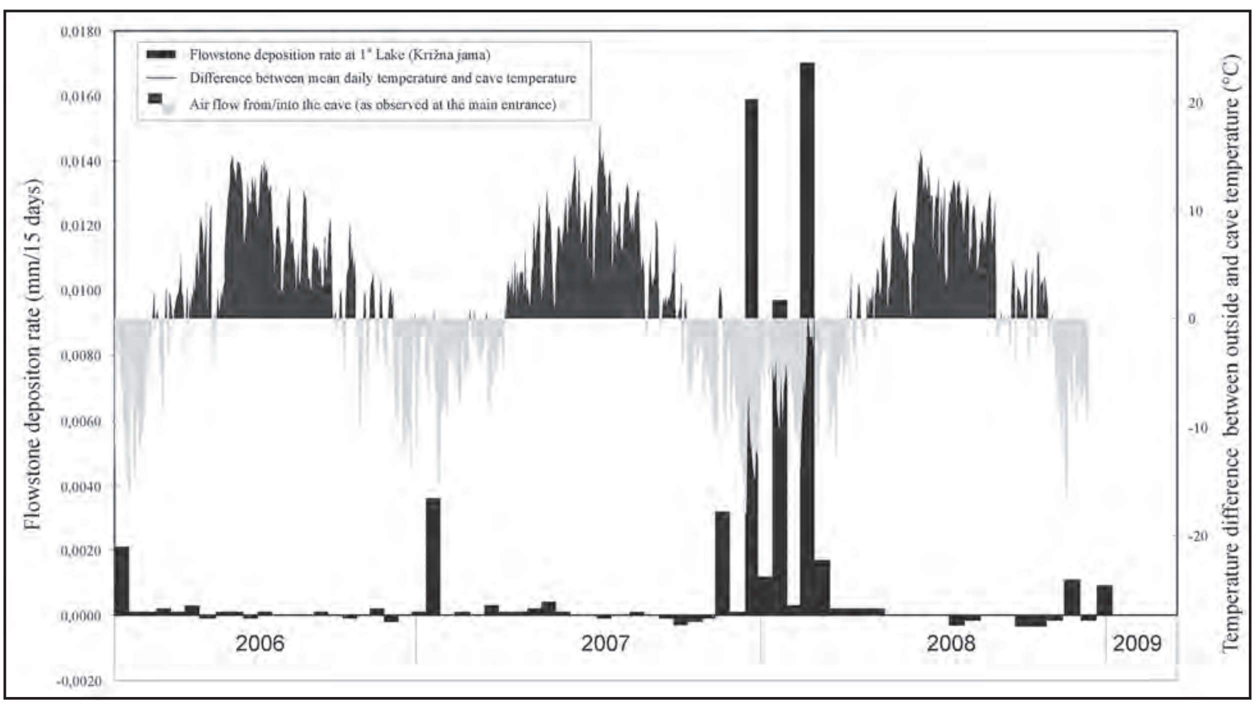

Figure 3: Difference between average daily outside temperature measured at nearest meteorological station and cave temperature (~8 °C; ≈intensity of ventilation), wind direction and corrosion or flowstone deposition rates in 2006, 2007, and 2008.

rates have to be related to some other months, when the conditions and influencing factors are much different.

4. Influence of Winter Ventilation in Križna jama

Only rare studies (i.e. Spötl, 2005) take into account also CO_2 concentration in cave air as a factor controlling flowstone deposition rates since it influences degassing of CO_2 from the dripwater. The study of Spötl et al. (2006) actually shows, how important is rate of degassing of CO_2 from the water – in winter time, when CO_2 concentration in a cave falls from 1200 to 500 ppmv, SI_{Ca} of dripwaters increases from +0.3 to almost +0.8. Much higher seasonal oscillation of CO_2 concentration were measured in Križna jama, where CO_2 concentration falls from more than 2000 ppm in autumn to atmospheric values (~380 ppm). In Križna jama, a response of flowstone deposition can be seen in Figure 3.

Distribution of flowstone deposition rates through the years 2006, 2007 and 2008 with resolution of 15 days (Fig. 3) show dependency of flowstone deposition rates on ventilation in winter months. The highest flowstone deposition rates are, quite irrespective to discharge, observed in winter 2007/2008, when the ventilation of cave was strong and long. A threshold for high flowstone deposition rates seems to be somewhere at temperature difference -11 °C, although duration also plays an important role in flowstone deposition rates (some temperature differences were below -11 °C but they were probably too short for high flowstone deposition rates). It is interesting that several days of weaker air flow into the cave quickly increase CO_2 concentration in cave air and that another period of strong ventilation is needed do reduce CO_2 concentration in cave air. Finally, amount of flowstone deposited in one year depends on coldness of winter – colder the winter is, more flowstone is deposited. Another interesting conclusion is, that a majority of corrosion rates were observed in autumn, when the CO_2 concentration and discharge was the highest. Only high discharge at low CO_2 concentration in spring seems to be insufficient for important corrosion rates. In spite of several very high discharges in the end of 2008 annual corrosion rate is still very small (-0.0016 mm/a).

5. Comparison Between Križna jama and Križna jama 2

What would happen in Križna jama in the case of weaker winter ventilation can be observed in Križna jama 2. The latter is located 242 m downstream from Križna jama and is its hydrological and morphological continuation. Caves are connected into KJ-KJ2 cave system through more than 50 m deep siphon, where at least one tributary with relatively high SEC and low pH was detected (Kogovšek et al., 2008; Prelovsek et al., 2008). In Križna jama, similar tributaries

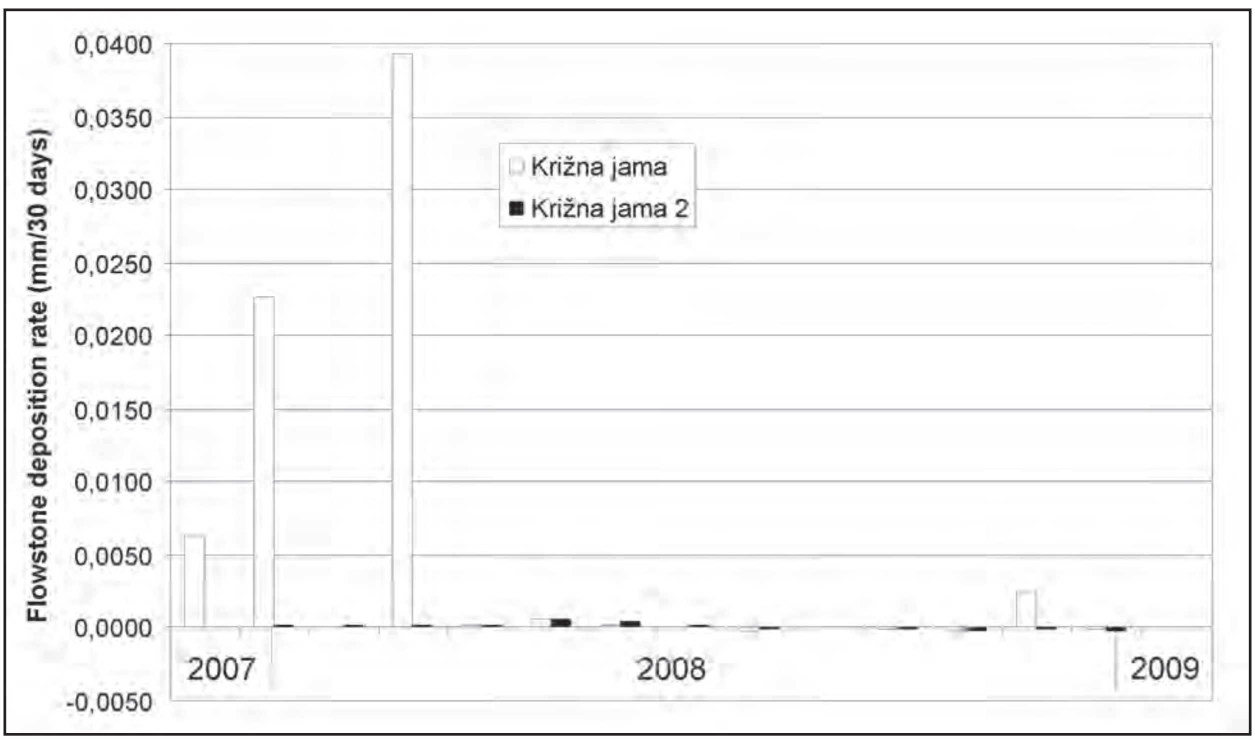

Figure 4: Flowstone deposition rates in Križna jama and Križna jama 2.

usually make a break in flowstone deposition due to higher CO_2 concentration in water and consecutive lowering of SI_{Ca} in combined stream. Further downstream, flowstone deposition rates increases due to outgassing of CO_2 from the water – this process can be nicely observed with growing pH. But, due to absent (or at least much weaker) ventilation of Križna jama 2, much smaller annual flowstone deposition rates are observed here. Comparison between flowstone deposition in Križna jama and Križna jama 2 is represented in Figure 4. In spring, summer and autumn flowstone deposition or corrosion rates are very similar while in winter time huge differences appear. Main cause is in ventilation since big differences are observed in CO_2 concentration – in December 2008 CO_2 concentration in Križna jama was about 500 ppm while in Križna jama 2 CO_2 concentration was about 3700 ppm. Consequently, annual flowstone deposition rates in Križna jama 2 are very low (only 0.0015 mm/a or 43-times lower than in Križna jama).

6. Conclusions

Although some studies stress the importance of discharge (or dissolved load) to flowstone deposition rates, ventilation of cave is the most important factor that controls flowstone deposition in KJ-KJ2 cave system. This can be explained with winter ventilation, which, in Križna jama, reduces relatively high autumn CO_2 concentration (from 2000 to 3900 ppm) to outer atmosphere concentration (~380 ppm) in winter time. Almost independently on water hardness, flowstone deposits from the underground brook if the cave air CO_2 concentration permit satisfactory degassing of CO_2 from the water. In Križna jama, this happens when the average outside temperature remain below ~ -3 °C for at least one day. Degree of ventilation, which is a function of outside temperatures, has strong influence on annually amount of flowstone deposited in Križna jama. Therefore, much lower annual flowstone deposition rates are expected in the future since the climate becomes much warmer, especially in winter months.

Križna jama 2 is closed for visitors and cavers because of its special beauty (thin and fragile flowstone coating in the water channel and sensitive rimstone dams). With much weaker ventilation as Križna jama, much smaller annual flowstone deposition rates are observed in Križna jama 2 since high winter flowstone deposition rates are absent here. These observations also bring some support on already established strict protection of Križna jama 2 – according to measured flowstone deposition rates, natural restoration of even millimeter deep damage in flowstone coating would take several hundreds of years. Therefore, strict control over visiting is well-founded.

Acknowledgments

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THE LOST CITY: HOT SPRINGS, MIXING AND A POSSIBLE MODEL FOR FOLIA DEVELOPMENT

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The Lost City is a recently discovered group of vents formed by thermal springs located 15 km off the axis of the Mid-Atlantic Ridge near the equator, in over 800 m depth. Individual mounds and towers of massive aragonite crystals and other carbonate precipitates rise as much as 60 m from the seabed. They have formed around porous axial zones, though which hot (75ºC), reduced and high-pH (10+) fluids escape. Leakage of the fluids through the porous tower walls also occurs. Carbonate precipitation probably results from mixing with seawater, raising the latter's pH and temperature and decreasing carbonate solubility. Abundant methanogenic microbiota live in and on the tower walls, forming a source of nutrients in an otherwise low-productivity deep-sea habitat, and contributing to the processes driving carbonate precipitation, Where waters leak from the sides of towers, inverted flanges of carbonate may form, which temporarily impede the upward flow of water and form an inverted dam, within which hot water floats on denser seawater. Flanges may exceed 1m in height. They flare outward and exhibit a more-or-less level lower surface. Photographs show well-developed pycnoclines at the contact between the waters, which reflect light from the strobes. Microbial colonies are common along the margin of the flange, where seawater, vent water, and carbonate substrate are all in contact. These flanges are considered to be analogues of folia and suggest an alternative mode of formation for these rare cave features. Models for folia growth that suggest they are the equivalent of gours forming at the water surface on vertical or overhung surfaces fail to explain why no comparable features are developed on upward-facing surfaces, nor why they are not equally developed on all overhanging surfaces within a particular area. However, if folia can form in mixing zones where fresh water seeps from porous wall rocks and rises through denser brines, then the peculiarities of their distribution and lack of association with gours and shelfstones are consistent with the model. Where this model is valid, folia should be preferentially developed on cave walls cut into rocks hosting the fresh water, and should not form on loose blocks and small columns isolated from sources of freshwater flow.

Where leakage takes place over a level or gently sloping sea floor (including the top surface of flanges), mounds and towers result, forming smaller versions of the spring vents. These are morphologically similar to some mound-like and tower-like cave precipitates (e.g., aragonite trees). In caves in the Guadalupe Mountains of southeastern New Mexico, aragonite trees are well developed in places and have been interpreted as forming from evaporation associated with dripping or splattering vadose water. Where these features are associated with well-defined drip sites, and without a central hole in the bedrock on which they have grown, vadose origins are supported. But if these aragonite trees lack an identifiable point-source of vadose flow, or if there is a central hole in the bedrock foundation through which water may have risen, then a subaqueous origin by mixing may be considered.

1. Introduction

This paper presents a case where a chance discovery in one environment (the deep ocean) led to potentially valuable insights regarding the workings of a seemingly unrelated environment (caves). Although the features described in the deep sea are only broadly similar to certain rare cave features, the similarities are sufficient to warrant consideration. Both environments may contribute to the understanding of an important environment – mixing zones. The resulting model leads to testable predictions, which should be tested at diverse sites.

2. Location and Origin of the Lost City Thermal Vent Complex

Mid-ocean ridges are known as sites of high heat flow due to the thin mantle and the associated implacement of igneous intrusives in the shallow subsurface (Blackman et al., 2002). In the last several decades a large number of high-temperature springs have been described from the axial zones of these ridges, which are the locus of significant metal-sulfide mineralization associated with "black smokers'. Generally, fluids associated with these black smokers are reduced, very hot (>300° C), low pH (3.5-5.0), and have high concentrations of iron, hydrogen, methane and hydrogen sulfide. These sites have attracted considerable attention due to their unique microbial flora, which form a nutrient base for diverse communities. In 2000 a new complex of vents was discovered, 15 km off the axis of the Mid-Atlantic Ridge at 30 N, in 700-900 m of water (Fig. 1). This off-axis setting is significant because even though the heat flux is less, the environments themselves are older than in on-axis springs. Magnetic data indicates the crust here is about 1.5 Ma old. Elevated temperatures in these settings results from serpentinization of peridotites in the subsurface, rather than from active igneous intrusion (Kelley et al., 2007). This has resulted in a series of hot springs issuing from the highly fractured bedrock of the rugged Atlantis Massif, with over 3000 m of relief next to the intersection of the Mid-Atlantic Ridge and the Atlantis Transform Fault. These have created mineralic towers of aragonite, calcite (both $CaCO_3$) and brucite ($Mg(OH)_2$), from the mixing of hot, metal-poor, hydrothermal fluids and oxygenated seawater. The tallest of these rises more than 60 m above the surrounding seafloor, which prompted the discoverers to call the site the Lost City (Kelley et al, 2001; Fig.2). Water discharged by the vents is significantly different than that discharged by the black smokers due to differences in the composition of the bedrock and the origins of the waters.

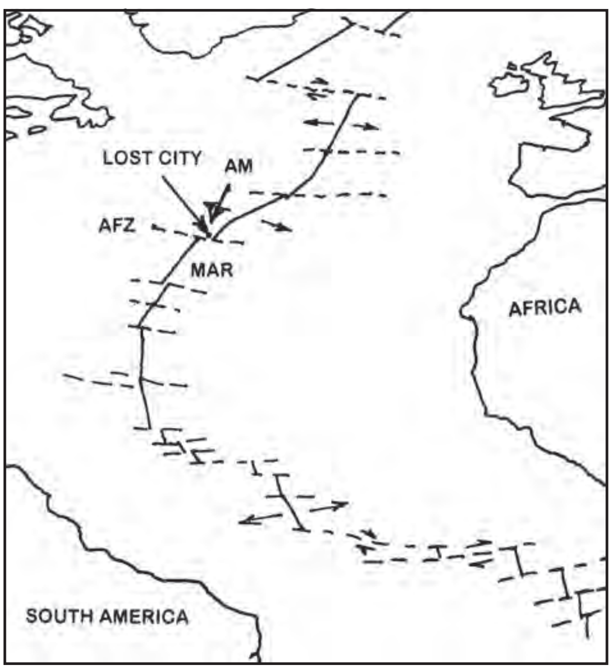

Figure 1: Map showing location of the Mid-Atlantic Ridge (MAR) and major transform faults in the central Atlantic. The Lost City is located on the edge of the Atlantis Massif (AM) and the Atlantis Fracture Zone (AFZ) (after Kelley et al, 2007).

Both on-axis and off-axis springs are reduced, but the off-axis springs are much cooler (40-91 ° C.), basic (pH 9-10.7), and have lower iron and higher calcium concentrations. Mixing of these fluids with seawater (T=2-3 ° C, pH approx. = 8) results in supersaturation of carbonate minerals, which is also promoted by abundant methanogenic microflora that live in the porous tower walls, reducing the concentrations of CO_2 and hydrogen. These environments are being studied as possible analogues of settings within which life may have evolved in the early Precambrian (Kelley et al, 2001; 2007), and in order to assess the nature and importance of chemical rock-water interactions in the continuing evolution of the oceans and atmospheres.

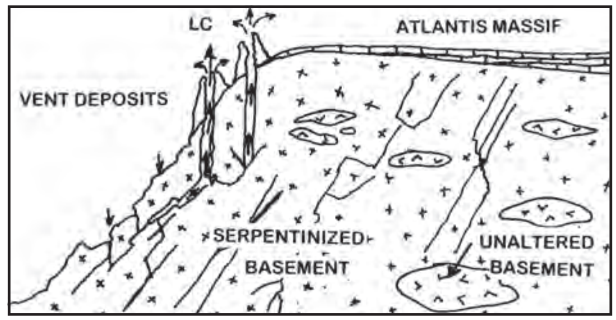

Figure 2: Cross-section of the Atlantis Massif showing relative location of the Lost City vent complex (not to scale: modified from Kelley, et al, 2007). Vents are fed by seawater heated by the serpentinization of ultramafic peridotites.

3. Morphology and Development of Vent Deposits

Where hot fluids rise upwards out of a porous, fractured and permeable substrate in off-axis settings, they mix with seawater, resulting in carbonate supersaturation. This produces steep-sided conical mineral deposits with a porous and permeable axial zone, of which the massive towers are the largest examples (Fig. 3). Although most of the water flows upward through the axis of the deposits, some seeps laterally out the sides of the towers, where it may be associated with canopies of carbonate and brucite precipitates having a more or less level lower surface enclosing a hollow, bell-like interior cavity. These were called flanges (Kelley et al, 2001). They may exceed 1 m in height. Pictures taken from submersibles reveal a reflective surface coincident with the lower edge of these flanges, which results from refraction and reflection of light at the interface (pycnocline) between the hot fluids contained within the flange and the colder, denser seawater below. Kelley et al, describe abundant microbial communities on the lower edge of the flanges, and in the porous walls of the vents, which would be where hot vent-water, cold seawater and the carbonate substrate are in contact. Smaller bushes and trees of mineral precipitates may be found on the upper surfaces of the flaring flanges, where they form from mixing, indicating that although the flanges may slow the hot water from rising freely into the seawater, they are to some degree permeable. Hydrologic and diagenetic development of these vents is discussed by Fruh-Green et al. (2003), who describe diffuse flow through porous deposits, which is progressively constrained to fewer flow-paths as pores are progressively filled with precipitates. The highly complex and porous interior of the vent deposit illustrated by Kelley et al (2007) is composed of convolute mineral septae, which define a labyrinth of interior pores. Fruh-Green et al (2003) describe mineral precipitation at the surface and within the deposit. Since mineral precipitation continues, it suggests that some of these septae may form at the interface between a network of pores carrying hot water out and pores providing a circulation of cold oxygenated water in, focusing the inorganic and organic processes that contribute to mineral superaturation. If this were the case, the septae should preserve mineralic and textural differences from one side to another, which might provide a clue of the unusual microenvironmental conditions that prevailed.

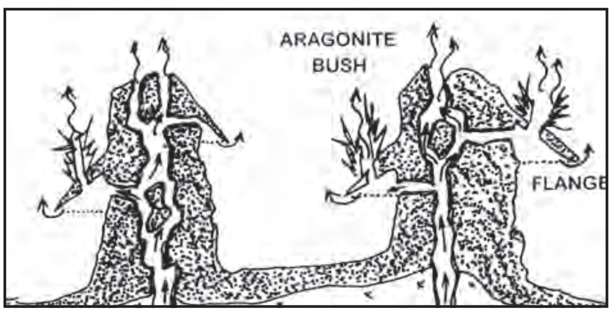

Figure 3: Cross-section of vent deposits, flanges and aragonite bushes, Lost City (reported by Kelley, et al, 2007).

4. Folia, Mineral Bushes

Among the most unusual speleothems are folia (Davis, 2000), which are generally composed of carbonate minerals. They occur on vertical and/or overhanging passage walls, where they resemble upside-down terraces or rice paddies. They have been described from very few caves in the world, including Carlsbad Cavern and Lechuguilla Cave in the Guadalupe Mountains, and elsewhere (Audra et al., 2009). Even in these caves folia are found in only a few particular sites, although where they do occur they are commonly abundant. Calcite folia are almost always associated with settings that were below the water table at the time of precipitation. Folia have not been found in perched pools. Examples studied by this author in Carlsbad Cavern and Goshute Cave display two general morphologies. The most common variety has an outer wall, which is thicker than it is high, and generally level. These commonly cover the entire wall, giving it the appearance of inverted rice paddies or microgours. The folia walls may be up to several centimeters wide and a centimeter or so high, and may extend horizontally up to several decimeters along the passage wall. When seen from below their outline may be simple or convolute, especially on highly overhung surfaces. These are here referred to as Type I folia (Fig. 4). A less common variety of folia, referred to as Type II folia, flare outwards from the overhung walls and ceilings, with walls that are thinner than they are high and a lower surface that may be inclined from one side to the other. In a nameless room of Carlsbad Cavern near the deep point, these may reach lengths of 2 meters and heights of 20 cm, with a wall thickness of a centimeter or so. Kevin Downey (personal communication) describes Type II folia from the Matansa region of Cuba, that may reach 1 m high and 50 m long. Whereas Type I folia occur in fields of similarly formed examples, Type II folia may occur with Type I forms but are rarely closely associated with other Type II examples. Although Type I and Type II folia are morphologically distinct, their co-occurrence suggests a genetic relation.

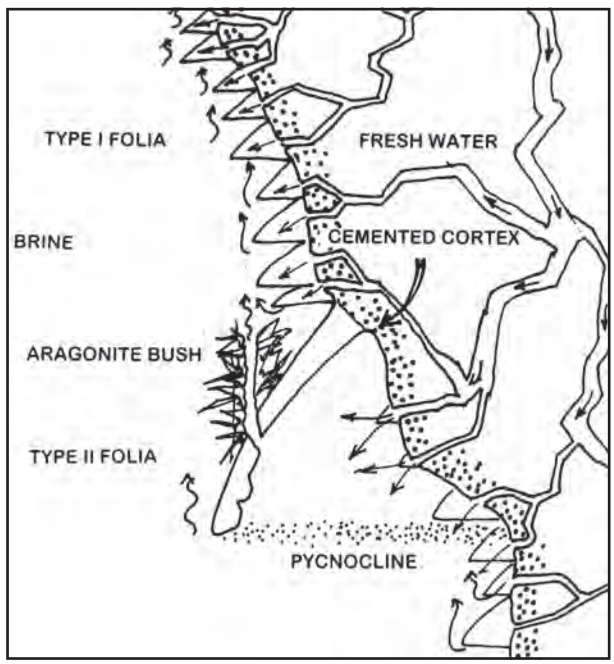

Figure 4: Folia form where fresh water emerging from the rock face mixes with brines in the cave passage.

Davis (2000, 2004) has proposed that folia result from evaporation and degassing at the water-rock contact at the top of pools in flooded caves, broadly comparable to microgours forming from water flowing over inclined surfaces, and with the trapping of suspended material. He compares the vent and flange deposits at the Lost City to tufa deposits at Mono Lake, California, which also form from mixing. Davis generally minimizes the similarities of folia with vent flanges. Although he accepts a mixing origin for both folia and helictites bushes, he ascribes them to different processes. A comparison of helictites bushes and mineral bushes associated with vents might be useful. However, it the pool surface was supersaturated due to degassing, precipitation should occur around the pools, not preferentially on overhanging surfaces. No explanation is given for the lack of precipitates at the surface of the pool where the rock surface faces upwards.

Green (1997) suggested that folia result from bubbles of CO_2 rising up along overhung walls and ceilings, with degassing of the CO_2 contributing to carbonate supersaturation. Audra et al. (2009) presents a list of most known folia sites, and like Green calls on degassing of geothermal groundwaters. Rising bubbles will expand as confining pressure decreases, which is cited as the cause of larger folia occurring near the top of the zone. This mechanism is consistent with the largest folia being found where angles and grooves in the overhung walls and ceilings channel gasses upwards. No explanation of is given of why precipitates are preferentially developed on overhung surfaces. Degassing could result from the upward flow of CO2-saturated hypogene fluids, but what drives this upwards flow?

5. The Lost City Model for the Development of Folia, Crystalline Trees and Parallel Tubes

Field relationships at the Lost City suggest an alternative model for the development of some folia. In this model less dense fresh water seeps out of a vertical or overhanging wall into a passage filled with brines and rises upwards. Mixing with the brines in the passage, in places associated with increased pH due to chemolithotrophic processes, results in supersaturation localized at the fresh water-brine-substrate contact (Fig. 4). Mixing zones have commonly been considered as potential environments of bedrock dissolution (Bögli, 1980; Plummer, 1975; Palmer et al., 1977; Queen et al, 1977; Palmer, 1991; Mylroie and Carew, 1990, 1995), in which two saturated solutions mix and generate an undersaturated solution because of the nonlinearity of the mineral solubility as a function of ionic strength, alkalinity, etc. However, depending on the initial chemistry of the fluids, the resulting mixed fluids may be supersaturated. This was recognized as a potential environment of dolomitization (Badiozamani, 1973). Carbonate precipitation in these mixed fluids may take place through inorganic processes associated with mixing, as well as due to biologic processes associated with chemolithotrophic microbes living at the interface between oxidized fresh water and reduced brines. If water rises out of an upward-facing surface into a brine-filled passage, bushes and trees of carbonate precipitates may result (Fig. 5). Davis (1987) describes subaqueous helictite bushes with rafts, which he ascribes to mixing. Although most aragonite bushes in the Guadalupe Mountains are thought to result from evaporation associated with spatter-sites around drip-points (Thrailkill, 1987), it may be that hollow crystalline bushes over and surrounding holes in the passage floor could be subaqueous features.

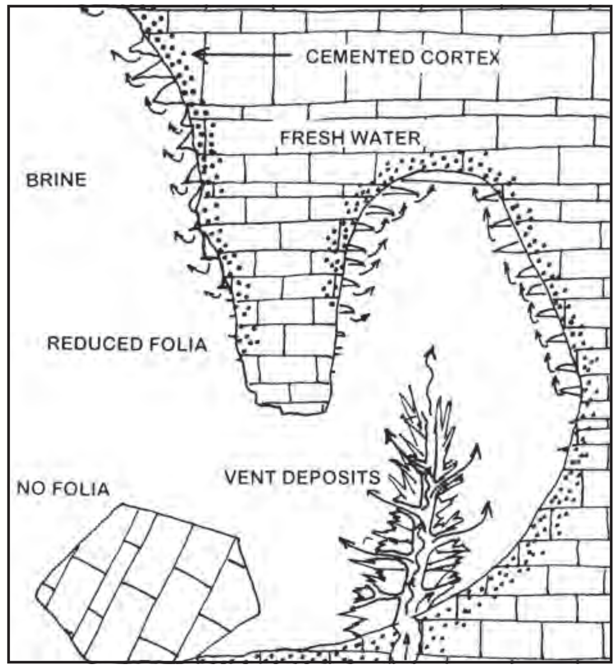

Figure 5: Large-scale relationships of folia to cave morphology.

In locales where this model is correct, folia should not be found on loose blocks, which would not have had a source of fresh water. On the lower part of narrow pendants the supply of fresh water would have been downwardly attenuated, and folia would be expected to be dramatically smaller or lacking compared to the upper part of the same pendants. This fits the observed distribution at Carlsbad Cavern but should be checked at other folia sites. Furthermore, folia formed in this manner might be expected to be accompanied by a well-cemented cortex of rock, through which small pores supplied fresh water to the inner recessed area of the folia. In this model folia may be developed on surfaces facing the fresh water lens but should not occur, or be active on surfaces facing the briny groundwater. As lighter density water emerges from the rock surface and flows upward, there will be a convergence of flow paths and an upwards increase in flow, which could result in an upwards increase in folia size along flow paths.

It is not suggested that all folia formed from mixing. The Davis (2000, 2004) and Audra et al (2009) models may obtain in particular environments. The products of these three models should show systematic differences., which result from different drives of supersaturation. In the Davis model, degassing and agitation near the surface of pools should result in supersaturation decreasing beneath the water surface, and carbonate precipitation on all surfaces, being pronounced at particular horizons. In the Audra et al. model, degassing above a base level results in precipitation on all surfaces above this level, with folia concentrated along and increasing in size upward along flow paths. In the vent-mixing model proposed here, folia will be preferentially developed on select surfaces from which fresh water emerged, but not on blocks and pillars cut off from sources of fresh water. Where they occur, they will be larger upwards along flow paths, but not uniformly larger at any one horizon.

Differences between Type I and Type II folia might result from the site-specific supply rate of water seeping though the porous wall, with greater supply rates or smaller differences in fluid density being associated with inclined fresh water-brine interfaces. Gradual cementation of the overall surface associated with precipitation of Type I folia might result in flow being progressively limited limited to fewer sites, which might then develop Type II over Type I features. Where fresh water emerges from upwards facing surfaces bushes and trees of precipitate may accumulate. It seems likely that the subaqueous helictites bushes described by Davis (2004) may represent this type of deposit.

6. Beyond Folia

It seems most productive to consider folia as potential products of evolving phreatic mixing environments, in which the waters may become either saturated or undersaturated. The folia would not have formed if there had not been a void. If the void had also formed from mixing, then the precipitation of folia would represent a change in the chemistry of end-member solutions or in the proportions, in which they were mixed. If mixing of waters emerging from a rock surface continues to result in supersaturation, the surface will become increasingly well cemented, so that outward flow is increasingly limited to major flow paths. This progressive carbonate precipitation in the rock cortex accompanied by canalization of flow, has been documented in the Lost City by Fruh-Green et al. (2003). In initially porous rocks, differences in the small-scale topography of the wall may result in the spatial concentration of areas of dissolution and precipitation. In the case of precipitation, this should lead to a situation where the surface adjusts to maintain a stable profile as areas closer to the source will attract flow, precipitate more carbonate as a cement within or on the surface, and consequently reduces flow rates and resulting mineral precipitation.. Where microbial activity is concentrated at a mixing zone, mineral precipitation may be concentrated, both because of mixing and because of the metabolic processes of the microflora. As the flow rates, patterns and chemistries evolve, so will the microbiological communities present.

Where fresh water flows out of the rock face and becomes more aggressive through mixing, a seemingly irregular pitted surface usually evolves. In rare cases, the surface recedes through the orderly growth of parallel tubes of different widths and lengths but similar longitudinal cross-sectional profile. These have been observed in Wingate's Cave Bermuda, in Carlsbad Cavern near Matlock's Pinch, and in the area near the S & M Crawl and Ghost Town in Lechuguilla Cave. As depressions in a surface deepen, they attract more flow, which in turn further dissolves the rock. This results in the progressive accentuation of the dissolutional surface. As low ridges become pinnacles, the supply of water, which might emerge at the surface, diminishes, so the pinnacles remain and may become more elongated and with attenuated bases. If this continues, collapse may ensue, obscuring the original field relationships. Inactive surfaces may become the site of mineral precipitation and diagenesis similar to that occurring in deep marine hardgrounds.

Consequently, it may be that folia only form in rare environments in which a balance between supersaturation and undersaturation occurs. If the main process associated with mixing were precipitation, then the process would be self-limiting as the flow paths were slowly occluded. If the main process associated with mixing were bedrock dissolution, then few precipitates might form and might be shortly redissolved. A stable, potentially long-lived environment could result if mixtures of small amounts of sea water with large amounts of vent water were undersaturated, while the mixtures with larger proportions of sea water resulted in supersaturated conditions.

7. Summary

As more and more is discovered about mixing zones, they continue to become more interesting. Understanding mixing zones not only helps answer some questions, but helps us ask more insightful ones. That there should be a new and significant type of deep-sea thermal spring is fascinating. That the thermal vents be associated with towers up to 60 m high is astounding That features associated with these hot springs should possibly shed light on the origins of some of the world's rarest speleothems is totally unexpected. It may be that just as deep marine vent systems provide clues to the workings of rare caves, caves can provide an insight into the operation and chemistry of even more inaccessible environments.

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MORPHODYNAMIC INCIDENCES OF THE TREPANNING OF THE ENDOKARST BY SOLUTION PIPES. EXAMPLES OF CHALK CAVES IN WESTERN EUROPE (FRANCE AND BELGIUM).

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The outlet of shaft zones in karst galleries is traditionally considered to be a logical continuation of the penetration of surface water towards the underground collectors. Subsequently, the observations are generally limited to simple morphological descriptions. The definition of two distinct dynamic sets - the introduction of surface waters (input karst) and the collecting/concentration/restitution of underground waters to the resurgences (output karst) - and the absence of systematic connection between input karst and output karst make it possible to consider an initially separate, even diachronic, evolution of these two dynamic sets. In order to check this assumption, we studied the impact of the trepanning of caves in two karstic networks of Western Europe. The first example develops in the fine chalk limestones of Normandy (France) where the bedrock porosity reaches 10 to 15 %. The second develops in the calcarenite layers of the Lower Meuse Basin near Liege (Belgium) where the effective porosity can exceed 50 %.

The Normandy cavity, mature and fossil, is largely filled in by Quaternary sediments (loess). It is explored for more than 600 m, of which a collector contributes 450 m to the development. The trepanning of this fossil and filled collector and its sequential functioning thus involved the ablation of the higher part of the fill and its substitution by terrigenous deposits from turbid introductary episodes, with sedimentation in conformity to the input water flow dynamics. Though the major incidence of these episodes is the installation of a specific morphology in an upstream-to-downstream organization: 1) dam effect in the upstream drain resulting in a deep alteration of the enclosing bedrock, 2) digging of a slope at the connection with the gallery roof, 3) development of a penetrable roof channel, 4) opening of a great empty chamber corresponding to an equilibrium reservoir over the original gallery, 5) digging of a smaller roof channel, which is progressively reduced downstream by the gradual absorption of the flood into the porous filling and walls of the collector. The Belgian cavity, recognized for a few tens of meters of development, is filled by terrigenous sediments, without any established karstic connection towards an emergence. The digging of a roof channel is prohibited by the absence of karstic continuity downstream. But we can notice the graded terrigenous filling beds, altered by the more recent episodes, and the development of a large tank chamber downstream where the high porosity of the calcarenite absorbs the introduced waters.

These two examples clearly illustrate two points. First, connection between the water input and the karstic output is not always ensured. Moreover, the digging of the input forms can be carried out independently of the output drainage. When the output karst is trepanned and is not functional any more, the effects of input dynamics are so recorded. The identification of these morphologies in the collectors can thus deliver major evidence concerning the evolution of the karstic system.

1. Introduction

The outlet of pit zones in karst galleries is commonly referred to as the logical connection of the penetration of waters from the surface to the underground collectors (MAIRE, 1990). As a result, the observations are generally limited to mere morphological descriptions which enlighten the enlargement of openings due to the thermal convection streams initiated by water falls. RODET (1992) proposes the concept of two distinct dynamic functions: one associated to the input karst as illustrated by the concentrated and/or diffuse surface water input and its circulation down to base level and, the second linked to the output karst with the collecting, concentration and restitution of water to the resurgences. This concept thus permits us to understand that those two dynamical sets can evolve independently without systematic connection (RODET, 1997).

This statement is largely illustrated by endokarst caving and by several hydrological studies carried out in the chalk limestones of the Western Paris Basin. In most cases, solution pipes (potholes) trepan the output drains. The diachronic genesis of input and output karst has been observed in several locations in Normandy (RODET *et al.*, 2006a) and Belgium (MINGUET, 2006; RODET *et al.*, 2006b; WILLEMS *et al.*, 2007).

2. Study Sites

Two different sites have been studied: the Petites Dales karst system and the CRSOA cave.

2.1. The Petites Dales karst system

This cave offers a mature mono-collector, two-meter wide, which meanders over 350 m from the *Espace des Six* chamber to the fossil outlet porch. One hundred meters upstream from the chamber, a solution pipe cuts into the ceiling of the gallery. Between those two points, we can observe the oversizing of the ceiling half tube (1 m large by 2 m high on average) developed over the filling of a three-meter large gallery. Terrigenous sediments covered by a layer of chalk boulders fill in the chamber up to the top of the ceiling half tube. Above it all, a two-meter high opening remains in the chamber. The solution features are limited; the clastic forms originated by the roof and wall collapse dominate (Fig. 1). This opening closes rapidly and becomes downstream a sloppy small ceiling half tube as a result of the water drainage. Along the collector downstream from the chamber, the non-linearity and section reducing of the roof channel point up the flood diminution and its gradual absorption into the porous filling and walls of the collector (Fig. 2).

Figure 1: Water storage chamber (Petites Dales cave). Over the terrigeneous sediment, one observes a chalky boulder and over the open space (J.P. Viard).

Figure 2: Ceiling half tube in the Petites Dales cave. Below the water storage chamber, a more or less well developed channel is opened at the roof of the collector (J. Rodet).

The lithological characterization of the Petites Dales karstic filling showed that sediments are essentially constituted by silts (LAIGNEL et al., 2004). Nevertheless, it is possible to distinguish three main families of sediments which present a rythmicity at several scales: brown clayed silts, beige silts, pale beige silts. The mineralogical and chemical comparisons of the karstic sediments with the likely sources (insoluble residue of chalk by way of weathering, clay-with-flints (CWF, Fig. 3) and loess by way of mechanical erosion) show that these sediments originate essentially from the superficial mechanical erosion of loess. The loessic particles are transported in suspension by the flooding water, introduced into the karst through sinkholes, and deposited within the karst aquifer. The insoluble residue originating from the chemical weathering of chalk, although sometimes present in the karstic sediments (brown clayey silts only), only represents a weak part.

The absence of allochtonous karstic deposits (from the CWF) could be surprising if we consider the important coverage of alterites and numerous dissolution vertical pipes filled with CWF in the study area. The discovery of a vertical pipe (about 430 m upstream from the cave entrance) connected to the main gallery would imply the

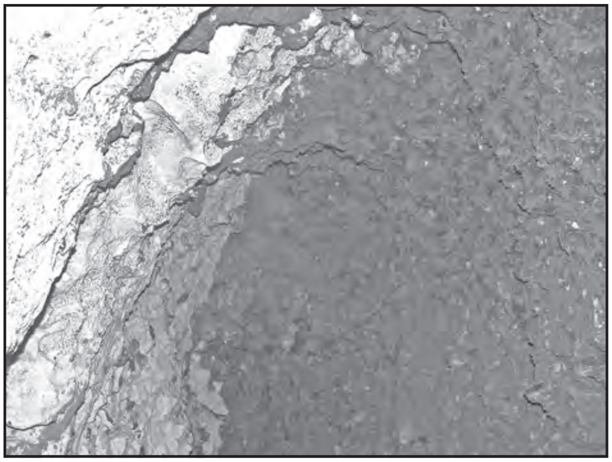

Figure 3: Chalk-with-flints at the base of a solution pipe (Petites Dales cave). On left side chalk, on right side CWF (J. Rodet).

existence of karstic deposits originating from CWF at the bottom of the filling. As no CWF have been observed at the top of the filling, we can suggest a hypothesis: the vertical pipe establishes a connection between the plateau and the endokarst. Thanks to the connection with the endokarstic horizontal network, the sedimentary content of the pipe (essentially CWF and loess at the top) is drawn downwards. Once the CWF within the pipe has been drawn, only loess would be eroded, transported and deposited in the karst. Indeed, it is proved that the unconsolidated loess coverage is particularly sensitive to erosion, whereas the CWF coverage is often compared to a concrete, highly resisting to erosion. Such a hypothesis supposes the presence of CWF at the base of the filling but only the superior 2 m were studied whereas the total thickness of karstic deposits is of the order of 8 to 10 m. To check this hypothesis, it would be necessary to access at the bottom of the filling with a borehole (contact between the chalk substratum and the filling). It is so verified that the sedimentary budget offered to the karstic domain is mainly of superficial origin (LACROIX *et al.*, 2000). The surface behaves as a sedimentary stock, the infiltration zones are especially transit zones and the karst is a sedimentation environment.

2.2. The CRSOA Cave

The CRSOA Cave develops in the *Montagne Saint-Pierre* hill, between Liege and Maastricht, on the Belgo-Dutch border. It consists in a fossil filled gallery which develops northwards and ends suddenly, without any sign of outlet drain (hydraulic leakages). Whereas the upstream part appears relatively narrow (1.5 m large by 2 m high) the downstream part exhibits a weighty volume, most of which develops at a higher level than the previous part. Porosity measures were conducted at the Department of Geology of the University of Liege on calcarenite samples: they give very high values that can exceed 50%.

A sedimentological study has identified 4 possible sources for the constituents of the karstic filling of the *Montagne Saint-Pierre*: solution residue of limestone/calcarenite (autochthonous, in place weathering), Tongrian sands, alluvial deposits and loess. The insoluble residue of limestone, the loess and the Tongrian sands have a mode of respectively 8-10 µm, 10-50 µm (LACROIX *et al.*, 2000, 2002) and 100-500 µm (JUVIGNÉ & RENARD, 1991). The lithological characterization and paleohydrodynamic study of the karstic sediments (MINGUET, 2006) specify that the filling is a mixing of the weathering residue of limestone/calcarenite (CWF) and of Tongrian sands. The sands necessarily originate from land surface and subsequently prove the opening of the system by means of the draining of solution pipes (Fig.4) and karstic transport. A linear sedimentary survey along the gallery exhibits a decreasing downstream grading from the introduction (coarse-grained sediments) towards the reservoir chamber (fine-grained sediments) associated with the decreasing flow velocity. More generally, the filling of the CRSOA cave is characterized by low hydrodynamic conditions.

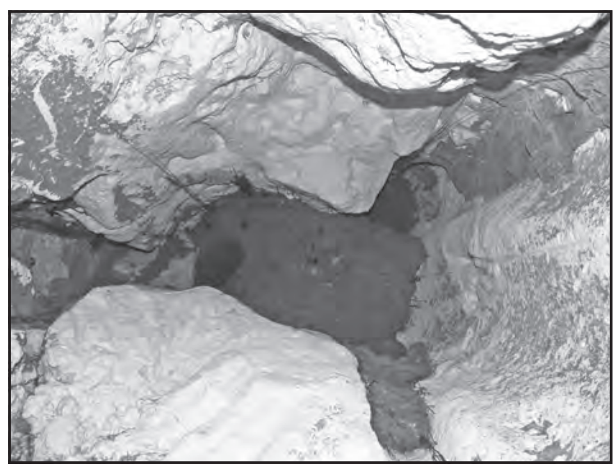

Figure 4: Solution pipe and its filling uptream the CRSOA cave. Roots indicate the proximity of the plateau surface (L. Willems).

3. The Functioning

In both study cases, we observe the diachronic development of a solution pipe situated hydraulically upstream of the karstified void; it clearly appears that the solution pipe is more recent than the horizontal conduit and that it discharged into the karstic void by cutting downwards into it. In both study cases, the sedimentological studies (granulometry, chemistry, mineralogy) clearly indicated the exogenous origin of the fillings and thus their introduction by trepanation. Moreover, spatial analysis enlightens longitudinal grading of the fillings, the coarse elements being deposited much more upstream than the fine ones. This granulometric classification demonstrates an oriented flow and identifies the solution pipe as the source. In both cases, the particle size shows at the beginning a high water dynamic whereas downstream the fine sediments largely prevail. One thus concludes that there is a rather fast loss of dynamic competence which authorizes the longitudinal grano-classification. This mechanism of sudden input is repetitive, involving episodes of gullying in the terrigeneous deposits which channel the flows (MINGUET, 2006), giving complex sedimentary organizations.

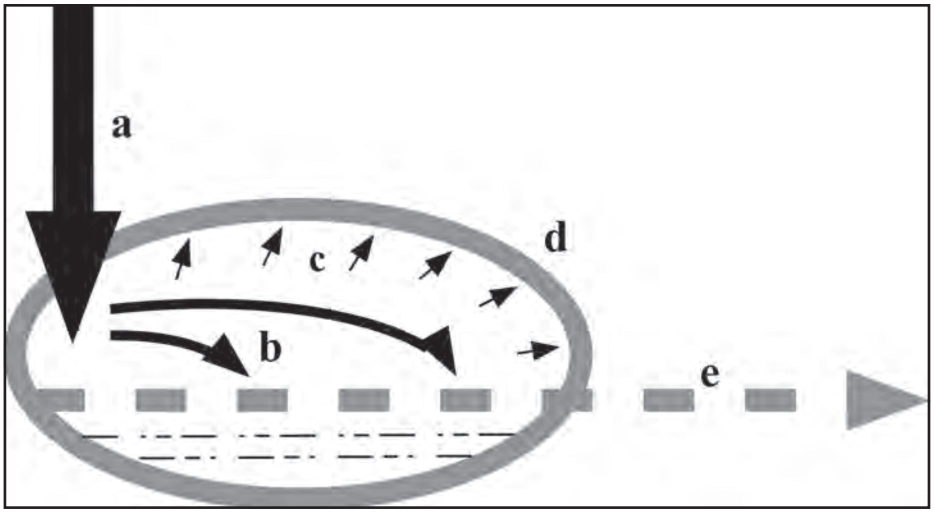

Figure 6: CRSOA Cave trepanning input conceptual model. In a node of weathered limestone within the calcarenite, a trepanation (A) introduced, in several sequences, terrigenous elements and especially enormous quantities of water (b). The flush effect runs up against the walls without fast evacuation which generates a fast sedimentation of the transported solid matters. Above, stored water exerts a peripheral pressure on the walls of the weathering node, and established little by little a typical morphology of storage (equilibrium chimney) (c). A vertical stratification is noted: at the base, the sedimentary filling partially sorted along the gallery; above at the top of the "perennial" (most frequent) water level, one can observe the maximum side opening with the development of peripheral pockets; and at the top develops a vast empty space (d), storage of the water surplus. The main part of evacuated water is absorbed by porosity (E).

4. The Question of the Hydraulic Outlet

In the Petites Dales mature karst system, there is a well organized hydraulic outlet illustrated by the collector but it was filled before the cavers' exploration. The sedimentary sections show erosional surfaces, tilting and outlier deposits. Erosional surfaces prove the succession of erosional powerful flows. The tilting deposits suggest destabilizations of the sediments by water inrush or by over-deepening. The outlier deposits seem to illustrate a sudden loss of transport capacity by stopping water flow. It thus gives rise to a morphology illustrating the succession of sudden, fast and spatially limited dynamic flows. This can illustrate the mechanism of sudden,

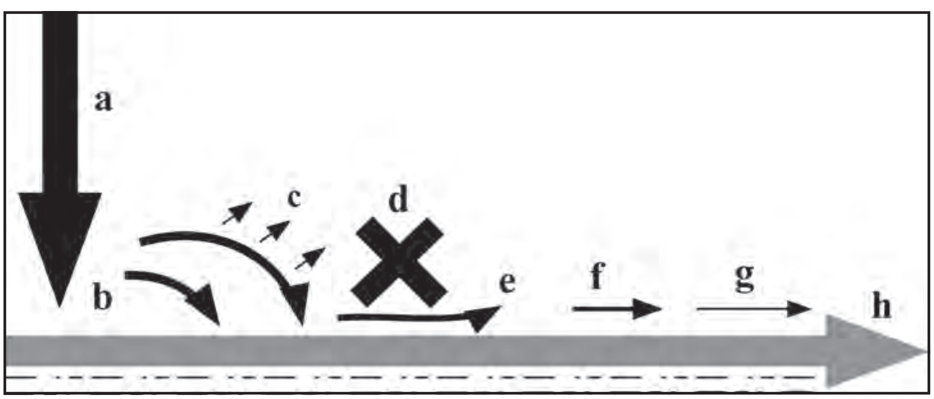

Figure 5: Petites Dales Cave trepanning input conceptual model. In a fossil and filled drain (h), a trepanation (a) introduced, in several sequences, terrigenous sediments and especially enormous quantities of water (b). The flush effect partially pushes the filling until it obturates the drain (d). Upstream the dam, the water storage develops a typical morphology of "equilibrium chimney" (c). Its form more lengthened than high is explained by the use of the joints installed in the axis of the karstic drain. A reduced part of the introductions (e) periodically manages to exceed the dam and digs little by little, a channel (f) in the roof of the collector which attenuates (g) as one moves away from the dam. While basing on dimensions of the ceiling half tube, one can estimate that half of the flow is evacuated by the channel downstream from the dam. The remainder is evacuated by porosity and especially by wall leakes.

violent and short water inputs into the drain (Fig.5). Dynamics such as this seem compatible with a mechanism of repetitive water inputs from a solution pipe into a filled karst drain.

In the CRSOA Cave, the part of the gallery below the solution pipe offers a consequent widening in width as well as in height, but all the walls finish in decimeter pockets without any visible exit. The output continuity is not obvious and it seems that most of the introduced floodwater is absorbed by the enclosing beds. If that is the case, it means that the hydraulic karst outlet is not organized and thus the underground vacuum is working as a reservoir for water introductions (Fig.6). This role of storage can then explain the over-sizing of the underground vacuum compared to the initial gallery size and especially compared to the absorbed volume of input waters.

In one and the other case, it appears that the lower part of the karstic system is under-sized compared to the flow introductions and thus that intermediate space, the chamber, is over-sized in order to temporarily store excesses floodwater inputs.

5. Conclusions

The two examples relate to floodwater introductions into poorly drained underground systems. The absence of an obvious direct connection with springs generates a specific morphogenetic behavior that might be termed “filling jam” or “filling dam”. It would be relevant to study examples of trepanation in open networks but their “open” status is not favorable for the examination of the dynamics of the input mechanism and its effect on the morphology of the output gallery. It would also be necessary to later examine the “traditional” connections and more specifically the morphological succession of passage volumes located in the immediate hydraulic downstream of the input connection. Undoubtedly new information would permit us to give better perspective to our observations.

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DEVELOPMENT AND FUNCTION OF A PERCHED AQUIFER IN THE COVERING LAYERS OF THE CHALK LIMESTONE IN THE PARIS BASIN (FRANCE)

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In the Northwestern Paris Basin, the evidence of a perched aquifer located in the overburden above the subcutaneous zone of the chalk limestones emphasizes the incidence of input waters on karst development. The Normandy plateau areas are mantled by a thick non-consolidated weathered coating and both Tertiary and Quaternary silty deposits. While chalky outcrops generally exhibit no major active karst features, these coated plateaus feature numerous significant karst phenomena, some of which are very active.

In the fillings of an active coastal karst system, the analysis of insoluble matters reveals that 20 % come from the output karst (phreatic zone), 50% from the roof of the chalky bedrock (epikarst) and the remaining 30% originate from the covering layers. More recently, geophysical prospecting gives prominence to the irregular surface of the roof of the chalk limestones. It permits the imaging of numerous depressions in which the solution pipes develop and at times affect the land surface in the way of dolines.

The installation of short piezometers in a plateau area and the geochemical monitoring of superficial water samples both indicate an important fluctuation of the perched water-table associated with rainfall and a significant mineralization of the infiltrating water stock. One can note the covering substratum is non-carbonated. Despite this fact, the bicarbonate content of superficial water is relatively high and close to the chalk aquifer content. It appears that the mineralization is due to diffusion from the weathered chalk contact. This mechanism also explains the high chloride content, much higher than the content of rainfall or of the chalk aquifer, notably during the relative dry periods or with the vegetal pumping. The observation of the contact between the overburden and the chalk bedrock shows the initiation of an impermeable layer. It results from the high weathering of chalk and its compaction under the superficial load and seems to limit the diffuse infiltration to the chalky porous medium, even when fissured. Though this specific layer is not continuous, it locally allows the infiltration, subsequently digging a solution pipe. This vertical development results from the quality of this weathered impermeable layer and not from the degree of chalk fissuration. Commonly, these solution pipes exhibit regular circumferences even when they intersect a diaclase.

The development of an aquifer in the covering layers is therefore an important factor for the karst development in the chalk limestone. The input karst is thus well-developed and dense when associated with this superficial aquifer. At the opposite, as a large part of the water stock flows to the chalk water-table, the output karst classically constrained by the efficient porosity of the enclosing bedrock is under-calibrated compared to the drainage basin.

1. Introduction

The karstification of coated areas has always been a problematic question (NICOD, 1994, 1995). The overburden is a complex object and covers a large variety of facies (LAUTRIDOU, 1985; LAIGNEL, 1997). Although the karstification under coverage is known for a long time as illustrated by dolines, the role of non-consolidated coating is still poorly defined (RODET, 1993). As described by BONTE (1971), the overburden is sometime considered as an obstacle to the karstification of the rock mass. Nonetheless it can still locally contain a perched water-table (RODET, 1992). In fact it appears that this aquifer is a more complicated object and it concerns a large part of the chalk limestones in the Paris Basin.

2. Observations

The number of observations on this perched aquifer has been increasing for several years and highlighted by various approaches. It demonstrates the complex functioning of the input zone to the chalk substratum. A Norman coastal karst system gives access on hundreds of meters in a river cave. The local geological context is particularly favourable to the study of solution origins. The basal Cenomanian Chalk formation which outcrops to the North is no more visible at the cave location as it dips beneath sea level. The nearby cliffs which are more than a hundred-meter high are essentially composed of Turonian Chalk and only their upper part is developing on a few meters in the Coniacian Chalk. Thanks to this stratigraphic disposition,

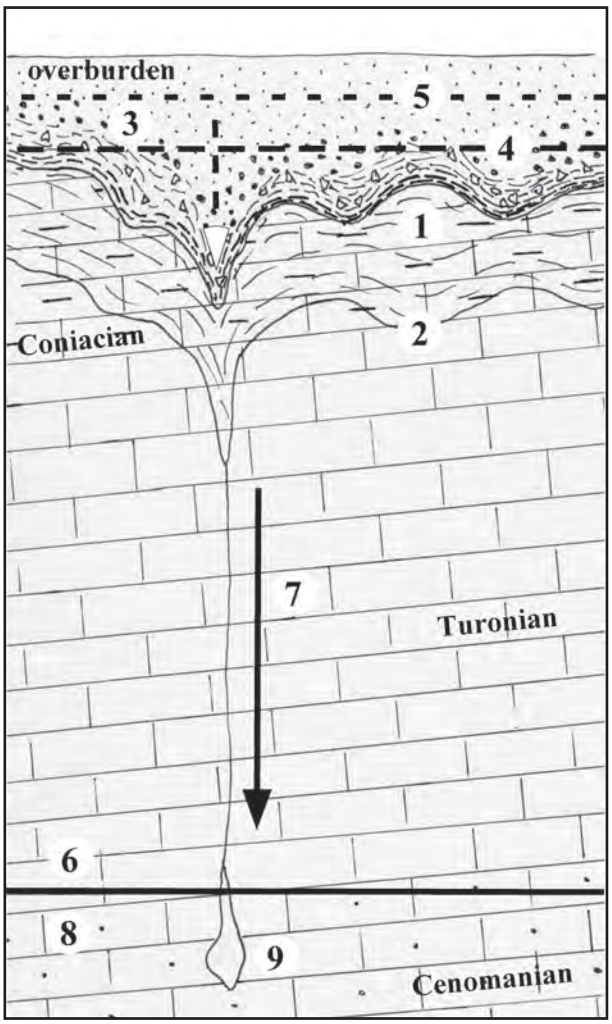

Figure 1 : Synthetic diagram of Le Heurt cliffs: (modified from Lacroix et al., 2000). 1- weathered chalk; 2- basis of the chalk weathering front (limit of the perched aquifer); 3- perched aquifer; 4- low water level; 5- high water level; 6- non saturated zone; 7- rapid infiltration; 8- saturated zone; 9- karst drain.

the analysis of samples from the karst filling and river gives surprising but valuable information on the origin of the chalk insolubles (LACROIX et al., 2000). At low flow, the particles contributed by the decalcification of the Cenomian Chalk represent 20% of all the contributions of particulate matter, while 50% come from the Coniacian Chalk and the final 30% from the covering layers. The absence of the decalcificate of the Turonian Chalk indicates a nearly complete absence of chemical alteration of these strata, corresponding to a zone of rapid vertical flow within an unsaturated zone. Thus the weathering of the chalk substratum, just beneath the interface with the surficial formations (Fig. 1), is therefore the main source of insoluble particles in the river cave (LACROIX et al., 2002).

A coupled geophysical and hydrogeological study carried out for a few years on a small catchment area near Rouen (Normandy) allowed the definition of a specific aquifer in the overburden of the chalk substratum. These surficial formations are siliceous and non-carbonated. The geophysical prospecting (electrical resistivity tomography and spontaneous polarisation) has confirmed the irregular contact between the roof of the chalk substratum and the weathered coating (Fig. 2). This topography is illustrated by the depressions associated with the genesis of vertical

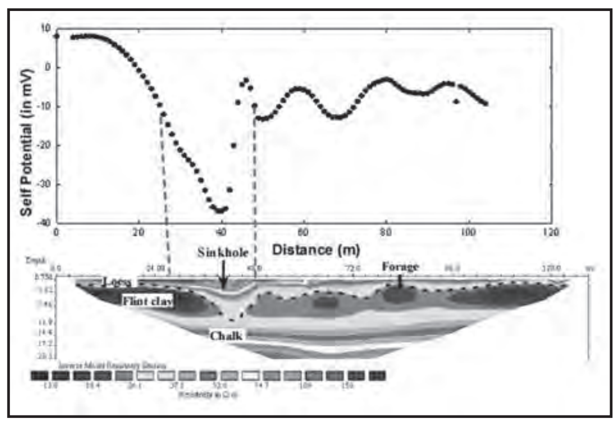

Figure 2: High-resolution self-potential profile along electrical resistivity pseudosection obtained at Bouville (modified from Jardani, 2006). The electrical resistivity tomography (Wenner-α array, electrode spacing of 3m) distinguishes the geometry of the different geological units according to their respective resistivity: chalk substratum, CWF and loess cover. The theoretical spontaneous polarisation (SP) signal corresponds either to the piezometric surface or to the first impermeable formation. A borehole is then used to correlate the two geophysical signals. The dashed line indicates the interface between the loess cover and the clay formation. The SP signal thus allows discriminating preferential groundwater flow pathways through sinkholes located as depressions in the CWF formation.

solution pipes that sometimes affect land surface in the way of dolines or sinkholes (JARDANI, 2006). Historically, such natural depressions have been voluntarily filled in for several reasons by the inhabitants who also use to dig other artificial depressions (ponds, various excavations in the surficial formations, marl pits...).

The monitoring of a network of boreholes located in the covering layers of this catchment allows the definition of a surficial aquifer behaviour. On the one hand, the piezometric follow-up highlights the great variation of the water-table under climatic constrain (rainfall, evapotranspiration). On the other hand, the hydrogeochemical analysis shows an important mineralization. Despite the fact the overburden is non-carbonated, the geochemical results notably show high level of bicarbonate, which are close to the chalk water content. The hypothesis is that the infiltrated waters reach the weathered chalk contact where they participate in the geochemical exchange (diffusion of ionic species) and the progression of the weathering front. The dry periods and/or the biological water uptake in soils are responsible for a relative increase in mineralization (Table 1). This mechanism is underlined by the high chloride values in this aquifer, much higher than the values of rainwater and chalk waters. The modalities of this mechanism still have to be precised but they bring emphasis on the major challenge of discriminating the evapotranspiration rates in the hydrogeochemical budget. The seasonality of these hydrologic transfers has been confirmed by the geophysical prospecting (Jardani et al, 2006).

		Surficial aquifer		Chalk aquifer	Rainfall
Species	Units	Winter	Summer		
SC	µS/cm	254	429	583	28
HCO_3	mg/l	128	151	295	nd (>0)
Ca^{2+}	mg/l	35	64	111	0,4
Cl^-	mg/l	10	24	20	3

Table 1: Table of hydrochemical values. SC: specific conductance, electrical conductivity of water at 25° C; HCO3- : internal method; Ca2+: ion chromatography; Cl- : ion chromatography. Surficial aquifer: data from Bouville study site (J. Brown, ongoing PhD thesis); chalk aquifer: ADES database, local annual mean values from Limesy; rainfall: RENECOFOR database, local annual mean values from Brotonne.

A fourth type of observations concerns the diagnosis of the contact between the overburden and the chalk substratum. In the absence of accessible potholes, it is necessary to visit numerous artificial pits which cross through the overburden to the chalk. In the underground quarries (for instance marl pits), the trepanation of solution pipes are other interesting observation sites. They confirm the development of an impermeable layer which consists in a hydrological screen (Figs. 3, 4) of highly weathered chalk compacted under the weight of the covering load. The hypothesis is that this horizon follows the weathered front at the top of the chalk and thus forbids the introduction of water into the chalk substratum even in the presence of a fissure or joint. Although, this screen is not continuous and locally, where an absence occurs, it allows the penetration of water into the chalk resulting in a solution pipe. The development of the input karst into the chalk thus depends on the failing of the screen and not on the occurrence of tectonics fissures in the bedrock. Other evidence is the common observation of the regular circumference of solution pipes even if they cut a diaclase.

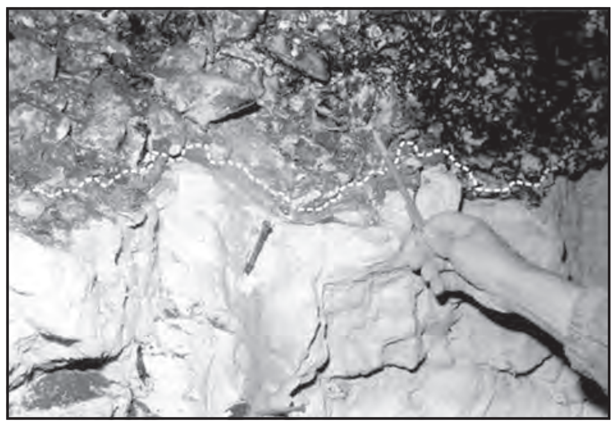

Figure 3: Contact between the overburden (CWF) and the chalk substratum (white). The dotted line delimits the hydrological screen consisting of compacted chalk alterites (photo. J. Rodet). One can distinguish the finely stratified structure in this impermeable layer of centimeter thickness.

Figure 4: The hydrological screen can trepan a fossil horizontal drain (photo. J. Rodet).

3- Discussion : Towards a Morphokarstic Model

The input conditions in the chalk karst have been in debate for a long time (RODET, 1992, 1997). As shown in classic massive limestones, some authors have given to the fissuration the guiding function of initiation and development of solution pipes, neglecting the impact of the bedrock porosity. Some others argue that the clay-with-flints (CWF) forbids the introduction except in places where CWF does not exist. Recently, other authors depicted the concept of a humid buffer zone ("humid sponge" of JAILLET, 2005) without further explanation on its functioning.

The description of an aquifer in the non-consolidated covering layers and its relation with the solution pipes gives a new insight about the general frame and function of these layers in the genesis of the input karst. It makes it clear that this perched aquifer plays a major role in the vertical progression of the weathering front of the chalk bedrock, from which it acquires its mineralization, and in the enlargement and digging of the solution pipes responsible for the input karst densification. However, this aquifer is not properly karstic (JARDANI, 2006) even if infra-formation voids benefit to rapid flow conditions. It has to be distinguished from the classic concept of epikarst aquifer in carbonate rocks (FORD & WILLIAMS, 2007).

Downstream, in the vicinity of valleys, one can generally observe that the output karst drains in chalk limestones are generally under-calibrated compared to the similar galleries in classic limestones for equivalent drainage basin in the temperate regions of Western Europe. This result has to be interpreted as the impact of the bedrock characteristics. On the contrary, the dimensions of input drains in chalk are comparable to those of classic karst (JAILLET, 2005; CHABERT & MAINGONNAT, 1977). In fact, as illustrated in the present paper, the introduction into the karst depends on the input conditions and not on the chalk bedrock itself, with no direct impact on the quality of observed input features. On the opposite, in the output karst, the matrix and fissural porosity ensures a reservoir capacity which is partially drained by the karst. It is clear that a part of the specific output in chalk basins is temporarily stored in the water-table and does not transit by the karst. As a result, the drains of the output karst are clearly under-sized.

4. Conclusions

The recent studies allow discussing the incidence of a perched aquifer and the associated water introductions on the karstification of chalk limestones in the Northwestern Paris Basin. While in the Northern part of the Basin large areas of outcropping chalk(almost without coverage) generally exhibit no major active karst features, the Western Norman coated plateaus feature numerous significant karst phenomena, some of which are very active.

The ongoing studies confirm the development of a perched aquifer in the overburden of the chalk limestones of the Paris Basin. It also confirms that the hydrochemical dynamic of this shallow aquifer is an important factor in the development of the karst in the underlying chalk mass (RODET, 1992). This fact explains why the input karst is so-well developed and dense as it is dependent on the surficial aquifer. On the opposite, the output karst depends on the global porosity of the rock mass. As a consequence, it is under-calibrated compared to the surface basin it drains, a large part of the water stock flowing by the chalk water-table.

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CYRENAICA KARST PROJECT (NORTH-EASTERN LYBIA)

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Investigations started in 2007 aims at studying karst morphologies of the Jabal Al Akhdar (Green Mountains) under a research agreement between the Earth Sciences Department of Garyounis University of Benghazi, Libya, and the HyIblean Speleo-hydrogeological Research Centre of Ragusa, Italy. The project's objectives include: developing a speleogenetic model consistent with the geodynamic evolution and climate changes that have taken place in the Tethyan-Mediterranean region since the Cretaceous; assisting the local socioeconomic framework addressing the discovery and protection of new water resources; mapping man-altered areas that are potentially at risk of instability and/or sinking because of the presence of karst voids; and the touristic use of caves with aesthetic interest.

Al Jabal Al Akhdar belt is in the northeastern part of Libya and consists of a promontory on the southern edge of the Mediterranean coast. It is 350 km long and 100 km wide. Tectonically, this belt is an inverted basin and has been affected by the Tethyan tectonic activities since its opening during the Jurassic. Lithologic outcrops of Al Jabal Al Akhdar belt include limited exposures of upper-Cretaceous carbonates that comprise E-W to ENE-WSW structural inliers emerged within extensive exposures of Eocene, Oligocene, and Miocene limestones. The series of geospeleological investigations carried out between the 2007 and 2008 have focused the karst area of the coastal belt of Benghazi, Sousa, and the plateau of El Marj, Al Bayda, and Derna. The study of a series of large collapse dolines, drained by a network of groundwater conducts the along the coast, was started in the area of Benghazi. In the same area, the Lethe karst system has a particularly interesting large underground lake that was a tourist attraction during the Italian colonial period. The project surveyed and documented the Brag Notta system, a significant karst outcrop in the coastal area of Sousa. Here, a collapse doline is hydrologically connected to a large, neighboring lake by a recent tectonic structure, which alternates between draining the brackish groundwater towards the sea and towards the hinterland, depending on the tidal excursions. In the raised areas of El Beida and El Marj plateau, a geomorphologic and hydrogeologic study discovered some big dolines and shafts within a typical cockpit topography. On the Derna plateau, the exploration of a complex labyrinthine cave revealed paleontologic and archaeological finds. Speleological explorations and geologic investigations of the above mentioned karst areas continue.

1. Introduction

A campaign of investigations started in 2007 for studying the karst phenomena of Cyrenaica; in particular: both surface and hypogeous morphologic characteristics, formulation of a speleogenetic model consistent with the regional geologic evolution including the climate changes contemporary to such an evolution, and, finally, the promotion and fruition of areas presenting geomorphologic singularities by proposing natural reservations and/or karst/speleological parks. Such a campaign originated from a research agreement stipulated between the Earth Sciences Department of Garyounis University of Benghazi and the Hyblean Speleo-hydrogeological Research Center of Ragusa (Abdelmalik & Ruggieri, 2007). The planned investigations, which have been going on in 2008 (Ruggieri, 2008), are still continuing and this paper aims at giving a first description of the results obtained so far.

2. Regional Structural Geology of Al Jabel Al Akhar

Al Jabal Al Akhdar belt is located in the northeastern part of Libya (Fig. 1) and it consists of a prominent promontory on the southern margin of the Mediterranean coast. It occupies about 350km in length by 100km wide. Tectonically, this belt in inverted basin and has been affected by the Tethyan tectonic activities since its opening during the Jurassic. Accordingly, its present shape is related to the Alpine tectonics by which Africa had been moved westwards relative to Eurasia during late Cretaceous to late Eocene times. Field observations and recent earthquake in Al Marj area added that the tectonic activities are still active particularly in the areas located close to the Tethyan coast. Lithologic outcrops of Al Jabal Al Akhdar belt involve limited exposures of upper Cretaceous that constitute E-W to ENE-WSW structural inliers emerged within extensive exposures of Eocene, Oligocene and, sometimes, Miocene. Paleocene outcrops are very restricted and missing mostly in the subsurface leading to a major unconformities underlain the Tertiary successions (El-Hawat & Abdulsamad , 2004).

Figure 1: Location of Al Jabal Al Akhdar.

Structurally, Al Jabal Al Akhdar has been evolved during two main successive phases of deformations. The first phase prevailed with the differential vertical movements and induced from the opening of Neotethys in late Triassic-early Cretaceous times. These movements created E-W to ENE-WSW normal fault trends to rift basins and, subsequently, resulted in lateral changes of the thickness and depositional environments of strata and creation many unconformities. The second phase of deformation started with the closure of the Tethys during late Cretaceous. This is attributed to the continuous rifting in the Atlantic Ocean and reversal separation between Africa and South America in late Cretaceous to late Eocene which, in turn, resulted in a right-lateral shear couple between Africa and Eurasia. In this context, the pre-existing normal fault trends are inverted or partitioned by strike slip components in style of wrenching tectonics and, elsewhere, transprission system. This explains the development of the ENE-WSW trending fold trains coeval with the formation of E-W to WNW-ESE right-lateral strike slip faults, ENE-WSW reverse and oblique thrust faults, N-S to NNE-SSW left-lateral strike slip faults and NNW-SSE normal faults in Al Jabal Al Akhdar.

3. Research Areas

The project is aiming at gaining the best possible insight on the karst morphologies present in Cyrenaica, underlining possible differences with respect to the various carbonates formation, structures and special local deformation case histories. The research campaign - started with an explorative phase and topographic documentary evidence - has concerned some areas located along the coast and in the hinterland, where significant karst phenomena were known and some of them had been investigated in the past years for drinkable water exploitation. In this regard, the selected areas to be investigated were: the coastal plain of Benghazi and Sousa; the plateau of Al Marj, Al Bayda and Dernah.

4. The Karst Area of the Plain of Benghazi

The city of Benghazi in the Mediterranean coast, main urban centre of Cyrenaica, develops in a plain involved with lagoon (Sebkha) and aeolian deposits of the Quaternary period, not far from the coast and a carbonate formation of the Middle Miocene (Ar Rajmah Formation), toward the hinterland, bounded to the north and south by the first escarpment of Al Jabal Al Akdar. Upon such a place, to the west of the city, fall the areas of Ayn Zaynah-Kuwiffia,Lethe-Abatny, and Magarin-Rommel Pools (Fig. 2), characterized by the presence of big collapse dolines, developed in the above mentioned carbonates formation, some of these connected with an extended network of conduits and active galleries draining toward the sea the water coming from of the facing plateau (Abdelmalik et al.,2004). In this regard, the charming small lakes, named Rommel Pools, in the Magarin area, and the system of springs of the Blue Lagoon constitute the cropping out of the water-bearing stratum inside collapsed dolines and one of the most obvious blowout of such a system along the coast, respectively. In this area two environmental criticalities, caused by the anthropic impact, have been pointed out, in the last years. One has been made up by the salification of the karst water-bearing system because of incipient sea-water intrusion which has brought on the gradual abandonment of karst drinkable water resources previously utilized; the other one is constituted by the presence of urbanized areas potentially at risk of sinking because of the presence of not too deep karst voids.

The investigations relative to the first phase, also aimed at reducing the above mentioned risks, started by studying the Lethe system consisting of four large dolines lined up along structural systems with NE-SW direction and by the homonymous Lethe Cave, involved with a big lake and an active water circulation. The preliminary results of the investigations, still going on, have pointed out conditions of geostationary criticality in correspondence with the accessible terminal zone of the cave, the top of which, already liable to relaxations of a certain volumetric

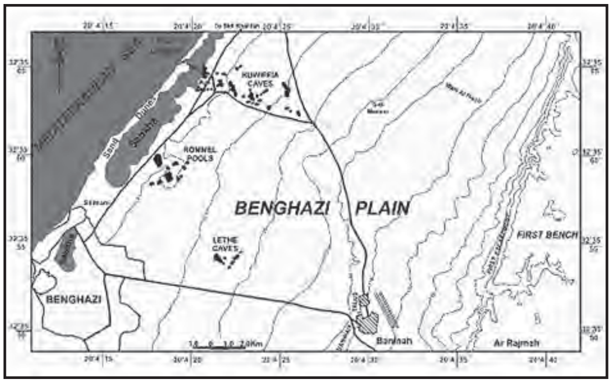

Figure 2: Map of Benghazi plain showing the geomorphologic setting of the area and the location of the three distinctive areas of karst development observed in Ayn Zayana-Kuwiffia, Lethe, and Magarin.

importance, seems today to find itself at a few meters of depth from the urbanized outside. A detail of historical interest concerns the presence of works of tourist fruition carried out during the Italian colonial period, both inside (landing-stage for visiting the lake, drains to lower the water level) and outside the cave (access staircases, recreational spaces, and so on).

An analogous situation of geostationary criticality was found in the area of Jabbah overhanging the homonymous cave (Fig. 3) from which, until about ten years ago it was drawn drinkable water, today polluted because of the above mentioned reasons of natural and anthropic disturbance. On the basis of the speleo-topographic survey evidence obtained, the continuation of the investigations shall anticipate, thus, the carrying out of further speleological explorations for defining the planimetry of both the accessible tunnels, in part flooded, and those under water, and geophysical and geostructural investigations for defining the thicknesses and the elasto-mechanical proprieties of the rocks forming the top, in order to make safe the areas at risk. It is being studied also a feasibility project to restore the Lethe Cave for its tourist fruition, in the framework of a broader design of protection and promotion of the geomorphological heritage of the previously mentioned areas for establishing a geopark.

5. The Coastal Belt of Sousa

At about 14 km to the west of Sousa (the greek Apollonia, port of Cyrene), along the narrow coastal belt, bounded to the south by a spectacular paleo-cliff, stretched out for about 21 km in the WNW-ESE direction, dissected by deep fluvial karst canyons, it is located the Brug Notta karst system, consisting of two dolines, at a short distance, about 30 m, from each other (Fig. 4). These structures, shaped in the limestone of the Middle Miocene of the Dernah Formation,

Figure 3: Building over the thin ceiling of Jabbah cave in the karst plain of Benghazi (photo by R.Ruggieri).

rise to about 20-25 m above sea level, from which they are 250-330 m distant. The main doline, intersected by NE-SW fault systems, has a sub circular shape with a diameter of about 110 m and accommodates a lake about 40 m deep. The minor one with a sub elliptic shape, with the larger axis 40 m long and the smaller one about 25 m long, is instead dissected by a fault in the NNW-SSE direction, upon which there is a shaft about 10 m deep, and it is also involved with fillings of likely sea transgression. Exploration of this last doline has allowed to reach the system of active conduits, positioned over a structure of new formation, that drains toward SSE the brackish water coming from the neighbouring karst lake. The future explorations will aim at clarifying such an apparent anomaly of the draining toward the mountain, rather than toward the neighbouring coast, likely linked with a capture phenomenon promoted by the opening of the structure oriented NNW-SSE generated as a consequence of late quaternary tectonics risings.

6. The Karst Area of Ras al Hilal-Dernah

Such a karst area includes a belt of about 50 km running along the coast in the NW-SE direction from the Gulf of Ras al Hilal to Dernah, extending toward the hinterland for about 20 km. Along the coast there are semi flooded sea caves, while along the escarpment there are several fluvial-

Figure 4: The limestone cliff and the lake doline Brug Notta along the costal belt of Sousa (photo by R.Ruggieri).

karst canyons in the average oriented in the NNE-SSW direction. Among these the Wadi Darna, with its mouth near the homonymous city, is surely the most interesting one, due to the expanse of the basin and the length of the cut running for about 40 km toward SE, then toward NNE to the sea for about 25 km more. In such a basin, along the middle course of the Wadi Ehtaiz, on the left slope at altitudes around 275 m above sea level there are some fossil karst caves, the most important of which, the Shingeia 1 has been an object of exploration and topographical survey. The cave develops in Eocene nummulitic limestone of the Dernah Formation, the structure of which, characterized by big blocks aggregated one another (because of likely slumping phenomena), has determined its labyrinthine state not linked with one or more particular structural discontinuities. Archaeological and paleontologic finds (Fig. 5) have been found in the caves during the explorations. The continuation of the investigations in this area will aim at correlating the paleo karst phenomena, present at various levels along the canyons and currently under water along the coast, with the tectonic liftings and the eustatic change that have deepened the karst water circulation of the plateau and at carrying out campaigns of paleontologic and archaeological investigations.

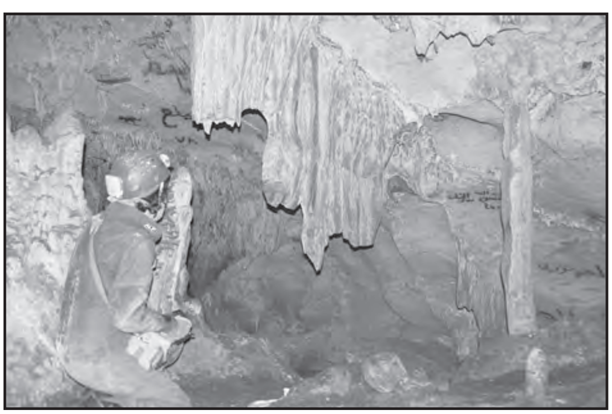

Figure 5: Corroded speleothem in the Shingeia cave (photo by G. Savasta).

7. The Karst Area of Al Marj and Al Bayda

Some areas in the districts of El Bayda and El Marj have turned out to be of great geomorphologic interest, due to both the shapes of the relief and the presence of karst macro morphologies. In the first area, during some reconnaissances, speleological explorations and topographic survey measurements, concerning some caves located at various levels on the slopes of the Wadi Al Kuf at about 16 km to SW of Al Bayda, were carried out. These last ones of fluvial-karst origin, started along bedding planes of the Dernah Formation, mark ancient and subsequent base levels of the valley with regard to the risings of the plateau and to the Pleistocene eustatic changes. There are three large dolines and a deep swallowhole in a belt a little less than 3 km at about 36 km to west of Al Bayda in the plateau located between the first and the second escarpment, at an altitude of about 140 m above sea level. The above mentioned dolines present a sub elliptical shape with larger axes between 180 and 370 m maximum, stretched in the NNE-SSW direction, smaller axes between 140 and 210 m and a depth of about 100 m (Fig. 6).

Figure 6: Big doline in the karst area of El Beyda (photo by G. Savasta).

The second and broader area of historical interest, not too far from the city of Al Marj, is located in a belt delimited to west by the second escarpment, positioned on a regional structure having a NE-SW direction. Such an area of about 250 km^2, about 32 km long and 5 km wide, at altitudes of about 450 m above sea level, shows a typical cockpit relief with depressions and low hills having from sub conical to elliptical shapes. In the depressed areas with flat bottoms there are deep swallow-holes among which the Hawa Bu Naiduah will be explored next. The continuation of the investigations in the above described areas will be addressed to the speleological exploration of the swallow holes and to the geostructural, morphometric, and speleogenetic study of the large dolines.

8. Conclusions

During the first campaigns of speleological investigations carried out in 2007 and 2008, various caves, some in part known and other not, were explored and documented; furthermore, several geomorphologic survey, both on the surface and underground, were carried out. The results so far obtained allow to draw a preliminary picture of the karst phenomena originated in the Al Jabal Al Akhdar. Such a picture is of great interest with respect to both the surface characteristics observed (cockpit relief, large dolines, deep swallow-holes) and to the hypogeous ones, fossils and active, these last ones marked by a widespread network of tunnels deep as far as about 80 m below the current sea level.

What has been so far described, although rich in unpublished material, does not certainly exhaust the karst phenomena present and the evolutionary geodynamics linked to them, taking into account also the vastness of the investigated area. Therefore, the continuation of the investigations of the Cyrenaica karst project for the next two years shall aim at reaching the preset objectives, both scientific – regarding the geological knowledge of the karst phenomena examined, included in the most general evolutionary geodynamic context of the southern Mediterranean area – and those of socio-environmental interest through the promotion and popularization of the karst geomorphological heritage which has the requirements to become a geopark for scientific and geoturistic ends.

Acknowledgments

Many thanks are given to the Earth Sciences Department of Garyounis University of Benghazi for their cooperation for realizing the Cyrenaica karst project, and to Dr. Giorgio Pirrello, former consul at the General Consulate of Benghazi for his assistance to start a cooperation relationship with the above mentioned university.

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MORMON LAKE – AN ARIZONA, USA, POLJE

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Abstract

Mormon Lake is the largest naturally occurring lake in Arizona, USA and may be Arizona's only polje. The lake is located in Coconino County, approximately 45 km southeast of Flagstaff and on the Coconino Plateau in north-central Arizona. The Coconino plateau makes up part of the southern Colorado Plateau uplift. Mormon Lake is a shallow lake approximately 18 km^2 in size but varies depending upon seasonal precipitation. Generally, the lake reaches it maximum size during winter months and is reduced during summer. During droughts, the lake may disappear entirely. Mormon Lake is located at an elevation of 2122 m and is elliptical is shape, internally drained, and contained within a relatively flat and broad topographic depression. The highlands surrounding the lake are composed of Pliocene or Miocene basalt flows associated with the San Francisco Peaks volcanic field. However, the lakes are underlain by the karstified Kaibab Limestone of Permian age. Water feeding the lake is derived from the surrounding highlands and has created alluvial deposits in and around the lake. The subterranean flowpaths for Mormon Lake have not been determine but may recharge the Coconino Sandstone underlying the Kaibab Limestone or may discharge to the northeast or south along the Mogollon Rim where the Kiabab Limestone outcrops.

Poljes are relatively uncommon in the United States in comparison to the Mediterranean and few are known from the United States west of the Mississippi River. Mormon Lake may be the best example of a Polje in the southwestern United States.

CAVES FORMED BY CAMBERING IN THE SOUTHERN COTSWOLD HILLS, ENGLAND

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Caves formed by cambering and mass movement are under-appreciated by the scientific community, both as objects for study in themselves and as repositories for paleogeographic information. In the southern Cotswold Hills, a sequence of interbedded limestones and mudstones has been deeply dissected by the (Bristol) River Avon and its tributaries. Cambering has opened up gull caves *within* the rock sequence by a system of sequential unweighting, whereby individual joint-bounded blocks of rock move independently while neighboring blocks support the overlying strata (which are not subject to extension). On confined hillslopes, the direction of extension is in the direction of topographic gradient; unconfined, the stratal dip direction has a significant influence on the overall direction of movement. If there are abrupt changes of hillslope direction, movement may be in two directions with a camber spreading axis running directly into the hillside.

Gull caves can also give paleogeographic information. In the southern Cotswold Hills, there are both archaeological deposits and placer deposits of clasts from an early Quaternary glacial drift. There are also speleothems, since the gulled strata are Jurassic limestones, which have been radiometrically dated to give a minimum age for the cambering. Solution features in the caves favor one joint set over the others, and show the direction of paleo-groundwater movement before cambering began. This joint set is parallel to the current course of the river, which provides evidence for river capture by the proto- River Avon of River Thames headstreams. The greatly enhanced flow in the Avon valley after capture caused the rapid overdeepening which triggered the original cambering and thus formation of the caves themselves.

1. Introduction

The Cotswold Hills are a linear feature of moderate elevation in the south-western part of the English midlands, about 100 km long and generally 20 km wide. They comprise a sequence of interbedded limestones and mudstones of Middle Jurassic (Bathonian) age, with a steep scarp slope facing to the west and a shallow dip slope. Rivers rising on the dip slope flow eastwards towards the River Thames and the North Sea, scarp streams flow west to the River Severn and the Atlantic Ocean. The exception to this is the (Bristol) River Avon in the southern part of the Cotswold Hills, which rises on the dip slope then cuts through the escarpment via the Claverton Gorge; it continues west, picking up scarp stream tributaries, and passes through the cities of Bath and Bristol before reaching the River Severn (Fig. 1).

This paper describes a part of the southern Cotswold Hills to the east of Bath which has been deeply dissected by the River Avon and by the By Brook, a major tributary which joins from the east. In the valley floor, the rivers have incised through the Middle Jurassic sequence into Lower Jurassic strata of the Lias Group, which are mainly mudstones with subordinate limestones. The lower part of the valley sides are cut in the Inferior Oolite Formation, a rubbly oolitic limestone up to 23 metres thick. Above this is the Fuller's Earth Formation, a series of calcareous mudstones with occasional beds of flaggy limestone, approximately 46 metres thick. The Fuller's Earth mudstones are overconsolidated, highly plastic clays prone to mass movement. Capping the interfluves is the Chalfield Oolite,

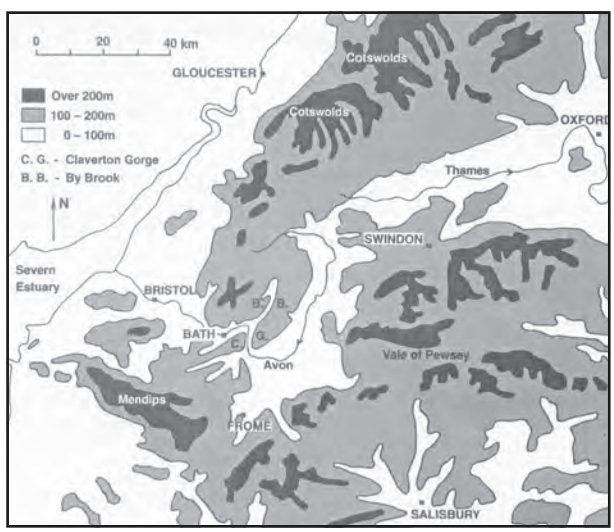

Figure 1: The southern Cotswolds and surrounding areas.

a succession of largely matrix-free oolitic limestones of 35 – 40 metres thickness. Succeeding these limestones on the dip slope is the Forest Marble Formation, a sequence of coarse bioclastic limestones and mudstones. The regional dip is about 2° to the south-east.

The valley sides of the River Avon and its tributaries have extensively foundered, with significant landslipping in and around the city of Bath. Where the well-jointed Chalfield Oolite outcrops, extension of the strata is obvious as the major joints have opened to form gulls. *Gull* (derived from gully) is an old quarryman's term, used to describe open joints in solid strata (Fitton, 1836). Natural exposures of the Chalfield Oolite are rare, but it is an excellent building stone and small abandoned quarries are ubiquitous throughout the area. There are also very extensive stone mine labyrinths, some of which are accessible to cavers. Gulls are seen throughout the mines and there are some *gull caves* large enough to be explored by cavers; the anthropomorphological element of this definition is important because it means that they are accessible to direct study. These gulls and gull caves have formed by the opening of joints within the rock sequence, with little or no extension of the overlying beds. Other gull caves can be accessed from small quarry workings on the valley sides; Murhill Rift and Sally's Rift each have more than 300 metres of accessible passages.

2. The Formation of Gull Caves

Gulls form on steep hillsides as a result of mass movement, when well-jointed strata are unsupported on their downhill side. In sedimentary rocks, extension takes place along bedding planes with bed-over-bed sliding and the opening of joints (Hawkins and Privett, 1981). Gulls are particularly common in flat-lying or gently inclined strata affected by cambering. *Cambers* are caused by the gravitational lowering of outcropping or near-surface strata towards an adjacent valley. They occur where competent and permeable rocks overlie incompetent and impermeable beds such as clays. The competent beds develop a local dip towards the valleys, swathing the hill-tops and draping the valley sides (Hollingworth et al., 1944). The incompetent material is extruded from beneath the caprock, initially as a result of stress relief.

Parks (1991) has suggested that as a camber develops, the competent caprock breaks up into joint-bounded blocks above a basal shear plane in the underlying material. A Quaternary cold stage with permafrost conditions is then required, since the underlying strata (if it is mudstone) is much more susceptible to creep when frozen. Thawing at the end of the glacial cycle increases the water content of the mudstone, potentially saturating it and drastically reducing its shear strength. This causes it to behave as a plastic fluid and the competent caprock migrates in the direction of slope, opening the joints to form gulls.

The Parks model shows how gulls that are open to the surface can form in a thin caprock. In the Cotswold Hills, the limestone caprock is much more substantial and the gulls and gull caves generally have intact roofs. They have formed in the lower part of the limestone strata, with little or no mass movement having taken place in the upper part. This requires not only a basal shear plane, but also an upper parting/ sliding plane within the limestone sequence. A possible mechanism, involving the sequential unloading of joint-bounded blocks, was suggested by Self (1986). As extrusion occurred, individual blocks were able to settle slightly and then move laterally with the mudstone. The blocks move in the same direction but independently of each other, with neighbouring blocks supporting the overlying strata, creating a gull network that propagates away from the valley.

The following classification scheme for gulls (Fig. 2) was proposed by Self (1986) and extends a scheme originally formulated by Hawkins and Privett (1981). For simplicity, the basal sliding plane is drawn at the lithological boundary, but the classification works equally well if the mechanism is plastic flow within the incompetent strata. Types A, B and AB are found in cambered strata where the caprock is thin, such as the Lower Jurassic strata of the Lias Group which outcrops just to the west of the study area. Type A is the classic single surface gull, with one slip plane at depth. Type B has bed-over-bed sliding across a broad zone at many levels, with many small voids at depth. Type AB is an irregular gull produced by a single major joint with sliding at many levels. These three types are often encountered on building sites during excavation for foundations, normally filled with material of surface origin.

Type C gulls are typical for the southern Cotswold Hills, though examples of types AC, D and E have been seen in the area. Type C is the classic gull cave with bedding plane sliding between two slip planes, to produce an open fissure at depth with a intact roof. In type AC, a block has been undermined and suffered a rotational failure to produce a gull with marked dip and fault structure within the rock sequence. Type D has more than one upper sliding plane, resulting in small gull caves above the level of the main gull cave at depth. Type E is a bedding plane cavity created by the sinking of unsupported blocks between inclined joint

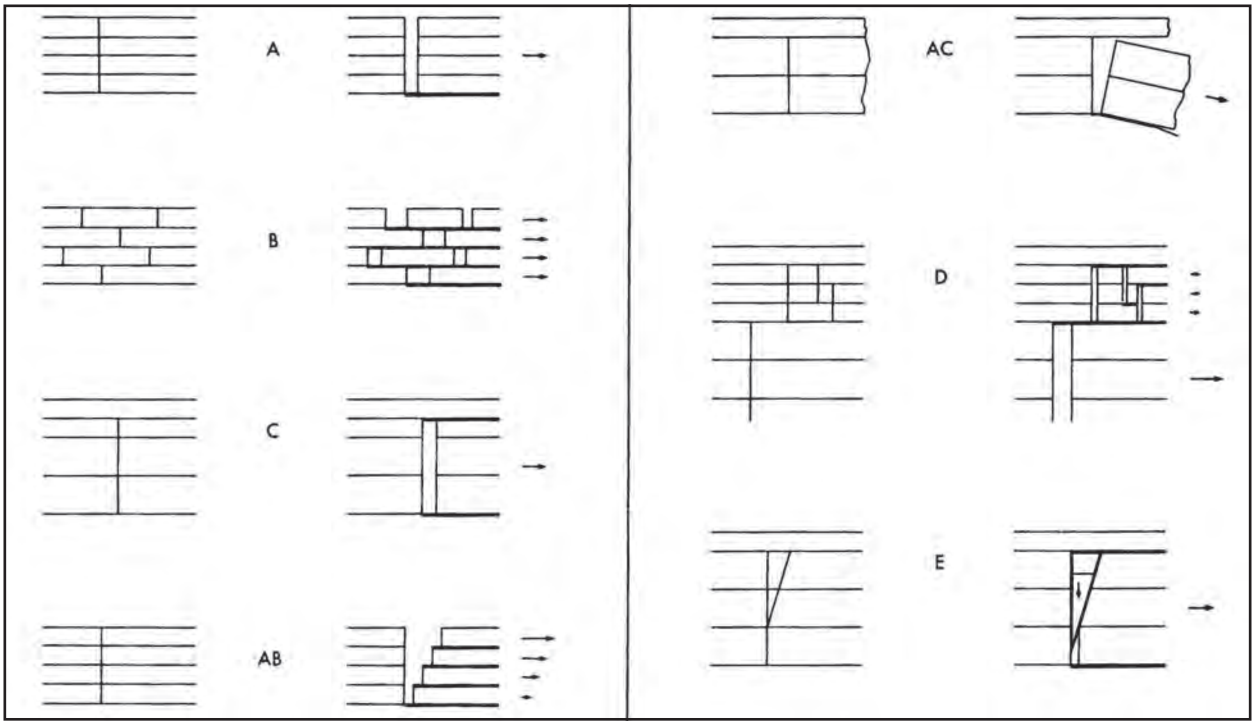

Figure 2: A classification scheme for gulls.

fractures.

Since gulls are formed by gravitational sliding, mass movement is usually in the direction of slope. Where major joints occur normal to the direction of extension, simple linear gulls result. These contour-aligned gulls always end abruptly at cross joints, with a new gull continuing en echelon. Where extension is oblique to the jointing, the extension may be taken up along more than one joint set. The most complex systems are created where extension occurs in more than one direction around spurs of the competent strata. If the spreading axis is at the hinge line

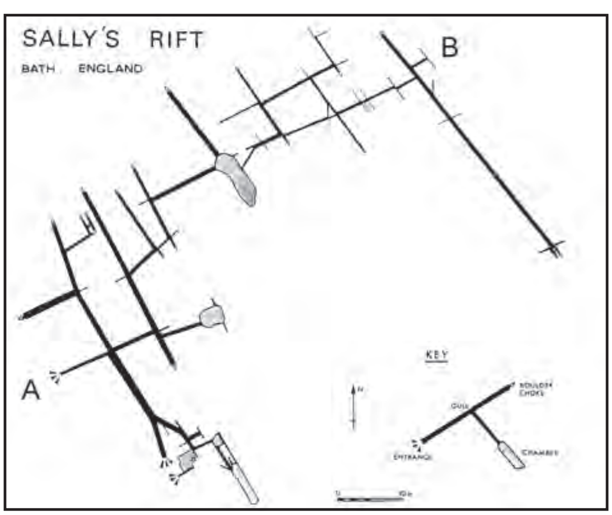

Figure 3: The gull cave Sally's Rift.

of the hillside, a network of gulls will form. If it is not at the hinge line, a sequence of gulls will develop along this camber spreading axis in addition to those formed by regular extension of the strata. Sally's Rift (Fig. 3) is an example of this.

On straight hillsides, mass movement is only possible in the direction of slope. The buttressing effect of neighbouring stratal blocks prevents movement in other directions, so the hillside is said to be *confined*. On promontaries and the curving sides of *unconfined* hillsides, the early stages of cambering are not necessarily towards the nearest valley. The original stratal dip has an influence, particularly on partially up-dip slopes, since cambering in the direction of strike is easier than cambering up-dip. As a result, a pattern of gulls may be produced that differs from the predicted pattern based on joint orientation and the direction of the contours. This is well seen in the stone mine complex on Box Hill, 8 km east of Bath.

3. The Caves

Within the Chalfield Oolite of the southern Cotswolds, a number of gull caves have been reported by Self and Boycott (2000). Some are single fissures a few metres long, while others form more extensive systems. The main jointing directions are NW/SE and NE/SW, so the more complex gull caves tend to be rectilinear networks. N/S and E/W joints are also present in the study area, but they generally have not been opened by mass movement. There is a considerable variation between the sites, but they all occur on north- or west-facing (up-dip) slopes, probably because such slopes are less prone to rotational failure. Typically, the cave entrances are in the cliff faces of abandoned small valley-side quarries. Many more certainly exist, but either do not intersect the surface or are buried under colluvium.

Guy's Rift is located in an abandoned quarry in the upper By Brook valley and has 42 metres of surveyed passages. Archaeological material in the cave includes the remains of four human adults, three children and pottery of early Iron Age.

The Rocks Rift is a substantial gull in a tributary valley to the By Brook, entirely filled with a heterogeneous mixture of sediments, including calcite flowstone fragments and oolite boulders. In previous centuries, it was excavated for 36 metres to provide the "cave" element for a garden folly.

The entrance to Henry's Hole is a narrow gull on the south side of the By Brook valley. This gives access to a small area of independent mine workings near to the vast Box Freestone Mine complex. The mine intersects other gulls, but one mined passage crosses (with intact roof) beneath a sustantial gull cave, 4 m tall and 40 cm wide. This is a high-level disturbance within the Great Oolite limestone and evidence for D type movement.

Several caves can be found on the east side of the Claverton Gorge, where the River Avon cuts through the Cotswolds escarpment. Gully Wood cave no 5 is a small network cave on several levels with a total development of 50 metres. Gully Wood cave no 4 is a 90 metres long contour-aligned gull with impressive passage dimensions. Murhill Rift contains a major passage of 80 metres development, but a complex disturbance close to the hillside margin has provided an additional six entrances to the cave. Passages on three levels associated with this disturbance increase the length of the cave to over 300 metres.

Sally's Rift is one of the Gully Wood caves on the east side of Claverton Gorge. There are 365 metres of generally large passages, which makes this the longest and most impressive gull cave in the Cotswolds. The passages are over 10 metres tall with widths mostly between 20 cm and 50 cm, while the largest passage is 15 metres tall and 2 metres wide. A few tens of metres north of the cave, the River Avon valley makes an abrupt change of direction from north-west to north. This has produced a zone of lateral extension across this part of the hillside. A series of contour-aligned gulls are linked by gulls of a camber spreading axis (marked A – B on Figure 3) which runs directly into the valley side. A detailed calculation (Self, 2008) has shown that the passage widths seen in this cave could not be produced by mass movement in any single available direction. Nor is the spreading axis a fault, as "fit features" are present whereby a ledge on one wall matches an overhang at the same level on the opposite wall. Flowstone is present throughout the cave and the gull furthest from the valley side has particularly fine speleothems. The cave has three entrances, the most southerly being a bedding plane gap formed by E type movement.

4. Palaeogeographic Studies

Caves are important repositories for palaeogeographic materials that are often lost elsewhere due to surficial erosion. Gull caves form within the strata; only a few have a direct connection to the surface and can become sediment traps. However, when material does enter a gull cave it has an even better chance of being preserved than in a karst cave. Gull caves are not former water courses, so there is little risk of a deposit being washed away during a flood. Guy's Rift is an important archaological site, having been used during the early Iron Age for human burials. Part of the cave has been lost to 19th century quarrying, but the archaeological material proves that this cave must always have had a natural open entrance.

In two places in Sally's Rift and one in the nearby Gully Wood cave no 4, deposits of "clay with flints" have entered via narrow side fissures in the roof of the caves. This placer deposit has pebble-sized clasts of Cretaceous flint and occasional clasts of Carboniferous rocks, similar to the high level plateau gravels recorded at other sites to the east of Bath. Donovan (1995) believes they are the remains of an early to middle Pleistocene drift deposit.

The gull caves of the southern Cotswolds have formed in limestone, so percolation water has coated the walls with a thin layer of calcite flowstone. In places of more concentrated percolation flow, substantial speleothems have formed. In Sally's Rift, the gull furthest from the entrance has particularly good decorations, including a pure white false floor spanning the rift. The southern end of the same gull has a floor consisting of boulders of a massive foundered flowstone deposit. A sample from this was radiometrically dated and gave a range of ages from 80ka at the top to more than 350 ka at the base (Self, 1995). The speleothem evidence suggests that the caves formed during a single substantial episode of mass movement some time earlier than 350,000 BP. Later episodes of mass movement have not significantly enlarged the caves and have caused only minor foundering.

The Chalfield Oolite is an important aquifer, but it is not karstic. Water travels mainly along joints, with a small contribution from movement through the poorly-cemented body of the rock. In gulls throughout the region, there is evidence of solutional etching of the joint walls. In Sally's Rift, this etching is very pronounced in the NW/SE joint set, (Self, 1995). Current bedding features in the oolite stand out in sharp relief and bedding planes may be corroded to a depth of 6-8 cm. This solutional etching is the result of slow groundwater movement which pre-dates the onset of cambering (and de-watering of the strata). Drainage could not have been down-dip to the south-east, because the permeable oolite beds pass beneath the Forest Marble which forms an impermeable caprock. The outlet was therefore up-dip. Up-dip springs contribute to the present drainage of some tributary valleys to the River Avon.

The significance of the up-dip palaeodrainage of the joints in Sally's Rift is that the nearby River Avon flows in this direction. The Claverton Gorge (and the entire River Avon valley system upstream) could not have existed at this time, or the groundwater movement would have been towards this valley using the conjugate joint set. This means that the proto- River Avon was an aggressive scarp stream, while on the Cotswold dip slope drainage was to the River Thames (Fig. 4). Eventually, headward erosion by the River Avon allowed it to break through into dip-slope territory and capture these former Thames headstreams. With a greatly enhanced flow, the River Avon rapidly overdeepened its valley and formed the steep-sided Claverton Gorge. The tributary valleys also cut down to this new base level and the entire valley system was primed for cambering. A minimum age for this river capture is 350 ka (from the speleothem dating) though, if the Parks model for gull formation is correct, a date during the Anglian cold stage is more probable.

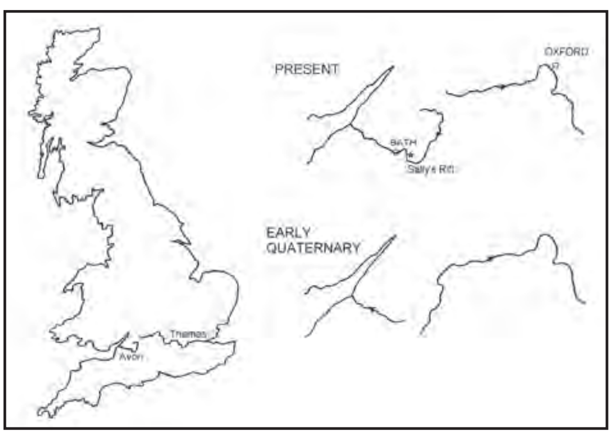

Figure 4: Capture by the River Avon of River Thames headstreams.

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KARST HYDROLOGY IN UTAH – AN OVERVIEW

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Karst aquifers in northern Utah are located primarily in alpine areas of the Uinta and Bear River Ranges, and localized areas within the Wasatch Range, all of which are part of the Middle Rocky Mountains physiographic province. In these ranges, groundwater flow systems are developed in limestone and dolostone ranging in age from Cambrian to Mississippian. Karst flow systems also are present in Tertiary limestones underlying basaltic volcanic rocks in the southwestern part of the State on the Markagunt Plateau. Dissolution of the Claron Formation and subsequent collapse of the overlying basalt have resulted in an extensive vulcanokarstic terrain and complex groundwater flow systems.

Karst aquifers in the Uinta Mountains are developed primarily within Mississippian limestones, which crop out on the flanks of this east-west trending anticlinal structure. In the southeast part of the range, surface water originating on the Precambrian sandstone core of the uplift sinks along the outcrop band of the limestone and moves down dip to large springs that discharge under confined conditions. Lateral movement of groundwater between adjacent surface-water basins in this area and along bedrock strike on the northern flank of the range has been documented by dye-tracer studies, which include some of the longest traces (23 km) in the western United States.

Karst aquifers in the Bear River Range are developed within Cambrian to Silurian limestones and dolostones. Groundwater that is recharged primarily by snowmelt runoff in high-altitude, glaciated basins discharges from large karst springs along the Logan River, the principal base-level stream in the northern part of the range. The Logan Peak syncline, a major regional structure bisected by the river, has a significant influence on groundwater movement in this part of the range and delineated groundwater basins for the major springs appear to be areally and stratigraphically separated. On the basis of dye-tracer studies since 1990, groundwater travel times from recharge areas as much as 1100 m higher than and 12 km from the springs, typically are less than 4 weeks.

1. Introduction

Utah is characterized by a wide variation in geography and geology, largely because the State lies at the junction of three major physiographic provinces – the Basin and Range, the Middle Rocky Mountains, and the Colorado Plateau (Fig. 1). Although karst geomorphic features are developed throughout these regions where soluble rocks lie at or near land surface, karst aquifers are developed primarily in high alpine areas where abundant precipitation is present, mostly in the form of snow. These include the Bear River Range in northern Utah, the Uinta Mountains in northeastern Utah, and localized areas within the Wasatch Range, all of which are part of the Middle Rocky Mountains province (Fig. 1). In these ranges, shallow groundwater flow systems are developed in limestone and dolostone ranging in age from Cambrian to Mississippian. Karst flow systems also are present in Tertiary limestones underlying basaltic volcanic rocks in the southwestern part of the State on the Markagunt Plateau (Figure 1). In addition, regional aquifers developed within carbonate rock are present in many of the mountain ranges that make up the Basin and Range province, which covers the western one-third of the State (Fig. 1). These aquifers consist of deeper flow systems that in some cases are hydraulically interconnected between mountain ranges (HARRILL AND PRUDIC, 1998). Shallow karst flow systems generally are not present in these areas, and springs often are located away from the mountain fronts, discharging upward through unconsolidated basin-fill deposits. Although some of the State's better known caves are developed in many of these mountain ranges, their origins are often attributed to upwelling thermal water rather than downward moving meteoric water, as evidenced by cave morphology, hypogenic cave deposits, and warm springs. This paper provides an overview of hydrologic investigations conducted in the State's principal karst areas, focusing on results of dye-tracer tests in karst aquifers that are characterized by shallow flow systems and contain groundwater that is non-thermal in origin.

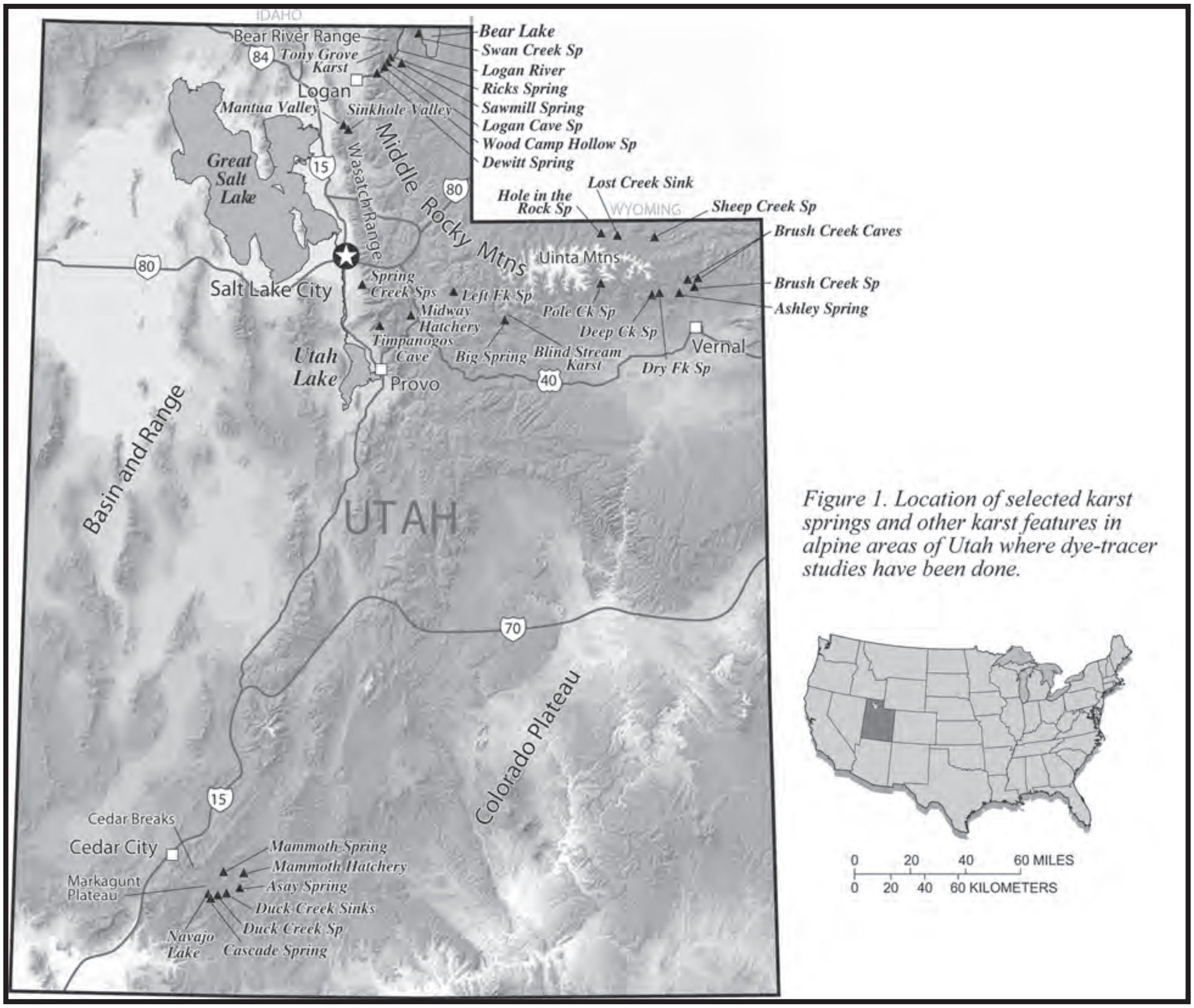

Figure 1. Location of selected karst springs and other karst features in alpine areas of Utah where dye-tracer studies have been done.

2. The Bear River Range

The Bear River Range is located in northern Utah and extends into southeastern Idaho (Fig. 1). The range is bisected by several westward flowing rivers, including the Logan River, which is the principal base-level stream into which groundwater discharges in the northern Utah part of the range. Karst features in this alpine region include large springs, losing streams in tributary drainages, caves and pits, sinkholes (dolines), and blind valleys. Glaciation occurred at altitudes generally above 2500 m during the Pleistocene, and speleothem age-dating and glaciofluvial deposits in caves indicate that karst development probably began during interglacial periods and has continued since then (WILSON, 1976). The Bear River Range consists in large part of a thick sequence (as much as 1500 m) of limestone and dolostone that ranges in age from Cambrian to Mississippian. North and west of the Logan River, the principal karst flow systems are developed primarily within the Ordovician Garden City Formation and Fish Haven Dolomite, the Silurian Laketown Dolomite, and the Devonian Water Canyon Formation (DOVER, 1987). The Swan Peak Quartzite appears to be a barrier to downward movement of water from the Fish Haven Dolomite to the Garden City Formation. All of the formations comprise the upper part of a large regional structure, the Logan Peak syncline, which plunges to the southwest at about 15 degrees. This syncline has a significant influence on groundwater movement in this part of the range (SPANGLER, 2001).

Recharge to the karst aquifer takes place primarily by snowmelt runoff in high-altitude glaciated basins (meadows) through sinkholes and pits where precipitation averages 1270 mm/yr, as infiltration into the underlying carbonate rocks through fluvioglacial deposits in drainages, and as diffuse infiltration. Recharge moves vertically downward along solution-enlarged fractures and bedding planes to conduits that discharge to large karst springs.

Although concentrated recharge is significant, direct infiltration along more diffuse fracture pathways probably is a more substantial component of recharge, contributing to long-term storage in the aquifer and base flow of springs.

Discharge from the karst aquifer is primarily from second and third magnitude (MEINZER, 1927) springs along the Logan River. Along the north and west sides of the river in the Utah portion of the range, these include, from downstream to upstream, Dewitt, Wood Camp Hollow, Logan Cave, and Ricks Springs (Fig. 1). Only two significant springs are known to discharge along the south side of the river. Discharge of individual springs is highly variable, with base flows of less than 0.03 m^3/s to peak flows of at least 2 m^3/s (MUNDORFF, 1971); collectively, the springs provide a substantial component of streamflow in the Logan River (WILSON, 1976). All of the springs respond primarily to snowmelt runoff, with peak discharge occurring from late spring to early summer and base flow during the winter months.

On the basis of dye-tracer studies since 1990 (SPANGLER, 2001), recharge areas for Dewitt, Wood Camp Hollow, and Ricks Springs are estimated to be between 20 and at least 40 km^2, with groundwater travel times from as much as 1100 m higher than and 12 km from the springs, ranging from 1 to less than 4 weeks. The recharge area for Dewitt Spring, which serves the city of Logan, largely coincides with the areal extent of the Logan Peak syncline. Discharge from Wood Camp Hollow Spring includes flow from the Tony Grove karst area about 11 km north of the spring (Fig. 1) and from the deepest caves in the State. Ricks Spring discharges along a normal fault and receives part of its flow from the Logan River upstream of the spring. Results of dye-tracer tests indicate that groundwater basins for the springs in this region appear to be areally and stratigraphically separated and surface-water drainage basins do not coincide with groundwater basins.

Tracer studies begun by this author in 2007 south of the Logan River indicate discharge to Sawmill Spring originates from a doline karst 3 km east of the spring (Fig. 1). Karst flow systems also are present in many other areas of the Bear River Range, particularly the part of the range that extends north into southeastern Idaho, as indicated by large karst springs, sinkholes, caves, and losing streams. Results of dye-tracer studies in the 1980s (JAMES WILSON, Weber State University, oral commun., 2006) showed that groundwater moves north from areas near the State boundary, rather than south toward the Logan River. Swan Creek Spring, the largest karst spring in Utah with a measured peak flow of about 9 m^3/s, discharges from the eastern flank of the range into Bear Lake (Fig. 1). As of 2008, no dye-tracer studies have been conducted in this groundwater basin.

3. The Uinta Mountains

The Uinta Mountains are a large east-west trending anticlinal structure (Fig. 1), with a core that is composed of Precambrian conglomeratic sandstones and shales (RITZMA, 1959). Late Paleozoic carbonate and Mesozoic clastic rocks unconformably overlie the Precambrian rocks along the flanks of the uplift and generally dip about 10 to 20 degrees away from the core, except in areas of faults and folds, and on the north flank of the uplift, where they dip considerably steeper. Superimposed on the Uinta Mountain anticline are regional faults and fractures, which have influenced the location of the larger karst springs (MAXWELL *et al*., 1971). Karst features are present in many areas of the Uintas where carbonate rocks are exposed at the surface. Sinkholes (dolines) and pits are more abundant in the southwestern part of the range where structural dip is lower and carbonate outcrop areas are more extensive. Losing or sinking streams can be found in many of the drainages, particularly where surface streams originating on the clastic core of the uplift cross the band of limestone that flanks the core. Big Brush Creek and Little Brush Creek Caves, the longest stream caves in the State (8 and 9.7 km, respectively) (Fig. 1), were formed by capture and entrenchment of surface streams flowing off the core of the Uintas onto the limestone. As a result, excellent examples of blind valleys have formed at the entrances of both caves and the dry valleys directly above the caves that represent the original surface courses of the creeks, which have been abandoned. These caves are characterized by complex anastomosing networks that have likely formed and are continually being modified by snowmelt runoff. Many of the caves in the Uintas were probably initiated or substantially enlarged during interglacial periods when excess runoff was available. Cave development has likely migrated down dip as the regional water table has been progressively lowered by canyon cutting (GODFREY, 1985).

The principal karst flow systems and cave-forming units in the Uintas are developed in Mississippian-age dolomitic limestones and include the Madison and Deseret Limestones, and the Humbug Formation (KINNEY, 1955). Average thickness of the carbonate units in this area is about 275 to 365 m. Results of dye-tracer tests have shown that groundwater flow directions along the southeast flank of the Uintas are generally to the south and southeast, following the geologic structure. Direction of groundwater flow is influenced in large part by the structural dip of the rocks, regional fractures and faults, and localized breccia zones (MAXWELL *et al*., 1971). Water typically flows down dip in the limestone to elevations as much as 640 m lower, where it discharges as large springs along the principal drainages that have dissected the flanks of the mountain range. Discharge of the larger springs has been measured to be as much as 5.7 m^3/s (MUNDORFF, 1971). In the southeastern part of the range, the Pennsylvanian-age Weber Sandstone overlies the carbonate units, and groundwater is generally confined. As a result, flow is typically upward from the deeper limestone aquifer along fractures and faults in the overlying sandstone to discharge at the surface. In addition, lateral movement of groundwater between springs located in different surface-water basins has been shown to occur during periods of high discharge (MAXWELL *et al*., 1971).

On the basis of dye-tracer tests carried out in the mid-1940s, mid-1950s, late-1960s, and in 1979, recharge areas for five major springs have been partially delineated along the southeast flank of the Uintas. From west to east, these include Pole Creek, Deep Creek, Dry Fork, Ashley, and Brush Creek Springs (Fig. 1). Detailed summaries of the hydrology of these springs can be found in MAXWELL *et al*. (1971), GODFREY (1985), and SPANGLER (2005). Pole Creek Spring discharges from fluvioglacial deposits overlying the Madison Limestone and as an overflow spring from nearby Pole Creek Cave. Deep Creek Spring rises along the upthrown side of a northwest-trending fault that serves as a pathway for upward movement of water from the underlying limestone aquifer. Results of dye-tracer tests from a sink 9.6 km northwest of the spring indicated a groundwater travel time of about 14 days. Dry Fork Springs are intermittent and discharge from the Weber Sandstone upward through alluvium at several locations in Dry Fork. Flow lost through fluvioglacial deposits in the channel upstream of the springs enters conduits in the underlying limestone aquifer and moves upward along fractures in the overlying rocks to discharge at the surface. Water lost in Dry Fork and its tributaries also appears to move through the underlying limestone aquifer to Ashley Springs, where fractures in the overlying Weber Sandstone allow upward movement of water back to the surface. Brush Creek Spring rises from the base of the Weber Sandstone where fracturing along the axis of an anticline has permitted upward movement of water from the limestone aquifer back to the surface. Results of dye-tracer tests during the summers of 1967 (Big Brush Creek) and 1968 (Little Brush Creek) indicate that much of the water discharging from the spring originates from both of these drainages via Big and Little Brush Creek Caves (MAXWELL *et al*., 1971).

On the northeast flank of the Uintas, the Mississippian limestones are very steeply dipping, and lateral flow of groundwater along bedrock strike has been documented by one of the longest dye traces in the western United States. Groundwater travel time from Lost Creek Sink, a blind valley, to Sheep Creek Spring 23 km to the east, is within 2 weeks, as documented initially by ANDREW GODFREY (U.S. Forest Service, oral commun., 2000) and subsequently verified by SPANGLER (2005). Dye also was detected at Hole in the Rock Spring 8 km west of Lost Creek Sink, indicating an apparent bifurcation of the flow system (groundwater divide) at the Sink (Fig. 1).

Dye-tracing investigations also have been conducted in the southwestern part of the range (Fig. 1). Tracer tests conducted by GODFREY (1985) showed that discharge from Big Spring originates in part, from the Blind Stream karst area about 5 km northeast of the spring at an altitude of about 3200 m and also from the Log Hollow basin about 10.5 km east of the spring. Tracer tests conducted by this author (unpublished data, 2005) showed that discharge from Left Fork Spring originates in large part from the Beaver Creek and Cedar Fork drainages northeast of the spring. Karst flow systems also are known to be present in other areas of the Uinta Mountains, as indicated by karst springs, sinkholes, caves, and losing streams. As of 2008, no dye-tracing studies have been done in these areas.

4. The Wasatch Range - Mantua Valley

Mantua Valley is located about 26 km southwest of Logan, Utah, in the northern part of the Wasatch Range (Fig. 1). Numerous springs discharge from Lower Paleozoic carbonate rocks along the perimeter of the valley, many of which are used for public supply. Maple Spring is the largest with a discharge that generally ranges between 140 and 225 L/s (Brigham City, written communication, 1995). The spring discharges from the Cambrian Bloomington Formation and serves as the water supply for a State fish hatchery. Sinkhole Valley, located about 4.8 km southeast of Mantua Valley and about 425 m higher (Fig. 1), is a polje-like feature of about 4.6 km^2 that has likely formed as a result of both faulting and dissolution of carbonate rock. Sinkholes along the margin of the valley provide an outlet for this closed basin, which is the largest in the State. Devils Gate Valley, immediately southwest of Sinkhole Valley, also drains internally through numerous sinkholes.

Results of dye tracing to Maple Spring from Devils Gate Valley indicated a groundwater travel time of about 5 days, or an average groundwater velocity of about 823 m/d. Because the sink points are developed in the Ordovician

Garden City Formation, groundwater flow from this area to the spring crosses major stratigraphic boundaries (RICE and SPANGLER, 1999). Northeast-trending faults in the vicinity of Maple Spring do not appear to be barriers to movement of water between the recharge area and the spring, but locally, could influence vertical movement of water between offsetting carbonate units. Although the recharge area for Maple Spring, estimated to be at least 9 km^2, may include Sinkhole Valley, dye-tracer tests conducted from this area to the spring have not been successful.

5. The Wasatch Range – Other Areas

Studies by CARREON-DIAZCONTI *et al*. (2003) to evaluate the source and transport of whirling disease have shown that water discharging from the spring at the Midway State fish hatchery, near Provo, Utah, (Fig. 1) originates in part, from shallow flow paths within cavernous tufa deposits. Results of dye-tracer and particle-tracer (non-pathogenic soil bacteria) tests indicated groundwater travel times of less than 1 day from fractured bedrock sites 1 km from the spring.

Studies conducted by the Spring Creek Irrigation Company (BORG, 1951, unpublished report) determined that part of the source of water to Spring Creek Springs, situated along the western flank of the Wasatch Range, in Salt Lake City (Figure 1), originates from Neffs Canyon. Dye injected in this drainage 4 km east of the springs, had a groundwater travel time of 27 hr, or about 150 m/hr. Streamflow in Neffs Cave, second deepest in the State (355 m), may also discharge to these springs.

Determining the source and discharge point for water that enters and leaves Timpanogos Cave (Fig. 1) has been of interest to the National Park Service (NPS) for many years. A dye-tracer test by the NPS and the Ozark Underground Laboratory was attempted in 1992 to determine the discharge point of water from the cave, but was unsuccessful (RODNEY HORROCKS, NPS, written communications, 2009). Water from the cave system presumably discharges to unidentified springs along or in the American Fork River, about 400 m below the cave.

6. The Markagunt Plateau

The Markagunt Plateau lies east of Cedar City, Utah, at an altitude of about 2750 to 3050 m (Fig. 1). Quaternary volcanic rock (basalt) caps large parts of the plateau and overlies the early Tertiary Claron Formation, a marly limestone that is locally cavernous. Exposures of this unit are spectacularly displayed at Cedar Breaks National Monument, which forms the western boundary of the plateau. On the Markagunt Plateau, dissolution within the Claron Formation has resulted in collapse of the overlying basalt producing an extensive vulcanokarstic terrain that is characterized by ephemeral sinking streams and sinkholes (dolines) as much as 300 m across and 30 m deep. Numerous large springs discharge from the basalt and limestone on the plateau. Recharge to the aquifer that supplies these springs takes place by focused and diffuse infiltration through the basalt and into the underlying limestone. Groundwater probably flows along fractures and in lava tubes within the basalt and along solution-enhanced fractures and bedding planes within the underlying limestone. Duck Creek lava tube, one of the longest lava tubes in the continental United States (3.35 km), carries a small stream year-round, which has been shown by dye tracing to originate from an adjacent spring-fed lake (U.S. Forest Service, written commun., 2007).

Mammoth Spring (Fig. 1), at an altitude of 2500 m, is the second largest spring in Utah, with a discharge that ranges from less than 0.14 to over 8.5 m^3/s (MUNDORFF, 1971). The spring appears to represent the principal discharge point for precipitation that infiltrates the vulcanokarstic terrain on the Markagunt Plateau. On-going dye-tracing studies by the U.S. Geological Survey (SPANGLER, 2008) have shown that part of the water from Mammoth Spring originates from as far as 13.5 km southwest of, and 450 m higher than, the spring. WILSON and THOMAS (1964) also showed that water lost from Navajo Lake discharged to Duck Creek Spring, was lost again at Duck Creek Sinks, and finally discharged at Asay Spring (Fig. 1). Water lost from Navajo Lake also was shown to discharge at Cascade Spring, indicating a bifurcation of the groundwater flow path that ultimately results in discharge to different surface-water drainage basins.

Dye-tracer tests also have been conducted at the Mammoth Creek State fish hatchery, about 18 km east of Mammoth Spring, to evaluate the subsurface transport of whirling disease (SPANGLER *et al*., 2005). Results of tracer investigations using fluorescent dyes, along with non-pathogenic soil bacteria and *Lycopodium* (club moss) spores as surrogate particle tracers, have shown a hydraulic connection between the adjacent creek and the hatchery spring. On the basis of dye analyses and recovery of particle tracers, groundwater travel time through fractured basalt from a losing reach in the creek about 885 m upstream of the hatchery, was about 8 hr.

7. Summary

Karst aquifers in northern Utah are located primarily in alpine areas of the Uinta Mountains and Bear River and Wasatch Ranges. In these areas, shallow groundwater flow systems are developed in limestone and dolostone ranging in age from Cambrian to Mississippian. In the southeastern Uinta Mountains, surface water originating on the sandstone core of this anticline sinks along the outcrop band of Mississippian limestones and moves down dip to large springs that discharge under confined conditions. Lateral movement of groundwater between surface-water basins in this area and along bedrock strike on the northern flank of the range also has been documented by dye-tracer studies, which include some of the longest traces (23 km) in the western United States. In the northern Bear River Range, groundwater is recharged primarily by snowmelt runoff in glaciated basins and discharges from large karst springs along the Logan River. The Logan Peak syncline has a significant influence on groundwater movement in this part of the range and delineated groundwater basins for the major springs appear to be areally and stratigraphically separated. On the basis of dye-tracer studies since 1990, recharge areas for the larger springs are estimated to be between 20 and at least 40 km^2, and groundwater travel times from as much as 1100 m higher than and 12 km from the springs, range from 1 to less than 4 weeks. Karst flow systems also are present in Tertiary limestones underlying basaltic volcanic rocks in the southwestern part of the State on the Markagunt Plateau. Dissolution of the Claron Formation and subsequent collapse of the overlying basalt have resulted in an extensive vulcanokarstic terrain and some of the largest sinkholes and springs in the State.

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GROUNDWATER/SURFACE-WATER RELATIONS AND WATER QUALITY WITHIN THE MAMMOTH SPRING WATERSHED, MARKAGUNT PLATEAU, SOUTHWESTERN UTAH, USA

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The Markagunt Plateau, in southwestern Utah, lies at an altitude of about 2900 m, largely within Dixie National Forest. The plateau is capped by Tertiary volcanic (basalt) rocks that overlie Eocene marly limestones of the Claron Formation, a cavernous unit that also forms escarpments on the west and south sides of the plateau. Volcanic pseudokarst (vulcanokarst) characterizes large parts of the Markagunt Plateau, as indicated by extensive sinkhole development in the basalt. Lava tubes occur within the upper part of the basalt and locally have collapsed; however, most of the vulcanokarstic terrain on the plateau likely results from dissolution of the underlying limestone and subsequent collapse of the basalt, producing sinkholes (dolines) up to 300 m across and 30 m deep. Numerous large springs discharge from the basalt and limestone on the Markagunt Plateau, including Mammoth Spring, one of the largest springs in Utah, with a discharge that can exceed 8.5 m^3/s. Mammoth Spring probably discharges from the Claron Formation; however, much of the recharge to the aquifer that supplies the spring likely takes place by both focused and diffuse infiltration through the overlying basalt.

Results of major-ion analyses for samples collected from Mammoth Spring during base-flow conditions in the fall (when most water is presumed to be from aquifer storage) indicate a calcium-bicarbonate type water containing dissolved-solids concentrations of about 110 mg/L. Results of analyses for sulfur-35, tritium, and chlorofluorocarbons in water from the spring indicate that residence times are a mixture of short- (months or less) and long-term (years) components. However, results of a dye-tracer test from 13.7 km southwest of and 450 m higher than the spring indicate a maximum groundwater travel time of 27 days during the snowmelt runoff period. Specific conductance and water temperature also show an inverse relation to discharge during snowmelt runoff and rainfall events. From November 2006 to October 2007, water temperature ranged from 3.8 to 5.4 ^{0}C, and specific conductance ranged from 127 to 170 microSiemens/cm (at 25 ^{0}C), while discharge ranged from about 0.14 to 1.47 m^3/s. Variations in water chemistry, discharge, and turbidity in addition to the presence of total coliform bacteria in the spring water indicate a significant potential for transport of contaminants from surface sources to the spring in a relatively short timeframe.

1. Introduction

In October 2006, the U.S. Geological Survey in cooperation with the U.S. Forest Service began a multi-year study to investigate the hydrology and water quality of the Mammoth Spring watershed on the Markagunt Plateau in southwestern Utah (Fig. 1). Encroaching development along the margins of the watershed, increased recreational vehicle use, and other activities have raised concerns about potential impacts to the water quality of the spring. The objectives of the study include delineation of the recharge area for Mammoth Spring and its relation to the surface-water drainage basin; identifying potential point sources, such as losing streams and sinkholes where surface water can rapidly recharge and impact the aquifer directly; determining groundwater travel times through the aquifer and the relation between groundwater flow in the basalt and the underlying limestone; and determining variations in water quality under base and peak flow conditions. This paper summarizes results of investigations for the first year of the study.

2. The Markagunt Plateau Vulcanokarst

In volcanic pseudokarst (vulcanokarst) terrains, karst-like features often develop that are similar to those developed in limestone terrains, such as sinkholes and caves; however, these features typically are produced by surface collapses into lava tubes, which previously served as conduits for molten lava rather than bedrock dissolution. On the Markagunt Plateau this terrain is particularly well-developed because the plateau is capped by volcanic (basalt) rock that directly overlies the Eocene Claron Formation, a marly limestone that is locally cavernous (MOORE et al., 2004).

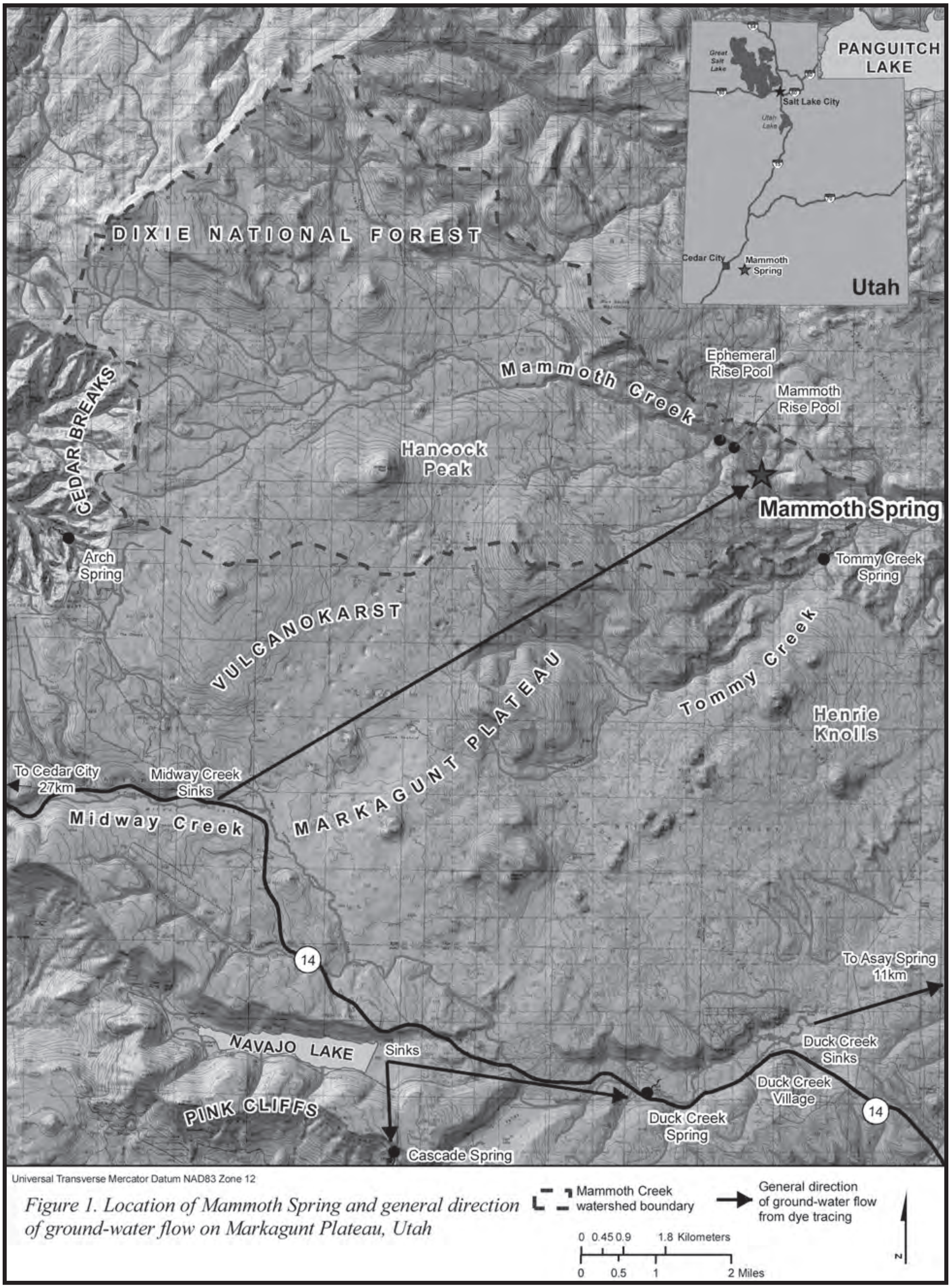

Figure 1. Location of Mammoth Spring and general direction of ground-water flow on Markagunt Plateau, Utah

Figure 1: Location of Mammoth Spring and general direction of groundwater flow on Markagunt Plateau, Utah.

Dissolution within the Claron has induced collapse of the overlying basalt, resulting in a landscape characterized by sinkholes (dolines) as much as 300 m across and 30 m deep. Some of these sinkholes serve as focused points of recharge during the snowmelt runoff period. Numerous large springs discharge from the basalt and underlying limestone on the Markagunt Plateau, including Mammoth Spring. Mammoth Spring is one of the largest springs in Utah, with a discharge that can range from less than 0.14 to 8.5 m^3/s (MUNDORFF, 1971) (Fig. 2). The spring discharges from multiple outlets at an altitude of 2500 m about 13.5 km east of Cedar Breaks National Monument, where an escarpment of the Claron Formation represents the western edge of the plateau (Figure 1). Flow from Mammoth Spring immediately merges with Mammoth Creek, the principal stream within the watershed and a possible source of water to the spring. Discharge from Mammoth Spring probably is from the Claron Formation; however, recharge to the aquifer that supplies the spring likely takes place by both focused (point source) and diffuse infiltration through the overlying basalt. Although precipitation on the plateau averages about 760 mm/yr, most precipitation is in the form of snow. As a result, springflow responds primarily to snowmelt runoff during April to June and to occasional intense summer thunderstorms (Fig. 3).

Figure 2: Discharge from Mammoth Spring generally ranges between 0.14 and 5.7 m3/s seasonally.

3. Previous Investigations

Prior to this study, WILSON and THOMAS (1964) investigated groundwater movement in the Navajo Lake watershed immediately south of the Mammoth Spring watershed (Fig. 1). Basalt flows have disrupted the natural surface-water courses in this area, resulting in subterranean piracy of the outflow from Navajo Lake. Releases of water from Navajo Lake resulted in discharge increases at Cascade Spring, 1.95 km to the south and Duck Creek Spring, 5.6 km to the east, within 1 and 12 hours, respectively. Results of dye-tracer tests (Fig. 1) subsequently indicated groundwater travel times through the underlying limestone to these springs of 8.5 and 53 hours, respectively (WILSON and THOMAS, 1964). Water rising at Duck Creek Spring also was shown to lose again at Duck Creek Sinks, finally discharging at Asay Spring about 11 km to the east (Fig. 1). Groundwater travel time from these sinks to Asay Spring through the basalt and underlying limestone was about 68 hours. Bifurcation of the groundwater flow path between the Navajo Lake sinks and these springs has resulted in discharge to different surface-water drainage basins. An investigation by the U.S. Forest Service in 1975 (written commun., 2007) to determine the source of fecal coliform bacteria to a water-supply spring discharging from Duck Creek lava tube, one of the longest lava tubes in the continental United States at 3.65 km, was shown by dye tracing to originate from seepage into the lava tube from Duck Creek Spring Lake.

4. Groundwater Quality

Samples for major ions, selected trace metals, nutrients (nitrate plus nitrite, ammonia, and orthophosphate), gross alpha/beta radioactivity, and total coliform bacteria were collected during base-flow conditions (less than 0.28 m^3/s) during the fall and winter of 2006-07 to characterize the quality of water from Mammoth Spring and several other springs. Results of chemical analysis of water from Mammoth Spring indicate a calcium-bicarbonate type water containing very low dissolved-solids concentrations (about 110 mg/L) that would be expected if groundwater flow to the spring is primarily within the basalt rather than within the underlying limestone. Water collected from Arch Spring, which discharges from the Claron Formation within Cedar Breaks National Monument (Fig. 1), is characterized by somewhat higher dissolved-solids concentrations (170 mg/L), more representative of flow within the carbonate rock in this area. Results of chemical analysis of water from Mammoth Spring during higher flows (2 m^3/s) showed a reduction in dissolved-solids concentrations of about 20 percent. Low dissolved-solids concentrations in water from Mammoth Spring may be attributed to a combination of dilution, rapid groundwater travel times and recharge through the overlying basalt. No concentrations of trace metals in water from Mammoth Spring exceeded drinking-water standards, and no concentrations of nutrients in water from the spring were found that were above background levels. However, significant concentrations (10-100 counts/100 ml) of total coliform bacteria have been detected in water from the spring on numerous occasions.

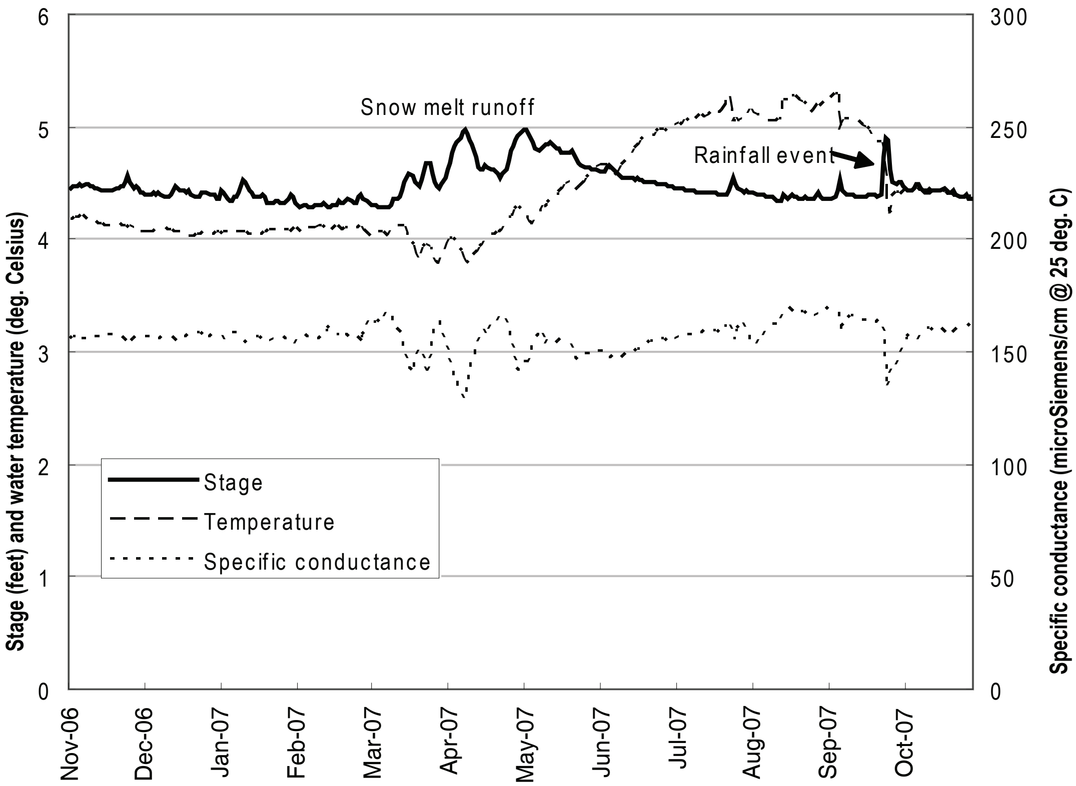

Figure 3: Relation between stage (discharge), water temperature, and specific conductance at Mammoth Spring.

Results of analyses of water samples collected from two rise pools 0.69 km and 1.1 km upstream of Mammoth Spring and adjacent to Mammoth Creek (Fig. 1) show intermediate values of dissolved-solids concentrations (130-150 mg/L) that indicate a possible mixture of water from both the basalt and limestone or possibly a mixture of ground water with water from Mammoth Creek. Significant seasonal variations in water temperature and specific conductance, and similarities in oxygen-deuterium ratios also suggest possible hydraulic connections between these springs and Mammoth Creek at certain times of the year. Discharge measurements along Mammoth Creek between these springs and Mammoth Spring indicate a substantial loss of streamflow through the streambed, particularly during flows of less than 0.14 m^3/s, where all flow may be lost into the streambed before its confluence with Mammoth Spring. Results of chemical analyses and dye-tracer tests do not indicate however, an apparent connection between these springs and Mammoth Spring.

5. Relation of Water Temperature and Specific Conductance to Discharge

Springflow (stage), specific conductance, and water temperature of Mammoth Spring have been continuously monitored on a 1 to 2-hr basis since November 2006; relations between these parameters from November 2006 to October 2007 are shown in Figure 3. During this period, water temperature of the spring ranged from 3.8 to 5.4 ^{0}C, and specific conductance ranged from 127 to 170 microSiemens/cm (at 25 ^{0}C), while discharge ranged from about 0.14 to 1.47 m^3/s. The pH of water from the spring ranged from 7.7 to 8.3 units over this same time period. A substantially greater snowpack and runoff during the spring of 2008 resulted in a peak flow that exceeded 5.7 m^3/s, or about four times the peak flow in 2007. As discharge increases during the snowmelt runoff period, specific conductance and water temperature generally decrease, reflecting the movement of snowmelt (low conductance) water through the aquifer that mixes with and replaces water that has been in storage. These effects may occur over very short time periods. During late September 2007, a 2-day rain event increased spring flow about 0.9 m^3/s, resulting in a decrease in specific conductance of 30 microSiemens/cm and a decrease in temperature of 0.63 ^{0}C (Fig. 3). Similar relations also have been documented at other alpine karst springs in the northern part of Utah (SPANGLER, 2001). Although not continuously monitored, turbidity was observed to increase in the springflow during the snowmelt runoff period and particularly after rainfall events. Mammoth Creek typically becomes turbid following summer thunderstorms, which originates from rapid overland runoff and erosion of the marly Claron Formation. These relations in addition to the presence of total coliform bacteria in the spring water indicate a significant potential for fractures or other permeable pathways to transmit particulate material and possibly contaminants from surface sources to the spring in a relatively short timeframe.

6. Groundwater Residence Time

A dye-tracing study on the Markagunt Plateau during the spring of 2008 showed that part of the water from Mammoth Spring originates from an area 13.7 km southwest of, and 450 m higher than, the spring (Fig. 1). Water from Midway Creek losing directly into the Claron Limestone discharged at Mammoth Spring within 27 days and at no other springs monitored. Because passive adsorption onto activated charcoal was used for detection of the dye, the groundwater travel time is considered to be a maximum. Results of this test also indicated that part of the water discharging from Mammoth Spring originates from outside the surface watershed boundary of the spring (Fig. 1) and that groundwater flow to the spring is likely along conduits within the Claron Formation. Mapped faults trending northeast through the Markagunt Plateau may influence groundwater flow to the spring (MOORE et al., 2004). Results of analyses for selected age-dating isotopes (sulfur-35 and tritium) and chlorofluorocarbons (CFCs) substantiate the results of dye tracing, and indicate that residence times within the aquifer that supplies the spring probably are a mixture of short- (months or less) and long-term (years) components. Samples collected during base flow when most water is presumed to be from storage within the fractured matrix, contained tritium concentrations of 28.4 picocuries/Liter (8.8 tritium units) and CFC-11, 12, and 113 concentrations that indicate an apparent age of about 6 years or younger since recharge. In addition, results of analysis for sulfur-35, an age-dating tool for waters less than about 2 years old (87-day half-life), contained concentrations ranging from 0 millibequerels/Liter (mBq/L) during base-flow conditions, indicating waters greater than 2 years old, to about 4.0 mBq/L during snowmelt runoff, indicating groundwater residence times that are probably less than 6 months.

7. Additional Work

Future work in the Mammoth Spring area will include 1) continued field reconnaissance to locate additional focused recharge sources to the aquifer that have the potential to directly impact Mammoth Spring, 2) collection of additional water-quality samples and continued measurement of field parameters (water temperature, specific conductance, pH) to further characterize water from the basalt and the underlying Claron Formation and to evaluate hydrologic relations between these units, and 3) additional dye-tracing studies to delineate groundwater basin boundaries for the spring and to determine groundwater travel times through the aquifer.

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KARST AND GROUNDWATER IN NORTHEASTERN COAHUILA: AN EDWARDS AQUIFER MIRROR

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The northeastern corner of the Mexican state of Coahuila contains some of the most extensive limestone outcrops in the country, yet the karst and groundwater have seen relatively little investigation. The western (recharge) portion of the area contains ridge tops of Lower Cretaceous rocks over 1500 m in elevation, which slope down to the east and south to plunge underneath less karstic Upper Cretaceous outcrops. This represents a confined aquifer zone where wells can flow under artesian pressure. In this respect it resembles the Edwards Aquifer across the Rio Grande in Texas, with similar carbonate lithologies and karst components.

Over 60 caves have been explored in the area, most since the year 2000. Upland portions of the recharge zone contain vertical caves that likely contribute to aquifer recharge, although numerous seep-spring caves in canyon walls disgorge some water prematurely. The canyons themselves are major zones of recharge, exemplified by El Abra, a horizontal stream cave that is the longest in Coahuila at 1841 m in length. In the lower part of the recharge zone close to the artesian zone, there are a number of caves which are estavelles. These have large funnel-shaped sinkhole entrances that slope down to pits, dropping up to 90 m to flowing streams. These normally take water, but during times of heavy rains in the recharge zone they can become springs.

1. Setting

The Sierra del Burro and surrounding areas in northeastern Coahuila contain the second largest carbonate outcrop in Mexico, surpassed only by the Yucatan peninsula. Cretaceous limestones range from elevations of 1500 m in the western part of the area down to less than 500 m to the southeast. Boghici (2004) considers this area to comprise just over half of the binational Edwards-Trinity aquifer. Like the Edwards-Trinity in Texas, caves and losing streams recharge via units such as the Glen Rose and Devil's River Formations, and resurge at low points in the Austin Chalk and other units (Fig. 1). On its eastern side the aquifer is confined, and drilled wells can flow under artesian pressure. At the eastern limits across the "bad water line" wells and springs become saline (TDS > 1000 mg/l).

2. Recharge Caves

The Sierra del Burro is heavily dissected by numerous canyons. Some upland areas contain vertical caves that can reach depths of more than 100 m. These typically consist of a series of vertical drops to rubble or dirt plugs, and contribute significant recharge. The deepest of these upland caves explored thus far is Sótano de Los Enriquez. Mapped in 2007, it is situated on a bench on the east side of the Sierra Santa Rosa that is at the southeastern end of a swath of Devils River Formation outcrop. The entrance pit measures 50 by 25 meters across, and is incised by surface drainage at its northern end. A vertical drop of 103 m (longest in the state of Coahuila) leads to a plug of flood-borne soil at a depth of 124 m.

Deeper caves such as Los Enriquez certainly recharge the aquifer, but a least some recharge reappears in canyon walls via seep-spring caves. Due to the sheer quantity of canyons dissecting the sierra, there are many caves exposed, some of which were likely water outlets. Cueva de San Rodrigo is one such cave that was mapped in 1998. It is located along the north wall of the Río San Rodrigo canyon, and at the entrance it is 8 m wide and 6 m high. The cave gradually slopes upward and becomes smaller, becoming too small to explore after 90 m.

As the canyons progress downstream water flow can be pirated into such features as El Abra, currently the longest surveyed cave in the state at 1841 m of passage, surveyed between 1998 and 2002. The entrance is a hole in the floor of Cañon San Dabe in horizontally bedded bedrock at the top of the Glen Rose Formation. Water pours into this entrance during wet periods, and also comes in from a sump just below the shallow entrance pit from an unknown source. This stream flows at a gentle gradient through the main route of the cave to the limit of exploration at a sump. The cave trend underlies the surface canyon, which at this point trends north, though its ultimate destination

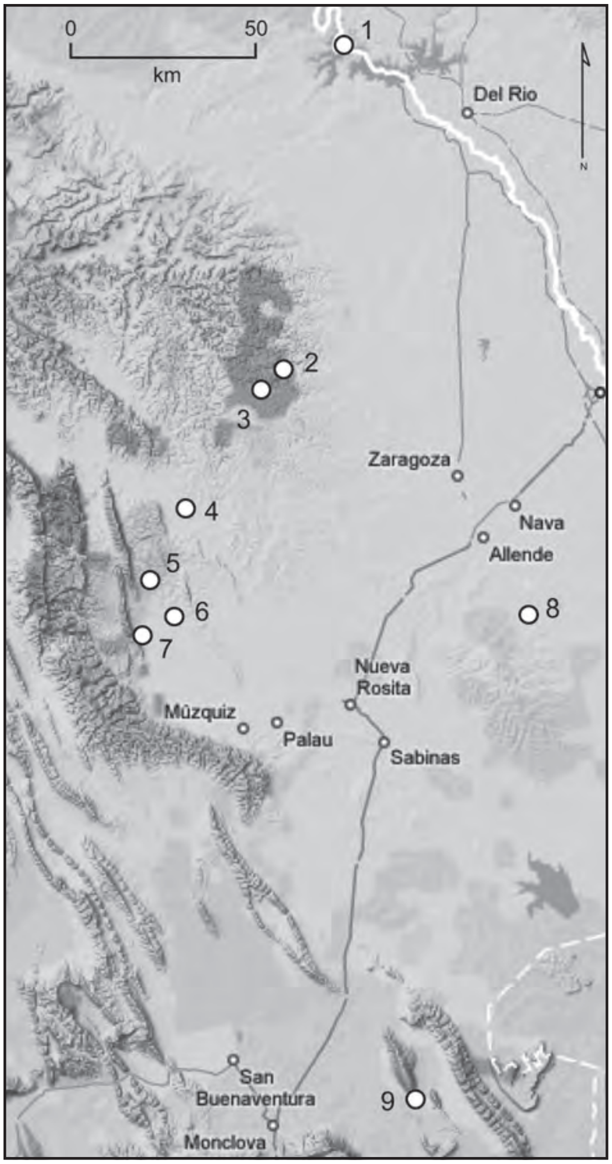

Figure 1: Karst sites of the Coahuilan Edwards-Trinity Aquifer: 1. Goodenough Springs 2. Cueva de San Rodrigo 3. El Abra 4. El Hundido 5. Sótano de Los Enriquez 6. Embudo de Huevos 7. Nacimiento Kikapú 8. Cueva de La Azufrosa 9. El Hundido.

is eastward toward the Río Bravo (Río Grande). The downstream sump lies 700 m north of the cave entrance. El Abra is quite shallow, with a depth of 16 m. A Texas analog for this cave is 5650-meter-long Indian Creek Cave in Uvalde County. It also sinks in the bed of a canyon at the top of the Glen Rose Formation, and after an initial vertical drop it is a horizontal stream passage that meanders underneath the bed of the surface canyon.

3. Discharge Sites

Groundwater rises at perennial springs in an arc around the northeast, east, and southeast sides of the Sierra del Burro, emerging from the Austin Chalk and the Salmon Peak Formation. The largest of these is the Nacimiento Kukapú, which rises in gravels from the Austin Chalk as the source of the Río Sabinas. None of these perennial springs have been found to be enterable. However, Goodenough Springs in Val Verde County, Texas may discharge waters from Coahuila. Though now inundated 45 m below the surface of Lake Amistad, this cave has been explored by divers to a depth of at least 115 m below the entrance (Stafford et al, in review). There is also the prospect of Edwards-Trinity groundwater traveling extensively to the southeast. Batzner (1976) concluded this in his study of the Lomerio Peyotes, a low anticlinal ridge of Austin Chalk that extends southeast through the municipality of Villa Unión for 100 km.

A cluster of sulfur and freshwater springs occurs on the east side of the Peyotes anticline near Villa Unión. Cueva de La Azufrosa is situated just above these springs and may have a shared genesis. Mapped in 2005-2006, this cave is a horizontal rectilinear maze with a small freshwater stream. Although the cave continues in the direction of the springs beyond the current 431 m of mapped passage, dense populations of Ghost Faced Bats (*Moormops megalophylla*) prevent further human exploration.

Two temporal resurgence caves north and northwest of Múzquiz are sites of particular importance to karst hydrology of the area. Embudo de Huevos was seen to be a resurgence on satellite imagery, and was investigated in 2008. It is a funnel-shaped estavelle in a channel that takes local runoff, but primarily acts as a resurgence, with a prominent channel leading from the site. The depression is 25 m in diameter and 15 m deep, formed in alluvium on top of what is probably the Austin Chalk. The bottom of the sink is a jam of rounded limestone cobbles over an apparent pit. It is possible to drop pebbles down the pit between the jammed cobbles, and airflow comes out of it. Attempts to excavate the entrance were thwarted by collapse.

El Hundido is another estavelle, situated in an isolated outcrop of the Buda Limestone near El Mulato that is surrounded by alluvium. It is a large diameter pit (Fig. 2) that drops 90 m to a streamway, with further drops in the downstream direction. During regional flooding in August 2008, water flowed out of this pit, forming a large lake (Fig. 3) with a raised fountainhead, evidence of significant hydraulic head originating in the Sierra del Burro to the north.

A study in the 1990's of the stygobitic catfish *Prietella phreatophila* by Hendrickson et al (2001) sheds further light on aquifer connectivity. Unlike the two species of blind

Figure 2: The 90 m entrance shaft to El Hundido at El Mulato during dry conditions

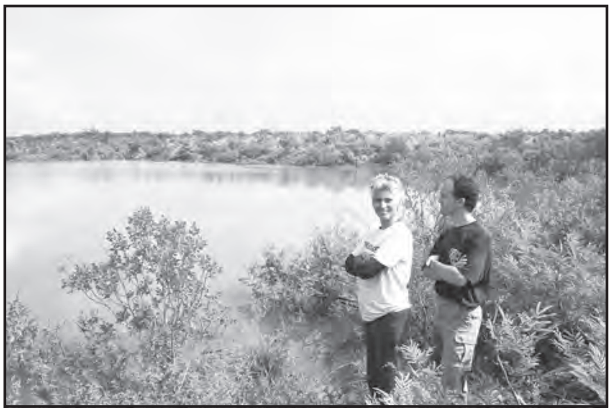

Figure 3: El Hundido at El Mulato during flood, after subsidence of fountainhead

catfish that live at depths of up to 600 m in the Edwards Aquifer below San Antonio, Texas, these fish live at the top of the aquifer and have been found in five caves across the study area. These sites are in a north-south line 170 km long. There are anecdotal reports of blind fish being expelled from another temporal resurgence at the south end of the Sierra la Rata, an isolated plunging anticlinal ridge east of Monclova. Also know as El Hundido, this is normally a 50 m pit to a bat guano covered sump. On 17 September 1988 Hurricane Gilbert flooded Coahuila, the second most intense Atlantic storm on record. Local witnesses reported a tall fountainhead issuing from the pit, carrying white fish. Efforts to obtain fish from the sump in July 2008 were unsuccessful. If *P. phreatophila* were confirmed from this site, it would suggest an aquifer extent of 270 km.

4. Conclusions

The Edwards-Trinity Aquifer of northeastern Coahuila contains recharge caves and springs that mirror similar features in the same rock units in the Edwards-Trinity Aquifer of Texas. Most of the area remains unexplored for caves, but caves will play a crucial role in understanding of this productive and increasingly important aquifer.

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MICROCLIMATIC CHANGES DURING THE TOTAL SOLAR ECLIPSE ON AUGUST 11, 1999 AND THEIR IMPACT ON BAT COLONY ACTIVITY

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Abstract

Many animals have an inner rhythm or biological "timepiece" for sensing periodic phenomena such as 24 hours, tides, seasons etc. The circadian system of Rhynolophus hipposideros bats depends on surface diurnal geophysical cycles under normal circumstances. Individual mechanisms of circadian nonrhythmicity of a bat colony composed of about 1400 individuals were investigated during the total solar eclipse on August 11, 1999. A biological experiment was conducted in the Karankat cave situated in the coastal part of the Kavarna region, Bulgaria. Data are interpreted as an effect of the total solar eclipse on the nonbiotic factors.

The dependences between phase evolution of the eclipse and discrete oscillators of bat physiological rhythm are discussed. An attempt is made to explain these effects by the fact that a bat circadian system consists of several relatively independent oscillators with different periods. These oscillators are activated by the change of atmospheric air barometric pressure on the Earth's surface and the following change of the speed and direction of the air flow in the cave galleries. The short term atmospheric reaction as a result of the screen effect of the lunar shadow on the solar radiation influx are discussed

Influence of the Solar and Geomagnetic Activity on Cave Climate

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Abstract

Climate change is defined as a long-term effect of weather change on Earth. Climatic trends connected with short and long-period variations of the solar activity occur as a reaction even in such conservative media as the air volumes of karst caves are. The generally accepted conceptual model considers karst systems as composed from three main zones: heterothermic zone near the surface, unsaturated homothermic zone and zone of the constant temperatures. In each zone air, water and rock temperature tend to equilibrium. Therefore, heat exchange between air, water and walls is the dominant process acting in all three zones.

Climatic trends connected with short and long-period variations of the solar activity occur as a reaction even in such conservative media as the air volumes of karst caves. The yearly mean air temperatures in the zone of constant temperatures of four show caves in Bulgaria (latitude 42.50°N, longitude 25.30°E) were studied for a period of 36 years (1968 – 2003). The examination was made by everyday noon measurements in Ledenika, Saeva dupka, Snezhanka and Uhlovitsa cave. The caves are situated at different altitudes and geographic latitude. Cave temperatures in the zone of constant temperatures (ZCT) are compared with surface temperatures recorded at meteorological stations situated near about the caves – in the towns of Vratsa, Lovech, Peshtera and Smolyan respectively.

The Hansen cave, Middle cave and Timpanogos cave from the Timpanogos cave National Monument, Utah, USA have also been examinated for comparison (latitude 40.27°, longitude 111.43°). Seasonal fluctuations of the yearly mean air temperature in the ZCT of the explored caves have been identified by Fourier analysis. The same analysis has been applied for the Sunspot number and Apmax indices, which are representatives of the solar and geomagnetic activity, for the same period of data available. Autocorrelograms have been used for examination of the seasonal patterns of the air temperatures in the ZCT in every cave and in Sunspot number and Apmax indices. Cross-spectrum analysis has been applied for retrieving the correlations between air ZCT temperatures in the caves and solar and geomagnetic activity.

It has been found that the correlation between ZCT temperature time series and sunspot number is better than that between the cave air temperature and Apmax indices. It has been found that $t°_{ZCT}$ is rather connected with the first peak in geomagnetic activity, which is associated with transient solar activity, i.e., coronal mass ejections (CMEs) than with the second one, which is higher and connected with the recurrent high speed streams from coronal holes. Our results can help in studying heat exchange between the surface and subsurface air and its influence on cave ecosystems.

INTERNATIONAL CAVING STUDYING THERMOGRAPHIC ANOMALIES OF CAVE OR LAVA TUBE ENTRANCES FOR NASA, ANALOG MOON AND MARS

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Abstract

Thermography of cave and lava tube openings is a scientific research tool that is starting to come into its own. NASA and cavers have come together in the study utilizing infrared thermograms to locate caves and lava tubes.

Research to determine which conditions and times are the best for subterranean entrance detection by use of infrared thermography and other detection methods are ongoing.

A comparison of timed thermographic images in the infrared band of cave and lava tube entrances for NASA's Spaceward Bound program have resulted in answers, as well as more questions, concerning this state of the art method of locating cave and lava tubes on Earth and possibly other planets.

Timed thermographic images of Cavernas de Quitor and other caves in the Atacama Desert, Chile caves are compared with Mojave Desert Lava tubes; Pisgah and Cima, as part of an ongoing NASA project to develop protocols to locate caves and lava tubes by their thermographic images.

Research methods include analysis of thermographic images taken every ten minutes over a twenty-four hour period of the Cima lava fields in the Mojave Desert of California.

By utilizing a hot air balloon as an airborne platform a study is being conducted to determine the best times and heights to obtain signatures of cave and lava tube openings.

A number of factors are entered in and examined: Time of day, ambient temperature, height, dew point, distance, specific humidity, platform, as well as wind velocity and atmospheric gases.

HIDDEN SPRING--A LONG-KNOWN RESURGENCE WITH A NEWLY IDENTIFIED CARBONATE AQUIFER CHEMISTRY IN SEQUOIA AND KINGS CANYON NATIONAL PARKS, CALIFORNIA, U.S.A.

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Hidden Spring, a perennial alluviated resurgence shown on U.S. Geological Survey topographic maps, discharges <3.8 L/s into a tributary to the Kaweah River's North Fork, and lies along a line that connects Big Spring in the Redwood Canyon karst and Crystal Cave in the Yucca Creek karst in Sequoia and Kings Canyon National Parks (SEKI). The spring thus lies between two major karst areas of the Parks and along a trend that subparallels the structural grain of the Sierra Nevada. The prior literature is mute on Hidden Spring's chemistry and discharge; published geologic maps show no exposures of marble or other carbonate rocks, but the spring has served as a reliable source of water for stock and for domestic use during the 20th century. In June 2008, Cave Research Foundation personnel hiked to Hidden Spring via trails unmaintained for at least three decades. Using standard U.S. Geological Survey protocols water samples were obtained for dissolved inorganic carbon (DIC), major cation and anion chemistry, and stable isotopes D, ^{18}O and ^{13}C. The significant cation concentrations reported in units of mg/L are Ca (41) and Mg (23) and the only anion of significance is HCO_3 (lab alkalinity of 242). The specific conductance of 330 uS/cm and DIC values (4.05) are in excellent agreement with the pH of 8.1 and are consistent with the lab alkalinity being essentially all HCO_3. The chemical characteristics are those expected of groundwater that flows through dolomitic rocks. The Redwood Mountain pendant carbonates hosting Lilburn Cave are known to range in composition from calcite- to magnesium-rich marble. The rocks contributing carbonate to Hidden Spring are neither gypsic nor sulfide-rich as SO_4 concentration is but 0.68 mg/L. The sample is high in silica (SiO2 = 42 mg/l) but that would be consistent with considerable contact with silicate or calc-silicate rocks, which are abundant locally and regionally as non-carbonate pendant lithologies. The stable isotopes and the DIC values, specific conductance, and major element abundances support a carbonate aquifer association, with strong evidence of contact with silicate rocks. What is not discernible from the chemistry alone is the distribution of carbonates relative to calc-silicates hence the true nature of the carbonate occurrence remains obscure. Intense wildfires (Hidden Fire) burned much of the area this past autumn. Following winter precipitation, many new exposures are anticipated and ridge-walking may reveal more details of the areal geology. Alternatively, the marble that is the apparent source of the bicarbonate hydrochemistry of Hidden Spring may simply not yet be exposed owing to vagaries of erosion or to geologic structure, or the carbonate may be distributed as many small masses within the metamorphic rock body. Hidden Spring thus drains a heretofore unrecognized carbonate terrane of uncertain extent and thus may or may not constitute an additional area of the Parks with cave resource potential.

1. Introduction

Sequoia and Kings Canyon National Parks (SEKI) in the southern Sierra Nevada of California are famous for deep canyons, rugged mountains and numerous groves of Giant Sequoia trees. The bedrock geology exposes mainly Jurassic and Cretaceous batholithic rocks that were the roots of a middle to late Mesozoic continental volcanic arc that developed along a convergent plate margin that persisted for tens of millions of years along the western margin of North America. These Sierra Nevada batholithic rocks range in composition from diorite to granite and intrude early Mesozoic and older marine sedimentary and volcanic country rock that contained pods of marine limestone. In the modern landscape, the areas of metamorphic rock are not contiguous and commonly are termed roof pendants. Parts of six of these metamorphosed rock terranes are mapped in the Giant Forest quadrangle by Sisson and Moore (1994) and the carbonate portions of these are metamorphosed to marble. The discontinuous bodies of marble harbor more than 240 extensive and well-decorated caves and karst features that together make SEKI not only a "mountain and tree" park, but also a "cave" park. See Moore (High Sierra)

USGS topographic maps show Hidden Spring drains to the North Fork of the Kaweah River. Historically the spring has provided water for stock and for domestic use as nearby now-abandoned roads and cabins attest. The geologic map of the Giant Forest 15' topographic quadrangle (Sisson and Moore, 1994) shows the spring to lie along a trend that subparallels the regional tectonic grain of the Sierra Nevada and that connects two well-known major karst areas. Northwest of Hidden Spring is the Redwood Mountain pendant, with the Redwood Canyon karst that contains Lilburn Cave and its ebb-and-flow resurgence (Big Spring). Southeast of Hidden Spring lies the extensive Crystal Cave Pendant and the Yucca Creek karst that contains the parks' show cave, Crystal Cave, and many other marvelous karst features. Yet, the literature contains no information about Hidden Spring, its chemistry or its discharge. Sisson and Moore (1994) map the spring near the contact between the granite of Skagway Grove and a body of biotite-feldspar-quartz schist commonly containing andalusite or sillimanite. They note these rocks (which are not well-exposed) also contain minor amounts of marble and calc-silicate schistose rocks and thin layers of micaceous quartzite. The contact between the granite of Skagway Grove and the above metamorphic rocks is mantled with alluvium (Fig. 1).

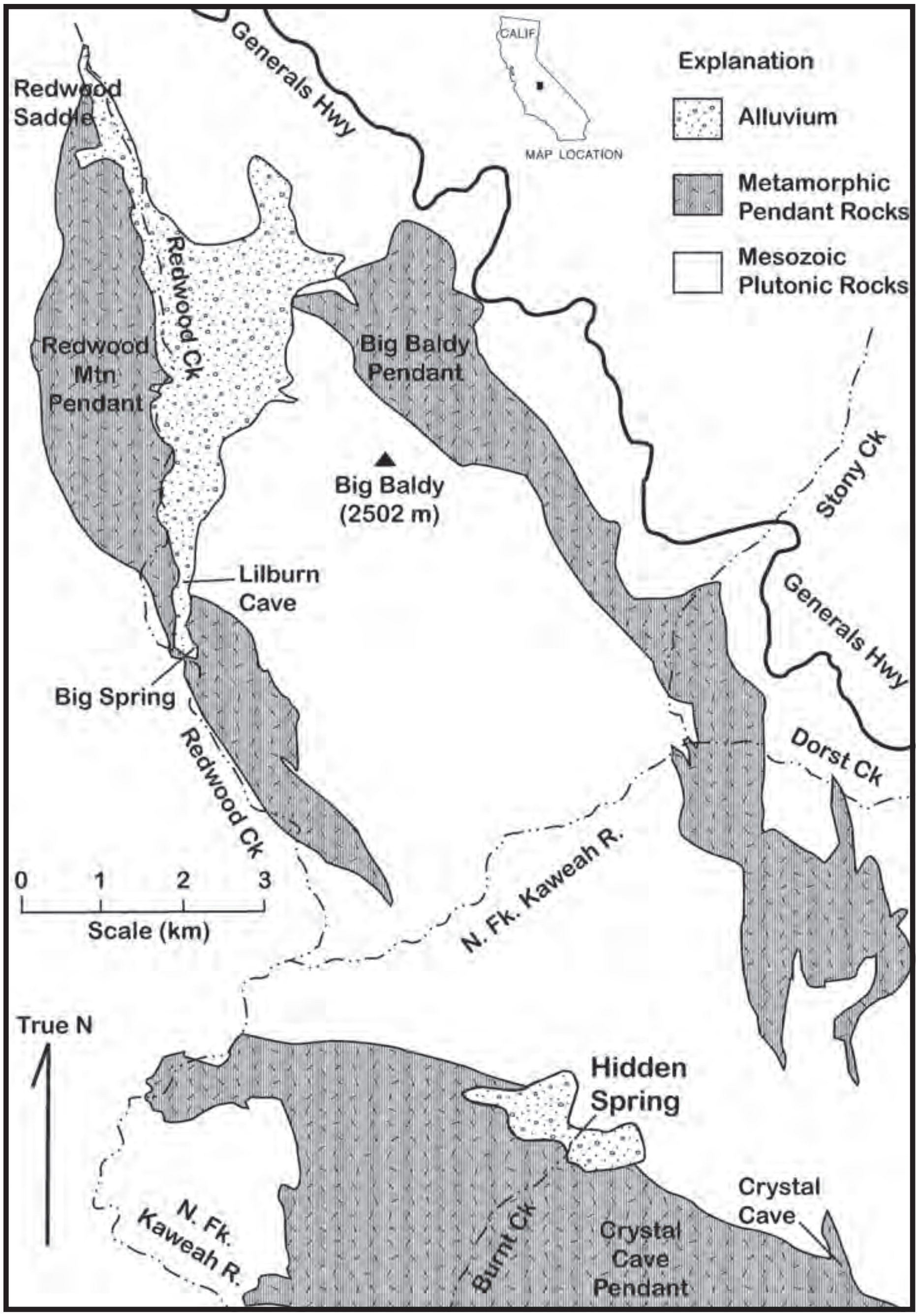

Figure 1: Map showing generalized geology, plutonics, pendants, selected physiographic features and cultural features near Hidden Spring, Sequoia and Kings Canyon National Parks. Abridged from Sisson and Moore (1994).

To try to learn more about Hidden Spring and to further evaluate it as a potentially unrecognized karst aquifer, personnel of the Cave Research Foundation visited the spring in June 2008 and obtained water samples to analyze for major cation and anion chemistry, dissolved inorganic carbon (DIC), and stable isotopes D, ^{18}O and ^{13}C thereby obtaining a snapshot of this spring and its chemistry.

2. Methods

Standard U.S. Geological Survey water sampling protocols were used (per Evans et al, 2002, p. 294-295). DIC samples were collected using a syringe to withdraw 50 cm^3 of water from the upstream most portion of the spring resurgence. The water was injected through a septum into pre-evacuated, pre-weighed 250 cm^3 Pyrex tubes, each equipped with a vacuum stopcock and containing 0.5 ml of 6 M HCl that immediatedly converted all DIC to CO_2 and preserved the sample for storage and transport back to the laboratory. In the lab, the CO_2 was extracted into a liquid nitrogen trap on a high-vacuum line. The DIC tube was shaken repeatedly until all (>99%) of the CO_2 was collected in the trap. The trap was allowed to thaw, releasing any CO_2 trapped in the ice, before the CO2 was dried and quantified using a calibrated electronic transducer. The DIC value was calculated from the quantity of CO_2 and the weight of water in the DIC tube. Samples of water for oxygen and hydrogen isotopic analysis were collected in tightly sealed glass bottles. The $\delta\ ^{13}C$ was determined using purified CO2 extracted from the DIC sample. The ^{18}O, ^{13}C and deuterium analyses were run on Finnegan MAT 251 and δ E mass spectrometers.

Field measurements of water temperature and pH were obtained at the uppermost accessible discharge point using a Markson Model 95 digital meter calibrated against standardized solutions. Specific conductance was measured using a temperature compensated Nestor Model 11 MICROMHO™ pen-type digital meter; the Nestor instrument was checked against laboratory standards pre- and post-field use and was found to be reasonably accurate over the range of 4 – 350 uSiemens/cm. The discharge at Hidden Spring was not directly measured, but was observed to approximately double along a 50 m reach downstream from the uppermost point at which flow appeared in the alluvium surrounding the spring. The maximum observable discharge was less than 3.8 L/s with underflow through the alluvium not accounted for.

3. Results

The field measurements and laboratory analyses for Hidden Spring are compiled in Table 1, along with selected values from Big Spring/Lilburn Cave for comparison from Urzendowski (1993). For dilute water ppm concentrations effectively equal mg/L within analytical accuracy. It is important not to over-interpret sparse data.

For Hidden Spring (Table 1) the geochemical snapshot from sample 2008-JCT3-HS shows that significant cation concentrations are: Ca (41 mg/L), Mg (23 mg/L) and SiO2 (43 mg/L). The charge balance (5.42%) is satisfactory and shows no indication of sampling or analytical problems or issues. The only anion of significance is HCO_3 (lab alkalinity as HCO_3 = 242 mg/L). The specific conductance of 330 uS/cm and the total DIC value (4.05) are in excellent agreement with the pH of 8.1 and are consistent with the lab alkalinity being essentially all HCO_3. Elevated silica is not surprising as abundant silicate lithologies characterize rocks upslope from the resurgence. Extracted versus calculated DIC values are 4.00 mmol/kg and 4.05 mmol/kg, respectively. The DIC extracted from both pre-evacuated sample tubes is in decent agreement with the quantity expected from the values of field pH and lab alkalinity, and shows good internal consistency in the sampling and analytical processes and confirms that alkalinity is essentially HCO_3. δD values are -80.7 $\pm$ 2 per mil and $\delta^{18}O$ values are -11.64 per mil for sample 2008-JCT3-HS. $\delta^{13}C$ measured on 2008-JCT3-HS7 is -14.33 per mil.

4. Discussion

The chemical characteristics above are quite similar to characteristics expected of groundwater that flows through dolomitic carbonate rock (see Hem, 1985, p. 98-99). While no rock compositions are available for the Hidden Spring area, a few kilometers to the northwest, the marble of the Redwood Mountain pendant that hosts Lilburn Cave ranges widely in composition from calcite- to magnesium-rich marble (Tinsley et al., 1981), so pendant lithologies in some pendants are known to have dolomitic composition. Hem points out that groundwater would be expected to dissolve roughly equal molar amounts of Ca and Mg until saturation is achieved. When all excess CO_2 acquired by water as it passed through the soil zone is nearly completely reacted in dissolution of carbonate minerals, the pH is driven up to approximately 8.

A SOLMINEQ88 (Kharaka et al., 1988) analysis (W.C. Evans, personal communication) shows that the sampled water is supersaturated with respect to calcite (Saturation Index, SI = 0.41, Table 1) and very supersaturated with respect to dolomite (SI = 1.89). This situation could occur if some CO_2 is lost as a gas somewhere on the way to the spring, raising pH slightly to cause the supersaturation. Calcite could precipitate but dolomite would not form thus leading to the saturation index values above. The Ca/Mg ratio in the water does not reflect bedrock Ca/Mg proportions.

The rocks contributing carbonate to Hidden Spring are neither gypsic nor sulfide-rich as SO_4 concentration is but 0.68 mg/L. The sample is high in silica (SiO_2 = 42 mg/L) but that would be consistent with water enjoying considerable contact with silicate or calc-silicate rocks. Sisson and Moore (1994) map such rocks in the vicinity of Hidden Spring; silicate-rich lithologies are abundant locally and regionally as non-carbonate pendant lithologies and can

Table 1. HIDDEN SPRING CHEMISTRY VS BIG SPRING/REDWOOD CYN KARST					
			Hidden Spg		Redwood Cyn
			2008-JCT3-HS		Big Spring
Cations			30-May-08		8-Mar-92
Na	ppm	mg/L	6.1		2.5
K	ppm	mg/L	1.3	meq/L	0.7
Ca	ppm	mg/L	41	2.05	19.4
Mg	ppm	mg/L	23	1.89	0.8
Fe	ppm	mg/L	<1		na
SiO2	ppm	mg/L	43.2		15.3
Li	ppb	ug/L	<3		na
Mn	ppb	ug/L	<1		na
Al	ppb	ug/L	84		na
B	ppb	ug/L	30		na
Mo	ppb	ug/L	<1		na
V	ppb	ug/L	2.4		na
Ba	ppb	ug/L	20		na
Sr	ppb	ug/L	97		na
As	ppb	ug/L	<2		na
Rb	ppb	ug/L	1.2		na
Cs	ppb	ug/L	<1		na
U	ppb	ug/L	<1		na
		meq/L cations	4.2511		
Anions					Anions
F	ppm	mg/L	0.08		na
Cl	ppm	mg/L	1.39		0.6
Br	ppm	mg/L	<0.01		na
NO3-N	ppm	mg/L	0.04		na
SO4	ppm	mg/L	0.68		1.3
PO4-P	ppm	mg/L	<0.01		na
Alkalinity as HCO3	ppm	mg/L	242		67.5
meq/L	Anions		4.0268		
balance %			5.42		
Water temp	deg C		9.1		6.0
Field pH			8.1		7.6
Field conductivity	uS/cm		330		107
					Urzendowski 1993
				2008-JCT3-HS-7	2008-JCT3-HS-8
DIC (extracted)	mmol/kg			4.00	3.98
DIC (calc)	mmol/kg		4.05		
delta 13C per mil				-14.33	
SI calcite			0.41		
SI dolomite			1.89		
Other Isotopes			delta	uncertainty	
delta D per mil			-80.7	-2	
delta 18O per mil			-11.64	-0.2	

Table 1: Geochemical data from Hidden Spring, Sequoia and Kings Canyon National Parks, sampled on June 3, 2008. Some geochemical data from Big Spring/Lilburn Cave/Redwood Mountain pendant included for comparison.

easily account for the silica.

Deines et al (1974) showed that $\delta^{13}C_{DIC}$ depends mainly on PCO_2 and pH for a given $\delta^{13}C$ of soil CO_2 and carbonate rock. They modeled the evolution of $\delta^{13}C_{DIC}$ of carbonate groundwaters for open- and closed-system conditions, soil PCO_2 from $10^{-0.5}$ to $10^{-3.5}$ atm, pH from 4 to 7.5, $\delta^{13}C$ of soil CO_2 between -21 and -25 per mil, and $\delta^{13}C$ of carbonate bedrock of +1 to +2 per mil. Their model accounts for fractionation factors of carbon isotopes between carbon-bearing species in water at 10 °C, with no influence of the carbonate rock on $\delta^{13}C_{DIC}$ during open-system dissolution. Thus, isotopic equilibrium was maintained between the reservoir of soil CO_2 and the carbon species dissolved in the water. In their open-system model, $\delta^{13}C$ evolved only in response to pH changing owing to mineral dissolution to the isotopic fractionation between soil CO_2 and and the carbon species in aqueous solution. In their closed system model, $\delta^{13}C$ evolution of DIC reflected equilibrium with soil CO_2 and carbon added owing to carbonate mineral dissolution. Their model (as applied to Nittany Valley diffuse-type wells and springs) showed $\delta^{13}C_{DIC}$ values averaging -13.3 per mil. Waters evolving under open system conditions were isotopically lighter in $\delta^{13}C_{DIC}$ averaging -18 per mil. Hidden Spring at $\delta^{13}C_{DIC}$ of -14.33 per mil likely reflects mainly a closed system than an open system with respect to DIC.

Comparing the major element chemistry of Hidden Spring to that of Big Spring, the resurgence for the karst of Redwood Canyon, is a speculative exercise, because we don't have comparable seasonal sampling, analyses, nor equivalent controls for discharge for the two systems. Nevertheless, broad similarities and apparently some important differences in rock chemistry seemingly are indicated. One Big Spring sample obtained on 8 March 1992 was reported by Urzendowski (1993) and is shown in the small box on the right-hand side of Table 1. In Redwood Canyon, March, is a time when Big Spring discharges at orders of magnitude greater than Hidden Spring's steady but unspectacular discharge, owing to fairly rapid melting of snow and relatively efficient conduit flow. Hidden Spring was sampled in early June, also following seasonal snowmelt. (Peak discharge in the region's rivers, such as the Kings River, typically occurs in mid-June, owing to when the high country of the Sierra tends to shed its snowpack as summer arrives. At an elevation of 4800 to 7000 feet, Redwood Creek is still slumbering with winter microbial activity levels in the soil. Diminished PCO_2 in Redwood Canyon's soils in March compared to May for Hidden Spring may account for some differences in pH. At the time of our visit, the Hidden Spring area, which faces southwest, was nearly fully leafed out. Differences in flow rate may account for slight undersaturation of Big Spring (field pH 7.6) versus the modeled saturated to oversaturated conditions at Hidden Spring (field pH 8.1) as noted above.

Both these springs have significant values of Ca, SiO_2, and alkalinity as HCO_3. However, Hidden Spring is carrying nearly thrice the silica and more than thrice the HCO_3 concentration as was Big Spring. Big Spring has significantly lower concentration of Mg compared to Hidden Spring and a bit more sulfate. Pyrite is known from Redwood Canyon where there is minor sulfide mineralization observable along the contact separating pendant carbonates from intrusive plutonic rocks on the east side of Redwood Creek. Hidden Spring apparently lacks much sulfur-based mineralization. Probably the silica, magnesium, and calcium differences are significant for these two hydrologic systems, with a greater preponderance of dolomitic carbonates characterizing the Hidden Spring system compared to Big Spring's more classic CO_2-H_2O-$CaCO_3$ chemistry.

The isotope data and the DIC values, specific conductance, and major element abundances seem most consistent with a closed system carbonate aquifer component to the Hidden Spring hydrologic system, with evidence of contact with silicate and calc-silicate rocks. Not apparent from the chemistry alone is the distribution of carbonate lithology relative to silicate and calc-silicate rocks in the bedrock traversed by waters feeding Hidden Spring. The chemistry indicates a mix of carbonate and silicate rocks nourishes Hidden Spring, but whether the carbonate component consists of a large body of cave-bearing marble or is distributed as small marble lenses within silicate and calc-silicate rocks remains unresolved. Sisson and Moore (1994) noted small quantities of marble occurr in the schist component of the pendant rocks, although these marble occurrences are not mappable as individual marble bodies.

The Cave Management Specialist at SEKI is planning an extensive campaign of ridgewalking, so as to take every advantage of the Hidden fire (October 2008) that has burned away much dense brushy chaparral and other sclerophyllous vegetation that formerly obscured the ground for decades in the Hidden Spring-Yucca Creek area. If precipitation during California's rainy season washes away much ash and fire residue, the distribution of marble and presence of significant karst features likely will become much better known.

5. Conclusions

Water from Hidden Spring apparently reflects the composition of the local rocks as described and mapped by Sisson and Moore (1994). Carbonate rock (likely dolomitic marble) in contact with Hidden Spring waters likely account for the significant calcium, magnesium and HCO_3 values. However, the fairly negative $\delta^{13}C$ value for DIC suggests that weathering of silicate rocks, soil CO_2 and weathering processes (and not solely marine carbonate rock as a DIC source) influence the water of Hidden Spring. Hidden Spring's chemistry has more to it than a classic karst aquifer with waters in contact solely with calcareous carbonate rocks. The likelihood of finding extensive karst resources associated with Hidden Spring seems small, given the proximity of extensive areas of plutonic rocks at elevations above the resurgence and the relatively high levels of dissolved silica.

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The author is indebted to personnel of the Cave Research Foundation, including Steve and Barbara Ruble and William Frantz who sampled Hidden Spring in autumn of 1994. The sample deserved a better fate, folks. Thomas Mathey, Mark Conover, Michael Cooper and Anne Rosinski gamely accompanied the author and assisted with the procurement of sample in June 2008. The Resources Management and Cave Management staff at SEKI granted pre-season access to Dorst Campground and thereby simplified our field logistics. William Evans of the US Geological Survey, Menlo Park, CA provided analyses and helpful interpretive commentary; David J. DesMarais of NASA-Ames and Daniel H. Doctor (USGS, Reston, VA) provided insights concerning pitfalls and interpretation of carbon isotopes. However, all errors of inference and interpretation are mine.

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ESTIMATING KARST CONDUIT LENGTH USING CONDUCTIVITY AND DISCHARGE MEASUREMENTS IN LILBURN CAVE, KINGS CANYON NATIONAL PARK, CALIFORNIA

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In the Redwood Creek basin, a tributary to the Kaweah River in Kings Canyon National Park, fluvial waters sink into a marble karst system and emerge at Big Spring, a single-orifice vauclusian resurgence. The lower 20% of this karst contains Lilburn Cave; currently mapped at 33.92 km (21.08 mi) Lilburn Cave is the longest in California. Lilburn Cave affords access to the upper and lower sections of the phreatic conduit system, each end of which has been dived to a distance greater than 300 m. The description provided by the cave diver indicates a single tubular passage approximately 3 m in diameter at either end, with no obvious large tributary passages connecting to these conduits. In 2006, a snowmelt flood pulse was recorded in Redwood Creek upstream of the karst and also at Big Spring, permitting an estimate of the volume of water contained within the flooded karst conduits. From this volume, the potential conduit length and associated cave passage length also were estimated. The time delay between the minimum value of stream conductivity observed above the karst and at Big Spring was approximately 0.30 day. The discharge curve for Big Spring was integrated across this time period, and the volume was corrected for contributions of water from the fractured rock matrix. The total volume of water discharged from the phreatic conduits connecting the sink at Redwood Creek to Big Spring was determined to be about 45,000 cubic meters. Assuming a single cylindrical conduit of 3 m diameter, a maximum conduit length was determined to be approximately 3.0 km. Based on the current known ratio of surveyed cave passage length to subterranean main stream passage length of 20:1, a potential cave length was estimated to be 60 km. This value approximately represents a doubling of the known cave passage to date.

1. Introduction

The Redwood Canyon drainage basin in Kings Canyon National Park, California, hosts Lilburn Cave, the longest cave west of the continental divide with over 33.92 km of mapped passages (Fig. 1). This cave and other associated karst features in Redwood Canyon are home to endemic, cave-adapted species, as well as unique mineral deposits. These critical resources are intimately linked to the surface by Redwood Creek, which traverses the marble karst of the canyon and emerges at Big Spring, a single-orifice vauclusian resurgence. The lower 20% of this surface drainage (from the highest sink point to the spring) contains Lilburn Cave. Through efforts of the Cave Research Foundation (CRF), the extent of this cave continues to be explored to further understand cave development within this drainage basin.

Cave research in Redwood Canyon was initiated in the late 1950s with attempts to map Lilburn Cave. Continuous research has been ongoing for more than 35 years and has proceeded under the auspices of the CRF since 1977. Products of this research include detailed maps of the cave system (BOSTED et al., 2003), interpretive reports and theses on sedimentology (TINSLEY et al., 1981;

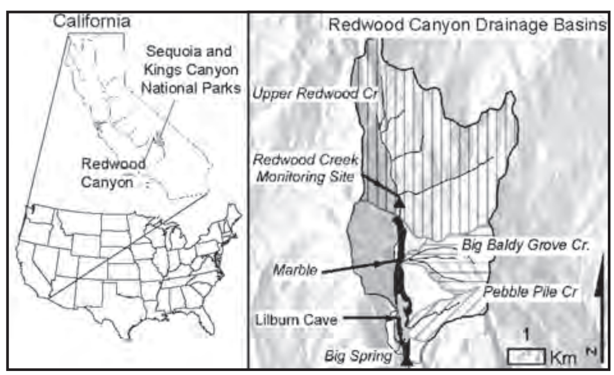

Figure 1: Map of the Redwood Canyon drainage basin.

TINSLEY, 1990; TINSLEY et al., 2003), and karst hydrology of Big Spring (SARA, 1977; URZENDOWSKI, 1993). In addition, several sensitive biological species have been identified that inhabit the cave and the karst, including a troglobitic species of aquatic amphipod (HOLSINGER, 1971) and a troglobitic aquatic isopod (LEWIS, 2001). Work by ABU-JABER et al. (2001) has also contributed to the understanding of this system by determining the current dissolution rate within the karst conduits. From this study, it was determined that the denudation rate of this karst system is extremely fast, on the order of 8.3 cm/yr.

Lilburn Cave also affords access to sections of the phreatic conduit system that discharges to Big Spring. Big Spring is a rare ebb and flow spring that exhibits periodic behavior only above a certain discharge threshold during times of high discharge, primarily in the late winter and during spring runoff. Hydrograph data for the spring show a periodic increase in discharge that is overlain by aperiodic changes in discharge associated with precipitation and snowmelt events (Fig. 2). Big Spring does not follow the classic model of an ebb and flow spring that functions via overflow conduits; rather, the ebb and flow nature of Big Spring is due to a sediment plug of fine sand in deeper reaches of the conduit system that is periodically dislodged (SARA, 1977). The conduits at Big Spring and within Lilburn Cave have been dived to a distance greater than 300 m at both the upstream and downstream ends. The survey by the diver (W. Farr) indicates a single tubular passage approximately 3 m in diameter at either end, with no obvious large tributary passages connecting to these conduits (FARR, 1997). These findings indicate that the phreatic flow near the outlet of the system probably occurs within a single conduit.

2. Methodology

Two research sites were used for this project, Redwood Creek and Big Spring, located above and below the karst, respectively (Fig. 1). Data loggers at both locations allowed for continuous monitoring of water temperature, electrical conductivity and discharge measurements from just prior to the snowmelt event of February 28, 2006 (Julian Day = 58) through the end of the event, March 3, 2006 (Julian Day = 60). In 2006, a snowmelt flood pulse was recorded in Redwood Creek upstream of the karst and also at Big

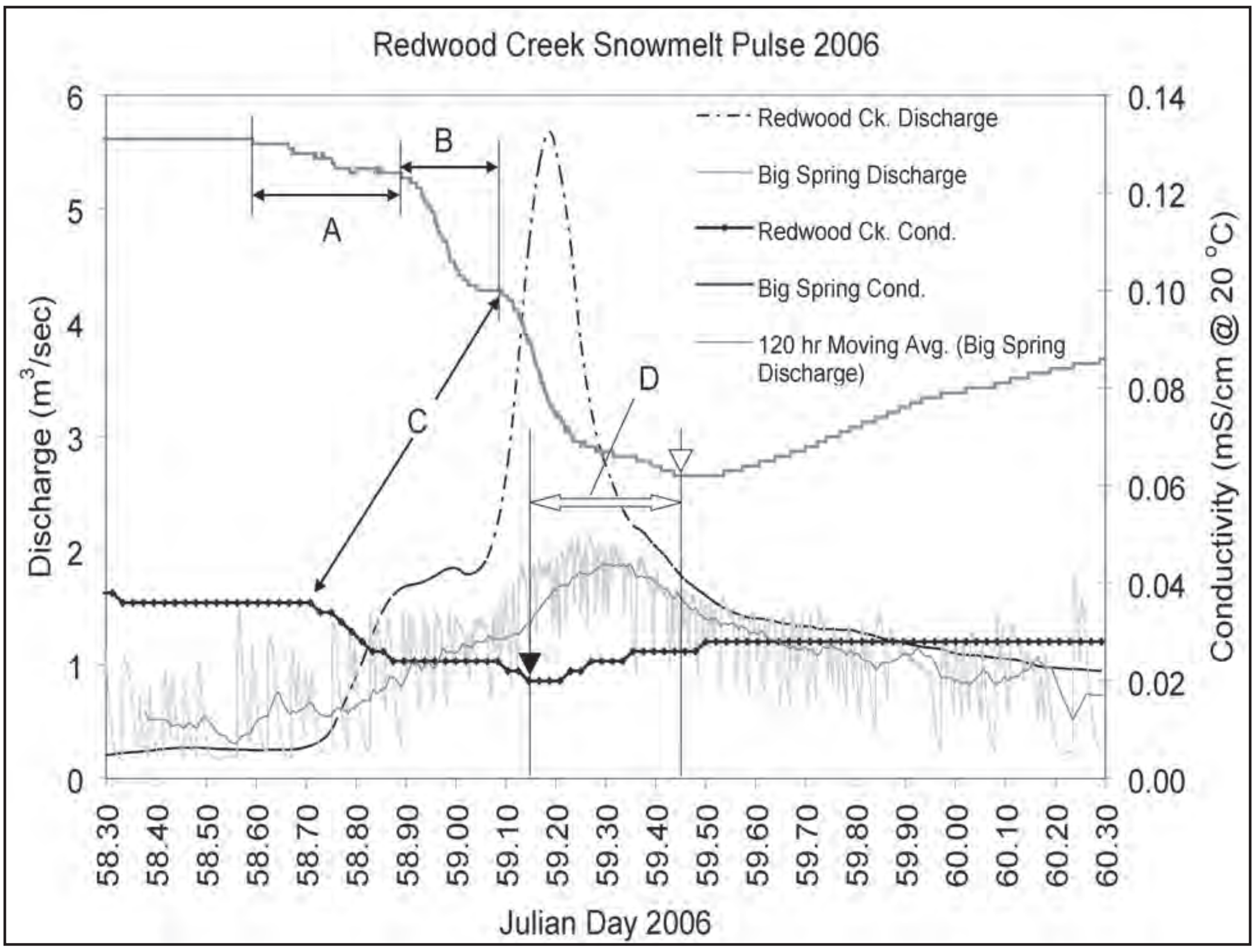

Figure 2: Discharge and electrical conductivity measured at Redwood Creek and Big Spring during snowmelt in 2006. A = period of influence of Pebble Pile Creek drainage on Big Spring conducitivity. B = period of influence of Big Baldy Grove drainage on Big Spring conductivity. C = initiation of the conductivity decrease within Redwood Creek, and its first expression at Big Spring. D = the period of integrated discharge for conduit volume estimation, during which the conductivity trough observed upstream at Redwood Creek (black triangle) passed through the conduit system and was ultimately observed at Big Spring (white triangle).

Spring (Figure 2). The travel time of this signal permitted an estimate of the volume of water contained within the conduit flow path. In this case, only the natural variation in the discharge and conductivity signal was used to trace the snowmelt pulse rather than an artificial tracer, such as a dye.

The method of determining conduit volume from spring discharge and transit time of a chemical signal within an aquifer is conceptually based upon the method of ASHTON (1966). The conductivity decrease associated with the 2006 snowmelt event was used as a tracer to determine water transit time through the Redwood Canyon karst system. The period of time elapsed between the observance of minimum conductivity at the sinking point to the arrival of that minimum conductivity signal at Big Spring was assumed to account for the time necessary for the volume of water present within the flooded conduit system to be completely discharged. Thus, the discharge at Big Spring was integrated across that time interval to determine the volume of the conduit system.

BIRK et al. (2006) employed a numerical model to simulate this approach, and concluded that the method tends to overestimate the volume of the conduit by as much as 50% because it neglects contributions to the spring discharge originating from within the fractured rock matrix. We took advantage of our measurements of the conductivity signal of the water at the sink and spring both prior to and at the time of its arrival at the spring to estimate the contribution of new (conduit) water discharged from the spring. This proportion was multiplied by the total integrated discharge volume to obtain a fraction that would more accurately represent the conduit volume.

Under the assumption that the system contains only a single phreatic conduit of constant cross section, the conduit length was determined by dividing the estimated conduit volume by the cross sectional area. Using the ratio of cave passage length to length of subterranean stream passage known throughout the entire cave system, the potential unexplored cave passage length was then estimated.

3. Conductivity Signal Interpretations

The change in conductivity at both Redwood Creek and Big Spring showed distinct stepped decreases (Fig. 2). The lag time between these steps is not exactly coincident between the sink point and spring. A likely explanation for this is the effect of the addition of water from tributaries within smaller drainages. At the Redwood Creek location, there are two main surface streams that join just upstream of the site. The variations in hill slope aspects, elevation, and vegetation cover likely account for different arrival times of the snow melt pulse from these two sources at the Redwood Creek site.

At Big Spring, the decrease in conductivity is more complicated, with four main stepped decreases (Fig. 2). The first two stepped decreases do not correlate to those seen at Redwood Creek. These appear to be related to influx of melt water from two major infeeders into the karst downstream of the main sinking point, Big Baldy Grove Creek and Pebble Pile Creek (Fig. 1). The relative timing and size of the first two steps in conductivity decreases observed at Big Spring correspond to the relative upstream distance and size of the tributary drainages. The lower elevations and closer proximity to the spring of these smaller drainages likely accounts for the early arrival of the snowmelt signal at Big Spring ahead of the Redwood Creek signal.

The initial decrease in conductivity at Big Spring occurred at Julian Day = 58.58 and is assumed to be associated with snow melt from the nearest tributary, Pebble Pile Creek (interval A in Figure 2). The second stepped decrease in conductivity was seen at Julian Day = 58.89 and was assumed to be associated with the next tributary, originating within the Big Baldy Grove drainage (interval B in Figure 2). The conductivity decrease observed at Big Spring between the third and fourth steps (from point C to the white triangle in Figure 2) correlate in relative size and timing with the record of conductivity dilution observed upstream at Redwood Creek (from point C to the black triangle in Figure 2). A regression of the two conductivity records between the initial drop in conductivity to the lowest value yielded an r-value of 0.90. Thus, this period of conductivity decrease at Big Spring was assumed to be solely the result of the snowmelt pulse originating from Redwood Creek, absent of any lateral tributary inputs.

The initial conductivity decrease associated with the Redwood Creek snowmelt event above the karst began at Julian Day = 58.71. This decrease was then seen at Big Spring at Julian Day = 59.08, giving a total time difference of 0.37 days. During this time, the hydraulic head in the conduit would have increased as the discharge in Redwood Creek increased. Since the peak in discharge at Redwood Ceek roughly corresponded with the minimum of the conductivity signal, this minimum in conductivity was used as the actual “tracer”. The period of time elapsed between observance of the conductivity trough at the sinking point and its observance at the spring was approximately 0.30 days, and represents the transit time through the conduit.

The discharge of Big Spring was integrated over the 0.30 day period beginning with the minimum conductivity signal of the snowmelt pulse from Redwood Creek and ending at the minimum in the conductivity observed at Big Spring (interval D in Figure 2). The volume of water discharged across this time period was assumed to represent the total volume of water contained within the flooded karst conduit system (Fig. 3). This value is likely an over-estimate, for it may include not only the flow through the conduit connected to the sink point on Redwood Creek, but the tributary additions and diffuse flow through the system as well (BIRK et al., 2006).

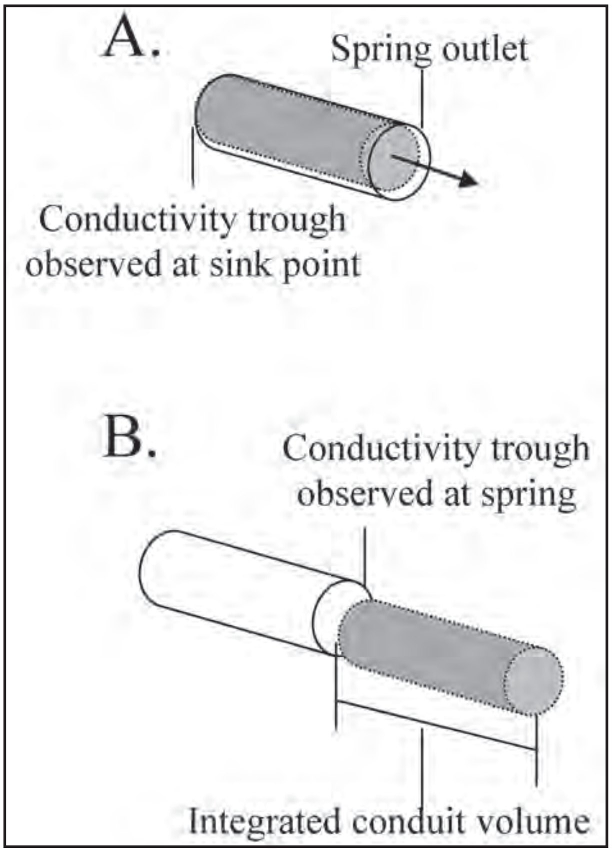

Figure 3: Conceptual diagram of the approach for determining conduit volume (assuming no lateral inputs). The gray cylinder represents the volume of the conduit. (A) The phreatic conduit system depicted at the time of maximum conductivity dilution at the upstream sink point. (B) The conduit depicted after the dilution signal has arrived at the spring. The spring discharge is integrated across the transit time of the dilution signal through in order to determine the conduit volume.

In order to correct for these non-conduit additions, the proportion of the "new" water in the total discharge volume was estimated by the following equation:

$$P_{new} = (C_{spring} - C_{old}) / (C_{new} - C_{old}) \qquad (1)$$

Where P_{new} is the proportion of new (conduit) water, C_{spring} is the conductivity of the spring water at the time of maximum dilution (white triangle in Figure 2), C_{old} is the conductivity of the spring prior to the arrival of the Redwood Creek conductivity signal (point C in Figure 2), and C_{new} is the conductivity of the Redwood Creek water at the time of maximum dilution (black triangle in Figure 2). Using the conductivity values from the graph in Figure 2, the proportion of conduit water in the Big Spring discharge at the time of maximum dilution was determined to be about 47%.

4. Results

The discharge curve for Big Spring was integrated over the 0.30 day period beginning at the initial decrease in conductivity at Big Spring associated with the Redwood Creek to the low point in the conductivity curve. This integration yielded approximately 45,000 cubic meters, the volume of water discharged from Big Spring during the passage of the signal of minimum conductivity from Redwood Creek to Big Spring. This value was then multiplied by 47% to account for the contribution from matrix inputs and determine the actual conduit volume (21,200 cubic meters). To convert this volume into a length, it was divided by the cross sectional area of the stream conduit. The wetted cross-sectional area, based on cave survey data, was compared throughout the main stream passage and then averaged with the cross-sections of the cave that had been dived. This provided an average cross-sectional area of about 7 m^2. Since we assume the entire volume was discharged through a single conduit, this calculation represents a maximum conduit length of approximately 3.0 km. Finally, to estimate the total potential cave length associated with this conduit, we used the current ratio of total surveyed cave passage length to known subterranean main conduit length of 20:1, assuming this ratio remained consistent throughout the entire karst system. From this assumption, an estimate of maximum potential cave length was determined to be approximately 60 km.

5. Discussion

During the 2006 snowmelt event, the majority of the flow in Redwood Creek did not sink into the karst, as can be clearly seen in the difference in magnitude between the discharge records of Redwood Creek and Big Spring. However, this does not invalidate the method because we do not assume all of the Redwood Creek water flows out of Big Spring. All that is necessary is that the signal of conductivity dilution be transmitted from sink to spring regardless of the quantity of water transmitting the signal. During large flood events such as the snowmelt event documented here, Redwood Creek flows on the surface throughout the length of the canyon. With greater stream discharge, the terminal sinking point of the stream shifts its position downstream. This means that the actual sinking point may not have been at the point of monitoring on Redwood Creek. Indeed, our results support this conjecture, since the conduit length estimated is 3.0 km, while the surface distance between the Redwood Creek monitoring point and Big Spring is approximately 6 km. Thus, we conclude that the primary sink point of Redwood Creek water was on the order of 3 km upstream of Big Spring. This places the sink point in the vicinity of the confluence of Big Baldy Grove drainage with Redwood Creek. Interestingly, this position within the canyon also coincides with a second known sinking point of Redwood Creek, along a contact between the marble and the siliceous schist bedrock.

Our results indicate that the potential total cave length may be approximately twice as great as the known passage length. This cave length estimate is based upon the assumption of a single conduit feeding the spring. From existing cave survey data, there is evidence that major cave development is also associated with surface tributary streams. The dive reports also suggest that these infeeders may play a major role in the complexity of Lilburn Cave. Although the assumed cave length is speculative, our use of the natural snowmelt pulse to estimate the potential conduit length provides some insight into the hydrologic system of the Redwood Canyon karst system. This information also provides some perspective on the potential subterranean aquatic habitat available for endemic, cave-adapted species, and a goal for ambitious cavers.

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CLASSIFICATION OF KARST DEPOSITS FROM THE FRANCONIAN ALB (SOUTHERN GERMANY)

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Karst areas are characterized by typical hydrologic and geomorphologic features. Due to the geologic and landscape history they differ distinctly in their geological structures and sedimentary content. After corrosion has created local or temporal depocenters at the surface or the endokarst karst deposits can be accumulated within these cavities. In the Franconian Alb, a karstic region showing limestones and dolomites of Jurassic Age in Southern Germany, karst deposits were studied at superficial outcrops and within several caves.

Clastic karst deposits formed at or near to the surface often exhibit allochthonous components and a wide range of petrographic attributes, mostly they show close relations to the specific geology of the surrounding area. They have to be interpreted as "pedo-sedimentary complexes". Characteristic of these deposits is the mixing of different components at which corrosive, gravitative, pedological and several sedimentary processes are acting. Different surface karst sediments characterised by their petrographic attributes were separated.

For the endokarst zone an actualistic approach was used for the sedimentpetrographic differentiation of clastic cave deposits. Conceptual purpose was the classification of cave deposits which did not exhibit relations to obvious forming processes.

Cave deposits of the Franconian Alb were classified as follows:

- Fluvial cave deposits (gravel, sand, silty sand / sandy silt, silt, clay) can be identified by their textural features or classical sedimentpetrographic attributes (e.g. shape, sorting, roundness). Mostly, the assignment of a sedimentary facies is possible by field or laboratory data.

- By gravitational action or slowly percolating water within small fractures or pores clay and loam descend within the vadose zone. These sediments show a close relation to soils or the loamy cover resting upon the surface carbonate rocks.

- Autochthonous sediments resulting from a gradual corrosion of carbonate rocks are formed within protected areas of open fractures where the transport of material is limited. Occurrences of these decomposition deposits are of local extent. Final products are pure clay or loam consisting of insoluble residues. The enlargement of cavities creates interconnections and the sediments are removed or mixed with allochthonous components from the surface.

- The breakdown of carbonate rocks from the ceilings or walls of caves can create individual deposits but mostly such material is incorporated into other sediments. Under the corrosive action of water these carbonate fragments will be removed especially within the phreatic karst zone.

Ultimately the present work focus both on a static view to the source resp. remainder of clastic material and a dynamic view to several acting processes. During transport through a karst area clastic sediments are formed and changed continuously by erosion, selection and resedimentation. Consequently, an individual clastic karst deposit represents a section of a cascade of different sedimentary environments interconnected between surface and the final depositional area.

1. Introduction

Karst areas are characterized by typical hydrologic and geomorphologic features. Due to the geologic and landscape history, they differ distinctly in their geologic structures and sedimentary content. After corrosion has created local or temporal depocenters at the surface or within the endokarst, karst deposits can be accumulated.

The sediment-petrographic setting of soils and superficial loamy deposits is heterogeneous. Allochthonous material is responsible for this, carbonate rock weathering accounts for an additional input by release of insoluble residues of carbonate rocks. Otherwise, dislocation processes cause a continuous modification of the sediments (e.g., ATALAY 1997, DURN 2003, ŠUŠTERŠIČ et al. 2008). Due to the polygenetic nature of soils and loamy sediments in karst areas, DURN (2003) and TRAPPE (2003) characterized them as "pedo-sedimentary complexes."

According to FORD & WILLIAMS (2007), karst cavities act as sedimentary traps and can be filled up partially or completely with clastic sediments and/or flowstones. Manifold processes are responsible for the formation of clastic cave sediments. Most studies focus on fluvial sediment forming processes (e.g. GILLIESON 1986, WHITE 2007, SASOWSKY 2007). Other processes were studied only in a few cases and their interrelations are not well known. In the example of the Franconian Alb, a karstic region with Jurassic limestones and dolomites in Southern Germany, karst deposits were studied at superficial outcrops and within several caves. For the endokarst zone, an actualistic approach was used for the sediment-petrographic differentiation of clastic deposits. The conceptual purpose was the classification of cave deposits that did not exhibit relations to obvious forming processes. Ultimately, the present work should focus both on a static view to the source with respect to remaining clastic material and a dynamic view to several acting processes.

2. Clastic Karst Deposits of the Franconian Alb

A wide range of sedimentary structures and sediment-petrographic attributes can be observed for loamy deposits resting upon karstified carbonate rocks. Besides clays and sandy to silty clays developed under tropical conditions during the Tertiary, there is a Pleistocene clayey silt (loess-loam. Additionally, coarse grained components (rock fragments, quartz gravels, cherts, limestone, and dolomite debris) can appear. Characteristic is the mixing of the different components at which corrosive, gravitative, pedological and several sedimentary processes are acting. The sedimentary conditions were controlled by surface relief.

By means of a silt/clay discriminant (100xsilt/silt+clay), superficial residual clays, mixed loam and loess-loam can be distinguished (TRAPPE 2003). In addition to the designation of the silt or clay dominance, the occurrence of coarser particles demonstrates a further potential for differentiation. It has to be noted that it is necessary to comprise more criteria for the identification of residual material than the simple application of a silt/clay discriminant. Heavy minerals indicate the allochthonous nature of most loamy deposits covering karstified rocks of the Franconian Alb. They originate from older stratigraphic units (Cretaceous and Miocene formations) than the loamy cover, which are also resting on the carbonate rocks.

According to FORD & WILLIAMS (2007), cave sediments differ in type of occurrence. A cave entrance facies and an inner cave facies have to be separated. Cave entrances are characterized by a direct material input from the surrounding area and diverse processes of dislocation. Filled cracks and other cavities near to the surface occur in every quarry or surface outcrop within karstified carbonate rocks. The direct transition of the crack fillings to the surface deposits is visible. For this domain the term crack filling facies is proposed. Larger cavities of the deeper vadose karst zone, which often shows fluvial activity of cave streams, and the phreatic zone represent the inner cave facies domain. Already in the field, different features of cave sediments from the crack filling and inner cave facies can be noted. The crack filling facies shows increased clay contents. As indicated by displacement structures and a gradual mixing of different materials slowly acting dislocation processes caused by gravitation can be assumed. Also, a successive percolation of water with a minor clay load occurs. Locally, bedding structures indicate fluvial mechanisms. The majority of the clayey to loamy crack fillings have to be interpreted as mixed sediments or residual and weathering products with additional debris.

By contrast, cave sediments of the inner cave facies exhibit mainly silty-sandy grain sizes or gravels, higher amounts of clay are unusual. Hence, the question come up, why do deposits of the crack filling and inner cave facies show different sediment-petrographic features? Answers were found only within a few caves that show a broad spectrum of cave deposits. A rare example is the Grubschwart cave system in the South Franconian Alb, where the relations between clay crack fillings and fluvial sediments were documented (Fig. 1). A gravitative sinking mechanism displaced the clayey material on top of fluvial deposits after the cave was left by the vadose stream. The sediment-petrographic features of the sediments differ distinctly

(Fig. 2). HILL (1999) reported similar features from the Kartchner Caverns, but there clay material from hanging cracks was deposited first.

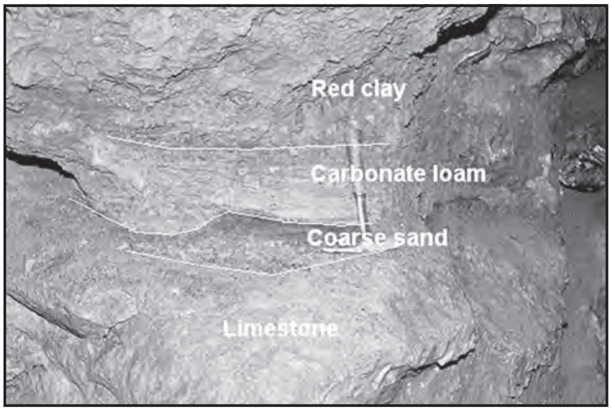

Figure 1: Clastic sequence of a lower fluvial coarse grained iron-bearing sand followed by loose carbonate loam (partly flowstone) and a final package of massive red clay rede-posited from the surface by gravitational activity through narrow shafts (Grubschwart Cave).

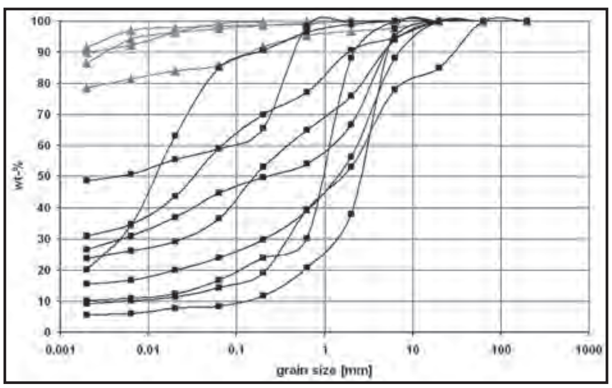

Figure 2: Typical cumulative grain size curves of clayey deposits formed by gravitational action (grey triangles) and fluvial sediments (black quadrangles) at the Grub-schwart cave site.

Transport processes of the inner cave facies modify cave sediments by selective variation and displacement. Especially the fluvial activity can be distinguished by these attributes from inkasion, decomposition, gravitation, and percolation, which are acting more locally. The selective enrichment of a specific grain size is one typical feature of fluvial cave deposits. Gravel, sandy gravel, sand, silty fine sand, or silt are each identified by a good sorting of material. Stratification, roundness, and sorting are the main criteria for the fluvial environment. Using several sediment-petrographic attributes of clastic cave sediments, BOSCH & WHITE (2004) separated different fluvial facies domains.

Samples of recent deposits taken with regard to the specific fluvial position can be separated well by granulometric analyses (Fig. 3). By means of such an actualistic approach, a comparison of fossil samples mostly is successful. The attribution of several depositional fluvial environments (e.g., stream bed deposits, channel bars, point bars, overbank deposits of proximate or distal position, levées) allows the interpretation of most cave sediments profiles (Fig. 4). Naturally, inkasion debris consists of carbonate rocks, the fragments always are angular. However, they maybe modified by corrosional activity. Mostly carbonate clasts occur as additional component within other clastic karst deposits.

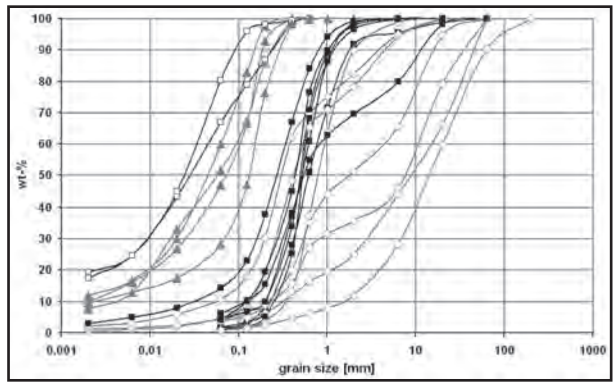

Figure 3: Cumulative grain size curves of fluvial cave de-posits from different facies domains at the Muehlbach cave site (actualistic approach). Unfilled quadrangles – limnic deposits, grey triangles – overbank deposits, black quad-rangles – side bar or point bar, unfilled rhombi – channel bed deposits.

Decomposition deposits are characterized by a gradual decarbonatization of the carbonate rocks (limestones, dolomites, marls), the gravel and sand grain size fractions consists mainly of rock debris. A carbonate bearing or free loam is developed at advanced stages of the rock decomposition. As long as fluvial activity cannot wash out these sediments, complete or partial decomposition successions can be observed only within protected cracks or interstices. A comparable observation was described by ZUPAN-HAJNA (2003) from several Slovenian caves.

3. Conclusions

Cave deposits of the crack filling facies and the inner cave facies observed in the Franconian Alb were classified as follows:

- **Fluvial cave deposits** can be identified by their textural features or classical sediment-petrographic attributes (e.g., shape, sorting, roundness). Mostly, the assignment of a sedimentary facies is possible

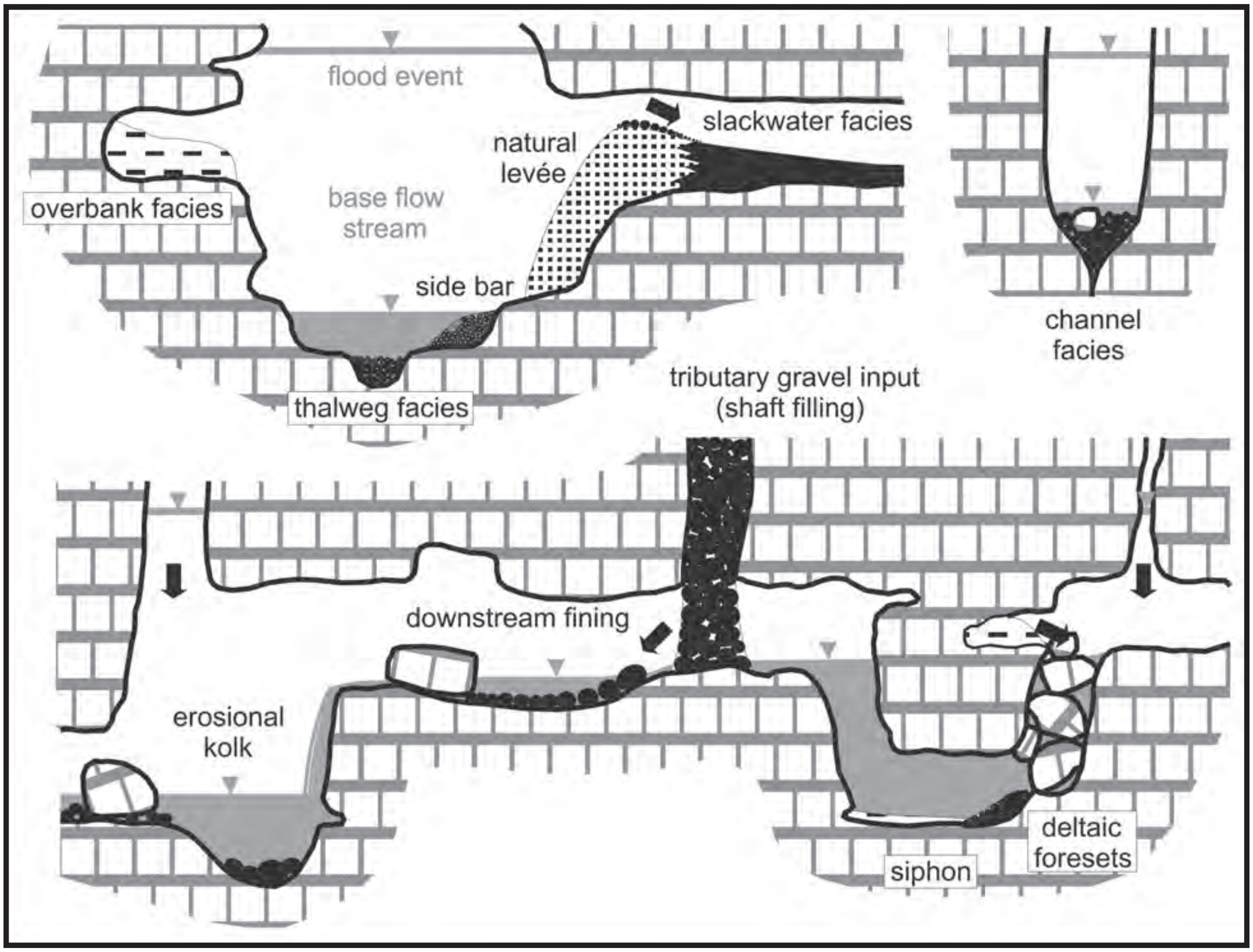

Figure 4: Occurrences of different fluvial clastic deposits and facies domains within caves.

by field or laboratory data (e.g., BOSCH & WHITE 2004; White 2007).

- By gravitational action or slowly percolating water within small fractures or pores, clay and loam descend within the vadose zone. These sediments show a close relation to soils or the loamy cover resting upon the surface carbonate rocks (**gravitative or percolative deposits**).
- Autochthonous sediments resulting from a gradual corrosion of carbonate rocks form within protected areas of open fractures where the transport of material is limited. Occurrences of these **decomposition deposits** are of local extent. Final products are pure clay or loam consisting of insoluble residues. The enlargement of cavities creates interconnections and the sediments are removed or mixed with allochthonous components from the surface.
- The **breakdown** of carbonate rocks from the ceilings or walls of caves can create individual deposits but mostly such material is incorporated into other sediments. Under the corrosive action of water, these carbonate fragments will be removed, especially within the phreatic karst zone.

Regarding the conditions of formation, transport, accumulation and modification of clastic sediments in karst areas, a network of different facies and subfacies domains can be observed between surface and the endokarst (Fig. 5). Due to the specific nature of karst, the environmental pattern of clastic deposits shows a spatial inhomogeneity at one moment. Over time, this spatial coexistence of facies is expanded by a temporal succession. Although clastic karst deposits can be removed or modified by later processes, one can observe a relict conservation of older sediments. These conclusions confirm the individuality of each karst region.

From a dynamic point of view, the different processes of displacement and accumulation show a diverse connectivity of the involved facies and subfacies domains within a single karst area. During transport through the karst domain, clastic sediments are formed and changed continuously by erosion,

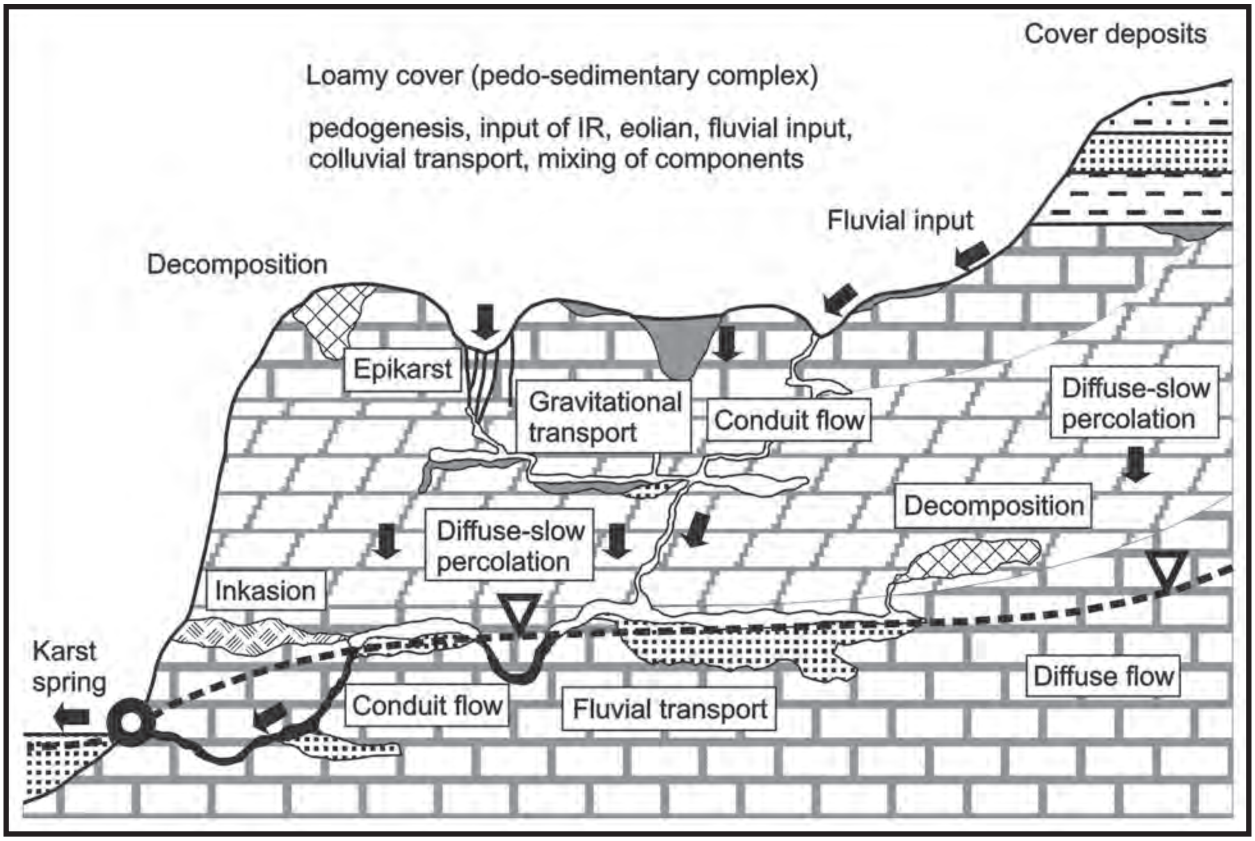

Figure 5: Facies zones, transport mechanisms and connectivity of several acting processes within a karst area.

selection, and resedimentation. Consequently, an individual clastic karst deposit represents a section of a cascade of different sedimentary environments interconnected between surface and the final depositional area.

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IDENTIFYING HYPOGENIC FEATURES IN GREEK CAVES

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Hypogene speleogenesis is studied during the last 5 years in Greece. Many caves considered previously as epigenic are now reinterpreted as hypogenic. In Central and Northern Greece hypogenic caves are related with confined speleogenesis and the dominance of impermeable rock exposures. Many characteristics indicative of hypogenic speleogenesis are distinguished and related to the general geological setting such as network mazes, gypsum concentrations and confined aquifers. Hydrothermalism plays a key role in hypogenic caves' speleogenesis in Greece. Several features indicative of H_2S concentrations have been identified in caves. Melissotrypa cave is the biggest cave in Central Greece where the speleogenesis processes are interpreted under the prism hypogenic processes. The cave has been developed under water table from hypogenic solutions following the main tectonic discontinuities.

1. Introduction

Carbonate rocks in Greece crop out over 50% of its surface. An extensional tectonic process in Greek mainland since Miocene (Pavlides & Mountrakis, 1987) has led to big areas being uplifted and to disclosure of underground karstic systems. The biggest karst regions with numerous caves are bounded mainly in Peloponnesus and Crete Island. However few studies have been conducted concerning speleogenetical aspects till last decade. Several caves, mostly in Northern Greece, are being studied last 5 years by speleologists of the Department of Geology in Thessaloniki. Cave exploration has been conducted by the Hellenic Speleological Society (Thessaloniki's Local Department) and the Thessalian Society of Speleological Research "Chiron". Many of the investigated caves contain subtle characteristics that imply their genetical history (Fig.1). Some of them have hypogenic features but in most cases it's very difficult to

Figure 1: Map of Greece showing the caves with implications of hypogenic solutions activity. Kaiafas, Loutraki and Agia Paraskevi caves are located to areas with thermal springs. Katsika mount is near to area with deep thermal fluids' activity.

define because of the epigenic overprint.

2. Melissotrypa Cave

Melissotripa cave is located in Larissa prefecture 12km west of Elassona town. The entire cave system is developed in the neritic carbonate “Kranea unit”, over which ophiolitic bodies and the Pelagonian nappe were thrust during the Alpine orogeny (Kilias & Mountrakis, 1987). The Kranea karstic aquifer starts its formation during the end of Oligocene. It covers an area of 90 km^2 and 1850 m thickness. The large spring of Kefalovriso, which is of overflow type, is formed by the northeastern edge of the aforementioned karst system and is its only discharge point.

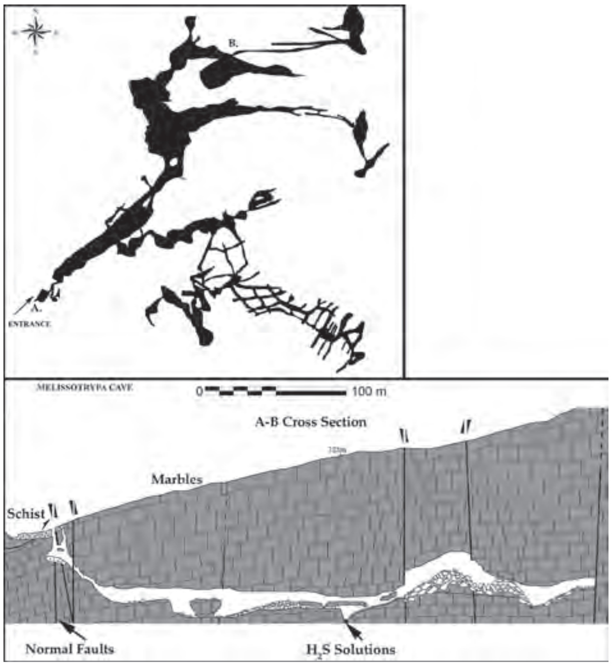

Figure 2: Map of Melissotrypa (left) and A-B cross–section (right).

The entrance of the cave (elev.299 m) forms a 14.6 m shaft, starting its developing at marble’s debris for 5.3m and continues at a fault zone inside the marble mass (Fig. 2). Melissotrypa can be conveniently divided into two distinctive segments: The main karstic tube at the northwestern part and the maze area at the southeastern part. More than 2000 m of passages and chambers were mapped during 2006. All the areas at the northwestern part are characterized of breakdown morphology, more or less and stop their widening in the marble’s normal faults. Some of the faults were found at the cave’s surface too.

Melissotripa cave has been developed under confined conditions from hypogenic solutions following the main tectonic discontinuities (Vaxevanopoulos, 2006). Joints and faults are the planar breaks that have served the principal structural guides for underground flows. The area’s uplift leads the phreatic formed cave to the vadose zone where the phreatic tubes are destroyed under the air filled corrosion phenomena (Fig. 3). Speleothems such as stalactites, stalagmites, columns, flowstone, coralloids, frostwork, boxwork, cave blisters, powder, pearls and helictites are found in Melissotrypa’s great chambers and big corridors. At present, hypogenesis still occurs under the water table where fluids enriched in H_2S dissolve the marbles.

Hydrogen sulfide and methane are the only seepage gases responsible for inducing biological effects in caves, while radon and carbon dioxide do not induce any biological effects (Forti et al, 2002). Several biocommunities were found at Melissotrypa’s speleothems with important relation with H_2S concentrations and they are now studied by biologists at University of Thessaly in Greece.

3. Kaiafa’s Cave

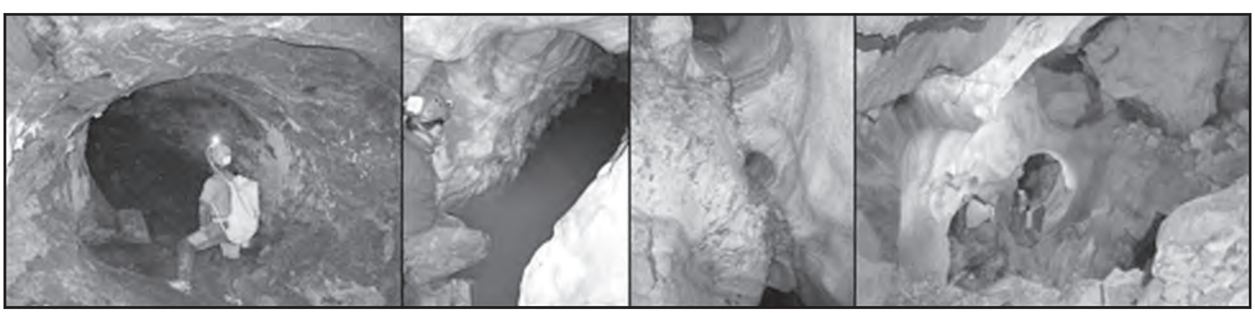

Figure 3: The inner part of Melissotrypa (a) Phreatic tube at the southeastern part (b) Lake with H2S solutions (c) Cupolas from the main tube’s ceiling cross-cut by a fault (camera angle is ~80° up from horizontal, looking toward the ceiling) (d) Scallops, cupolas and breakdown domes from the western part of Melissotrypa.

Kaiafa's cave is located in west Peloponnesus at a thermal spring's area. The entrance of the cave has been developed for touristic reasons. There is a big lake at the cave's first part with thermal water where tourists are having their hot bath. The cave consists of a big cave gallery and its western part is described by maze like cave corridors. Hypogenic thermal waters seem to have exclusively influenced the cave's maze part.

4. Loutraki Cave Complex

Loutraki constitutes a very common Greek name for a village with vicinity to a thermal spring, meaning "small bath". One of the most famous Loutraki villages is located in the Pella Prefecture, Northern Greece (Macedonia). The cave complex consists of 16 cave formations in a steep gorge with altitude range from 400 to 650 m. The caves are formed at the Pelagonia Zone's recrystallized limestones. Hypogenic features such as feeders, pendants, network mazes, hypogenic outlets are found in most of them although vadose processes are destroying the phreatic characteristics (Fig.4). Thermally ascending water was probably responsible for the formation of the caves where thermal springs occur even today (Lazaridis, 2006). The majority of Loutraki Caves exhibit hypogene origin.

Figure 4: Pendants from the Antarton Cave in Loutraki Cave Complex.

5. Katsika Mount

Katsika mount is located in Chalkidiki Prefecture (Macedonia) and hosts the cave of Petralona where many paleontological remains have been excavated. The most interesting finding was a transitive from *Homo erectus* to *Homo sapiens* skull dated to Middle Pleistocene (Stringer et al, 1979). Three other caves have been investigated under the prism of hypogenesis. The presence of thermal fluids in deep drills shows a thermal fluid circulation. Combining with the maze formation of the Petralona cave and the speleothems in the Bat Cave (500m south of Petralona cave) we can assume fluid circulation through a fault zone N-S trending (Vaxevanopoulos, 2003).

6. Synopsis

Many caves in Greece present hypogenic characteristics. We assume that 20% of the horizontal Greek caves exhibit hypogenic origin. This is caused by the plurality of areas with geothermal activity affecting karstic aquifers. Melissotripa is the most representative hypogenic cave in central Greece. Other caves present fewer implications for hypogenic origin like the Maronia cave, Agias Paraskeyis cave and Skalas Marion. At Latte??, crystals of barite were found in its upper part. More speleological studies have to be conducted because there are many examples of hypogenic caves previously considered to be epigenic.

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PRELIMINARY HYDROGEOLOGIC SURVEY OF PETRALONA CAVE, CHALKIDIKI, GREECE

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Petralona Cave, a show cave located in the Chalkidiki Peninsula of northern Greece, is best known for containing remains of an archaic hominin known as Archanthropus. Its age is debated and requires continued investigation. The cave occurs in a small upthrown fault block mountain of thickly bedded Upper Jurassic limestone. The block is roughly 6 km north-to-south, rises from about 300 m to 645 m above mean sea level, and has a north-south fault delimiting its western boundary. The limestone dips east from the fault for 3 km where it is unconformably covered by a surrounding plain of Miocene and possibly Pliocene marls, sands, clays, and lacustrine limestones. Paleokarst bauxite deposits occur throughout the mountain.

The cave is a fracture-guided maze surveyed at over 2 km in length. It ranges in elevation from 313-336 m above sea level; major fractures are joints generally bearing around 25°. Hypogenically formed, pits in the floor mark sources of past rising water. Passages radiate outward from the pits, generally decreasing in size with distance. Parts of the cave are partially collapsed, masking some of the original passage morphology. Gypsum covers several areas of flowstone, although the sulfate cannot yet be attributed to a deep or shallow source. Airflow and associated corrosion patterns suggest either an unknown extensive section of the cave and/or an undiscovered entrance. The cave's two natural entrances were formed by surface erosion truncating passages. The small modern entrance captures little surface water and sediment. The ancient entrance was perhaps about 3 m in diameter, or possibly larger, and formed a debris cone that hominins probably used to enter the cave during the Pleistocene; sedimentation has since completely filled this entrance. Further study of the cave's origin should provide a better understanding of the geological context for the archaic human remains, and to recommend additional sampling that will more precisely establish their age.

1. Introduction

Petralona Cave is located in the Chalkidiki Peninsula of northern Greece, 45 km southeast of the city of Thessaloniki. Its small entrance was discovered in May 1959 and dug open to reveal a rectilinear maze with over 2 km of passages (Figure 1). In September 1960, a human skull was discovered; later excavations (identified in Figure 1) revealed other hominin fossils and rich paleontological deposits (e.g. Kurten and Poulianos, 1977; Kretzoi, 1977; Poulianos, 1995). In 1974-1975, a 50-m long tunnel was dug into the central part of the cave to facilitate excavation of the deposits and allow public access. In 1979, Petralona Cave was opened as a show cave with about 260 m of trails in its passages. The cave is highly decorated with dripstone, shelfstone, subaqueous, coralloid, eccentric, and other speleothems.

The human skull, recovered from a small room called the "Mausoleum" (Excavation D), proved highly controversial. Only the cranium exists; other skeletal material was accidentally lost or destroyed soon after discovery. Known as Archanthropus, the skull was identified as an intermediate form between *Homo erectus* and *Homo sapiens* (e.g. Poulianos, 1982, 2004; Wolpoff, 1980, Stringer, 1980) and alternatively as *Homo heidelbergensis* (Stringer, 2006), but its age has been especially debated. Dating has focused primarily on material deposited on or adjacent to the cranium. Electron spin resonance analysis of calcite coating the cranium yields ages from 150-250 ka (Grün, 1996) to 670 ka (Ikeya, 1988), paleomagnetic study of associated sediments suggest a maximum possible age of 620 ka (Papamarinopoulos et al., 1987), and paleontological studies indicate an age between 550-750 ka for the associated faunal

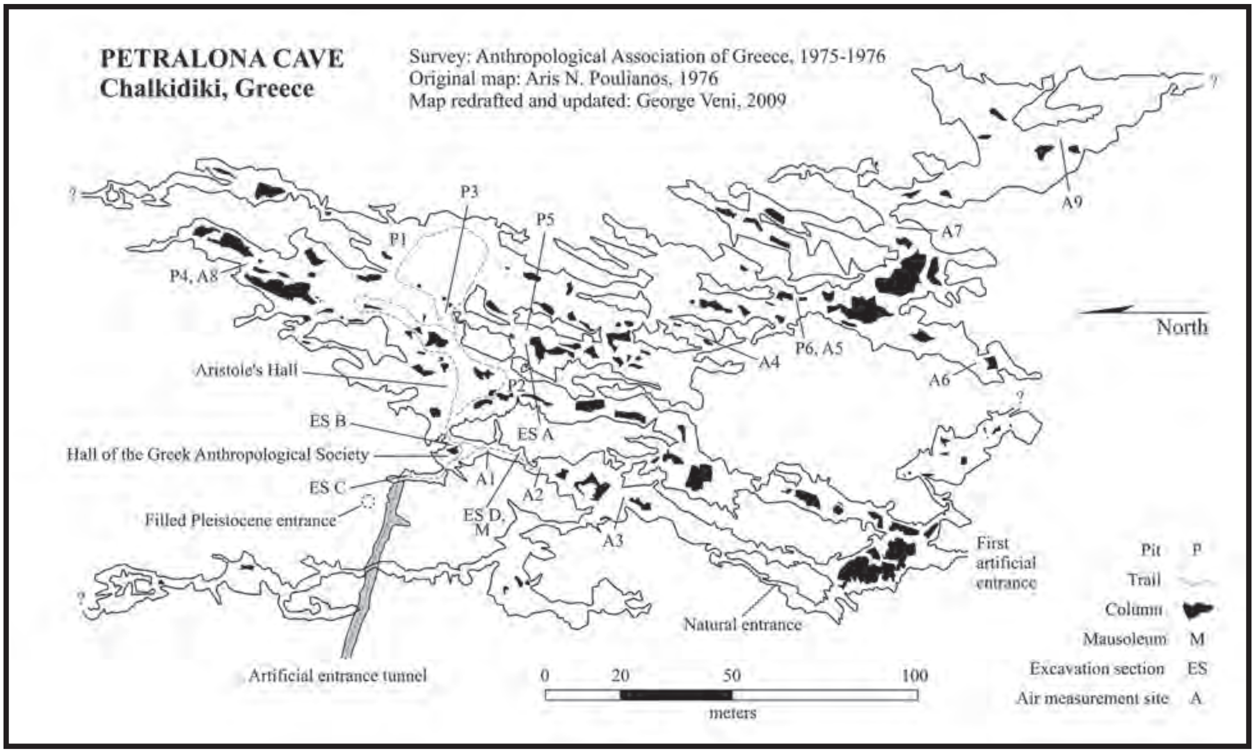

Figure 1: Map of Petralona Cave.

material (Belluomini et al., 1990).

The purpose of this study is to evaluate the origin and hydrogeologic conditions that created the cave. Prior descriptions of the cave's genesis have been general (e.g. Petrocheilos, 1960) and/or focused on sediment and speleothem deposition associated with the cranium (e.g. Poulianos, 1982). This research is based on interpretation of observations and non-destructive measurements made in the cave and surrounding area. No samples of any material were collected. A sound hypothesis will first be developed that can be tested at a later date by a focused and effective sampling plan.

2. Geologic Setting

Greece is geologically and tectonically complex. Three geotectonic zones cross the Chalkidiki Peninsula. Petralona Cave occurs in the easternmost zone within an isolated block of uplifted Upper Jurassic limestone which forms Kalavros (Katsika) Mountain (Christaras 1984). Figure 2 is a geologic map of the mountain and adjacent area. The uplifted block is roughly 6 km north-to-south and rises from about 300 m to 645 m above mean sea level. A north-south fault of unknown displacement marks its western boundary. The limestone is gray, thickly bedded, and dips from the fault 10-50° down to the east for 3 km where it is unconformably covered by a surrounding plain of Upper Miocene to Lower Pliocene marls, sands, clays, and lacustrine limestones; the 11° dip shown on Figure 2 near the cave was measured during this study and is not from the cited geologic map. The north end of the fault block contains small outcrops of Upper Jurassic to possibly Lower Cretaceous shales with intercalated limestone and intruded by Mesozoic granodiorite. Aerial photographs and field measurements show a strong structural grain, with prominent fractures bearing 20-30° across the central part of the mountain where the cave is located. Most of the fractures are near-vertical joints; those measured dip 74-82°E.

Bauxite deposits occur throughout the mountain. They are clearly paleokarstic, clayey, occurring within solutionally-formed cavities in the limestone, and appear typical of the karst bauxite deposits found in Greece and nearby countries (Jones et al. 1996). None have been observed within the cave; they have no known association with its development.

3. Cave description

Four entrances are known for Petralona Cave. The natural entrance is in the cave's southwest section. It formed by hillside erosion truncating a narrow dome to create an 8-m deep pit into the cave. It was excavated to allow entry and refilled by 1965 for security. Little sediment was observed in the cave below this entrance. About 50 m to the south is the

Figure 2: Geologic map of the Petralona Cave area (simplified from Institute of Geologic Mining and Research, 1978).

second entrance, which is artificial and opened in 1959. The third entrance is the artificial tunnel. The fourth entrance was open during the Pleistocene and supplied the cave's hominin and paleontological materials. That entrance was an open collapsed sinkhole that had filled naturally. It had no topographic relief when the cave was discovered but was located by digging test pits in the area near the underlying debris cone in the cave. The filled sinkhole has since been excavated as a 2-m square pit to a depth of about 5 m. Based on the concentration of sediment washed in from the surface, material from the sinkhole probably entered the cave in or near the Hall of the Anthropological Association of Greece. The adjacent 12 m of the west wall of Aristotle's Hall is part of the collapse, and unmapped passages extend into the breakdown.

Over 2 km of surveyed passages occur in Petralona Cave within a 300-m long (north-south) by 150-m wide (east-west) area. Typical dimensions are 2-4 m high and wide. Several passages exhibit some of level of modification by collapse. Most of the passages are oriented along joints that bear 25°, with some following a secondary orientation of about 160°. The closely-spaced passages form a rectilinear maze, made even more complex by large speleothem columns dividing passages. Extensive calcite deposits occur throughout the cave as common speleothems, such as stalactites, stalagmites, draperies, flowstone, rimstone, coraloids, and coatings, as well as less common speleothems such as helictites, shields, and mammillaries. Gypsum covers some dry flowstone in layers about 5 mm thick with knobs up to 2 cm thick. Some gypsum grows out of fractures in the flowstone.

The passages generally occur from 323-330 m above mean sea level, with domes extending to 336 m and pits down to 313 m. Papamarinopoulos et al. (1987) reported pits as deep a 50 m, an almost certain exaggeration even if measured from the passage ceilings; the deepest pits explored during this investigation and surveyed previously drop no more than about 10 m below the mean floor level. The locations of six surveyed pits are marked on Figure 1, although several others occur in the cave. All of the pits examined during this study are formed along fractures and narrow with depth, filling with calcite.

An anecdotal report of possible hydrogen sulfide gas in one pit was disproven with an Oldham MX-2100 portable gas detector. The MX-2100 was used in much of the cave (locations in Figure 1) to measure carbon dioxide (resolution ± 0.1%), hydrogen sulfide (± 1.5%), and oxygen (± 2%). Temperature was recorded with a glass thermometer (resolution ± 0.1°C). The results are in Table 1. No hydrogen sulfide was detected. Oxygen (O_2) and carbon dioxide (CO_2) varied inversely and usually proportionally, except when CO_2 rose to more than 3%. Passages along the southwest margin of the cave had the freshest air, where air circulated between the natural and artificial entrances. Most of the cave air was close to surface air quality. Elevated CO_2 was found with increasing depth in one of the two pits tested. Air flow toward the north was detected at A9. Daily atmospheric measurements at Excavation A from October 1977 through October 1978 recorded no major in changes in temperature (16 °C) or humidity (90%) with atmospheric pressure (Poulianos, 1990).

Figure 1 shows unexplored passages at or near the four corners of the cave. Three are possibly too small to explore. Two occur at the end of passages that have characteristics not found elsewhere in the cave. The passage at the northwest corner is not developed along the fractures which guide most of the cave, and it is not part of the maze. Additionally, its mean floor elevation is about 2-3 m lower than most other passages. The passage leading to the cave's

Location	Date	Time	O_2 (%)	CO_2 (%)	Temperature (°C)	Note
A1	29 April 2009	10:27	20.9	0.2	18.8	
A2	29 April 2009	11:05	20.9	0.2	18.8	
A3	29 April 2009	12:15	20.9	0.1	18.5	
A4	29 April 2009	19:22	20.6	0.5	18.5	
A5	29 April 2009	20:38	20.6	0.6	17.5	Top of pit P6 at main passage level
A5*	29 April 2009	20:42	20.6	0.6	17.5	~2 m down pit P6
A5**	29 April 2009	20:47	18.2	3.2	--	~4 m down pit P6
A5***	29 April 2009	20:54	17.7	4.4	--	~5 m below main passage level in passage at the base of pit P6
A5****	29 April 2009	21:00	17.1	5.0	--	~6 m below main passage level at end of passage at the base of pit P6
A6	29 April 2009	21:16	20.7	0.5	18.2	
A7	29 April 2009	21:33	20.6	0.6	18.7	
A8	30 April 2009	13:05	20.8	0.4	17.5	Top of pit P4 at main passage level
A8*	30 April 2009	13:15	20.8	0.4	17.9	2.8 m down pit P4
A8**	30 April 2009	13:24	20.7	0.4	18.0	~6 m down pit P4
A8***	30 April 2009	13:35	20.7	0.4	17.5	~10 m down pit P4
A9	30 April 2009	20:35	20.7	0.6	17.2	

Table 1: Atmospheric gas and temperature measurements in Petralona Cave (locations keyed to Figure 1); hydrogen sulfide measurements at all locations were 0.0%.

southeast corner is among the largest passages, rather than narrowing with distance from the central part of the cave like the other passages. It contains old, 1-m deep guano deposits, air flow, and air flow corrosion features.

4. Analysis

The maze pattern of Petralona Cave indicates that it did not form by epigenic underground streams. The passages generally radiate out from the central part of the cave, diminishing in size with distance. Domes are few and provide little vadose water. Significant sediment is present only near the filled entrance. Several fracture-guided pits occur in the cave, mostly distributed in or near the central area. More probably exist, covered by breakdown and calcite deposits. These features point strongly to a hypogenic origin for the cave, where groundwater rose along the pits to dissolve the maze, per the model of Klimchouk (2007). The essentially horizontal character of the cave, apparently unaffected by the dip of the limestone, suggests a past, unconfined, water table controlled much of the cave's development. Mammillaries indicate a shallow phreatic origin. The cave's northwest-bearing passage may have formed to drain some of the cave's water. It is oriented perpendicular to a valley 200 m to the north, which could have provided a spring outlet. No observations support the presence of a confined hypogenic system, although much of the cave's original solution-formed morphology is hidden by breakdown and speleothems. Currently insufficient information prevents determination of the cave's age, if the hypogenic water was thermal, or if dissolution was primarily driven by carbonic or sulfuric acid.

Paleontological evidence suggests the filled Pleistocene entrance was open to the cave, or at least a topographic sinkhole able to transmit sediments and bones into the cave, by 750 ka and possibly earlier (Belluomini et al., 1990; Poulianos, 1995). Speleothem dating indicates the sinkhole may have filled around 200 ka (Schwarcz et al., 1980). Based on its small size and minimal contribution of sediment, the present natural entrance probably developed during the Holocene. The old guano at A9 demonstrates the presence of an entrance, and the absence of guano elsewhere in the cave suggests it is from an undiscovered entrance near the cave's southeast corner. The entrance is probably not humanly passable, considering how well the surface has been examined in that area, but air flow indicates it is incompletely filled or filled with loose material.

The geologic isolation of Kalavros Mountain from other limestone outcrops likely results in endemism of Petralona Cave's troglobites. One species of blind millipede was observed. The lack of organic nutrients throughout most of the cave restricts most fauna to the passages near and between the natural and artificial entrances and the old guano deposits.

5. Conclusions

Petralona Cave was hypogenically created under water table conditions. Water rose along fractures associated with the fault along the western margin of the Kalavros Mountain fault block. The recharge area has not been identified, but may be an upland area about 20 km to the north. Studies of local landscape evolution and denudation rates may serve as proxies for estimating the period when the cave was hydrologically active and developing. The cave's northwest-trending passage possibly drained the cave to a nearby valley to the north. Two natural entrances are known, one of which filled during the Pleistocene, and an undiscovered filled entrance probably exists southeast of the mapped portion of the cave.

A more detailed study of the cave, to include sampling of rocks, sediments, speleothems, biota, and groundwater, is needed to verify and refine the hypotheses of this paper. Within this framework, a careful study of the context of the hominin material may provide a better understanding of their age and significance. Ultimately, direct sampling of the skull for age and potential DNA may yield more definitive and useful results if non-destructive analyses remain inconclusive.

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CAVE CLIMATE STUDIES AND THE POTENTIAL EXTENT OF THE JEWEL CAVE SYSTEM

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Research at Jewel Cave has shown a direct relationship between airflow at the entrance and the prevailing atmospheric pressure. A previous study of this barometric airflow estimated a total minimum cave volume of 1.1×10^8 m^3, of which less than three percent has been discovered.

This study estimates the extent of undiscovered air-filled cave passages for Jewel Cave, as well as for nearby Wind Cave. The estimate is based on: 1) the thickness and distribution of the Madison Limestone; 2) the potentiometric surface of the Madison aquifer; 3) the location and extent of potential geological obstacles; 4) the three-dimensional distribution of the cave systems within the host rock; and 5) the “cave density” at Jewel Cave and Wind Cave.

Based on the minimum cave volumes and an estimated 9.3×10^{10} m^3 of available limestone, the overall cave-to-rock ratio is 0.18%. This is at the low end of the range of known “cave density” values for Jewel Cave and Wind Cave, 0.15-0.59%.

A more recent airflow study indicates a larger minimum cave volume of at least 2.0×10^8 m^3. With that value, the overall ratio of cave to rock volume would be nearly the same as the average “cave density” for the known portions of Jewel Cave and Wind Cave.

Most of Jewel Cave’s volume extends toward Wind Cave, and vice versa, and the data supports the possibility that the two volumes could be part of one large cave system.

1. Introduction

Over 233 km of passages have been documented at Jewel Cave. Studies of the cave’s barometric airflow have demonstrated this may be less than three percent of the total volume. In simple terms: if the atmospheric pressure increases one percent, an additional one percent of air will be compressed into the volume contained by the passages of Jewel Cave. Ongoing measurements have shown this “one percent” to be about 1.4×10^6 m^3. If this is accurate, the total volume of the cave (including the undiscovered passages) would be about 1.4×10^8 m^3 – roughly 8.0×10^3 km of average-sized passages.

Because of its extensiveness, Jewel Cave requires an unusual approach to management. It is appropriate to seek an understanding of how far and where the cave might extend, even before the remaining passages are discovered, so that the Park can begin formulating management strategies before any human impacts might occur.

2. Boundaries of Maximum Extent

Virtually all of the caves in the southern Black Hills are found in the Madison Limestone, but only where it is capped by the Minnelusa Formation. Altogether, over 420 km of cave passages conform to this relationship, with two caves exceeding 200 km of passages. In contrast, there are no caves known to be over 60 m in the uncapped Madison (hundreds of thousands of hectares). This is compelling circumstantial evidence for assuming the modern-day geological contact is a boundary to how far the cave can extend, even if the reason is not yet understood.

Based on this assumption, ArcGIS was used to construct a three-dimensional model of the limestone available to host the rest of the cave system – at least the air-filled portions responsible for the barometric wind. It is bounded by the geological contact, the upper and lower surfaces of the limestone, and the water table, and was adjusted with controls such as the Jewel Cave’s water wells.

One possible obstruction was the eastern extension of the Dewey Fault system, with up to 135 m vertical displacement at its western end; but there was no information on the amount of displacement at its eastern extremity, where it could potentially interfere with the continuity of a large cave system. However, recent field checking has determined the easternmost five kilometers to be nonexistent, possibly the result of cartographic error in the newest version of the map. Lineaments visible on aerial photographs seem to represent an obstruction, but even these have been successfully crossed, and do not represent an inherently impassible boundary (Fig. 1).Jewel Cave was formed under confined phreatic conditions (Deal, 1962; Palmer, 1999), when the piezometric surface was above the top of the limestone and perhaps also above the ground surface. In a monoclinal or anticlinal structure (Fig. 2), extensional fracturing would open a path for some of the water to escape to the surface. In principle, the water would open fractures in the limestone by dissolution, but would have less effect on the permeable, but relatively insoluble, sandstone just above the Madison. Eventually, some of the basal sandstone would collapse and plug the passage. Later the collapse material would be cemented together. Additional dissolution would open small holes in the cemented breakdown, but in most cases not enough to create a passable connection across the linear obstruction. Nonetheless, once the cave was drained, the obstruction would be permeable enough to allow significant airflow to pass through.

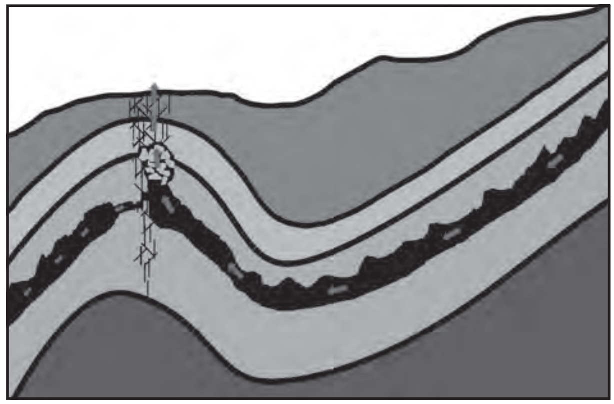

Figure 2: Water flowing past an anticline under phreatic conditions.

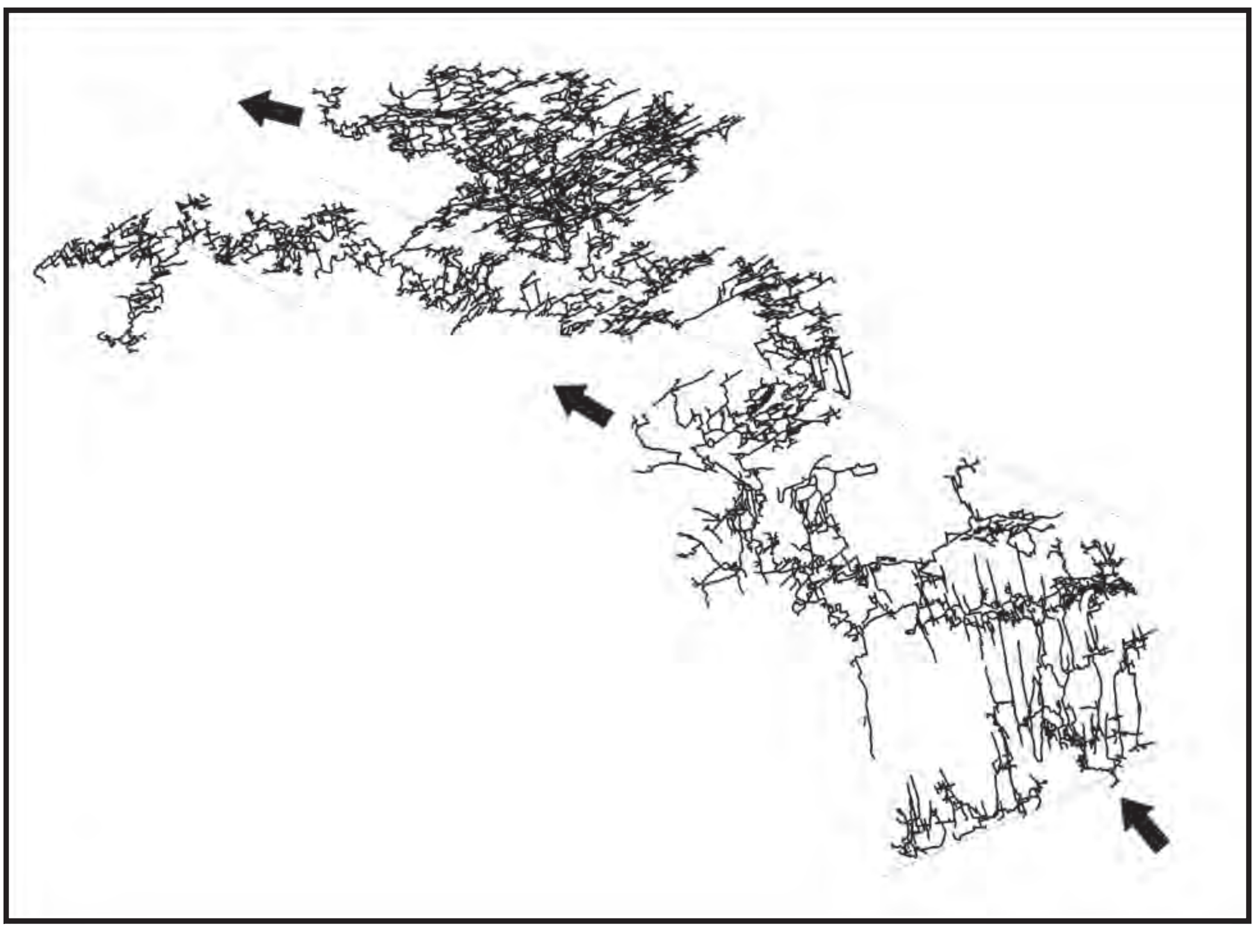

Figure 1: Relationships of cave passages and lineaments. Arrows show direction of airflow when cave is exhaling.

In fact, passages have been discovered precisely in the vertical plane of the fold axis. One such passage becomes a chimney extending up about 3 m, only to be plugged with large blocks of cross-bedded sandstone that are identical to the basal sandstone subunit of the Minnelusa, as observed in surface road cuts. The sandstone apparently was already lithified when the collapse took place.

Lateral boundaries are defined north of Wind Cave, where all of the Minnelusa-capped Madison is completely filled with water, and northwest of Jasper Cave. The latter is based on ground water divides and flow paths (Fig. 3) delineated by Rahn and Gries (1973), based on a water balance of springs and available recharge areas, as well as geochemical signatures. This boundary is less certain, though reasonable. While it is possible the paleohydrology was significantly different from that observed today, our observation is that the caves themselves align surprisingly well with the modern geologic contacts (Fig. 4), suggesting that the paleohydrological flow patterns could be very similar to those observed today.

If all the assumptions are correct, these boundary features define a control area (Fig. 5), beyond which the undiscovered air-filled portions of Jewel Cave (and Wind Cave) cannot go.

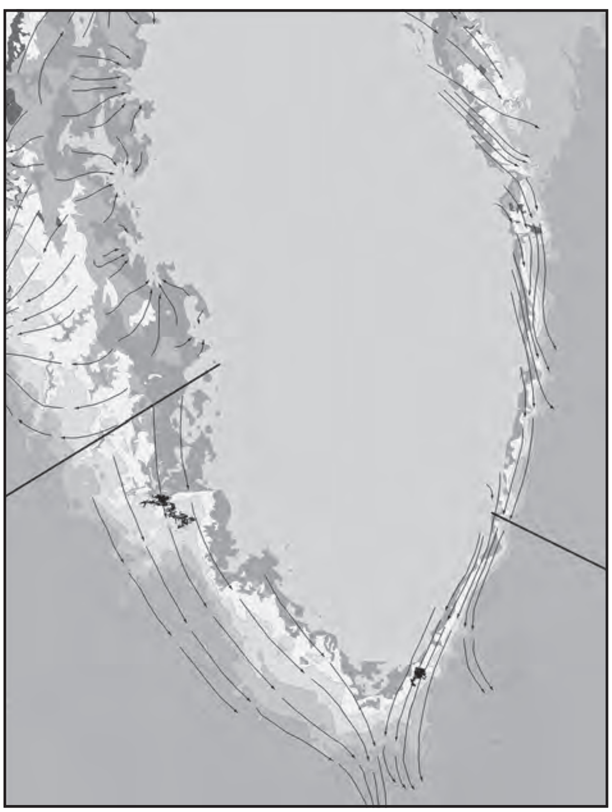

Figure 3: Arrows represent ground water flow paths. Straight lines represent assumed lateral limits of air-filled cave passages.

Figure 4: Cave passage and geology. Dark gray = exposed Madison Limestone; light gray = overlying Minnelusa cap; black lines and dots = mapped caves; white circles = blowholes

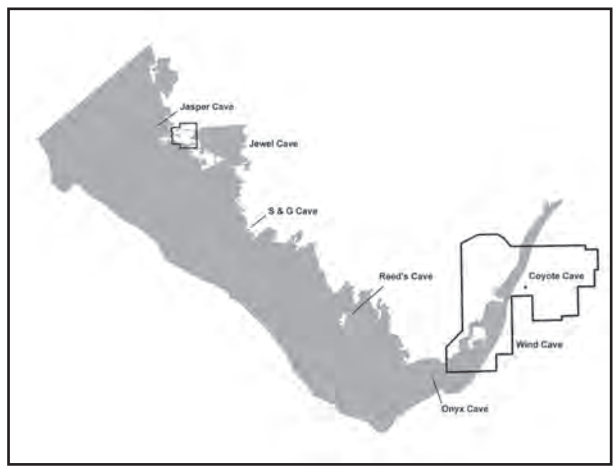

Figure 5: Gray represents the control area of Madison Limestone that is both above the water table and capped with the Minnelusa Formation.

One additional assumption is the cave development in the southern Black Hills occurs only the upper 75 m of the Madison. In over 400 km of known passages at Jewel Cave and Wind Cave, less than 0.5 percent extends stratigraphically deeper than 75m. This reduces the "available" limestone volume to 9.3 x 10^{10} m^3.

Wind Cave sits just above today's water table, dipping into it at the southern end. On the other hand, the Madison contains no water in the immediate vicinity of Jewel Cave. GIS analysis has shown that, between Wind Cave and Jewel Cave, there is nowhere less than 60 m of unsubmerged limestone with a Minnelusa cap. In other words, there is no compelling evidence that either Jewel Cave or Wind Cave are bounded by a sump located somewhere between the two. Hence, there is no obvious obstruction to continuous air-filled cave passages between the two entrances.

A further consideration is the difference in “cave densities” – the ratio of cave volume per unit rock volume – between Jewel Cave and Wind Cave. A weighted average for Jewel Cave is 0.22 percent, and 0.59 percent for Wind Cave.

Using Conn’s (1966) conservative estimate of 11.2×10^7 m^3 for Jewel Cave and 5.6×10^7 m^3 for Wind Cave, the total is 0.18 percent of the available volume of limestone, and is at the low end of values for both Jewel Cave and Wind Cave. However, barometric airflow at other cave entrance represents even more volume, so the actual value will be higher.

Filling the available limestone with the minimum predicted volume of air from each end of the control volume, using known “cave densities,” we find that there would not be enough volume to make a continuous cave system between Jewel Cave and Wind Cave.

However, using the same mathematical model as Conn, and years of continuous airflow data (Conn collect data for about two weeks), Andreas Pflitch (2007) has estimated a minimum of 20.0×10^7 m^3 represented at the Jewel Cave entrances, and at least 2.0×10^7 m^3 represented by airflow at the Wind Cave entrances. With these values, there is just enough volume to extend from each cave and meet in the middle, using the known weighted average density for each cave!

One unresolved question relates to the accuracy of the “cave density” numbers. Conceivably there could be enough undiscovered passages, and impassible cracks, to skew the estimated average. Even a completely explored area might contain a significant unaccounted volume that could never be discovered.

At least at Jewel Cave, this seems unlikely. The passages seem to end fairly “solidly,” and do not appear to branch into ever-smaller voids and pore spaces. Nonetheless, this uncertainty can be resolved by establishing an airflow mass balance (Fig. 6).

Using an ultrasonic anemometer at the entrance the total volume of the cave can be predicted. The placement of anemometers in the air paths that leave the “control area” will allow the calculation of the volume beyond the control area. The difference will be the true volume of the control area, which can then be compared with that value estimated from survey data. It will provide an estimate of how completely the volume of explored passages represents the true volume. This work is currently in progress.

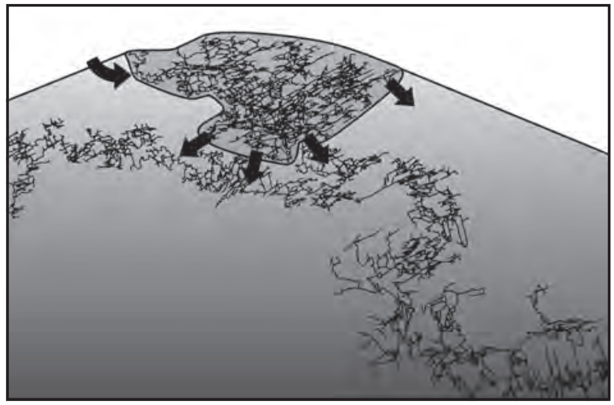

Figure 6: Airflow mass balance. Volume within the control area is equal to the total volume minus the volume beyond the control area. Arrows indicate airflow direction when the cave is inhaling.

3. Conclusions

The reason for this study is that Jewel Cave is a large cave system that is far beyond the park’s ability to manage directly, but the cave potential model provides a tool for interacting with neighboring agencies and landowners. It doesn’t show precisely where the undiscovered passages are, but it provides a good rationale for convincing neighboring agencies and landowners of where we would have concerns. It supports a position of taking preemptive action to managing the cave, even though only three percent has been discovered.

Acknowledgements

The authors are grateful to Marc Ohms, for providing details on the passages at Wind Cave. Rod Horrocks, for initially pursuing the idea of a cave potential – even though we have come to very different conclusions; Dwight Deal, for first observing a relationship between the cave and the Minnelusa cap; and Herb and Jan Conn, for both predicting and demonstrated that Jewel Cave was much more extensive than anyone had previously imagined.

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THE CADMIUM FORMS IN THE SOIL OF KARST REGION AND THEIR EFFECTS ON WATER EQUALITY

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According to petrographic differences, the rocks and topsoils of the Cambrian, the Middle Devonian and the Permian in southern Guangxi province, western Hunan province and Chongqing city were sampled by layers to study water-soluble, ion-exchangeable, carbonate-bound and total cadmium. Sampled are the water from karst spring, underground river and the original soil and the soil 1to 10mg/kg added in the pot experiments of peanut to analyze cadmium content.

The results show that the cadmium content in the rocks averages 0.10μg/g, up to the highest 0.16μg/g. Total cadmium in the soils range from 1.28 to 5.18μg/g, averagely 2.70μg/g. The mean contents of water-soluble, exchangeable and carbonate-bound forms are 3.4, 39.3 and 213ng/g, respectively, the former two of which amount to 0.45 to 2.86% of total cadmium, averagely 1.88%. The exchangeable and carbonate-bound fractions correlate positively with total cadmium.

The cadmium amount of soil water are usually less than 0.0006mg/L, whereas cadmium content in the water flowing from karst springs , subterranean rivers and pot experiments are 0.0000mg/L.

This study indicates that the cadmium of soils in karst area, if the content is less than 10mg/kg, almost has no impact on karst underground water. Meanwhile, water-soluble cadmium abstracted under the lab conditions is completely different from soil water cadmium in the field.

1. Introduction

Southwest China has vast area of naked karst richer in the poisonous element cadmium, than non-karst areas. However, cadmium toxicity is determined not only by the total amount, but also by its chemical forms. Water as a solvent is an important medium to transport soil minerals. So, to study cadmium forms and their shift by/into water is meaningful to understand water environment health.

2.Materials and Methods

2.1Soil collection and analysis

Soils were sampled according to petrographic differences in some karstic areas of Guangxi Zhuang Autonomous Region, Hunan province, and Chongqing city of Southwest China, and analyzed for different forms of cadmium by the Institute of Geophysical and Geochemical Exploration Laboratory, and for total cadmium by the National Center for Geoanalysis, CAGS, P.R. China.

Aqueous cadmium: 2.5000g of soil was taken, put into a 25 mL test tube and 25 mL of deionized water were added to it. After 2 hours of oscillation on an oscillator, the test tube was centrifugalized for 10 minutes under 6000 rev/m, and the supernatant from the test tube was taken and prepared to be tested.

Ion-exchangeable cadmium: 25 mL of 1 mol/L NH_4Ac solution was added into the test tube where the water-soluble cadmium had been abstracted. Following the same oscillation and centrifugalization as above described, the supernatant was obtained to be analyzed.

Carbonate-bound cadmium: 25 mL of 1 mol/L HAc solution was put into the remaining test tube after an ion-exchangeable form had been abstracted. After the same oscillation and centrifugalization, the supernatant was measured.

2.2Water Collection and Analysis

Water samples were gathered in the field from soil, karst springs, and subterranean rivers. A patch of peanut pot experiments were carried out outdoor at the Institute of Karst Geology (IKG). Trial soils were taken from karstic area of Guilin and added with 0, 1, 5, 10 mg/L of $CdCl_2$ solution, respectively. During the experiment, soil water leaking out of pot base holes were collected. All water samples were tested indoor by IKG Laboratory.

3.Results and Discussion

3.1Soil cadmium forms in karstic region

In karst region of Southwest China, total cadmium in soil ranges from 0.61 to 6.77μg/g, averaging 2.5μg/g, which is 28 times mean value of Chinese soil. Water-soluble cadmium means 3.8 ng/g, varying from 2 to 6.9 ng/g. The ion-exchangeable form is 63.1 ng/g, ranging from 9.9 to 299 ng/g. Carbonate-bound cadmium averages 268 ng/g, changing from 44 to 1196 ng/g (Table 1). Aqueous and ion-exchangeable forms account for 2.66% of the total, varying from 0.45 to 7.42%, while carbonate-bound cadmium makes up from 2.85 to 23.66%, averagely 10.63%.

Positive correlations between total cadmium and ion-exchangeable or carbonate-bound form exist under 99% confidence level, while total cadmium correlates positively with aqueous form under 95% confidence level. So do the water-soluble and ion-exchangeable or carbonate-bound forms. Ion-exchangeable and carbonate-bound forms relate positively to each other, too (Table 2). These indicate that mutual transformation between total cadmium and different forms may take place, and so do mutual conversion between different forms of cadmium.

3.2Water cadmium content

Cadmium contents of soil water collected in 0.3 m and 0.6 m below the surface are both less than 0.0006 mg/L. Cadmium concentrations from karst springs range among 0.0000 and 0.0010 mg/L. Subterranean rivers pose 0.0000 mg/L cadmium, and cadmium amounts of surface creeks and streams flowing through karst areas vary from 0.0000 to 0.0009. Seeping water in the peanut pot experiment contained 0.000 0mg/L cadmium (Table 3). These results show that in natural situations, karst water is safe for organisms to use in terms of cadmium content. Under the man-made condition of added cadmium up to 10 mg/kg, soil seepage water still has no cadmium which demonstrates that karst soil pose a great ability to absorb cadmium. Therefore, only if exogenous cadmium pollution does not directly go into underground conduits, karstic soil can alleviate less than 10 mg/kg cadmium toxicity by powerful absorption.

3.3 Comparison of soil aqueous cadmium abstracted inside lab with collected in the field

Soil aqueous cadmium abstracted inside lab is at least 6 times that collected in the field. The result demonstrates

Cadmium forms	Total μg/g	Aqueous ng/g	Ion-exchangeable ng/g	Carbonate-bound ng/g
Mean values	2.52	3.80	63.1	268
Standard deviation	1.3668	1.3001	66.9615	267.0337

Table 3: Cadmium contents in the water related to karst.

	Cd	Cd_a	Cd_e	Cd_c
Cd	1			
Cd_a	0.406*	1		
Cd_e	0.744	0.679	1	
Cd_c	0.817	0.451*	0.830	1

Subscript a, aqueous; e, ion-exchangeable; c, carbonate-bound.
***, p=0,05; without *, p=0.01.**

Table 2: Correlation among different forms of cadmium in the soil.

Water sources	Soil water	Creeks	Karst springs	Underground rivers	Pot experiment
Cd(mg/L)	<0.0006	0.0000-0.0009	0.0000-0.0010	0.0000	0.0000

Table 3: Cadmium contents in the water related to karst.

the evident difference between lab conditions and natural ones if the two kinds of cadmium are the same in nature, or otherwise.

4.Conclusions

From our research, some points may be concluded as follows:

- In the karst region of Southwest China, soil poses 2.52 μg/g of the total, 3.8 ng/g of water-soluble, 63.1 ng/g of ion-exchangeable, and 268 ng/g of carbonate-bound cadmium, respectively, which obviously correlate positively and can transfer each other.
- Whether in natural soil or polluted soils by less than 10 mg/kg cadmium, soil water contains less than 0.0006 mg/L cadmium, which is safe for drinking.
- Aqueous cadmium abstracted from soil is not equal to one in soil water from amount which may show that lab conditions can not completely simulate the nature in the field.

Acknowledgments

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STUDY ON SOIL FACTORS AND KARST PROCESSES OF DIFFERENT LANDUSES OF VERTICAL ZONED CLIMATIC AREA, JINFO MOUNTAIN, CHONGQING, CHINA

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Land use results in a series of variations of soil physicalchemical property, furthermore influencing on karstification direction and intensity. Taking two spring basin at different elevations in Jinfo Mountain, Chongqing, China, the authors analyzed the soil water and CO_2 variation, soil water characteristics, solution rates in soil and their driving factors etc. The results showed that solution of tablets mainly occurs during the rainy season, with the mean weight loss in soil account for 65.5% and 71.9% of annual loss in Bitan and Shuifang spring respectively. It was also proved that soil CO_2 is an important driving factor for the ground carbonate rock denudation. Soil CO_2 and the residence time of the water are two major controlling factors which influence the weight loss in tablets placed in the soil. The intension of soil water transmission might be the decisive factor of solution rate in soil in dry season.

1. Introduction

It was proved that soil has taken important role in karst processes and karst ecosystem (Wang et al. 1999; Cao et al. 2003; Li et al. 2004a; Jiang 2000), soil organic matter (OM) and soil microbes can improve limestone corrosional rate remarkably (Li et al. 2004b; Tao et al. 1998). It seems to be more important in karst research field owing to the sensitivity of karst dynamics system to environmental change (Zhang et al. 2004, 2005; Yuan 1993) and the fragility of karst soil and karst ecosystem (Cao et al. 2004). Land use results in a series of variations of soil physicalchemical property, furthermore influencing on karstification direction and intensity. Previous study on karst processes was always focused on karstification intensity and its variation under different geologic setting, climatic and hydrology conditions in view of macroscale CO_2 sink (Yuan, 1997; Yoshimuri et al., 1997) Lesser attention was paid to impact of landuse cover on karst processes (Zhang et al. 2008).

Soil moisture in karst area always has a large variability in spatial and temporal constrained by special two-layer structure and human activities. Meantime, in order to improve the estimating accuracy of carbon sink result from the karst processes, more and more attentions have been paid to landuse patterns and allogenic system in the study of karst processes and carbon cycle, which is a considerable part of global change study field. Taking two spring basin at different elevation(Bitan 760m asl and Shuifang 2000m asl) in the study area, the author analyzed the soil water and CO_2 variation, soil water characteristics, solution rates in soil and their driving factors etc. using different methods, such as standard tablets measurement, karst dynamic system monitoring, GASTEC-CO_2 measurement and SPAW-soil water characteristics(computerized model) analysis.

2. Study Area

Jinfo Mountain National Park is located in the south of Chongqing and in the southeast of Sichuan Basin (Zhong Zhangcheng, 1997). The area of the main scenic spots occupies 441km^2. Jinfo Mt. is a syncline mountain. The plateau surface is underlain by Permian limestone (P1) in the upper part with about 2000m a.s.l. Meanwhile, karst forms in large scale on the surface or underground are found. The shale and sandstone of Silurian lay in the middle of Jinfo Mt. from 1000m to 1500m asl.. The lower part of Jinfo Mt. is composed of the limestone and dolomite of Cambrian and Ordovician. Plenty of small- and microforms of karst are formed in this area.

Jinfo Mt. is in subtropical humid monsoon zone with a rainy season from April to October. In the upper part, its annual average air temperature is 8.2 °C with an annual mean rainfall of 14345.5mm. In the lower part, the annual air temperature is 16.6 °C with an annual mean rainfall of 1286.5mm.

3. Study Method

Two spring basins at different elevation(Bitan 760m asl and Shuifang 2000m asl) in the study area were selectetd in order to analyze the soil water and CO_2 variation, soil water characteristics, solution rates in soil and their driving factors etc. using different methods, such as standard tablets measurement, karst dynamic system monitoring, GASTEC-CO_2 measurement and SPAW-soil water characteristics(com puterized model) analysis.

4. Soil Moisture and Soil CO_2 at Different Depth and Land Uses

4.1 Soil moisture

Soil water content from different landuse soil profiles near Bitan spring is less than that in Shuifang spring, most content in Bitan is smaller than 30%W, while larger than 40%W in Shuifang spring (Table 1). And the water content of soil profile has relative stable distribution near Shuifang spring owing to more precipitation recharge and lower air temperature favored for moisture holding. Soil water of surface layer in tilled land is very low, which showed that vegetation degradation or human activities can influence remarkably the soil water content and water holding capacity. Water content tends to decrease with the depth.

4.2 soil CO_2

Soil CO_2 shows distinct temporal and spatial variety. In rainy season mean CO_2 content at Shuifang spring is as high as 7000×10^{-6}(ppm), whereas 4700×10^{-6} at Bitan spring and 3900×10^{-6} at vicinity(tilled land)(Table 2). In dry season the normal CO_2 is about 1000×10^{-6}, average values of soil CO_2 in Shuifang and Bitan are 1200×10^{-6} and 970×10^{-6} respectively.

Sampling point		Soil moisture at different depth(%W)			
		-5cm	-10cm	-20cm	-40cm
Shuifang spring	woodland	40.80	43.00	49.09	45.03
	bamboo land	47.57	49.94	49.94	49.26
	grass land	36.23	35.89	49.43	49.60
Bitan spring	woodland	24.21	23.70	24.21	26.75
	tilled land	16.09	16.76	19.47	21.84

Table 1: Soil moisture at different depth and land uses (July 2006).

Soil CO_2 in different landuses in descending order is: bamboo land > grassland (Shuifang) > woodland > tilled land (Bitan) in summer, and is grassland (Shuifang) > woodland(Bitan) >bamboo land(Shuifang) > woodland (Shuifang)> tilled land (Bitan) >bush-grass(Bitan) in summer.

5. Soil Water Characteristics

Soil water characteristics (Saxton and Willey, 2004; 2005) are also different under the various landuse patterns. Generally, soil water holding and transmission capacity in Shuifang spring basin is much better than that in Bitan

Sampling point		CO_2 concentration at different depth ($\times10^{-6}$					
		-20cm	-30cm	-40cm	-20cm	-30cm	-50cm
Shuifang spring	woodland	-	-	-	500	1000	1100
	grass land	4000	7000	7000	1200	2200	2100
	bamboo land	7000	13000	9000	1100	700	1000
Bitan spring	woodland	2000	8000	4000	1000	1100	1500
	bush-grass	-	-	-	800	800	600
	tilled land	500	4000	-	1200	5000	4500
	□	July 2006			January 2007		

Table 2: CO2 concentration of soil profile at different land uses.

spring at the same water potential (tension). Saturation conductivity (0KPa) of woodland is larger than that of grass or bush, with the maximum value of Shuifang spring woodland (Table 3). The property of rapid fall of unsaturated conductivity at low tension (0-33KPa) in

soil position		field capacity (%V)	saturation (%V)	available water (%V)	saturation conductivity (mm/hr)
Shuifang spring	grass land	27.1	54.9	15	54.10
	woodland	22.9	62.0	12	138.26
	bamboo land	30.5	62.4	17	80.18
Bitan spring	bush-grass	17.2	49.3	9	81.00
	woodland	21.2	54.8	11	90.17
	tilled land	25.7	57.7	13	77.84

Table 3: Standard parameter values for soil water characteristics.

woodland soil at Shuifang spring is favored to prevent moisture evaporation (Table 4).

6. Seasonal Tablet Weight Loss

Limestone solution rates derived from standard tablet

soil position		0KPa	33KPa	50KPa	100KPa	1500KPa
Shuifang spring	grass land	5.41×10^{1}	7.20×10^{-3}	2.26×10^{-3}	3.69×10^{-4}	3.15×10^{-7}
	woodland	1.38×10^{2}	3.58×10^{-4}	1.11×10^{-4}	1.75×10^{-5}	1.60×10^{-8}
	bamboo land	8.02×10^{1}	1.28×10^{-2}	3.59×10^{-3}	5.81×10^{-4}	4.70×10^{-7}
Bitan spring	bush-grass	8.10×10^{1}	2.32×10^{-4}	5.51×10^{-4}	8.77×10^{-6}	7.04×10^{-9}
	woodland	9.02×10^{1}	2.41×10^{-4}	8.34×10^{-5}	1.43×10^{-5}	1.37×10^{-8}
	tilled land	7.78×10^{1}	1.11×10^{-3}	3.60×10^{-4}	5.93×10^{-5}	6.05×10^{-8}

Table 4: Water transmitting rate of surface soil layer at different soil suction interval(mm/hr).

loss in weight showed that annual weight loss in tablets in Shuifang spring basin both placed in soil and on the surface is generally greater than that in Bitan spring, and in Shuifang spring basin the rate in soil under forest is higher than that in soil under grass(Table5). The tablet weight loss in soil in Shuifang spring basin is three times of that in Bitan spring. Maximum and minimum annual weight loss are

218.15mg/a and 3.9mg/a, and happened at 20cm soil depth of forest in Shuifang and at 50cm soil depth of grass in Bitan respectively.

Generally, in rainy season weight loss in various landuse decreases from bamboo-land, woodland, grass in Shuifang; and from tilled land, woodland to bush-grass in Bitan (Table 6). The data also showed that solution of tablets mainly occurs during the rainy season, with the mean weight loss in soil account for 65.5% and 71.9% of annual loss in Bitan and Shuifang spring respectively.

site		buried position	annual mean weight loss (mg)	daily mean weight loss(mg/m²·d)
Bitan spring	bush-grass	-5cm	50.60	40.80
		-20cm	11.55	9.31
		-50cm	3.90	3.14
	wood land	rock surface	44.95	36.24
		-5cm	106.85	86.15
		-20cm	41.65	33.58
		-50cm	39.80	32.09
Shuifang spring	wood land	rock surface	67.10	54.23
		-5cm	187.75	151.74
		-20cm	218.15	176.30
		-50cm	191.75	154.97

Table 5: Annual tablet weight loss in soil at different land uses.

The following linear equation was also developed between solution rate in soil(Y) and soil $CO_2(X_1)$, soil moisture(X_2), soil porosity(X_3) using multiple regression analysis method: $Y=0.01046X_1-1.432X_2+5.342X_3-231.738$, $R=0.988$, $P=0.035$.

site		mean weight loss in soil (mg)		
		rainy season	dry season	yearly
Bitan spring	bush-grass	13.68	7.13	22.02
	woodland	20.44	16.03	62.77
Shuifang spring	bamboo land	126.73	45.20	
	grassland	72.32	53.17	
	woodland	83.48	55.67	199.22

Table 6: Seasonal tablet weight loss in soil at different land uses.

7. Discussion

Shuifang basin's weight loss of tablets in soil in rainy season is generally greater than that in Bitan, with the maximum in bamboo-land, it has a remarkable positive relationship with soil CO_2 resulted from the GASTEC measurement. The soil CO_2 content under bamboo-land reached 7000-13000×10^{-6}. At the end of rainy season(summer) soil CO_2 of woodland is highest, grass second, but in dry season(winter) soil CO2 of grass is much higher than that of other landuse. This is why the solution in bamboo land decreases during dry season and is less than that in woodland and grassland. Accordingly, CO_2 is an important driving factor for the ground carbonate rock denudation.

Soil water characteristics assessment also shows a good relationship between soil water holding capacity and solution rate. The soil water holding and transmission capacity in various landuse in descending order are: bamboo land > grassland > woodland in Shuifang spring basin, and tilled land > woodland > bush-grassland in Bitan spring, i.e. the better the water holding capacity is, the more its contribution to solution rate is. Moreover, the intension of soil water transmission in woodland is much better than that in grassland and bamboo land, which is favored for prevention of soil moisture evaporation during dry season, thus extend the water residence time. So winter's solution rate in woodland is higher than that in grassland and bamboo land. The intension of soil water transmission might be the decisive factor of solution rate in soil in dry season.

8. Conclusions

Soil water content from different landuse soil profiles near Bitan spring is less than that in Shuifang spring, most content in Bitan is smaller than 30%W, while larger than 40%W in Shuifang spring. Soil CO_2 shows distinct temporal and spatial variety. In rainy season mean CO_2 content at Shuifang spring is as high as 7000×10^{-6}(ppm), whereas 4700×10^{-6} at Bitan spring. The tablet weight loss in soil in Shuifang spring basin is three times of that in Bitan spring. The data also showed that solution of tablets mainly occurs during the rainy season, with the mean weight loss in soil account for 65.5% and 71.9% of annual loss in Bitan and Shuifang spring respectively.

Solution rate shows a distinct climatic control and seems directly dependent on water surplus (P-E) rather than on temperature. Soil CO_2 and the residence time of the water are two major controlling factors which influence the weight loss in tablets placed in the soil. Solution of tablets on the surface and in soil is less at lower elevations than at higher elevations(at least in year 2006), although the opposite appears to hold for solution rate calculated from water hardness and runoff data. Solution tablets data must therefore be interpreted cautiously.

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AGE OF CAVE FILLS IN SLOVENIA

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Abstract

The territory of Slovenia, with its numerous karst regions from the Alps to the Mediterranean, long history of karst evolution and relatively good knowledge of karst sediments represents an ideal place for dating of cave sediments with different dating methods. The results enable to interpret the time span of karst evolution, age of karst surfaces, speleogenesis and rates of the processes. The majority of karst sediment dating has been carried out in the south-western Slovenia (Kras) where Eocene flysch is the last marine deposit preserved in the geologic record. The Oligocene to Quaternary period represented mostly terrestrial phase with prevailing surface denudation and erosion processes related to tectonic evolution of the area. Therefore only karst sediments can record karst evolution and its age.

The palaeomagnetic research was carried out in Slovenia from 1997 to 2007. There were a total of 21 sites (19 in Slovenia and 2 in Italy) with 36 profiles; all except one were cave or karst surface sediments. The sites are located mainly in the Dinarski kras (Kras, Matarsko podolje, Podgorski kras, Notranjski kras, Dolenjski kras) and four of them in other areas, especially due to the fact that localities with suitable sediments are nearly absent in the Alps. Two sites from Julian Alps, one inn the Isolated Karst of the pre-Alps and Plio/Quaternary fluvial sediments from the tectonic Velenje Basin were also analysed.

The most important result is the discovery that cave fills have substantially older ages than generally expected earlier (max. about 350 ka). Palaeomagnetic data in combination with other dating methods, especially biostratigraphy, have shifted the possible beginning not only of the speleogenesis but also of the cave filling processes in Slovenia far below the Tertiary/Quaternary boundary. Results suggest that there were probably some distinct phases of massive deposition in caves. The oldest one took place from about 1.8 to more than 5.4 Ma (with two phases at 1.8 – 3.6 and about 4.1 – 5.4 Ma). The data support and better define the estimated ages of the surface and cave sediments that were based on geomorphic evidences, especially from unroofed caves. The evolution of caves took part within one karstification period, which began with the regression of Eocene sea and exposition of carbonate rocks at the surface. Complicated overthrusted structure of the area was formed principally during Oligocene to early Miocene.

Research of cave fills in the Dinaric, Alpine, and isolated karst opened new horizons for the interpretation of karst and cave evolution, both of individual geomorphologic units and of extensive areas. The data inform us that a number of common features and evolutionary trends exist in all the studied areas. On the other hand, there are distinct differences of evolution of smaller geomorphic units within the more extensive ones, which result mostly from different post-Eocene tectonic regimes.

CONTRIBUTED PAPERS IN EXPLORATION

EXPLORATION IN DRY CAVE 2005–2009, GUADALUPE MOUNTAINS, NEW MEXICO

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Dry Cave is an extremely complex, rectilinear, multi-level, maze cave located in the Guadalupe Mountains of New Mexico. The first documented trip to the cave occurred in 1933. Approximately 8 km of cave were surveyed from the mid 1960s to the late 1970s. Many additional passages were explored but never surveyed during this time period and numerous unexplored leads exist.

A resurvey of the cave initiated in 2005 uses modern survey techniques such as backsights, detailed survey notes and inventory. Digital cave maps are updated immediately after each survey trip utilizing the Walls/Illustrator roundtripping process and greatly aid further exploration and survey. In January 2006, this systematic cave survey resulted in the discovery of the McKittrick Avenue Section. More than 4.5 km of cave have been surveyed in the McKittrick Avenue Section. The cave survey is over 13 km with 5.7 km of the current survey have been done in previously unexplored cave. Numerous unexplored leads exist and there is potential for much more cave to be discovered.

Observations based upon exploration, survey and cartography have shown that the major passages are aligned with the local bedrock dip. Strike oriented passages are often smaller but have proven to be the key to the discovery of extensive new areas. The cave appears to have formed in a dome-like shape that is wrapped around a topographic and geological high point. In May 2008 an area called Dirty Deeds was discovered in the northeastern part of the cave. This area has airflow and leads that may be the key to following the cave completely around the high point revealing a doughnut shaped cave footprint.

1. Introduction

Dry Cave is located in the Guadalupe Mountains of Southeastern New Mexico, USA at the northern end of the Chihuahuan Desert. Dry Cave is located on McKittrick Hill, approximately 20 kilometers west of the City of Carlsbad. There are four other major caves on McKittrick Hill with surveyed lengths between 1.2 to 5 kilometers. There are 23 kilometers of surveyed passage within a square 1.5 km area on McKittrick Hill, with potential for much more. Dry Cave is the longest, deepest and most complex of the McKittrick Hill Caves. Dry Cave is managed by the Bureau of Land Management (BLM) for research, survey and exploration. Dry Cave is the third longest cave in the Guadalupe Mountains with 14 kilometers of surveyed passage as of January 2009. Survey and exploration are still in progress and there are many unexplored leads and kilometers of known passages to survey.

2. History

Native Americans were aware of Dry Cave as indicated by the two ring middens located on the surface adjacent to the entrance. These earth ovens were used to cook the hearts of the prolific Agave and Sotol plants found in the Chihuahuan desert. The first documented trip to Dry Cave was in 1933 when a man named Carter led amateur paleontologist and archeologist R.M. “Bill” Burnet approximately 200 meters into the cave to what is now known as the Balcony Room and the Camel Room. Burnet named the cave “Carter’s Cave” in honor of his guide. Burnet later returned to Dry Cave to do paleontology excavations of the significant Pleistocene bones found near the entrance and Balcony Room. Burnet also surveyed and drafted a map of the 200 meters of passage he had visited (Kunath 1978). In 1934, Robert Nymeyer, Dave Wilson, and Sonnie Kindel found Carters Cave, and unaware that it was a previously known cave, they renamed it Dry Cave (Nymeyer 1978). They didn’t get much further than the Burnet group and were unimpressed with the cave’s dry, dusty crawlways. Very little exploration was done for the next thirty years.

It wasn’t until 1964 that Jim Peck explored across the top of the Balcony Room rather than climbing down to the floor as previous explorers had done and discovered an area with unexplored passages going everywhere (Kunath 1978). Peck, Pete Lindsley, Larry Register and Tom Meader returned to the cave in 1965 and explored to the top of the 40 Foot Chimney. Lindsley and Register explored over 1 kilometer of highly complex maze passage at the bottom of the chimney and made their way to the Chamber of the Vanishing Floor (Kunath 1978). This breakthrough led to a surge of exploration and survey that lasted until the late 1970s. In 1975 Bill Hinson and others made a breakthrough east of the Chamber of the Vanishing Floor to the Recovery Room and what is known as the New Section (Kunath 1978). The New Section extended the cave to the east. In 1976, Pete Lindsey produced a map showing approximately five kilometers of passages. Approximately 6.5 kilometers of passages had been surveyed by 1976. The exploration and survey of Dry Cave was done mainly by cavers from the Sandia Grotto in Albuquerque, New Mexico and the Dallas-Fort Worth Grotto in Texas (Kunath 1978, Lindsley 1978). From 1976-2004 there were no major discoveries, although some additional survey was done during this time period.

3. Geology

Dry Cave is located on an anticline and is formed in the lower Yates Formation and the upper Seven Rivers Formation. Both of these formations formed in backreef environments (Smith 1978). Dry Cave is a hypogenic, sulfuric acid cave with a network maze pattern (Palmer & Palmer 2000). Passages in Dry Cave are closely related to bedrock stratigraphy with passages following the dip along bedding planes. Dip of the bedrock ranges from 0-20 degrees but is typically 10 degrees (Lindsley 1978). The maximum extent of passage development along the dip is 200 m.

Six known tiers of passage are located within about 30 meters of bedrock making for an extremely complicated maze cave. In some areas tiers are separated by as little as one meter of bedrock. Overall cave depth is 85.3 meters which is relatively shallow for a significant cave in the Guadalupe Mountains. Passage sizes in Dry Cave tend to average 1-1.5 meters high. Passages tend to be much wider than they are tall with regularly-spaced bedrock columns 1-3 meters in diameter. Much crawling is required when exploring Dry Cave. The 20° c cave temperatures make exploring Dry Cave a hot and sweaty experience.

Most of the passages are dry and floored with gypsum related to its sulfuric acid speleogenesis. This gypsum averages 0.3-0.6 meters thick but can be as thick as 2.5 meters. In some places it is possible to observe bedding planes and other bedrock features continuing from bedrock into the adjacent gypsum, indicating direct gypsum replacement of the bedrock. The ubiquitous gypsum, multiple tiers and the vertical conduits that connect these tiers create a perfect environment for the formation of gypsum rims. Dry Cave has many well-developed gypsum rims ranging in diameter from a few centimeters to several meters that surround humanly traversable routes between tiers.

Although the cave is located in the Chihuahuan Desert and receives only an average of 30 centimeters of rain per year, some areas contain typical calcite formations such as flowstone, rimstone, stalactites, stalagmites, columns and popcorn. There are also a few small pools in the cave and some of the lower passages have small, seasonal streams of running water after monsoonal rain events. These intermittent streams transport surface sediments into the cave. These sediments often limit exploration in the down dip direction. In areas of the cave with older sediments and clays, a distinct petrochemical smell can be detected when these sediments are disturbed. Perhaps this is a clue to the cave's speleogenesis. Dry Cave contains interesting clay deposits related to hydrosulfuric acid speleogenesis including endellite and alunite (Polyak 2000). Alunite from nearby Endless Cave has been dated to 4 million years before present. This is presumed to be the date of speleogenesis for Dry Cave as well since both caves are located at 1280 m above sea level. (Polyak 1998).

4. Paleontology & Biology

Dry Cave is a significant Pleistocene fossil site. Most of the paleontology work done in the cave after R.M. "Bill" Burnet's work in the 1930's (Kunath 1978) was done by Dr. Arthur Harris in the 1960s-1970s (Harris, 1978). Large fauna found during this work include American lion, Dire Wolf, bison, sloth and camel. Dr. Harris found that there were two main fossil sites in Dry Cave. Fauna found near the current entrance date from the last 15,000 years. Fauna found near a series of former entrances that form a north/south line near the Chamber of the Vanishing Floor date from 25,000-33,000 years ago (Harris, 1978).

Over 24 species of vertebrates and invertebrates have been documented in Dry Cave although there has never been a thorough biological study of the cave (Elliot 1978). Prior to the installation of an entrance gate in 1970, an estimated 10,000 Mexican free-tailed bats inhabited the cave (Lindsley 1978). Large piles of guano in some areas are evidence of their past use of the cave. Western diamondback rattlesnakes are frequently found in the twilight zone of the cave making most visits to the cave even more exciting!

5. Methods

In 2004 Stan Allison and Aaron Stockton submitted a proposal to initiate a resurvey of Dry Cave to Jim Goodbar, BLM National Cave & Karst Program Manager. There were several reasons for completely resurveying Dry Cave. The original surveys were sketched at the survey standards of the 1960s and 1970s meaning that much detail and even some leads were not documented. Profile views were generally not drawn and many of the old survey stations were no longer recoverable. In addition the task of attempting to track down all of the old survey notes appeared daunting. Goodbar approved the proposal and led Stockton and Allison on the first project day in January 2005.

The project uses modern survey techniques including detailed, plan, profile and cross section sketches. Compass and clinometer foresights and backsights are used to improve the accuracy of the survey. Stations are marked in a manner that will allow the stations to be recoverable in the future. A station by station inventory of all of the features in the cave accompanies each survey trip in order to produce more information about the cave. Features inventoried include geology, mineralogy, meteorology, biology and cultural items. In addition, photographs are taken as the survey progresses in order to better photo-document the cave. All of the survey notes, trip reports, photographs and cave maps are stored in a digital format for ease of sharing between project members and for archival purposes.

One of the project goals is to maintain up-to-date digital cave maps. Up-to-date digital cave maps aid in further exploration, survey and research. Drafting a cave map as the survey progresses greatly increases the chance that a finished map will be produced. Drafting up-to-date digital maps creates a problem of maintaining the relationship between the lineplot produced by the survey data and the walls and floor detail of the map in a maze cave survey where new loop closures would constantly be shifting the lineplot away from the map. Three options exist: 1. Leave survey loops unclosed in data processing software so that the map will always relate to the data produced lineplot. 2. Close survey loops in data processing software and then modify the map artwork so that it matches changes in the data produced lineplot. 3. Utilize the roundtripping of Scalable Vector Graphic (SVG) WALLS software lineplots with Adobe Illustrator produced SVG maps. Option 3 is the best method of ensuring that the map artwork maintained its relationship to the survey data and was chosen for the Dry Cave Project.

Roundtripping SVG cave maps is a process created by David McKenzie in his WALLS cave survey data management program. This process solved the Dry Cave cartography problem of ongoing cave survey data diverging from the map. The idea of the process is that the cave map is dynamic and changes as the cave survey data changes. Map artwork shifts to adjust to the nearest survey station as those survey stations move due to loop closures and survey blunder corrections. The process involves first producing a SVG lineplot from WALLS. The cave map artwork is then drafted around this lineplot in Adobe Illustrator and saved as an SVG file. When new survey data is entered into WALLS, the software will adjust the new loops created and then will modify the map SVG file produced by Illustrator so that the map will match the new data. The process can be repeated over and over again as new survey data is entered and the map is updated. (McKenzie 2008) (Fig. 1)

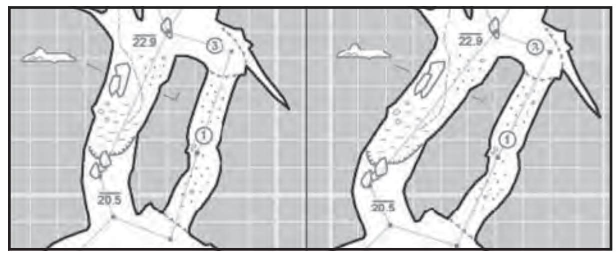

Figure 1: The above image shows the result of SVG roundtripping. The image on the left is the original map. The image on the right is the same map with the azimuth and length of one shot modified. Note how WALLS has modified the map to match the new loop closure and resulting shift in the lineplot.

Another cartography problem facing the project was how to draft a cave with 6 different stratigraphic tiers. Attempting to draw all of the tiers at once would quickly result in an incomprehensible mess. Once again the WALLS software enabled an elegant solution. The six different stratigraphic tiers in Dry Cave were quickly and easily divided up into separate cartographic levels using the Segment command in WALLS. This allows for each cartographic level to be drafted as a separate map in order to make a comprehensible map of the cave (Fig.2)

6. Results

In 2005 a thorough survey of an area within 50 m of the entrance located a blowing crawlway that was partially sediment filled. In January 2006 Aaron Stockton and Jennifer Foote dug open this 9 m long belly crawl and soon found themselves standing in the relative spaciousness of an unexplored room they called the Azotea Rotunda. Further exploration in this area led to McKittrick Avenue a 300 m long passage, 1-3 m tall and 2-10 m wide. Numerous leads off of McKittrick Avenue led to much passage including Endellite Blues, Changes and the Sock Monster Maze. The McKittrick Avenue Section is the farthest northwest section of Dry Cave and contains over 4.5 km of survey with many

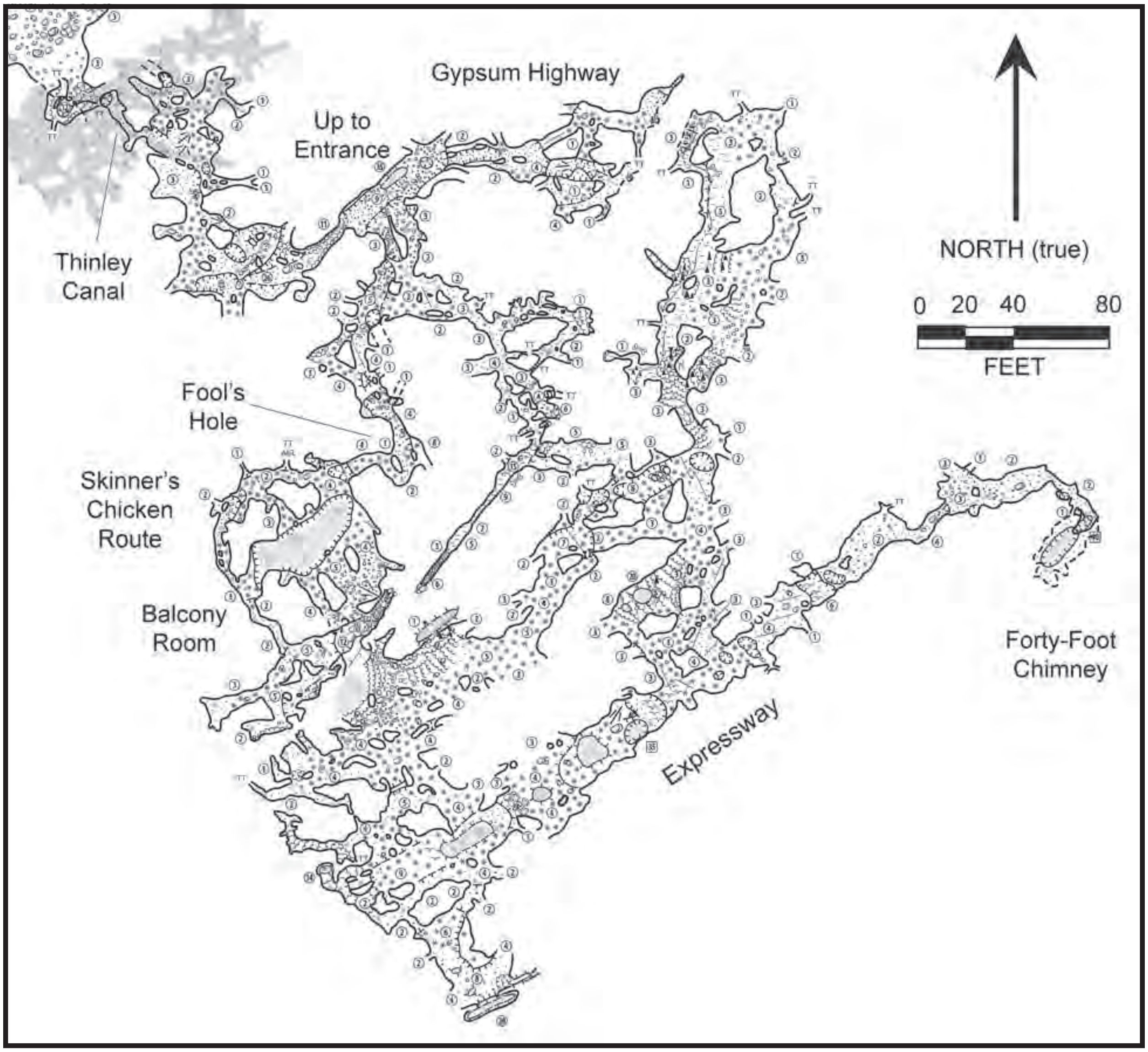

Figure 2: This is a small portion of one of the 6 cartographic level maps of Dry Cave. 14 kilometers of cave have been drafted to this level of detail.

more unexplored leads to survey.

Other previously unexplored areas were discovered and surveyed for an additional 1.2 km of survey. The most significant of these is an area called Dirty Deeds on the north side of the cave. Dirty Deeds was discovered by rappelling 6 m down the 27 m deep Whiz Pit and entering a hands-and-knees crawl. This crawl led to an area with close to 500 m of survey and leads remaining on the northeast edge of the cave.

The total survey length of Dry Cave is over 14 km with many more passages to survey. All of the survey stations have been inventoried and the six different cave level maps are up-to-date with over 14 km of survey drafted. Roundtripping the SVG cave maps with WALLS has worked extremely well. Numerous photographs have been taken of the cave and every survey station has been inventoried.

7. Conclusions

Exploration, survey and cartography of Dry Cave have revealed a fascinating pattern that is closely related to the structural and topographic high point that the cave partially encircles (Fig. 3). Passages to the north of this hill dip north; passages to the west of the hill dip west; passages to the south of the hill dip south and the easternmost passages dip east. Exploration of dip oriented passages in the up and down dip directions has been limited to a maximum of 200 m. Down dip passages often end in sediment plugs and up dip passages often become too tight. Exploration of passages

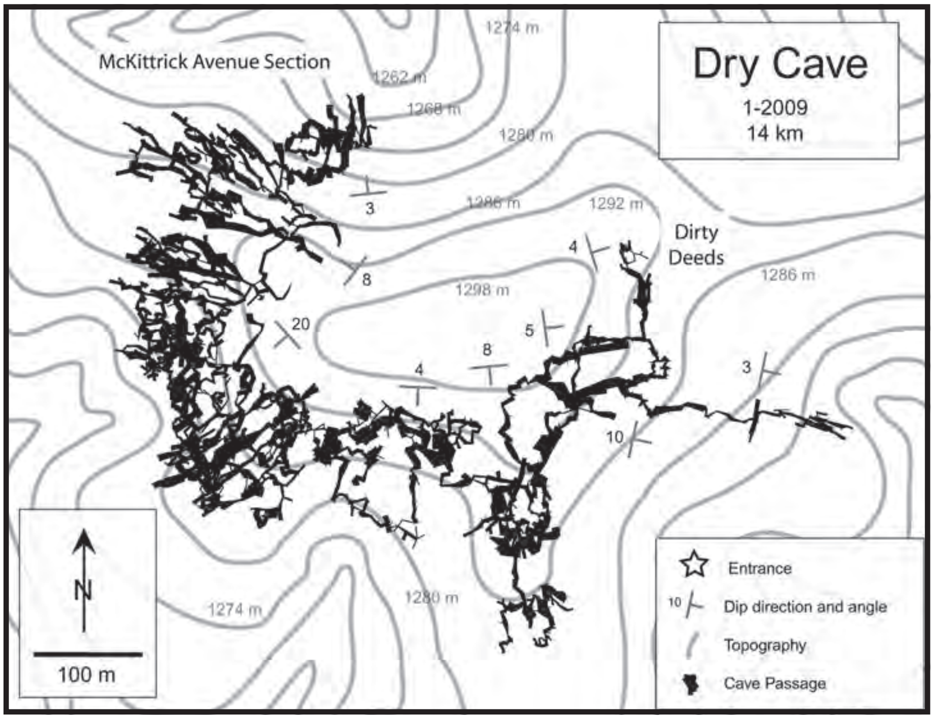

Figure 3: This map demonstrates the relationship between the bedrock dip of Dry Cave passages and the topographic and geologic high point that the cave is draped around. Note the recently discovered McKittrick Avenue Section and Dirty Deeds area.

and leads along the strike has repeatedly proven to be the way to find more passage. Currently known passage encircles 270 degrees of the high point that Dry Cave underlies. Exploration of the McKittrick Avenue Section from 2006-2009 has revealed the passages on the northwest flank of the high point and exploration in Dirty Deeds from 2008-2009 has revealed passages on the northeastern flank of the highpoint. The McKittrick Avenue Section and Dirty Deeds Section are only separated by 220 m and future exploration may reveal that the cave completely encircles the high point making a donut shaped network maze!

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TWO HUNDRED KILOMETERS IN LECHUGUILLA CAVE

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In 1986, a group of cavers dug into the only entrance of what has been called the "Jewel of the Underground," Lechuguilla Cave. Located in the backcountry of Carlsbad Caverns National Park in southeastern New Mexico, the cave has been a source of delight for explorers, and a source of amazing scientific discoveries. As exploration enters its 23rd year, speleothem discoveries that seemed unbelievable have been surpassed by even grander finds. The cave penetrates deep into the Permian Capitan reef, and exploration at the extreme ends is best done in multi-day explorations, using established camps in each branch. Exploration has involved cavers from all over the United States and from dozens of other countries. Management policies for the cave have evolved to ensure that delicate and unique areas are protected to the greatest extent possible, while continuing to support exploration, mapping and scientific goals.

Many of the original explorers have gone on to other projects, or retired from strenuous caving, but some of the "first generation" of cavers involved continue to work in the cave, mentoring younger cavers to continue to push in complex areas where new discoveries may reward their efforts. Many of the second and third generation of cavers are leading expeditions, and taking-on significant portions of the map, carefully checking for leads after studying the original survey notes. Climbs and tight crawls are physical obstacles that are often encountered, both having potential to lead to additional passage in this cave. Many were passed-over in the early years of exploration, when great boreholes and walking passages seemed endless.

Discoveries of significant new areas have continued in all three branches of the cave. Much work has been in the largest, the Western Branch. Zanzibar, Promised Land, and Zombie Zoo extended the westernmost edge of the cave. Work in the beautiful Mother Lode chamber has established several new connections back to known cave. The Hahd Coah maze was explored under Rock 'n' Rillen room at the top of Southern Climes. Closer to the Western Borehole, Frostworks, Weasels Ripped My Flesh and Friday Night Fever were found just off the main trail. Underneath the Borehole, extensive boneyard was explored beneath breakdown, in Paris, Texas. The Transuranic Way led to Nucular Winter. A long-sought connection was pushed from the Mirage room to Jackpot, through an airy route named Spaah Haabah. Crinoid Casino was then found under Jackpot. A short but obscure crawl not far from the borehole led to the large passages of Emerald City, with much green mineralization and a significant climb lead. In the Southern Branch, major climbs have led to Flatlands, connecting to the airy but scary Lechy's Lair attic. Other climbs led up Trepidation Dome in the ceiling of the vast Prickly Ice Cube Room. Work in the complex Chandelier Maze and the deep Voids maze continues to find passage. In the Eastern Branch, teams have focused on extending the Far East, using the most difficult-to-reach camp. Deep in the Outback they have found new areas such as Coral Sea, Wasp's Nest and, in 2008, the Nor'easter route, leading to another big climb. Last year the survey project exceeded 200 km of new passage in the cave, making Lechuguilla the world's fifth longest cave.

1. Introduction

In 1986, a group of cavers dug into the only entrance of what has been called the "Jewel of the Underground," Lechuguilla Cave. It was previously known as a small, vertical cave in the backcountry of Carlsbad Caverns National Park. Lechuguilla is now known as one of the world's most beautiful caves. It is also one of the more bizarre, formed hypogenically by sulfuric acid. The action of this acid on limestone creates gypsum as a byproduct. The cave displays some of the world's most spectacular gypsum speleothems, including its signature selenite chandeliers. It is a challenging cave to explore, continuing to yield new discoveries 23 years after its opening.

There are three generations of Lechuguilla explorers. The first generation got involved in the cave through the Lechuguilla Cave Project (LCP) in 1987-1991. A second generation of cavers started during the LEARN years, which gave more opportunities for cavers to work there. LEARN stood for Lechuguilla Exploration and Research Network, an organized democratic group of cavers who replaced LCP. LEARN operated in the cave from 1993 until 2004. The third generation consists of cavers that have gotten involved in the last several years through private expeditions after LEARN dissolved. Many of the original explorers have gone on to other projects, or retired from strenuous caving, but a few of the first generation cavers involved continue to work in the cave, mentoring younger cavers to continue to push in complex areas where new discoveries may reward their efforts. Many of the second and third generation of cavers are leading expeditions, and taking-on significant portions of the map, carefully checking for leads after studying the original notes. The authors are second (Lyles) and third (Armstrong)-generation Lech cavers.

Since 2005, all exploration in Lechuguilla has taken place on private expeditions. The trip leaders request permits by submitting detailed proposals to the Carlsbad Caverns National Park. All proposals to work within a calendar year are submitted at the end of the previous year. Significant research is involved in planning these expeditions as the Park expects a high level of detail in the proposals. Each year about 10 expeditions are awarded permits, with most of them involving a week of camping underground in one of four established camps to reduce impact. Camping in the cave allows for a favorable ratio of survey work versus travel time. Exploration has involved cavers from all over the United States and from many other countries.

2. Western Branch

The Western Branch of Lechuguilla is the most extensive of the three branches with nearly 80 kilometers of passage. The West is a place of contrasts. It is considered the easiest of the branches, and the most appropriate for first-time Lech cavers, because the Deep Seas camp is the closest of the 4 camps to the entrance (4-5 hours). Ironically, this makes for very long survey days away from camp in order to reach the outlying areas. Daily survey trips can involve many kms of travel and last upwards of 18 hours. Just beyond camp is the beginning of the Western Borehole. It is the longest continuous passage in the cave, stretching linearly nearly three kilometers. Most days away from camp involve long hikes in the Borehole to reach the turnoffs to survey areas. Teams often feel like they are "out of the cave" once the survey day is over and they are hiking the Borehole back to camp. There are several short nuisance ropes that must be climbed on this route.

Near the western end of the Borehole is Keel Hall. Crawling through a nearly forgotten tight lead during a 1999 LEARN expedition led John Lyles's team into Northern Exposure. The route eventually reached the large chambers, Birthday Present and Zanzibar, featuring massive dogtooth spar and a forest of aragonite trees. Nearly a km of new passage was surveyed and an enticing airy lead entered the flowstone-floored Nativity Chamber. It remained unexplored at the time, because of the extremely fragile and decorated nature. Through three expeditions cavers sought an alternate route to reach the expected passage beyond this chamber. After finding no easier way, the park allowed a small team led by Art Fortini to continue across it in 2003. They surveyed 0.8 km of new passage in Promised Land, continuing west beyond the known boundary of the cave, crossing from decorated fragile passage to dirty walking passage again. This was the beginning of a new trend in caving in Lechuguilla, to switch from dirty to clean clothing and gear, and back again in order to preserve clean areas. It required considerable planning and stamina from the cavers, and would be repeated in future discoveries in the cave. A subsequent expedition in 2004 led by Fortini and Ron Miller completed exploring and surveying passages beyond Nativity Chamber, through Eden and finally to the terminus in the 150 meter long Congo. Later in 2004, Lyles' team pushed another tight squeeze in Zanzibar to open Zombie Zoo, and the sharp low crawl into ihop (International House of Pain). This pushed the western edge beyond Rainbow Room, the old limit past Keel Hall, but not as far west as the Congo had already penetrated. These two areas have remained the western limit of cave exploration since 2004.

Figure 1: Decorated passage in the Promised Land.

During a 2002 LEARN expedition, cavers pushed under the borehole below breakdown, eventually reaching boneyard and "breakyard" passage about 25 m below the trail. The team named this extensive network of passages Paris Texas in deference to French and Texan cavers involved and a strange film of the same name. Explored over the next three years of expeditions, Paris Texas eventually formed a bypass route under the Borehole that reemerged beyond the closed Haupache Highway camp. In 2003, a passage called the Transuranic Way, named for its radioactive Tyuyamunite mineralization, led to a medium-sized room named "Nucular" Winter. Comprising more than 2 km, Paris Texas still has additional leads that could be pushed, but requires considerable crawling.

Southwinds, discovered in 1994, is an extensive area south of the Borehole from the Leaning Tower of Lechuguilla. Efforts since 2003 have focused on the Mother Lode area, discovered in the mid 1990s. Developed high in the backreef, Mother Lode is 60 meters high and over 60 meters in diameter, floored with multicolored dripstone speleothems with stalagmites over 10 meters tall. The soft, silty walls of Mother Lode rise out of reach of headlamp beams toward possible climbing leads at the top. An examination of this area has led to some additional footage in nearby Zonker Maze, and the designation of 10 leads in Mother Lode itself. One of these leads named Another Lode drops 50 meters in a parallel fissure along the wall to a connection with Wild Wild West. In 2008, a Peter Bosted/John Lyles expedition team descended a dirty tight fissure to find walking passage ahead, probably another connection to old surveys near Wild Wild West, but unproven at this date as the sketcher was unable to fit through the constriction.

Southern Climes is another section of Southwinds reached by a 100 meter rebelayed rope climb. At the top of the rope, the Trade Winds Maze leads upward to the Rock'n' Rillen Room. Teams in 2004 discovered a boneyard maze just underneath the room named Hahd Coah. Featuring gypsum snow and aragonite, hopes were high for Hahd Coah that it might open into a blank area to the east of Southern Climes. It unfortunately refused to break out from underneath Rock 'n' Rillen, instead circling around in loops resembling a bowl of spaghetti. The next three years saw more than 400 meters documented in the Hahd Coah Maze but few leads remain.

North of the Learning Tower is the Jackpot – discovered early during the exploration of the cave. Most work stopped in this area after 1998, following the discovery and exploration of Sanctuary to the northwest of it, by first and second generation cavers with LEARN. Further along the Western Borehole before Keel Hall, cavers discovered another large room in the early years. They named it Mirage, and over the years it was largely ignored. In 1995, cavers managed to follow a tight fissure along one wall beyond the Mirage chamber, to a series of tight but airy spar-lined crawls in boneyard. Nothing seemed to go, so the lead was abandoned, as only small cavers could reach it. In 2005 and 2006, expeditions led by Bosted and Lyles sent teams back to this area, to continue pushing. They had success in 2006, when a team continued through the tight spar and followed airflow, to find the passage character changing to breakdown with aragonite bushes and frostwork. Following air, the eventually emerged at the bottom of Jackpot. The connection route was named Spaah Haabah (playing on the name of Bar Harbor, Maine) and contains over 300 meters of new passage, leaving more leads.

Also underneath Jackpot is the Crinoid Casino, discovered by accident in 2007. A team of third generation cavers found a 1997 tape marking a lead there that declared that it had been "checked 75' (23m) – ends in breakdown, no leads". They began to survey the scooped passage and accidentally dropped their laser distance meter down into the rocks. The search for the instrument was successful, and because the team had to squeeze through small holes to get it, they discovered rooms and more passages underneath the breakdown. The Crinoid Casion was full of fossils and much more extensive than 23 meters. So far, this breakyard has kept two expeditions busy. It displays excellent examples of Permian crinoid, cystoid, and sponge fossils. Cavers have discovered more than 500 meters of mostly boneyard maze there so far.

In 2007, another Peter Bosted/John Lyles expedition began a thorough sweep of an area east of Jackpot that explorers had largely ignored since the early years of discovery in the cave. A vein of green crystalline minerals on gypsum was found near the Spinning Room, in an airy corner not far from extensive gypsum beards. As they were photo-documenting Emerald Aisle, one caver crawled through a constriction into blackness. Beyond the tight spot, the cave opened up into a large trunk passage and the team discovered Emerald City. In addition to fantastic gypsum beards and needles, the green band of minerals continued through this area. Emerald City filled in a blank region of the map between Hudson Bay, the Northwest Passage, Jackpot and the Western Borehole. Several climbs in 2008 added a small amount of new passage to the area. However, an enticing lead remains at the terminus of Emerald City, up a 65m dome that will be the subject of an upcoming climbing expedition.

Figure 2: Large passage in Emerald City area.

3. Southwestern Branch

Cavers sometimes jokingly call the Southern or Southwest Branch of Lechuguilla the "Hollywood" branch, due to it being featured in several films, including National Geographic's *Mysteries Underground,* NOVA's *The Mysterious Life of Caves,* and most recently the BBC's *Planet Earth Series, Caves* episode. The Southwest Branch owes its stardom to its spectacular scenery. This branch is home to some of Lechuguilla's most notable places including Chandelier Ballroom, Underground Atlanta, Tower Place, Prickly Ice Cube Room, Vesuvius, Hoodoo Hall, and the LeBarge Borehole. The speleothems found here have made Lechuguilla world-famous, even among non-cavers.

Pushed in the early days, many Lech cavers had written off the Southwest as finished. Over the past four years, diligent Southwest expeditions have added nearly 3 kilometers to the cave's length – much of which was due to the efforts of technical climbers. Climbing has led to many discoveries in Lechuguilla, including the Far East (Aragonitemare ascent). The last few years have seen a revival of this effort by third generation climber/cavers. In 2006, climbers on an expedition led by Patrick Cicero began the ascent of Trepidation Dome in the ceiling of Prickly Ice Cube Room. Positioned directly over the main trail, this dome had enticed cavers with its shadowy heights. They reached the ceiling of the dome at the culmination of a two-expedition effort. There were no leads at the top, but at least the team got to enjoy the 50-meter rappel back to the trail and being able to cross another question mark off the list. Also in 2006, cavers climbed another more obscure dome at the end of Fluted Hall. It was marked as a climbing lead in 1988, and then it lay dormant for 18 years. Andy Armstrong organized an expedition to climb it. Leading upwards for 60 meters, Anvil Cloud Dome was the key to the discovery of 800 meters of cave called Flatlands. Most of Flatlands is remarkably flat, with survey inclinations near zero degrees. It features bat skeletons, large crinoid fossils, water-washed silt deposits and severely corroded bedrock. On a subsequent expedition led by Armstrong, cavers connected Flatlands and Lechy's Lair. The new route forms a very long loop that crosses over the top of the Prickly Ice Cube Room, with several exposed holes looking 20-30 m downward. Work continues in the Southwest branch, especially in the Chandelier Maze.

Figure 3: Trepidation Dome.

4. Eastern Branch

The eastern part of Lechuguilla is divided into two distinct passage blocks: the Near and Far East. In recent years, teams led by Mark Andrich, Doug Warner, Peter Jones, and Dan Legnini have done new exploration in the Near East, but the bulk of newly discovered passage has been found in the Far East. The Far East is the most remote area of Lechuguilla Cave, and requires the most technical rope work of any branch. It takes a swift team about eight hours to reach the Grand Guadalupe Camp there, with around 30 ropes to negotiate along the route. The route goes down to -275 meters and then rises back to -200 meters at the camp level. Stratified into two layers, the Far East has a tiered appearance when viewed in profile. Camp is on the top level. Connecting this to the lower Outback level is the Gorilla Pit, (also known by other names that cannot be printed here). Most survey days in the Far East involve a rappel down the dirty Gorilla Pit and travel through the Outback, a barren area of large tilted and fractured passages. In the last four years, leads in the Outback have yielded three breakthroughs. Two of these are major in scope, while one is interesting for its bizarre speleothems.

The first major breakthrough was the discovery of Coral Sea in 2005 on an expedition led by Ron Miller and Steve Maynard. A lead near the Purple People Eater revealed an area of popcorn and wet flowstone rooms and passages, very uncharacteristic of the bleak Outback. There are large diameter coralloid formations and multicolored flowstones in shades of purple, brown and orange. The area contains many cave pearls and pools, and is often extremely delicate, requiring multiple clothes changes. Having pioneered such techniques in the Promised Land, Miller's team has mounted numerous expeditions to continue pushing the many leads found. In 2007 a large new extension was added, named Wasp Nest, due to extreme acid-eaten rillenkarren everywhere, that resembled the inside of an insect's nest.

Nearly 450 m below the entrance, near the deepest point, cavers led by John Lyles made a remarkable discovery in 2005. In an area called El Malpais, named for its resemblance to sharp, angular volcanic fields in New Mexico, they continued downward into highly-corroded fissures. The cavers discovered rusticles coated with folia, a previously unknown combination. The fissure named Rust Never Sleeps then led upwards and as it did, the folia coating faded away. This exposed rusticles in different shades of orange and brown. The most fascinating one is the Rusty Wire, a meter long strand that branches with interconnected loops. It is speculated that these may be of microbial origin, but further study is needed.

January 2008 saw another exciting breakthrough with the discovery of 900 meters of large passage named the Northeast Corridor. A diligent team led by John Lyles pushed through tight, grabby belly crawls to a small room, ZZ Bottom, with a 50 degree inclined fissure in the ceiling. Named Mt. Vernon, this low airy crawl goes upward for 20m to reach La Grange Hall. Popcorn and frostwork along with scoured ceilings indicated that this was a major airflow route. The Nor'easter takes off from here with a large, ascending tube leading northeast. A colorful silt dike in the ceiling guided the surveyors up this passage northward off the known map. Spectacular gypsum flowers grow from the floor and walls. After the

Figure 4: Rusty Wire in El Malpais.

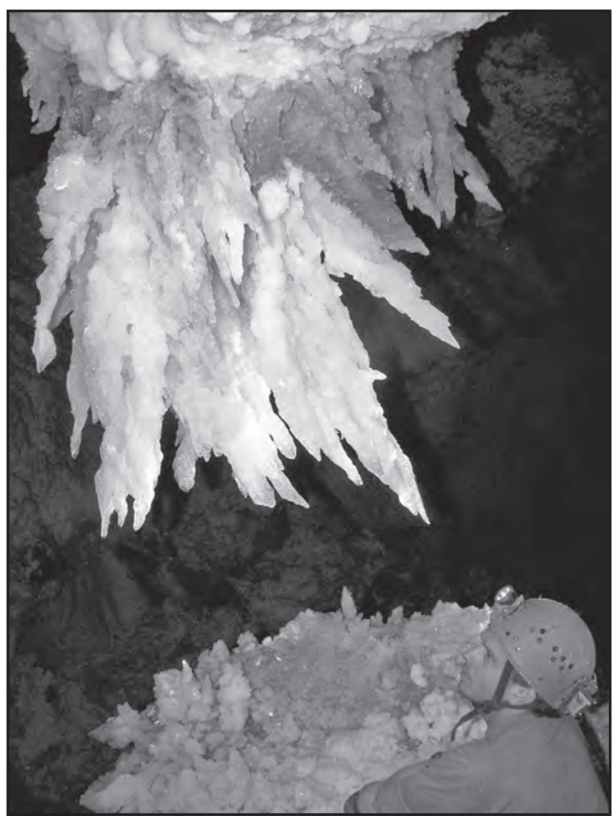

Figure 5: Gypsum chandelier in Northern Lights.

team had surveyed about 250 meters of easy cave, the walls and ceiling receded further and the passage became 15m in diameter. Soon the floors were covered in long, ropelike flowers and chandeliers hung from the walls and ceilings, the first chandeliers of this magnitude discovered in the Far East. This large passage named Northern Lights includes at least 20 clear and ocher chandeliers, masses of angel hair, and large needles. A short lead climb up a gypsum-crusted spongework wall led the cavers to the base of Mt. Washington, a large dome room. Mt. Washington is 35 m in diameter and over 50m tall with a taunting lead in the ceiling. Reaching this high lead will require another major climbing effort. The Northeast Corridor projects northward into blank territory, heading towards an area of the Guadalupe Anticline with no known cave passage. Air flow here at the end of the cave may suggest that there are many more miles of cave ahead.

5. Resurveys

In all three branches of the cave, dedicated teams have resurveyed, located/repaired blunders, and resketched passages with a better scale than when they were rushed through in the early years. Notable are the talented teams on expeditions led by Pat Kambesis, Joel Despain, Vivian Loftin, Hazel Barton, Mark Andrich, Andrea Croskrey and Johanna Kovarik.

6. Conclusion

Twenty-three years after its discovery, Lechuguilla continues to reward three generations of explorers who are willing to research leads, search diligently, and push the endurance barrier. Cavers find an average of 3-4 new kilometers per year. For every team that explores the frontier, there are others checking and repairing blunders and re-sketching complex areas with higher survey standards than two decades ago. New techniques are being implemented, such as multiple clothes changes, ultra-light camping, use of PDAs and ultra small PCs in-cave, along with laser rangefinders. These efforts by dedicated volunteers continue to contribute the understanding of this complicated and exceptional cave (Fig. 6).

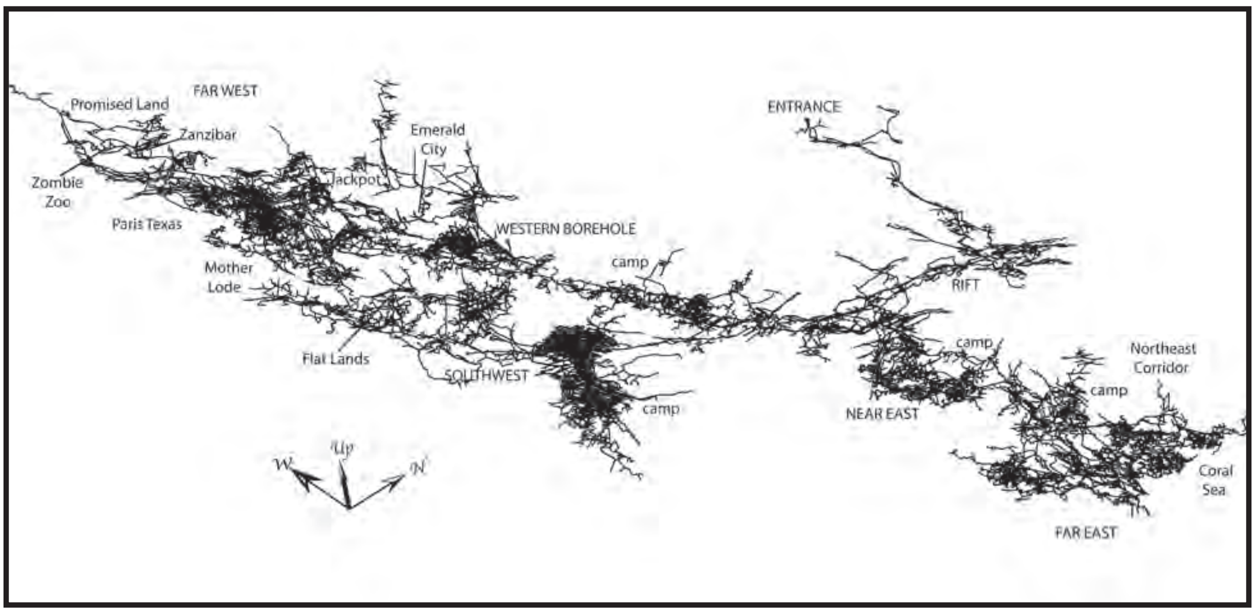

Figure 6: Map of Lechuguilla Cave.

RESURVEY OF SITTING BULL CRYSTAL CAVERNS, SOUTH DAKOTA, USA

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Sitting Bull Crystal Caverns is a geologically interesting cave on the eastern flank of the Black Hills in western South Dakota. Shown as a tour cave since 1934, Sitting Bull has delighted thousands of visitors with its extremely large dogtooth spar crystals. The cave had not been mapped since an effort in the 1970s by the Paha Sapa Grotto. While the 1976 map was found to be mostly accurate, it did not show much detail. In 2005 an effort was begun to resurvey and map the cave at a higher level of internal detail. The project was born of three interests, the desire of the owner to have a more detailed map for display, a desire to teach cave surveying to grotto members and other local cave enthusiasts, and the desire of the author to see and explore more of this fascinating cave.

Formed in the bottom of Rockerville Gulch in the Madison Limestone, Sitting Bull serves as a catchment for major floods. The flood of 1972 that killed over 200 people in nearby Rapid City had major effects on the cave. Virtually the entire cave was flooded to the ceiling, the wooden tour structures were destroyed, new areas opened up, and old areas were filled. The lower levels of the cave received a fresh blanket of sand derived from the crystalline core of the Black Hills. This sand is granitic in nature, sparkles with mica, and provides a pleasant, glittering floor surface for the many long crawls that make up the cave. Many “artifacts” of the flood were found in remote areas of the cave during the resurvey.

The resurvey project has resulted in a more modern, detailed map of the cave that is useful to cavers, tourists, and cave managers. Two smaller caves on the property; Two Bear and Packrat Caves, were also remapped. The project provided a first surveying experience for many new cavers and documented new digging leads, including an exciting one that blows barometric air.

1. Introduction

Situated in Rockerville Gulch on the eastern flank of the Black Hills, South Dakota, Sitting Bull Crystal Caverns is operated commercially as a tour cave. Like most other caves in the Hills, it is developed in the upper Madison (locally called Pahasapa) Limestone of Mississippian age. Unlike the other caves in the Hills, which contain small spar crystals, very large dogtooth spar decorates the ceilings and walls of Sitting Bull. There are three caves on the property: Sitting Bull, Packrat, and Two Bear. Two Bear is underneath the same drip line as Sitting Bull, so it could be considered an upper level side passage of Sitting Bull instead of a separate cave.

The Duhamel family, owners of the property, began exploring the cave in 1929. Named for Lakota chief Sitting Bull, the cave has been open for tours since 1934. The Duhamels and family friend Black Elk, the well-known Lakota medicine man, organized the Sioux Indian Pageant on the property to promote the cave. It was Black Elk who suggested naming the cave after his friend Sitting Bull, who is said to have camped at the entrance of the cave in the late 1800s.

In 1972, an epic flood event hit the eastern Black Hills. In 6 hours, 380 mm of rain fell. In nearby Rapid City, a dam broke, sending a wall of water crashing through town. Two hundred thirty-eight people lost their lives in the flood. Just to the south, Sitting Bull Crystal Caverns did not escape the event. Residing in the bottom of normally dry Rockerville Gulch, the cave took massive amounts of water. The flood destroyed the wooden tour structures and carried them off to distant reaches of the cave. The cave floor received a fresh blanket of mica-rich sand derived from the granitic core of the Black Hills. After the flood, the Duhamels rebuilt the tour with metal stairways and trails and the cave reopened to the public.

The cave offers visitors a 30-meter descent on steep stairways down to the main, horizontal level of cave. From there, the tour winds through chambers decorated with progressively larger spar crystal on the ceiling. Many visitors and locals agree that Sitting Bull is the most unique of the many commercial show caves in the Black Hills. The author knows of no other cave quite like it.

2. Project Beginnings

In June 2005, five cavers visited Sitting Bull Crystal Caverns for a tour. While waiting for the tour to begin, they hiked up Rockerville Gulch and came across the entrance to another cave. Wondering about this hole in the ground, the cavers approached Peter Heffron, owner and manager of Sitting Bull. He told them that the cave was called Packrat after its best-known inhabitant. One of the cavers, the author, asked Peter about surveying Packrat Cave. Armstrong had been looking for a survey project in order to hone his sketching and cartography skills. He suggested that once Packrat was finished, if Peter was happy with the map, that maybe they could remap the Caverns for him. Peter looked skeptical and replied, "How much is all this going to cost me?" Once assured that the work would be done on a volunteer basis, Peter gave his support to the project. In fact, for some time he had wanted a new, more detailed map of the cave to show to his visitors.

The Paha Sapa Grotto of the National Speleological Society surveyed the cave in 1976, and created a viable map. However, as is historically typical of Black Hills cave cartography, the cavers sketched very little detail. Therefore, their map shows an outline of the walls with no floor detail and no vertical control. The map is drawn at a small scale and the copy that Heffron had was hard to read. Armstrong decided to do a complete resurvey of the cave to Carlsbad Caverns survey standards. He was familiar with these due to his volunteer caving at the park. The Carlsbad standards require a high standard of detail. They include profile and cross-section views, back sights that must agree within two degrees, and an emphasis on floor detail. However, before the Sitting Bull survey could begin, the team needed to produce a map of Packrat Cave.

Andy and Bonny Armstrong, and Kelly Brownson surveyed Packrat Cave over two trips (Fig. 1, 2). They were able to view the cave's namesake in his nest. Packrat is very similar to Two Bear Cave and the upper level of Sitting Bull. Massive spar that displays a black layer of manganese covers the walls. There are also large chert nodules in the walls covered by crystal. On the second survey trip, the cavers made it to the back of the cave, near the Buddha Room before they realized they had left the survey tape at home. Wanting to continue with the survey the cavers improvised. The author removed the yellow webbing from his new Swaygo Pack. Using the sketchbook ruler and a sharpie, the cavers converted the pack strap into a seven-foot survey tape. Impressed with their own resourcefulness, they mapped the remaining 20m of Packrat Cave. Because of this incident, the cavers sometimes referred to Packrat as Packstrap Cave.

Figure 1: Surveying in Packrat Cave.

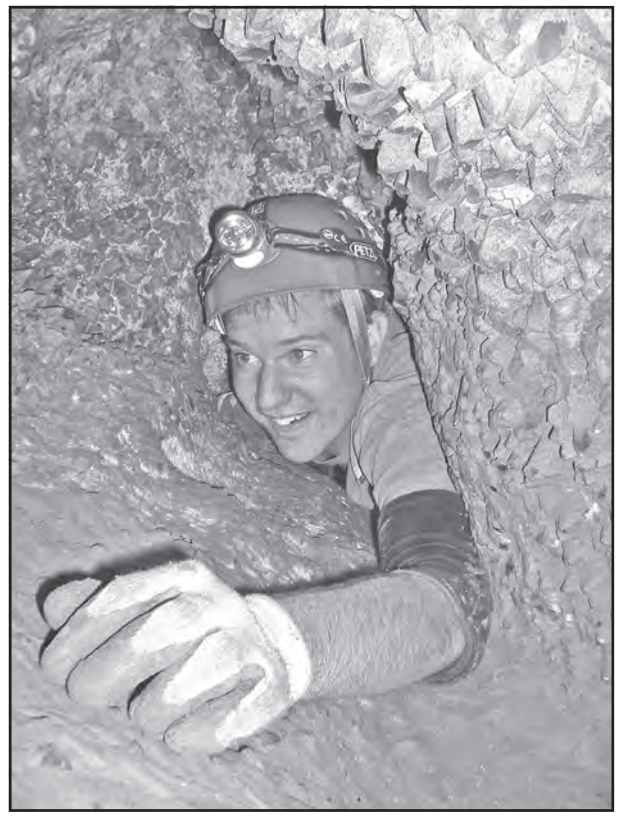

Figure 2: Negotiating a tight spot in Packrat Cave.

3. Surveying the Cavern

When the cavers showed Peter Heffron the map of 81 m long Packrat Cave, he was pleased with its quality and gave his full support for a resurvey of Sitting Bull Crystal Caverns.

Armstrong saw the project as a chance to involve newer cavers and get them involved with cave survey. It would be a chance to see parts of an amazing cave that few get to see. In addition, the surveyors could work at night, after the tours closed for the day. This allowed cavers to be involved that normally worked weekends, excluded from weekend-only survey efforts like those at nearby Wind Cave. Most survey trips into the Cavern lasted about 4-5 hours. This was about as long as anyone wanted to survey in there as the temperature is about 7 degrees Celsius. When coupled with damp mud and persistent airflow, it made for some chilly survey trips. It became customary to meet at the cave at about 6 pm and work until 10 or 11. The trips into Sitting Bull were great fun and were way better than sitting in front of a television for the evening (Fig. 3).

Figure 3: Entrance to Sitting Bull (left behind door) and Two Bear Cave.

First, the cavers surveyed the tour route as the A survey. While it was nice to stay clean, the tour was a challenge to survey accurately. Surrounded by metal tour structures, a myriad of wiring, and steel roof supports, it was very difficult to get backsight agreement. Some creative measures were taken in order to survey this magnetic wonderland (Fig. 4, 5).

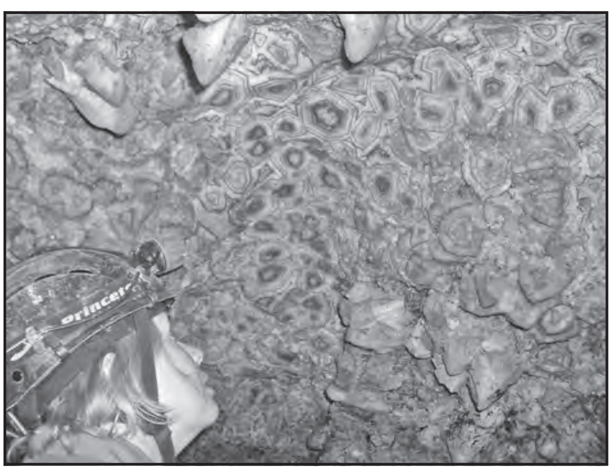

Figure 4: The Byzantine Attic.

Figure 5: Wild Patterns in spar, upper Sitting Bull.

Beyond the Flood Room at the end of the tour, the cavers continued the survey through sandy crawls. The dogtooth spar formed a thick coating on the ceilings while the floor was soft, sparkling mica sand. The A survey is the lowest "downstream" end of the cave and seems to take a majority of the floodwater. In several places, the survey teams noticed stratified sand deposits, suggesting a pattern of flooding. Considered a 500-year flood event, the 1972 flood was just one in a long history. Survey teams found fragments of the old wooden tour structures throughout the cave where the pressurized floodwaters had transported them.

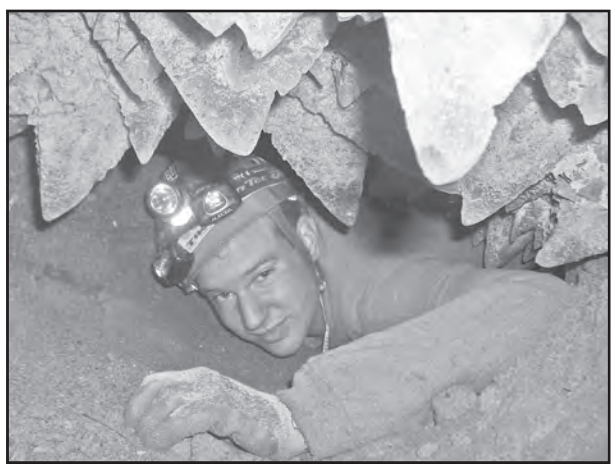

Figure 6: Crawling under spar in Guides' Discovery.

In 2004, guides at Sitting Bull opened up a room at the A survey end of the cave by digging out a plug of sand. This Guides' Discovery contains some of the largest spar in the entire cave (Fig. 6). It is quite an experience to crawl in a passage 0.5 meters high with 40cm long scalenohedral daggers hanging over your head! In the ceiling of Guides' Discovery, there is a ceiling channel containing boxwork

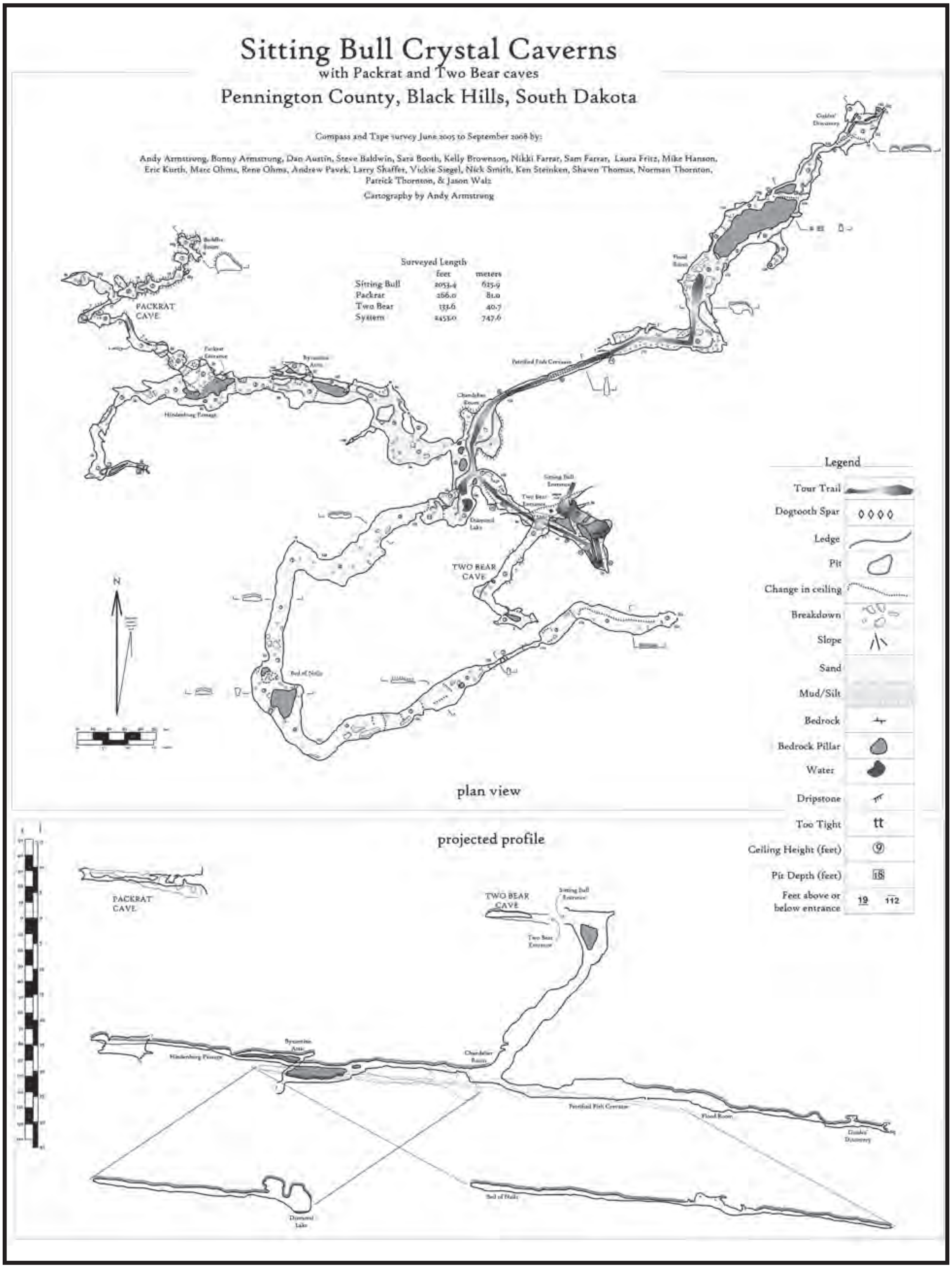

Figure 7: Map of Sitting Bull Crystal Caverns.

where the cave goes into more of a vertical cross-section as it does in several places including the Petrified Fish Crevasse on the tour. The continuation of this fissure at the eastern end of the room is the best lead in the cave.

Throughout the resurvey, Sitting Bull exhibited strong airflow that is believed to be barometric. Many involved with the project were Jewel Cave National Monument employees. Taking note of Jewel's famous airflow before they left work to drive over, these cavers observed that Sitting Bull always seemed to be blowing in the same direction. The fissure at the end of Guides' Discovery has the strongest air of any lead in the cave. One night when a dig team worked on it, it was almost unbearable to sit and wait for a turn at the face because of the cold wind. Digging further in the fissure will likely require chemical persuasion, but there is also a chance that the sand dig below it might reach the same area. The strong wind here hints at many kilometers of cave, most likely filled with fantastic crystals.

The Hindenburg Passage that heads west from the Chandelier Room also contains good leads and interesting geology. This passage is the muddiest of the three, although it does dry up in certain times of the year. The upper area named Byzantine Attic displays beautiful eroded crystal. The patterns it makes reminded the 1976 explorers of the domes of a Byzantine cathedral. The Hindenburg passage is noteworthy in that it contains numerous soda straws growing off the tips of spar crystal on the ceiling. Presently the B survey ends at a tight fissure pit that may be downclimbable by a caver of minute stature.

The C survey is the southernmost of the three passages and the only one that is under the same side of Rockerville Gulch that the entrance is in. Marc and Rene Ohms led the trips that surveyed this area. The passage takes off from Diamond Lake as a muddy crouchway that quickly becomes a sandy crawl. An area where the spar uncharacteristically covers the floor as well as the ceiling gives this passage its name, the Bed of Nails. After this, the crawl again becomes sandy and leads to another fissure, parallel to the others that contain boxwork and silt deposits. In all, the Bed of Nails passage crawls 120 meters to a sand dig, where surveyors noted no airflow.

4. Conclusion

This project lasted three years, partly due to the procrastination and propensity for distraction of the author. The project hastily wrapped up with two final trips in September 2008, when the author learned he was moving out of state. The length of Sitting Bull stands at 626 meters, 667 if Two Bear is included, and 747 meters for the system including Packrat Cave (Fig. 7). However, leads remain in the Cavern. Most are digs, but the one in Guides' Discovery is promising and very intriguing with its barometric air. Hopefully this survey effort will be a step towards greater discoveries. All that water had to go somewhere, and it is the author's belief that the known cave is only the tip of the iceberg.

Acknowledgements

The author would sincerely like to thank Peter Heffron and the staff of Sitting Bull Crystal Caverns for their support, encouragement and trust. Thanks as well to everyone who contributed to the survey. Support and data will be provided to anyone that wants to continue the project in the future.

THE GRAND COYER KARST, EXPLORATION AT THE COULOMP SPRING (ALPES-DE-HAUTE-PROVENCE, FRANCE)

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The Coulomp Spring (elevation 1306 m) is the largest of the Var River watershed (Q ≈ 1 m^3/s). The catchment of the Coulomp Spring is about 30 km^2. It culminates at the Grand Coyer (elevation 2693 m), which is located east to Annot City, between the Var and Verdon rivers. Almost no cave is known in the catchment, excepting the Lignin lake sinkholes. The grotte des Chamois is an ancient outflow of the Coulomp Spring. The pumping of sumps allows us to enter into the cave system, which is made of several levels of large galleries (20 x 30 m at the maximum), with a strong air flow. Currently the cave is 3 km long.

Résumé

LE KARST DU GRAND COYER, EXPLORATIONS À LA SOURCE DU COULOMP (ALPES-DE-HAUTE-PROVENCE, FRANCE). La source du Coulomp (alt. 1306 m) est la plus importante du bassin du Var (Q ≈ 1m^3/s). Elle draine un bassin d'environ 30 km^2, culminant au Grand Coyer (alt. 2693 m), situé dans le secteur d'Annot, entre Var et Verdon. Hormis les pertes des lacs de Lignin, qui alimentent probablement la source, la surface est pratiquement exempte de cavité. Le pompage de siphons dans la grotte des Chamois, ancien exutoire de la source du Coulomp, a donné accès au réseau organisé en plusieurs étages de galeries de grandes dimensions (max. 20 x 30 m), avec un fort courant d'air. Le développement est actuellement de 3 km.

1. Location and Access

Castellet-lès-Sausses, Alpes-de-Haute-Provence, France

Chamois Cave (Lambert II, after Créac'h 1987): X = 949.35 – Y = 203.87 – Z = 1370

Coulomp Spring: X = 949.85 – Y = 203.995 – Z = 1306

The Grand Coyer (2693 m) massif locates in the French Southern Alps, about 100 km northward to the French Riviera and to Nice, between the Verdon River to the North and the Var River to the South (Fig. 1). The Coulomp River is a Var tributary. Its spring locates at 1306 m elevation, in a middle of a wild area, with no roads and no inhabitants. Only the Aurent hamlet is occupied in summer for vacations. Wild fauna is often encountered, such as foxes, chamois, ibex, bighorn sheep, eagles, vultures, and sometimes wolves. A 40 minute walk leads to the Aurent hamlet, which has no road access (Fig. 2). Then 1.5 hour more walk is required to reach the spring, either following the river in summertime, or by a dizzy track along steep badlands. A 60 m high scenic waterfall indicates the position of the spring (Fig. 3). The cave opens 64 m above the spring, 15 m above the foot of the cliff, as a 4 m wide portal.

2. Previous Explorations at the Chamois Cave

- First mentioned by Martel [1921 p. 576, 586; 1928 p. 73], who visited the cave in October 1908 and June 1909 (Fig. 3) [comm. D. André].
- Bertrand [1914], in June and September 1913, carried out a study of the spring and its catchment for the water supply of Nice city. Capturing the spring has begun, but was definitely stopped because of the declaration of the First World War.
- **1971-74**: The Caving-Club of Nice (R. Bergamo) makes a survey up to the first sump. They open the

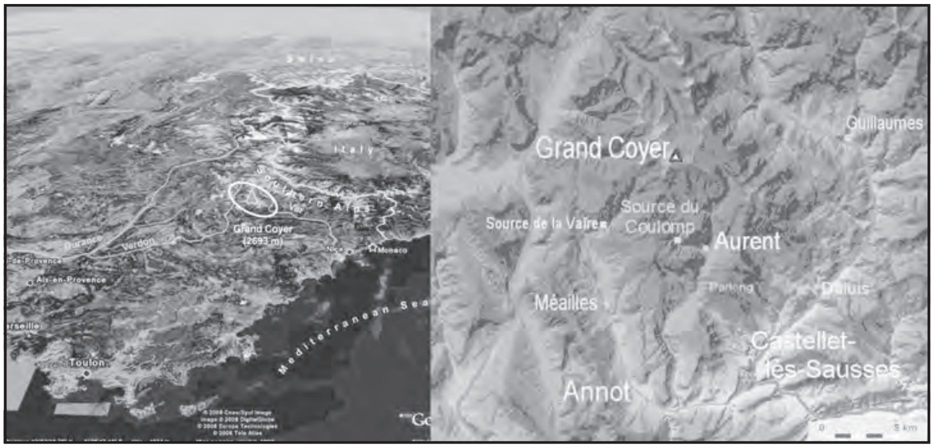

Figure 1: The Grand Coyer (2693 m) massif locates in the French Southern Alps, about 100 km north to Nice. The catchment area of the Coulomp spring extends up to the Grand Coyer. The Chamois Cave locates just above the spring. 3h walk in the mountain is required from the last road to reach the cave.

Figure 2: View toward Aurent hamlet and Beaussebérard. Following the Coulomp in high water (4 m3/s). The dizzy track to the spring.

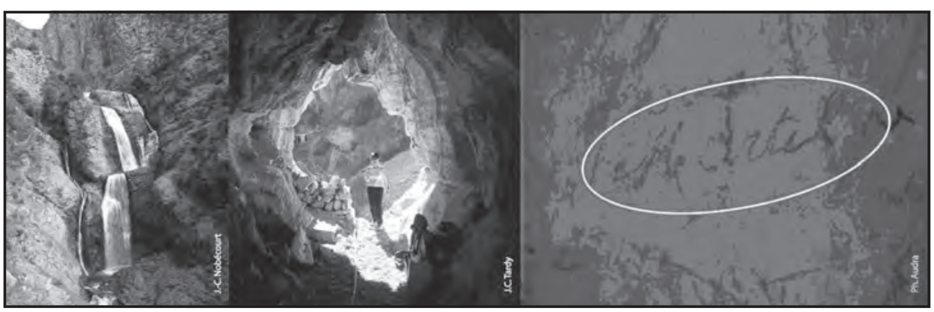

Figure 3: The 60m-high waterfall originates from the Coulomp Spring. Chamois entrance. É.A. Martel signature in the Chamois cave entrance.

squeeze to the window [Barbier 1978].

- **July 1982**: Ch. Peyre (Club Martel of Nice) crosses the 3rd sump and explores upstream up to a squeeze. A survey is done.

3. Hydrogeological Setting

The Coulomp springs locates at 1306 m elevation (Fig. 4). It is probably the largest karst emergence of the Var catchment. Its mean discharge ranges about 1 m^3/s, with low water at 400 L/s, and high water above 12 m^3/s. Its watershed is about 30-35 km^2; it encompasses the Valette and Pasqueires valleys, up to the summit of the Grand Coyer. The Lignin high basin, where lakes are drained by impenetrable sinkholes, probably also belongs to the watershed. This last area belongs to the topographic watershed of the Verdon River, which locates northward.

The aquifer mainly develops in the Cretaceous limestones, which pass upward to marly limestones. Thereafter, the Cretaceous series is covered in unconformity with the Nummulitic trilogy, made of a thin layer of limestone, then of Priabonian marls, and then of Annot sandstone. This famous formation constitutes most of the pyramidal summits. Nummulitic and Cretaceous limestone only outcrop along valleys cliffs (Fig. 2). Consequently, most of the catchment is covered with impervious layers or semi-permeable layers, mainly the cretaceous marly limestone. No karst feature is visible, and infiltration through Cretaceous marly limestone is mainly diffuse. Some discrete sinkholes may occur at the bottom of some valleys, where marly limestone is thin and could provide some concentrated recharge to the Cretaceous limestone. Up to now, the Chamois Cave remains the unique access to the underground karst system of the Coulomp spring.

4. Our Explorations

After several attempts to find the access to the spring, the first exploration was begun in July 2007. Each step needed several attempts, exhausting transports, and perseverance. Four attempts were required to overcome the emptying by gravity of sumps 1 and 2. Then, in October, two dives of the S3 allow us to pass the previous end, and to discover 450 m of new passages of unexpected size: galleries 8 x 15 m and a

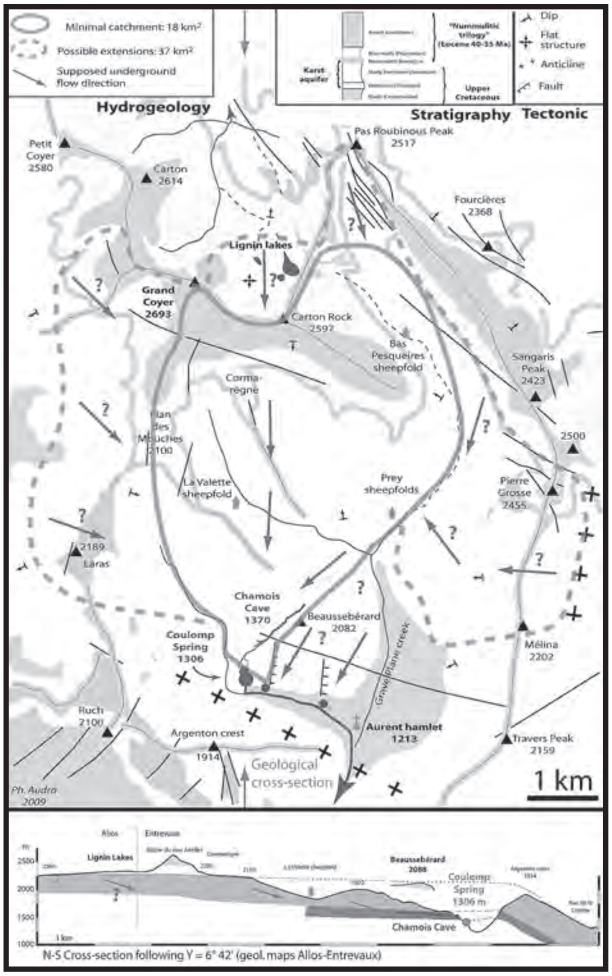

Figure 4: Hydrogeological setting of the Coulomp Spring catchment.

30 x 50 m chamber (Fig. 5, 6). To continue exploration, the S3 needed to be emptied. However, gravity emptying could not apply here, as the flow had to rise up 10 m. By chance, a helicopter allowed us to bring all the required material: a 45 kg weight generator, pump, gas, pipes, electric wires, *etc*. During the 11th of November week-end, the S3 has been drained, a film was shot, and the survey was done to the boulder choke, which closes the downstream part of the fossil passage (Fig. 6). The survey shows that the large gallery almost reaches outside; however, a 20m-thick scree still blocks the passage. Between the end of 2007 and the beginning of 2008, the exploration did not move forward because of high water regularly refilling the sumps. However 8 week-ends were spent to improve our pumping technique and to put safe lines along the dangerous footpath (Fig. 2). In March 2008, a 4-day week-end allows us re-opening the sumps, and a large canyon was discovered upstream. Unfortunately, a rock fell and injured Ph. Audra, who broke his pelvis and several vertebral apophyses, stopping any exploration for a while: 24 hours of rescue, with difficult transport by stretcher across the narrow and wet passages. Due to strong rainfall, exploration only restarted in July 2008, but the sumps remained open until November. About 10 week-ends were required to improve the vertical equipments, to climb some steps, and to survey new passages [D'Antoni-Nobécourt & Audra 2008]. At the end of September, after descending a 16 m shaft, we discovered in one day more than 1300 m of new passages. The huge Hormones Gallery (20 x 30 m) enters about 1 km into the mountain (Fig. 4, 5). We stopped both downstream and upstream only on some small shafts. Since November 2008, heavy rain then deep snow stopped exploration.

5. Pumping Technical

Each sump is drained by 25 mm and 32 mm polyethylene pipes, controlled by gates. The shallow S1 and S2 are gravity-drained, after priming with the pump. A 3 m^3/h pump, located into the S3, is connected by a 300 m-long cable to a 230V generator located outside. The water is flows up 10 m, before flowing outside through a 300 m long pipe. Altogether, the pumping requires between 18 and 30 hours, according to the S3 level.

6. Brief Description of the Cave System

The Coulomp spring discharges cold water (5 °C), pouring out from a low flooded passage about 8 m long. Several

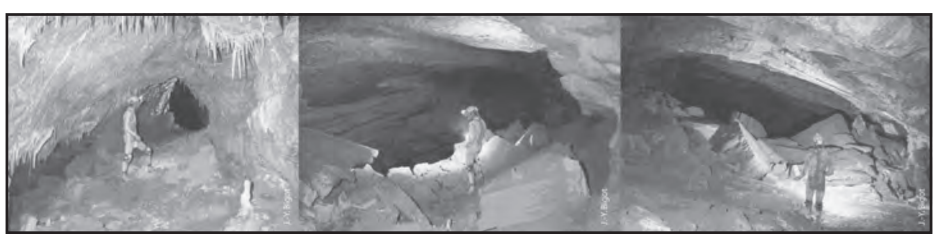

Figure 5: Profile of the Chamois Cave. First crossing of the S2.

Figure 6: Downstream part of the main gallery. Balcony above Diver's Chamber. The boulder choke closing the downstream part of the main gallery.

overflows spread up to 35 m above the spring become active in high water. The Chamois Cave corresponds to an old outflow, located 64 m above the Coulomp spring. Currently, only some percolations feeding the first sump flow out during high water. The first 450 m correspond to underflow passages of the main gallery. They are narrow, with numerous cold pools and moonmilk. S1 and S2 are only fed by surface infiltration. Several times a year, during high water, backflooding occurs in the lowest passages of the system. The water rises about 10 m and floods the S3. After flooding, the passages upstream to the S3 are covered with decantation clay.

After these narrow and wet passages, the scenery abruptly changes: it opens into tubes up to 8 m wide, canyons up to 15 m high, sometimes up to 40 m high when the 3 levels are connected by the main fault. Downstream, after the Divers Chamber (50 x 25 m), the gallery ends on a boulder choke, only at 20 m distance from the surface (Fig. 6). Upstream, several hundred meters long tubes (the Anapophysis Gallery) lead to a 16m-deep shaft, which drops into the Hormones Gallery. The Hormones Gallery acts an overflow passage. It was dry last summer, but it displays clear marks several m^3 discharge during the high water (Fig. 8). Downstream, after some hundreds of meters, a sump closes the active part, while the dry canyon remains unexplored (Fig. 7). Upstream, the Hormones Gallery extends about 1km in a huge passage (20 x 30 m).

During summertime, the airflow originates from the upstream part of the Hormones Gallery, and it disappears downstream across the boulder choke. Part of it may flow toward the Chamois Cave when the sumps are drained.

Figure 7: Diverse aspects of the downstream part of the Hormones Gallery: collapse gallery, scallops, sump.

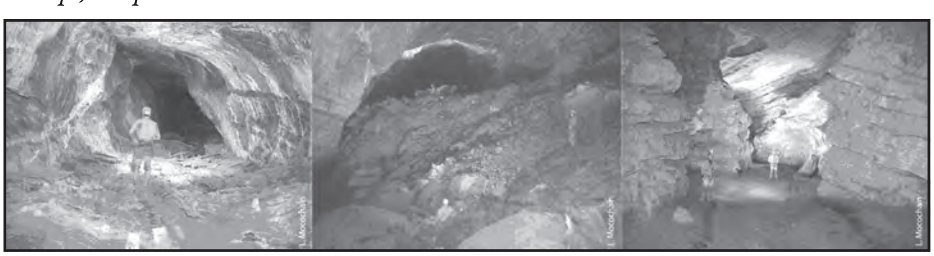

Figure 8: Diverse aspects of the upstream part of the Hormones Gallery: dry tube, huge collapse gallery, canyon.

Conclusion

Currently, the Chamois Cave system extends on 100 m elevation, and 3 km of surveyed passages. During the first year, the pumping hazards and the accident slowed the exploration. The second year provides us the extraordinary discovering of the huge Hormones Gallery. Currently, the pumping is under control; however the access is still restricted by rainfall and deep snow. Our expectations for the future are now turn toward the potential of discovery upstream: the Lignin sinkholes are almost 1000 m higher and 6 km away (Fig. 4). We also expect finally to find the river that pours out at the Coulomp spring. To promote the exploration in this cave we organize in August 2009 an international expedition, which is sponsored by the European Caving Federation (FSE). We hope, not only to increase our discoveries, but also to share our passion for this area of wild nature and demanding caving.

Acknowledgements

The Municipality of Castellet-lès-Sausses, the sponsors (Cozzi, Saint-Cézaire Technique, Société monégasque des eaux), the caving administrations (departmental, regional, the French FFS, and the European FSE). During the accident, the rescue team was composed of Alpes-Maritimes Cavers, Mountains Rescue firemen and policemen, and the helicopter from the civil rescue.

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THE KRONIO PROJECT: A FIRST NOTE

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Mt. Kronio is a limestone massif fronting the sea near Sciacca, in the eastern part of Sicily; a very active volcanic region. It is well known and has been cited since classical antiquity due to the presence, at the summit (370 m asl), of many cave entrances (Stufe di San Calogero and others) with strong, exiting hot airflow (37°C, RH=100%), which have represented an interest for *calidaria* since the Roman times. In past centuries, these caves were explored several times, but the hot atmosphere and a shaft allowed very limited visits.

We will present a general overview, some recent explorations and the first microclimatic results. The mountain is crossed by very intense airflows, in part entering in the lowest part (Cucchiara Cave) but the first simultaneous studies with sonic anemometers have shown a strong gap between the known entering and exiting airflows. External and internal thermal and airflow mapping are showing a complex heat flow structure inside Mt. Kronio. The cave complex probably descends to sea level, where it touches a volcanic thermal water table. It is then probable that deeper explorations are going to face higher temperatures and dangerous gases.

1. Introduction

Mt. Kronio is a limestone massif fronting the sea near Sciacca, in the eastern part of Sicily; a very active volcanic region. Some 40 km south of Sciacca there is an underwater volcano (Empedocles) which in 1831 gave rise to the Ferdinandea Island, which then quickly disappeared.

Mt.Kronio is well known and has been cited since classical antiquity due to the presence, at the summit (370 m asl), of many cave entrances (Stufe di San Calogero -now Antro di Dedalo- and others) with strong, exiting hot airflow (37°C, RH=100%), which have represented an interest for *calidaria* since the Roman times. In past centuries, these caves were explored several times, but the hot atmosphere and a shaft allowed very limited visits.

Cavers from Trieste (CGEB) have explored this cave system since 1953, discovering important archaeological deposits in the deeper parts, yet to be studied; some quick surveys have shown that they belong to pre-Greek civilizations, some 4000 years ago. Until then the caves were probably used for cultural purposes but abandoned due to the sudden arrival of hot vapor flux. At the end of the 1990s, a total of 1500 m of conduits and 20 caves where known; the most important being Cucchiara Cave (development 560 m, depth 127 m) and Antro di Dedalo (development 555 m, depth 56 m).

The Antro di Dedalo and other smaller entrances show a flux of out flowing air, seasonally constant, whereas the Cucchiara flux is inflowing, and the cave temperature is well below that of the Dedalo Cave.

CGEB and the association La Venta have recently made an agreement to collaborate for a multi-disciplinary project, named “Pogetto Kronio”, to study this cave system, probably the most extensive in Sicily, and one of the most interesting worldwide from the historical and speleological point of view.

In 2008 the first two expeditions where done in order to estimate temperature variations, fluxes and technical problems.

2. Internal Air Temperature

The Dedalo and Cucchiara inner temperatures where measured in the period February-July 2008 at 0.1 °C of accuracy (Fig. 1). The Cucchiara temperature, not far from the entrance, is obviously very near the external one, and it is interesting only to show important meteorological variation.

The Dedalo air temperature is remarkably constant. It shows a significant decrease at the end of May, apparently correlated with a general external temperature increase, and

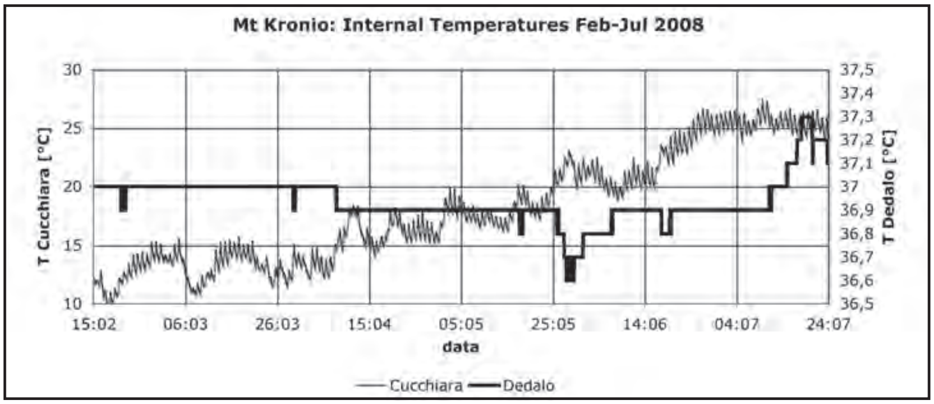

Figure 1: Dedalo and Cucchiara temperatures, February–July 2008.

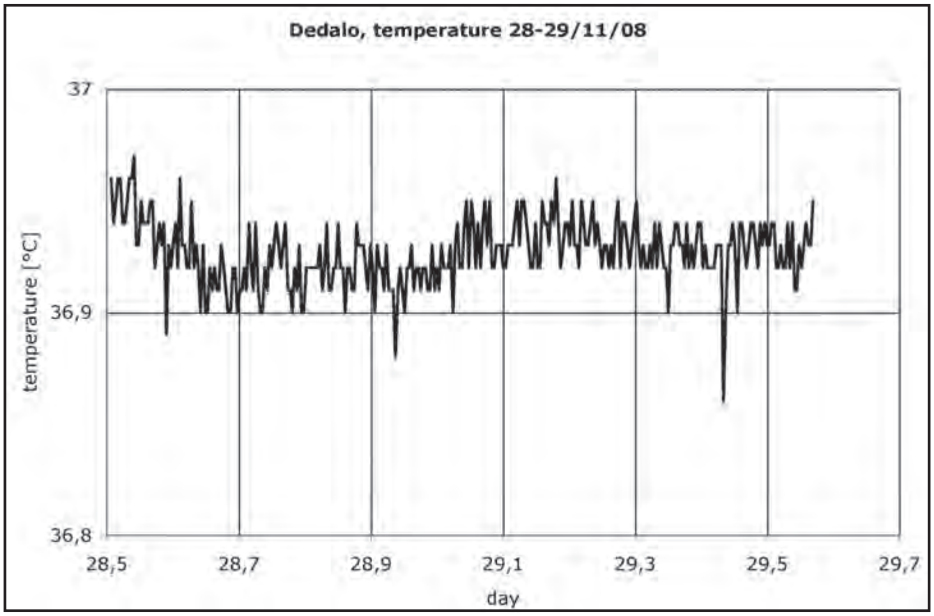

Figure 2: Dedalo temperature micro-variations.

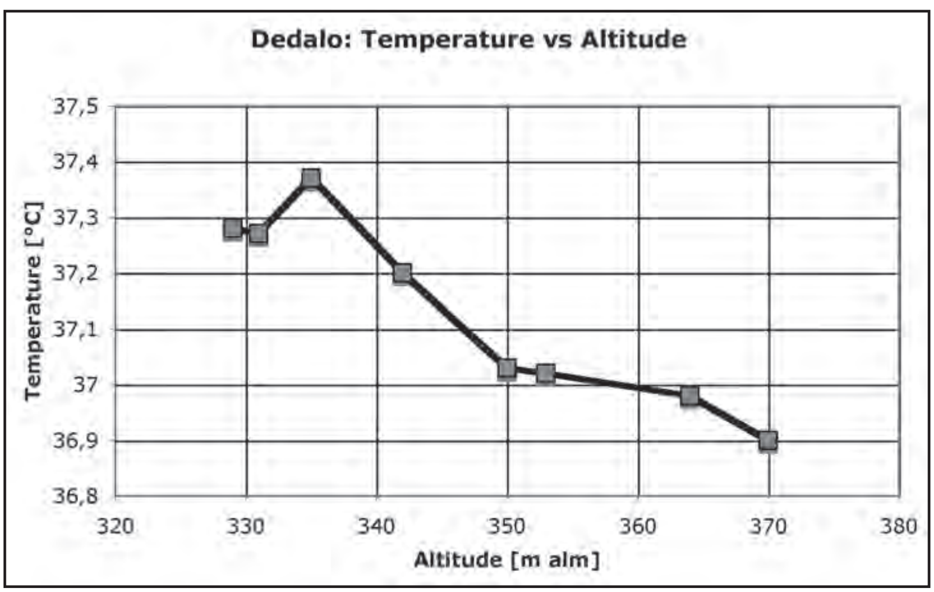

Figure 3: Internal Dedalo lapse rate.

a significant increase at the end of July (Fig. 1).

At the end of November we have measured temperature variation of the Dedalo air flux with an accuracy of 0.01 °C and 5 minutes interval time. In spite of human activity (15 people with powerful lights during the afternoon), its temperature appears to be very stable and not correlated with external temperature variations (Fig. 2).

3. Internal lapse rate and condensation

Internal, stationary clouds result from the condensation due to the global ascending air movement in the Antro di Dedalo, easily observable in photos. It appeared reasonable to suppose that the thermodynamic transformation of ascending air was then moist adiabatic, with its typical cooling lapse rate. In this case (altitude 350 m asl and T=37 °C) the moist adiabatic lapse rate is -3.2 °C/km.

We have measured the temperature along the descent between the entrance and -40 m, with an accuracy of 0.01 °C; results are shown in Figure 3.

The air temperature regularly increases from the entrance (36.90°C) to the deepest point at -40 m (37.27°C) which corresponds to a cooling rate of -10°/km, three times more than expected.

This shows that the ascending air is cooled by the contact with rocks, two times more than by its expansion. This is quite reasonable because at this point the cave is quite near the surface and in thermal contact with external atmosphere and infiltrating water. We remember that the average yearly temperature in Sciacca is 19.5°C; therefore it has to be around 17°C at the top of Mt Kronio.

If we suppose that as far as -100 m the temperature lapse rate would be anomalous, then it is possible to estimate a temperature of 38°C at 250 m asl. Below this "external" layer we can expect that the air be cooled only by its expansion, then with moist adiabatic lapse rate. In this case the temperature of the deepest part of the Mt Kronio cave system, at sea level, is around 39°C.

We have not detected any differences between the air temperature at the top and at the bottom of galleries. The strong condensation processes and the turbulent movements are then able to suppress any thermal sedimentation.

4. Air draughts

On 14 and 15 February 2008 we measured the air fluxes at Dedalo and Cucchiara, simultaneously with two sonic anemometers, in their narrowest parts, together with external temperature and pressure. The air velocities were 2.5-3 m/s at Antro di Dedalo and 4-4.5 m/s at Cucchiara, which corresponds to air discharges of 2.5 m^3/s and 0.6 m^3/s respectively (Fig. 4).

The water content of Dedalo's air is 44 g/m^3, then it releases some 85 g/s to the atmosphere.

The two air circulations are remarkably constant ($\Delta v<10\%$), and only the Cucchiara inflow seems to be weakly correlated with atmospheric pressure.

It is necessary to remember that if the global air movement inside Mt Kronio is due to convection, it is almost independent on external air temperature, unlike usual cave convective draught, because the internal temperature is very high, then the inside-outside temperature difference T_{int}-T_{ext} term is quite constant year-round.

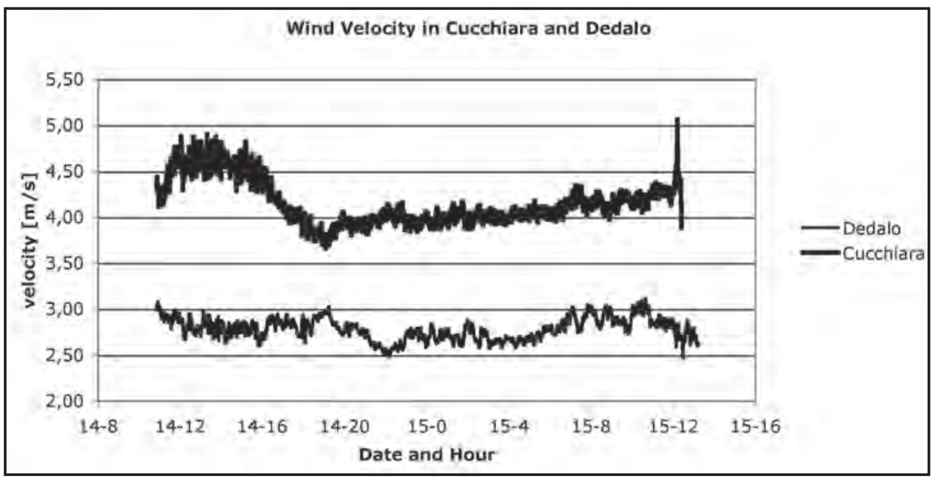

Figure 4: Wind velocity in Cucchiara and Dedalo, February 14–15, 2008.

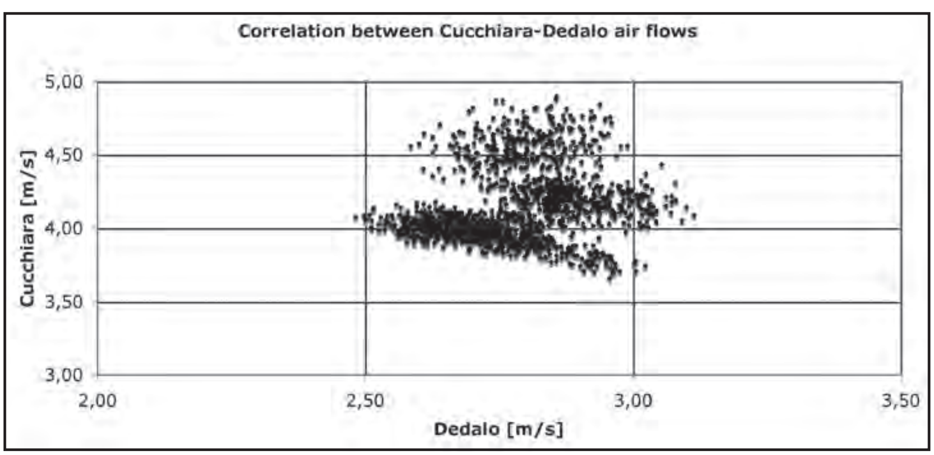

Figure 5: Correlation between wind speed in Cucchiara and Dedalo.

The two air discharges do not show any correlation between them (Fig. 5), but the strange form or correlation clouds and the airflow variations (which are small, but much bigger than the estimation by a trivial convective model) suggest that the structure of internal air flow is more complex than expected.

5. Energetic and water balances

The global airflow inside Mt Kronio, including its secondary exits, can be estimated at 5 m^3/s. The external air is heated to 15-30°C and added at 30-35 g/m^3 during its underground travel.

These transformations, on the total air flux, require 150 kW for heating and 400 kW for air evaporation. The total dissipated power of the Mt Kronio cave system is therefore around 0.5 MW, a large figure: for comparison we can note that corresponds to the average geothermal power on 10 km^2.

The total water flux released is around 0.15 kg/s, that is 5000 tons per year. With typical water infiltration rate in this region (200 mm/a) it corresponds to the infiltration on 25,000 m^2: it is not large.

6. Conclusions

Temperature data stability, air draughts structure, conduits morphology and simple energetical considerations suggest that the Mt Kronio cave system is much wider than expected, probably may kilometers long and able to reach the sea level.

The archaeological interesting parts are surely the most epidermal, and then the excavations are not going to pose extreme technical problems, but such deep explorations in a so adverse environment are going to be really difficult and dangerous.

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THE NAICA CAVES SURVEY

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The Naica caves survey is posing important technical and conceptual problems, in order to save the memory of these marvelous structures. A large effort was made to create a database of the main mega-crystals inside the Cueva de los Cristales.

Caves dimensions recorded to date are:

Cueva de los Cristales. Length (survey plots): Main chamber: 109 m, SE branch: 42 m, NE branch: 68 m. Surface: 1100 m^2. Volume: 5000-6000 m^3. Vertical Range: 12 m.

Cueva de las Espadas. Length: 105 m - Surface: 600 m^2 - Volume: 1400 m^3.

Cueva de las Velas. Length: 75 m - Surface: 400 m^2 - Volume: 1500 m^3.

Cueva Ojo de la Reina. Length: 15 m - Surface: 50 m^2 - Volume: 150 m^3.

Cueva del Tiburron: Length: 22 m - Surface: 50 m^2 - Volume: 70 m^3.

We have measured each giant crystal in Cristales (position in space, position relative to the others, and dimensions). In total, we have mapped 149 crystals, which we estimate to be more than 90% of the total. The largest crystal is Crystal Cin, in the northeast part of the main chamber. Its length is 11.40 m, with a volume of 5.0 m^3.

1. Introduction

There is general agreement between specialists that the Naica's caves, and especially Cueva de los Cristales, are the most amazing underground wonder on Earth. Unfortunately for mankind, not for the caves, we are going to lose them. In the short term, it is impossible to hope that it will be visited by a significant number of people and, in any case, its long term destiny and fortune is to return below 170 m of hot and supersaturated water. Cristales will forget us and return to its natural state. This is the cave's long-term fate. Our mission is, then, to preserve the memory of its appearance in our world as well as possible. There are many aspects of these caves that have to be understood and remembered, but surely the first to be fixed in human knowledge is their shape. To obtain a general survey of these caves has been the first goal of Proyecto Naica. The extreme adverse environmental conditions have forced us to develop new techniques and approaches to data acquisition and drawings, which are described in this work.

2. Difficulties

Any complex undertaking in Cristales meets the hostile operating environment. Surveying is particularly difficult because it requires prolonged effort, cumbersome suits, to speak one has to take off the mask and feel the hot vapor that tries to enter the lungs, and a lot of physical activity. One must, therefore, carefully prepare before entering; think a lot about what and how to do things, in order to perform them in the shortest possible time. The phase that precedes outfitting in the antechamber is, therefore, complex and tense, then "the descent" is intense and risky. For these reasons, one tends to operate with a little anxiety, in a hurry, clumsy, time passes, must hurry, finish up... and that is exactly what should not be done. Movements must be slow and deliberate; otherwise it leads to agitation, hyperthermia, and mental confusion.

Then there are the difficulties hidden in the details, first of which is the accuracy that we want to obtain. The cave is pretty small, but it is necessary to change the level of "reproduction" here, as a normal survey isn't nearly good enough. There is another problem. What must be surveyed? In Cristales, we do not know what is important. It is a forgotten window open onto another world, a cave fundamentally alien to our speleological culture. So here, poor surveyor, even if your hands didn't tremble for other very good reasons, they would tremble in any case from uncertainty. You know that you have to collect far more information than usual, without however being sure of knowing how to select it and of actually being able to collect it.

Another very serious concern were decisions of what to draw into the map. Are the crystals the stuff that fill up the cave, or is "the cave" the one in which we pass through, that is, the part outside the crystals? Then there is the problem of the time needed in order to survey, which is very limited. A survey is an operation that should not be interrupted.

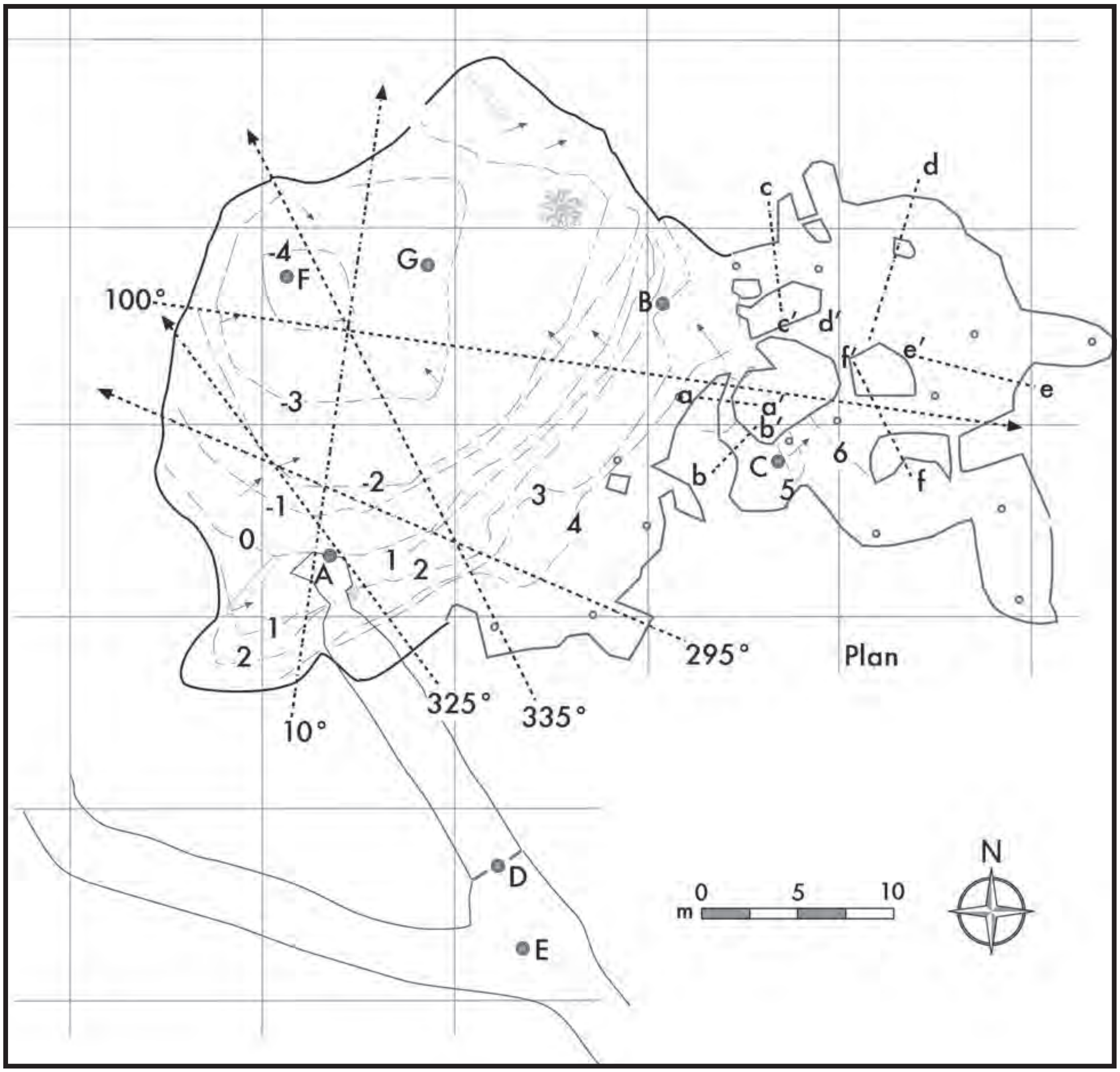

Figure 1: Plan of Cueva de los Cristales.

It should begin and end in a single session, especially if accuracy is a main goal. But, to achieve this task in that hot oven is not at all easy. Until now, the cave had never been surveyed; it is impossible to map Cristales in dozens of sessions consisting of three blistering minutes each. In addition, there is the problem of drawing. One is in a hurry, hands have great difficulties making precise movements, they shake too much; drawing is a nightmare. We noticed this problem almost immediately and found the solution: To photograph each shot, with the subject indicating the survey station number with fingers and then make the drawing itself outside. As would be expected, the instruments do not work well either. They must first be warmed up before entering (even the note pad); otherwise condensation will prevent any reading or annotation. It also goes without saying that the laser rangefinder does not work on the crystals and therefore, after practically "boiling" it in a sealed container, one must aim it at a companion or at one of the rare rock tracts that emerge from the sea of crystal. Aim is obviously often off and one tries and retries, while the clock ticks away and uneasiness transforms itself into suffering. One is tempted to resist finishing the job. To resist? That is another thing that definitely should not be done. When an explorer finally decides to exit because the situation has become intolerable, he discovers that the planned time to exit has long passed and a crisis is by now in progress.

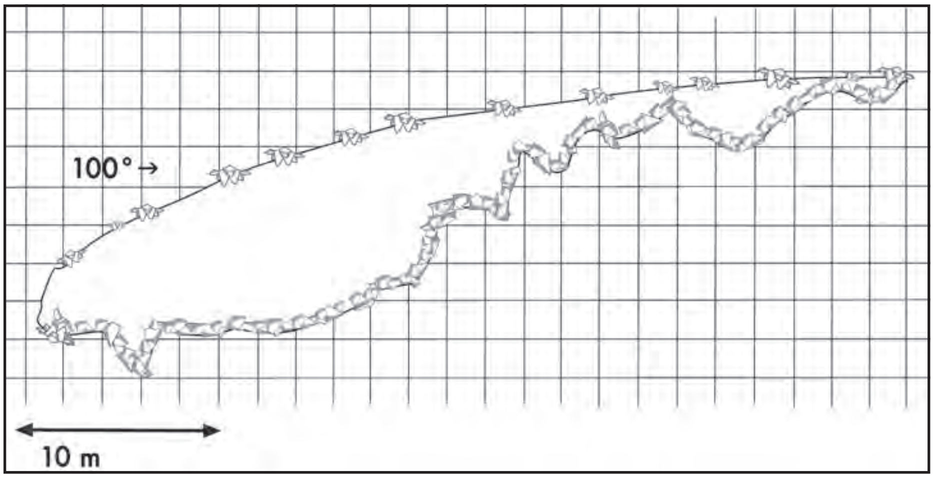

Figure 2: Section of Cristales along the 100° plan.

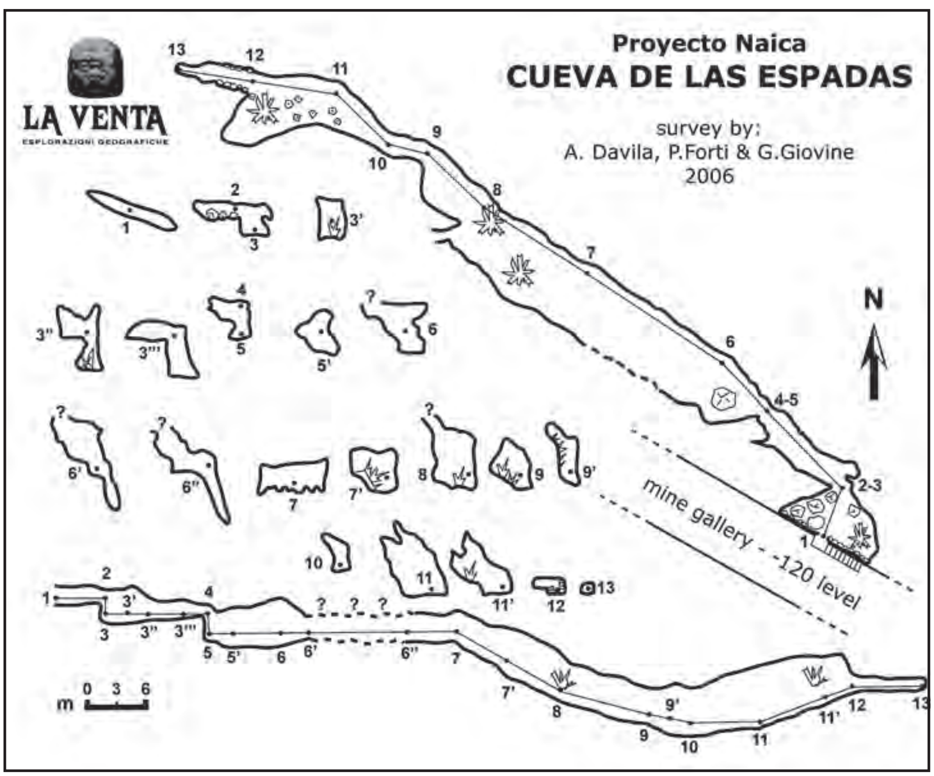

Figure 3: Plan and Sections of Cueva de las Espadas.

3. Results

Caves dimensions recorded to date are:

Cueva de los Cristales: Length (survey plots) - Main chamber: 109 m, Southeast branch: 42 m, Northeast branch: 68 m. Surface: 1100 m^2; Volume: 5000-6000 m^3; Vertical Range: 12 m (Fig. 1, 2).

The Cueva de las Espadas is the most important after the Cueva de los Cristales: Length - 105 m; Surface: 600 m^2; Volume: 1400 m^3 (Fig. 3).

Other caves into the mine are: Cueva de las Velas: Length - 75 m; Surface: 400 m^2; Volume: 1500 m^3. Cueva Ojo de la Reina: Length: 15 m; Surface: 50 m^2; Volume: 150 m^3. Cueva del Tiburron: Length: 22 m; Surface: 50 m^2; Volume: 70 m^3.

4. Mega-Crystals

We are creating a data base for a general overview of crystals in order to quantify the deposition and, possibly, for a better understanding of their formation. We measured direction and plunge of each crystal, its position relative to the surrounding ones, and estimated its length and width. In total, we mapped 162 crystals, which we estimate to be more than 90-95% of the total.

We have made many short visits, for a total of over 15 hours-man, during which we were able to measure and number a few crystals each time. Measurements were made by Konustar 10 Professional geologic compass-clinometer with direct readings to 1 degree resolution by the compass and 2 degree for vertical angle measurements. There is no correlation between direction and plunge of crystals, and the structure of these gypsum aggregates does not seem perpendicular to substratum as in most other geodes. A preferred orientation in two directions occurs (290° and 320° N).

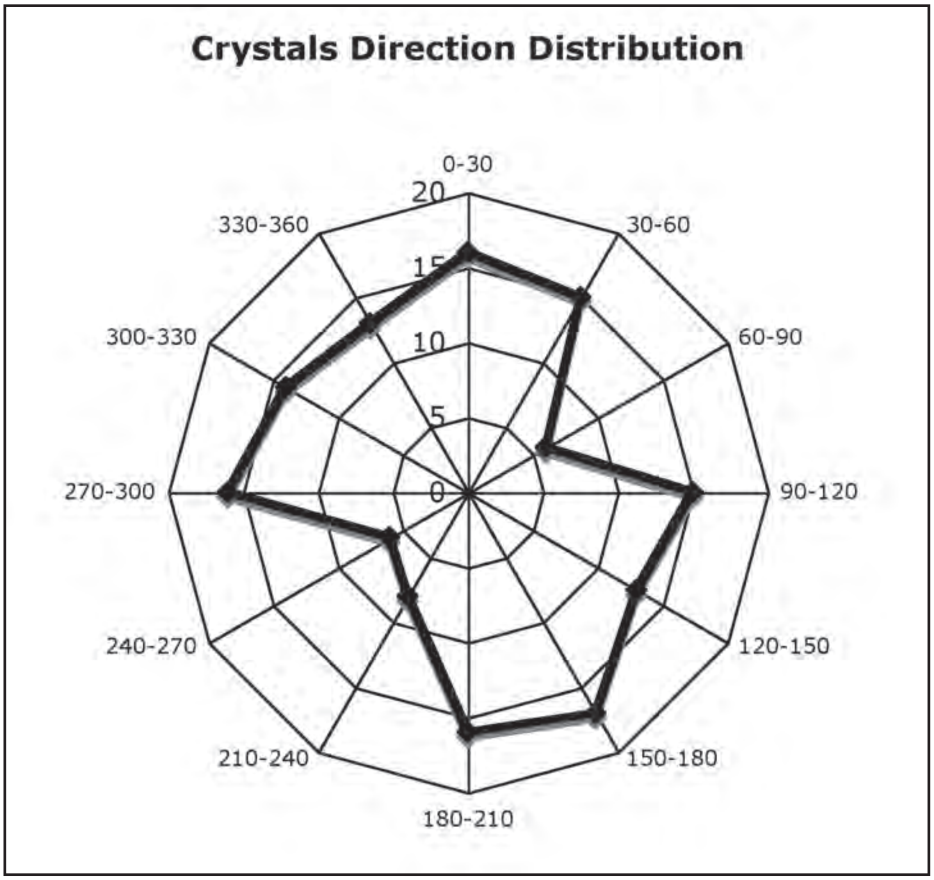

Figure 4: Cristales, distribution of crystals directions (Nm).

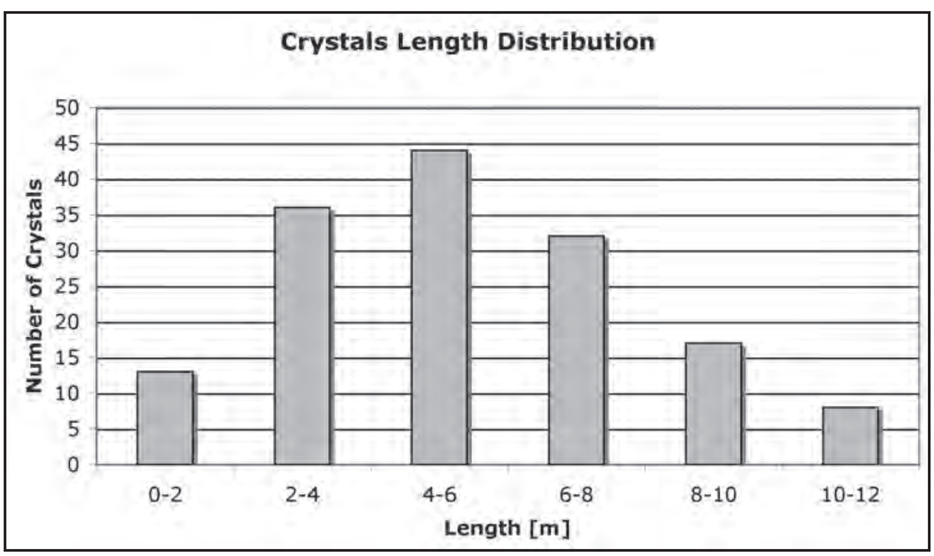

Figure 5: Cristales, distribution of crystals lengths.

In Figures 4–9, a general overview of geometrical distributions is given. In many cases, and especially where the crystals are in reality the cave wall, it was very difficult to differentiate each independent crystal. This caused some bias in the estimation of crystal volume distribution because the coalescence of different crystals was sometimes considered as a single crystal of very large volume.

Together with statistics of crystal growth, it is possible to say that, in general, we described Cristales with a detail very high for caving standard, but which is not sufficient in this case.

5. Cin Crystal

The largest crystal in Cueva de los Cristales is, until now,

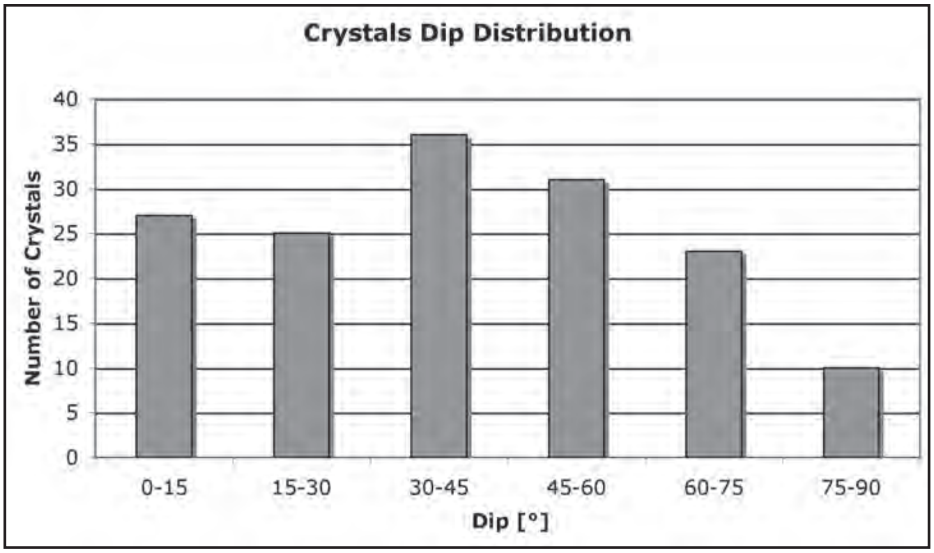

Figure 6: Cristales, distribution of crystals dips.

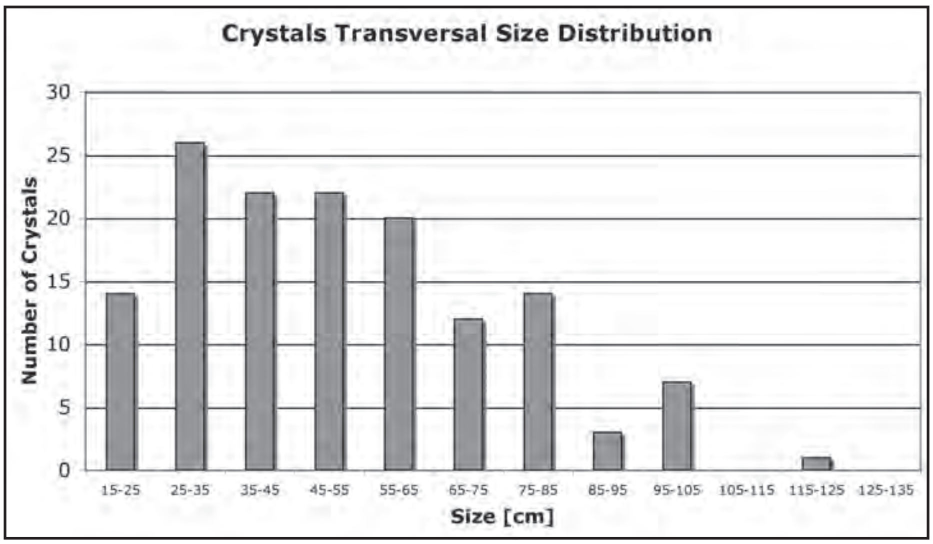

Figure 7: Cristales, distribution of crystals transversal sizes.

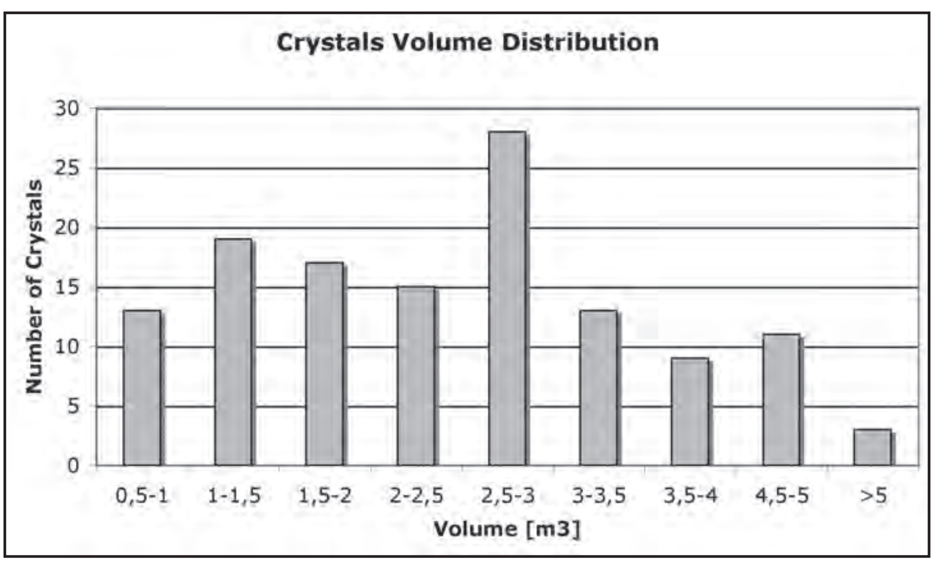

Figure 8: Cristales, distribution of crystals volumes.

a crystal in the northeast part of the main chamber. Its length is 11.40 m, with a volume of 5.0±0.2 m^3, with an estimated mass of 12 tonnes (Figs. 10 – 12). We dedicated it to the memory of Francesco Dal Cin, one of more prominent Italian cavers and member of La Venta team, recently passed away.

6. Conclusions

We worked some 20 man-hours on the Cristales cave survey, 15 for crystals measurements and 4 hours for the single Cin Crystal survey. The result is a very good cave map that is absolutely inadequate for this spectacular Cueva. Therefore, we want to make an extremely detailed 3-D survey of the Naica caves by using the best technology existing nowadays: laser scanning. Our first tests of laser measures inside Cristales gave absolutely negative results because the crystal surfaces did not return a good signal to the emitter. The standard laser-scanner has been shown unable to detect the crystal surface. Recently, we found a special model of FARO that is able to do the work. In May 2007, the company VirtualGeo performed a first test in Naica, showing that the work is feasible. We hope complete it in the middle term.

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Figure 9: An AutoCAD 3-D model of the cave has been made. Cristales general axonometry, from NW: 149 crystals. The arrow indicates the Cin Crystal.

Figure 10: Cin Crystal, view from southwest during its survey.

Figure 11: Cin Crystal, view from west.

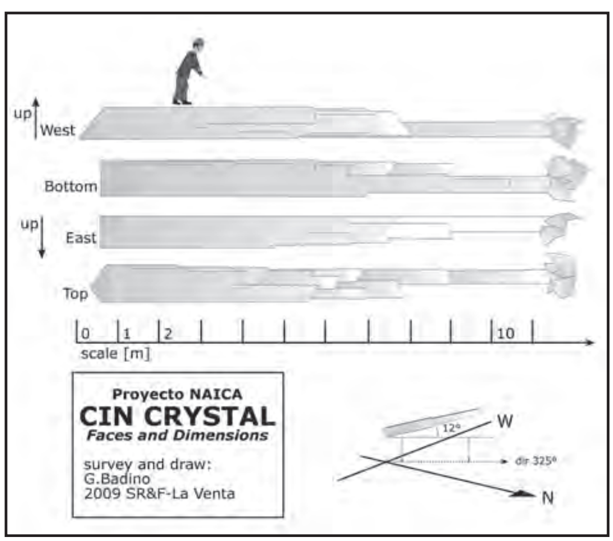

Figure 12: Faces and dimensions of Cin Crystal, the largest one.

EXPLORATION IN MAMMOTH CAVE

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Abstract

The Mammoth Cave System, in south-central Kentucky, USA, is the longest cave in the world with over 600 km of surveyed passage. Exploration has occurred, more-or-less, continuously since its discovery by modern man in 1799. Most of this work has been well documented up through the most recent major cave connection (with Roppel Cave) in 1983.

Since 1983, sustained efforts by both the Cave Research Foundation (CRF) and the Central Kentucky Karst Coalition (CKKC) have lengthened Mammoth Cave by over 110 km. Careful work in many sections of the cave, particularly in Proctor and Roppel Caves, has resulted in several significant discoveries.

Many of the new discoveries have been the result of either new or refined techniques in exploration. The vast distances necessary to reach new leads (often 8 km, or more) has been commonplace in Mammoth Cave for many years. However, application of aid-climbing techniques has been employed heavily in Roppel Cave, and has led to many tens of kilometers of previously unreachable cave passages. Also, the use of in-cave camps or shorter bivouacs in the more remote areas has been very successful and has resulted in many productive trips and new discoveries.

CRF's and CKKC's continued success and ability to sustained efforts in the exploration of the Mammoth Cave System is the result of a very deliberate approach in documentation and administration of the project, by taking advantage of new technologies and making data and maps available digitally to our participants. The rapid dissemination of data has been a strong foundation to many of the discoveries made in the last several years, and promises to be no less useful for the foreseeable future.

The Mammoth Cave area is vast, and there are many square kilometers of surface that should be underlain by cave. The Mammoth Cave area is also host to a number of large, unconnected cave systems that should, one day, be proven to be part of the largest cave in the world.

THE KARST OF REMOTE HOUAPHAN PROVINCE IN NORTHERN LAOS

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Abstract

The explorations in January 2007 and 2008 targeted a new caving area in the remote Houaphan province of northeastern Laos close to the border of Vietnam. Here, in a tower karst landscape known for several hundred cave entrances, the communist Pathet Lao party chose its headquarters during the Vietnam War. Extensive military use of caves was made in this heavily bombed region as secrete underground cities, including cave bunkers, subterranean hospitals and even theatres. The Northern Lao – European cave project is the first expedition to obtain permission to survey and document the caves in this fascinating area. Underground river courses with huge cave passages were found and many of them are through caves. The longest cave of Northern Lao, the 5 km long Tham Nam Long was surveyed as well as other several km long caves giving a total of 21 km of mapped passages in 42 caves. Hydro-geochemical water analysis was done on five stations in Tham Nam Long for temperature, pH value, alkalinity, total hardness and conductivity.

THE TENG LONG DONG SYSTEM AND THE CAVES AND KARST FEATURES OF LICHUAN COUNTY, HUBEI PROVINCE, SOUTH WEST CHINA

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Teng Long Dong is arguably one of the most spectacular caves yet found in South West China. It is located in Lichuan County in North West of Hubei Province. It is currently one of the longest caves in China and contains some of the largest volume passages discovered anywhere in the world. It is located in impressive karst scenery that includes large cave entrances, dolines, tiankengs, natural arches and poljes. The British China Caves Project have been assisting the Institute of Karst Research (in Guilin), the Research Institute of Tourism development, China University of Geosciences, and the Government of Hubei Province in trying to achieve Geo-Park status for the area that includes and surrounds Teng Long Dong. This cave system is made up of both extensive high level abandoned passage, which contains a fascinating show cave, and active river passage, which has proved challenging to navigate. The system as a whole would form the impressive center piece of a Geo-Park in Lichuan. As with many caves in China, the caves in Lichuan have witnessed generations of speleothem removal that has resulted in sometimes extensive damage to a fragile environment and this continuing problem will present a serious challenge to those involved in cave conservation for the area.

1. Introduction

The cave exploration expedition to Teng Long Dong in 2006 took place during the months of October and November. They were part of the British China Caves Project, which for many years has been an informal programme of co-operation between a variable team of British cavers, under the auspices of the British Cave Research Association and members of various Chinese research institutions.

2. Background

The study area for this expedition was the Lichuan Karst which lies south of the Yangse River, in the northwestern part of Hubei Autonomous Region. Access to this area was previously allowed only after receiving special permits from the Ministry of Land and Resources. However, more recently economic and tourist development in China has been accompanied by a considerably more relaxed approach to foreign interest in exploration in these areas.

Such is the potential of the area for scientific investigation and tourism development that the local government of Lichuan has applied for Geo-Park status. The 20th field programme of the British China Caves Project was invited to assist the Karst Research Institute (in Guilin) and Wuhan University of Geosciences in trying to achieve this status. Teng Long Dong was first explored and surveyed by two Belgian Expeditions in 1988 & 1989. The China Caves Project however, surveyed additional passages of this system and other caves and features in the locality. This cave system, now recorded as one of the longest systems in China would be the centre piece of a Geo-Park in Lichuan. Exploration in 2006 was by 17 cavers from Europe, 8 members of the Karst Research Institute in Guilin, and members of an Adventure Clubs in Lichuan.

3. Lichuan County

The county of Lichuan covers an area of around 4600 sq. km and has a population of over 700,000 people mostly of Han origin with Tijia and Miao minorities groups interspersed in the smaller villages.

The countryside is worked extensively by farmers and the main agricultural yield comprises tea, tobacco, and peppers. Tobacco plays an important part in the local economy and the large Tobacco factory near the city centre bears testament to this. Developing tourism in Lichuan provides an increasingly important source of employment for the local population, the TLD show cave itself employs many staff, has a impressive laser display show and in excess of 80 dancers who take part in daily ballet performances.

4. Cave Formation in South Central China

Along with most of the caves in south central China, they occur in a limestone sequence that extends in age from Cambrian to Triassic. Karst development in the region is closely linked to the geologic and tectonic evolution and to the paleogeography. The limestones largely post-date the Caledonian orogeny, and were folded in orogenic phases in the late Triassic and in Cretaceous times.

Palaeozoic palaeo-karst is known across large areas of the limestone in China. From the early Triassic to the late Jurassic, most of central southern China had a humid, tropical-subtropical or humid-temperate climate that greatly favoured karst development. Karst from this period is to be seen in many sites at Lichuan. From the middle Pleistocene onwards, the climate in south central China became hot and humid, and has remained so to this day. Karst therefore developed over very long periods of time. China has about 2.6 M km^2 of karst, with about half of it (and most of the mature karst) concentrated in the central and southern regions (Yuan, 1991; Zhu, 1986).

The area of exploration was generally over 1000m. in altitude although some surrounding hills exceed 2000m. The karst in this area is typical of karst landscapes in central southern China consisting of cone karst punctuated with gently sloping hills where poljes intersect with canyon morphology, a landscape classified as 'qiufung-uvala (Zhang Shouyue in Maire et al. 1991). The extensive but truncated dry valley that lies above the length of TLD system from sink to resurgence is very uneven and varied in feature. It is some times wide and at other times steep and narrow and is undoubtedly the inception horizon for the older, relict caves including the huge phreatic conduit of Three Dragon Cave. The presence of cave remnant on the opposite sides of the valley suggests that the overall drainage direction might even have flowed across the present line of the Qingjiang gorge. Within these beautiful intersected karst valleys nestle dolines, uvalva, wooded areas and mysterious surface balancing lakes which appear and disappear. Farmers have however somehow managed to cultivate these inhospitable but lush enclaves even where they are guarded by steep and precipitous sides. (Fig. 1). The relict through-caves and small gorges often provide spectacular access from one section of the valley to another. The landscape around Lichuan is dominated by asymmetrical folds with northeast-southwest axes and continuous lowering of the base level by the

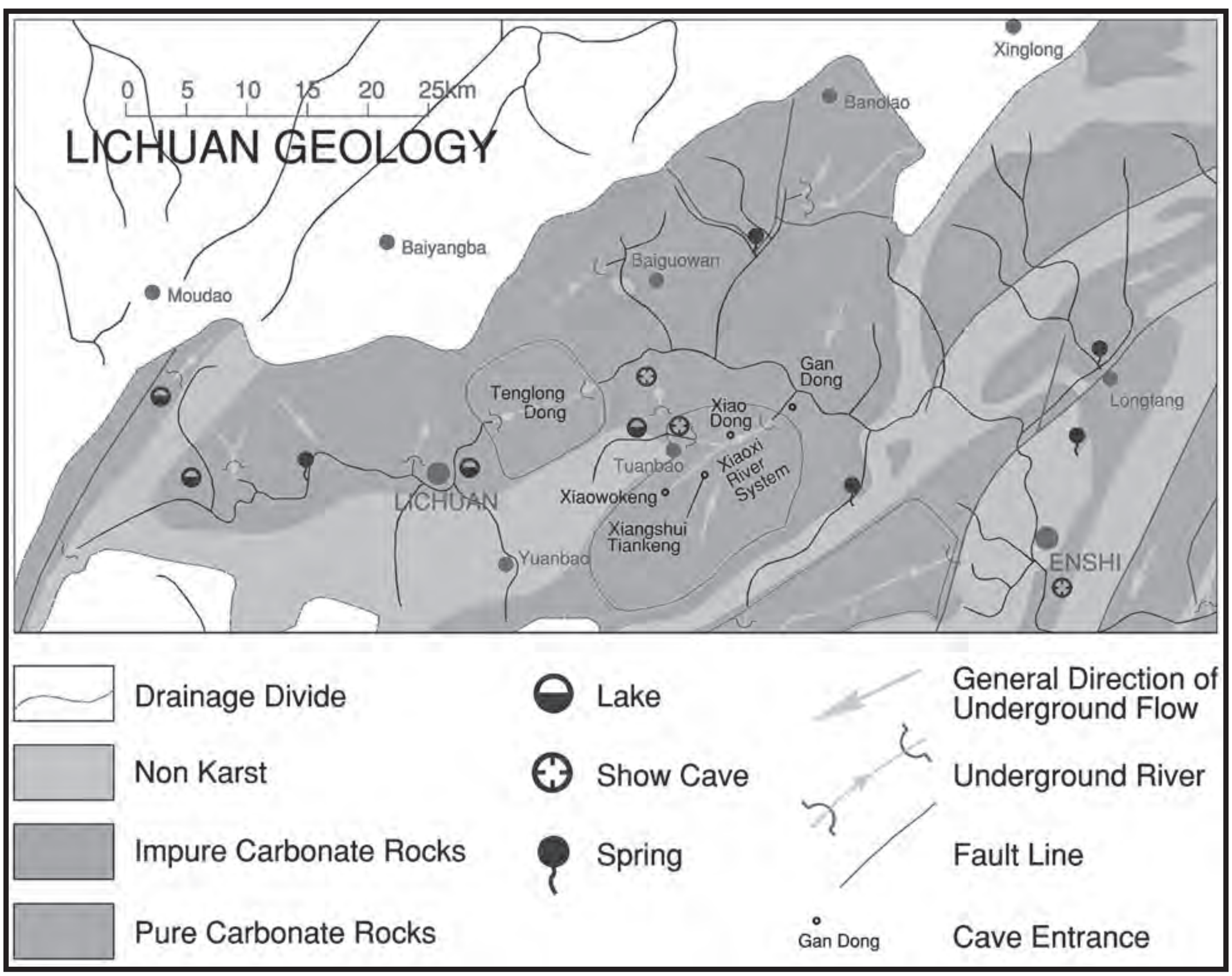

Figure 1: Geology of Lichuan.

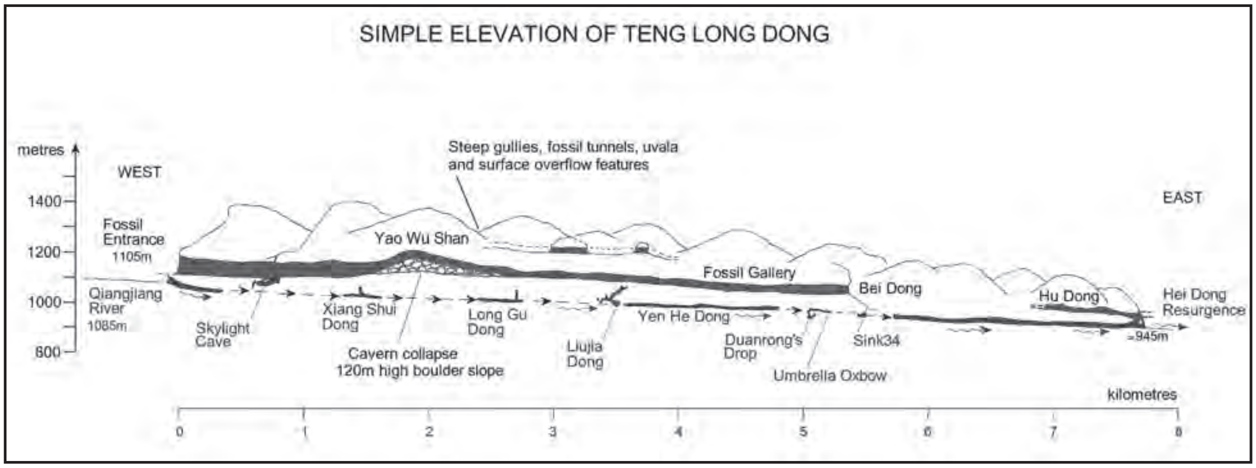

Figure 2:Elevation of TLD and surface valley features.

Quigjiang and the parallel Xiaoxi rivers so the resurgences and surface features have become incised spectacular canyon/gorges. In essence the topography is dominated by eroded ridges, aligned along the limbs of the anticlines and valleys along the axes of the synclines and anticlines.

5. Observations on the Speleogenisis of Teng Long Dong.

TLD is a multi entrance system stretching 10km in an east west direction. There are 10 entrances that provide access to often truncated sections of the cave that are randomly located along the full length of the intersected valley that lies directly above the cave system. The system has a well developed high level abandoned series and an active river system beneath. The TLD abandoned series entrances, Fish Cave, Oxnose cave, Beidong , for example, can be accessed

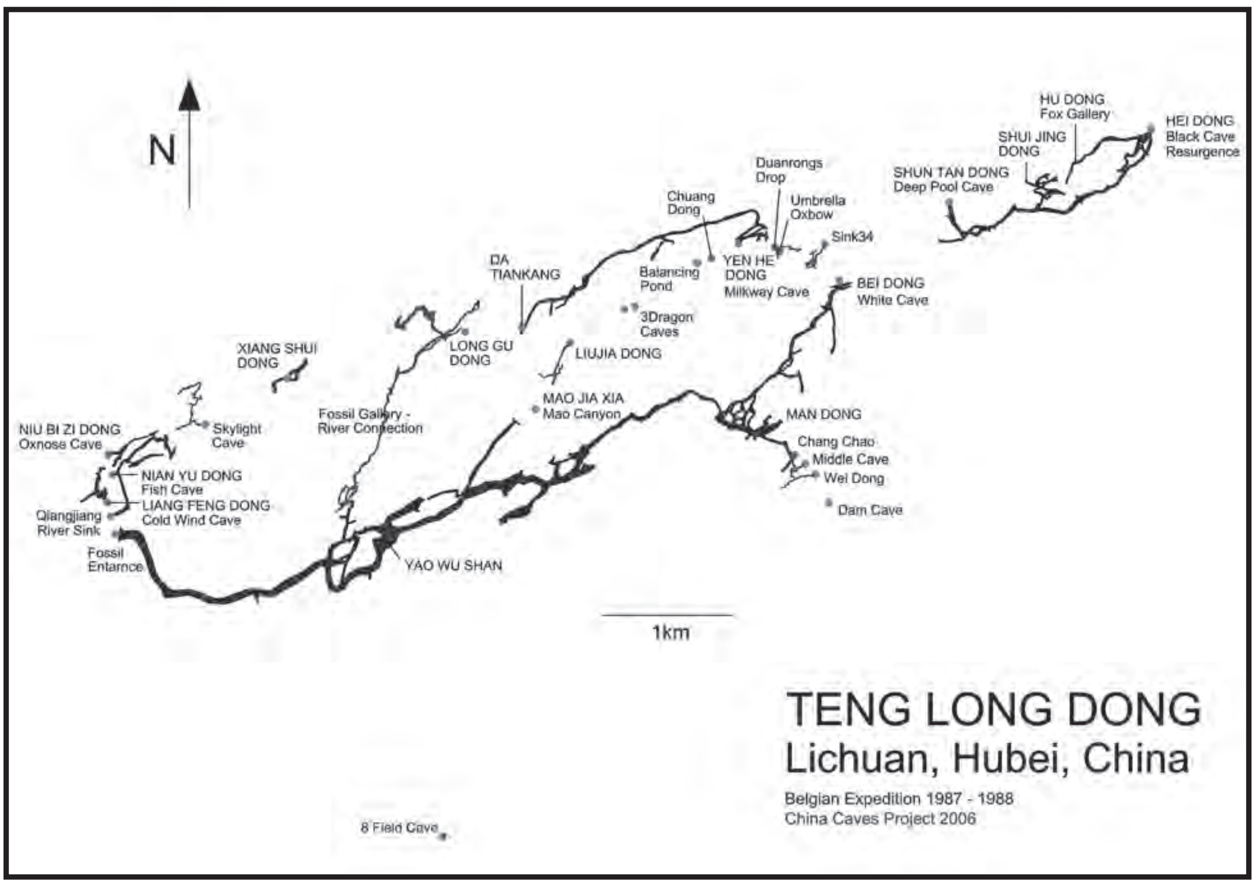

Figure 3: Plan of Teng Long Dong.

by simply walking in, whereas Xian Shui and Longu Dong require equipment and provide sporting pitches and spectacular river traverses into the system. (Figs. 2, 3)

The entrance to the river cave must also rank as world class with the Qingjiang river pouring into the cave mouth down a 12 metre waterfall with ferocity impressive even by Chinese standards (Fig. 4). The river flows along a canyon with steep walls and the water disappears into the darkness beyond. It emerges almost 10 kilometers to the north east and then continues to join the Yangse River near Gulingtao.

Figure 4: Teng Long Dong River Entrance (12m waterfall). Photo J Whalley.

TLD is formed in massively bedded transitional limestone of Triassic age dipping from the north-east to the south-west. These beds reach a thickness in excess of 1000m and their sequence of finely laminated calcilutites is interrupted by beds comprising red and yellow shales with boulders of sandstone and limestone with irregular textures suggestive of olistostrome. The development of the main river trunk of the cave has been controlled by strong flow and percolation along the strike of the gently dipping beds causing widespread dissolution along joints. Under favourable conditions a cave can enlarge from a tube 10mm in diameter into a passage 10m in diameter within a time span of 5,000 to 20,000 years (White, 1988). Additionally, there are many tributaries to the main river within the system and there is much evidence of how they back up during flood periods (the Long Dong fossil connection). There are also immature secondary surface sinks away from the main trunk of TLD that have small flow emerging in the system, for example, Eight Field Cave. The Qingjiang river has formed the main TLD river passage in an almost straight line 10 km long with a cumulative fall from entrance to resurgence of 140 metres. Its flow rate is impressive. Ministry of Land and Resources Information has confirmed the river to discharge at an average of 15.5 m3/s in normal conditions but in the rainy season this can increase to over 50 m3/s.

The huge abandoned entrance of TLD is 30 m in elevation above the river entrance and is 70m high and 50m wide (Fig. 5). The fossil galleries series also conform to joint control and fracture direction as a result of dissolution and collapse. The impressive height of the fossil galleries is due to widespread cavern collapse where intervening joint blocks have been subject to hydraulic influences along joint planes. Progression through the lithology shows that the frequency of joints increases in the Lower Triassic beds where there is far more evidence of shale. As a result breakdown of these beds has resulted in passage obstructions and widespread silting and the presence of sandstones and olistostromes which has inevitably prevented access to otherwise open cave passage (Zhang Shou Yue). The huge thickness of finely laminated limestones have tended to respond to tectonic stresses by kinking and folding that in turn has influenced the development of TLD, although the average dip of the Triassic beds in the Lichuan area is 10-20 degrees, local anticlines in some parts have increased the dip to 60 degrees and where these anticlines predominate faulting has occurred often interrupting critical phases of cave development.

Figure 5: Teng Long Dong Fossil Cave Entrance. Photo J. Whalley.

The cave system has developed in three main stages (Shouyue & Masschelein, 1988). The first occurred when the underground river eroded the abandoned trunk to its present day level from 1140m to 1100m above sea level, (approximately 230,000 years ago). The second stage is characterized by the widespread fracture and collapse of the large abandoned galleries (Yao Wu Shan, figure 2) towards the north prompted by a redirection of flow of the underground river (approximately 150,000 years ago). The

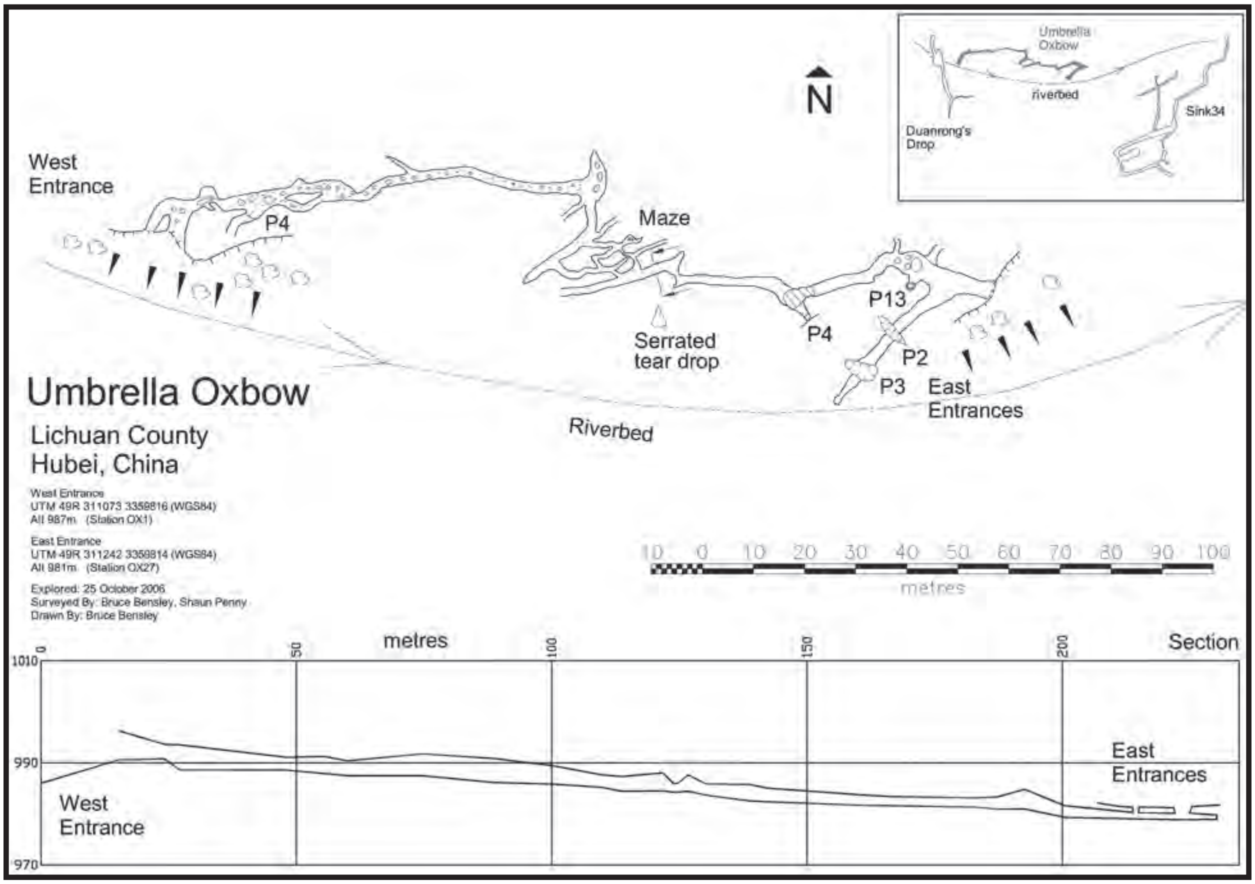

Figure 6: Umbrella Oxbow.

third stage is evidenced by the present day level of the river where active erosion of the current base level still continues. There are a number of small cavities and galleries above the existing cave system for example, Umbrella Oxbow (Fig. 6) Skylight Cave and Sink 34 which initially we believed to be related to TLD's spelogenesis but the absence of surface percolation through joints and fractures and the considerable thickness of the cave roof throughout the length of the system would suggest these smaller features are relict caves that have been invaded by secondary surface stream in the rainy season.

Although the expedition's initial priority was the exploration and development of TLD, the Xiaoxi river valley 10km to the south-east of TLD was also explored and truncated sections of the underground river passage were mapped and surveyed. Important karst features including Tiankengs near the town of Tuanbo give access to active phreas, and even further east towards the provincial capital Enshi at the White Tiger Gorge, (resurgence) Gang Dong, a large abandoned cave above the resurgence of the Xiaoxi river was explored (Fig. 7.) This underground system is parallel to TLD following the same dip in Triassic beds but

Figure 7: Xiao Underground River Resurgence. Photo G. Salmon.

entirely independent structurally and hydrologically. Also the Xiaoxi is a considerably smaller and younger river than the Qingjiang, the Xiaoxi system nonetheless is illustrative of the TLD type cave development at a much earlier stage of its speleogenesis, (Fig. 8).

Figure 8: Xiao River Resurgence Valley. Photo G.Salmon.

6. Man's Impact on the Caves.

It would seem that generations of local villagers have explored many of the fossil cave passages, and have even descended some of the shorter vertical shafts risking life and limb to remove speleothems for financial gain. This has left well-worn paths penetrating even the most remote parts of the system, and has inevitably caused despoliation of the speleothems and removal of many of the most impressive features. The development of the show cave has however provided considerably security for many parts of the system and, as an employer, the show cave appears to have given local people a more positive ownership of the valuable resource.

7. Conclusion.

TLD is an impressive multi layered cave system dominated by a powerful underground river which has formed in thick, dipping Triassic limestone beds. From the middle Pleistocene onwards, the hot and humid climate in southern central China favoured rapid un-interrupted cave development on a massive scale. TLD conforms with a 'classic' model of cave development with active and abandoned passages formed by the constant erosion of an allochtonous river disappearing beneath a large dry valley.

The legacy of TLD provides the local population with an immense opportunity. If the area were to receive Geo-park status this will ultimately help the population in the area become more aware of the unique resource that they have in their possession, in terms of tourist potential, and also of the long-term economic benefits a Geo-park could have for the locality.

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MEXPÉ: SISTEMA TEPEPA AND AREA

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Mexico has always been a prolific area for cave exploration. The Mexpé project, headed by the Quebec Speleological Society, began in 1987 when a hard-to-access region of the Sierra Negra (at the extreme southeast of Puebla State) was seen for the first time by cavers. Important discoveries came quickly including the descent of Sótano de Alhuastle, with its 329 m in-cave free drop; then a world record. During 15 expeditions so far, tens of caves have been explored, surveyed, and connected to form various large cave systems, the most notable being Sistema Tepepa (28 km, -899 m). No less important, these expeditions have allowed friendships and collaboration to develop with our Nahuas and Mazateca hosts. For many, Mexpé has served as an "expedition school" where the friendly environment allowed quick integration. Exploration continues with several kilometers of new discoveries each years but the potential still appears endless in this region where karst is continuous for some 3000 vertical meters.

México ha sido siempre una zona más prolífica para la exploración de cuevas. El proyecto Mexpé, encabezado por la Sociedad Quebequense de Espeleológia, empezó en 1987, cuando una región de la Sierra Negra, difícil de acceso (en el extremo sur-este del Estado de Puebla) fue vista por primera vez por espeleólogos. Importantes descubrimientos fueron instantáneos con, entre otros, el Sótano de Alhuastle con sus 329 metros de caída libre en la cueva, un récord mundial en este época. Durante 15 expediciones hasta ahora, decenas de cuevas han sido exploradas, investigadas, y conectadas para formar diversos sistemas grandes, el más notable siendo Sistema Tepepa (28 km, -899 m). También, estas expediciones han permitido el desarrollo de amistades y colaboración con nuestros anfitriones Nahuas y Mazatecas. Para muchos, Mexpé ha sido una «escuela de expedición», donde el ambiente agradable permite la integración rápida. Exploración continúa con muchos kilómetros descubiertos cada año y a pesar de todo el potencial de nuevos descubrimientos parece ser siempre ilimitado en esta región donde el karst se desarrolla sobre un desnivelado de 3000 metros.

Résumé

Le Mexique demeure une des régions les plus prolifiques sur terre pour la spéléologie. Le projet Mexpé, chapeauté par la Société québécoise de spéléologie, a vu ses débuts en 1987 alors qu'une région difficilement accessible de la Sierra Negra (au sud-est de l'état de Puebla) a été vue pour la première fois par des spéléologues. Les découvertes importantes furent instantanées avec entre autre la descente du Sótano de Alhuastle avec son puits intérieur et plein vide de 329 mètres; un record de l'époque. Au cours de 15 expéditions jusqu'à maintenant, des dizaines de grottes ont été explorées, topographiées et jonctionnées pour former divers grands réseaux, le plus notable étant le Sistema Tepepa (28 km, -899 m). Non moins importants, ces expéditions on permis de fonder des liens d'amitié et de collaboration avec nos hôtes nahuas et mazatèques. Pour plusieurs, Mexpé a servi d'expédition école où la convivialité entre les participants a permis une adaptation rapide. L'exploration continue avec plusieurs kilomètres de première à chaque année et malgré tout le potentiel de nouvelles découvertes semble être toujours sans limites dans cette région où le karst se développe sur un dénivelé d'environ 3000 mètres.

1. Introduction

In December 1987 and January 1988, a group of Quebec cavers, members of the Société québécoise de spéléologie (SQS) set out to explore a previously unvisited karst area in the Mexican Sierra Negra (Fig. 1). This mountain chain, composed mostly of Lower Cretaceous limestone, is part of the Sierra Madre del Sur and is located between the Sierra Zongolica and the Sierra Mazateca in the southeastern corner of Puebla State, Mexico, very close to the states of Veracruz and Oaxaca. This general area of Mexico was already well known for its cave potential as it is located some 20 km north of Sistema Huautla (then the deepest cave in Mexico) as well as several other deep cave systems. The exact location of the expedition was chosen because of a huge sinkhole, some 1.5 km long that jumped to the eye on topographic maps.

Figure 1: Location map for the Mexpé study area.

It turns out that this sinkhole was not even bottomed during the first month-long expedition, partly due to its remoteness, but also because countless (smaller) sinkholes and caves were discovered on the way, keeping everyone busy and satisfied. Not being able to fulfill all the objectives of an expedition because of other discoveries being made has been a recurring situation ever since.

The study area is situated in elevation between about 300 m and 3200 m, with the focus in the 1000 m to 2200 m range. Precipitation is over 2500 mm per year and the mean temperatures are around 18 to 22° C. Most of the rain falls during the summer and fall rain season. Vegetation varies greatly with altitude, from tropical jungle to pine forests. Agriculture is present at all elevations under about 2100 m, and on slopes up to about 45°. Indeed, the rare flatter lands being reserved for grazing, the communities survive by growing corn (for consumption) and coffee (for consumption and export) wherever they can. This type of farming leads to excessive erosion and deforestation, an obviously unsustainable business model with the rapidly growing local population.

Since this first expedition in December 1987, several cavers where hooked and nothing would have stopped them from returning year after year for more discoveries and adventures. Thus, a series of expeditions known as Mexpé began.

2. The Early Days: Caves Everywhere!

Base camp for Mexpé I (1987-88) was right in the center of the village of La Cumbre, located 3 hours by mule path from the nearest road that ended in Tlacotepec de Porfirio Díaz. Villagers were quick to show us their "sótano": a steep-sided sinkhole with an apparent cave at its bottom, just outside the village. The bottom of this sinkhole contains a 220 m free-drop that eventually leads to a sump after a series of other large free-drops: 122 m, 105 m, and 70 m. Within a few days, -694 m Sótano de Los Planos was bottomed. Not bad for a first cave in the Sierra!

Next was a much smaller sinkhole near the trail to Los Planos. After a few small drops, there's a large one; one in which a rock was heard hitting bottom after some 5 seconds. The 95 m rope that was on hand on that day was not enough, but the bottom could be seen, or so they thought. The next day another 160 m of rope was brought in. The first person down made it to a ledge, after a small pendulum: he was out of rope. As he waited there for more, he decided to throw another rock: 8 seconds! The remaining rope was rigged, but it wasn't enough. On the third day, the team finally made it to the bottom of this 329 m pit! Sótano de Alhuastle was to contain the then 10th deepest pit in the world; the deepest one that didn't open to the sky! That record was surpassed not long after, but that doesn't take anything away from these two incredible discoveries in so little time.

Unfortunately, interaction with the locals was difficult; most of them only speaking Mazateca. After some time, the word was that the gringos were stealing treasures from the caves and we were asked to leave.

Luckily, exploration was taking place in parallel around the nearby village of Tepepa where the villagers were most welcoming. The caves there descended less rapidly, but covered more distance. These were to become parts of what is now know as Sistema Tepepa.

It is to Tepepa that two dozen cavers returned a year later (1988-89) for Mexpé II, setting-up camp in a field just outside the village that was soon called "Plan de Canadá" by the locals. Its location being ideal, it is there that camp was to be set-up for many expeditions to come. Our relationship with the locals was good, and we made sure to help them with communal chores and participated in religious celebrations. We also took the bravest of them caving. Although located just two kilometres from La Cumbre, the locals in Tepepa are of Nahua descent. Indeed, our exploration sector is located right on the division between the Nahua and Mazateca cultures. Moreover, we're also located on the border between two "municipios": Coyomeapan and Tlacotepec de Porfirio Díaz, making the speleo-politics all the more confusing.

Again that year, discoveries were significant with Sistema de Angel reaching -533 m and almost 5 km long, and Olfastle Niebla at -518 m and over 3 km long. Moreover, another area, to the southwest and higher in altitude was reckoned with caves going to -400 m. La Ciudad was discovered further to the south with its huge 100 x 200 m room. Everywhere we went, there were caves; significant caves.

Exploration continued with expeditions in 1990 and 1990-91. Mexpé III (1990) was a very small expedition where Olfastle Niebla was extended by 2 km and 200 m more depth. Mexpé IV (1990-91) was split between the Tepepa valley where most recent activity had taken place and the plateau to the west. Calling that area a plateau is a misnomer, as altitude varies from 2000 m to 2300 m, but it is less steep than the surrounding landscape. Las Brumas was discovered (-388 m, 3.5 km), as well as an important resurgence to the northwest, Xalltegoxtli, which was in the right location for potentially being the resurgence of some of the caves around Tepepa, as its upstream waterfall, that stopped exploration after 1 km, was just 200 m away and 100 m lower than the furthest point reached in the Ehecatl section of Sistema de Angel. Olfastle Niebla is extended again, this time to 8 km and -800 m. This expedition also marked the beginning of collaboration with Mexican cavers with three members of the Sociedad Mexicana de Exploraciones Subterraneas (SMES) participating.

Mexpé V (1991-92), another very small expedition, established a base camp on the plateau. Mexpé VI (1994) returned to the same location with a larger team, but later retreated to Plan de Canadá because of the weather; the same day-after-day wet weather other teams had encountered at that altitude. There, most caves sump around -300. Another 2 km was added to Olfastle Niebla and several other significant but unconnected caves were surveyed.

1996-97 (Mexpé VII) added another 3 km of various discoveries in the Tepepa area, but it is only after the expedition that it was realized that major connections could probably have been made. This set the stage for the next expedition.

3. The Later Years: Connections Everywhere!

After many years of finding long stretches of disconnected virgin caves, the 1999-2000 expedition was all set to connect some of them. Unfortunately, in late December 1999, as Mexpé VIII had just begun, one member fell down 8 m at -400 m. This turned the expedition into a rescue effort. Chaos followed as cavers, the army, and the Red Cross all tried to help. The injured was eventually taken out of the cave several days after the accident. Luckily, by that time, he had started to recover and was able to help himself through tight meanders. It was not long after this accident that the Espeleo Rescate México was put together. This organization has since grown into a well-organized and efficient group.

Almost all expeditions up to this point had taken place in December and January, mostly to take advantage of the availability of cavers during the winter holidays. The weather at that time is sometimes good, sometimes awful, turning camp in to ankle-deep mud baths. From this point forward, expeditions were systematically held in the early spring with warmer weather and systematically dryer climate.

Mexpé IX, a joint SMES-SQS expedition held in the spring of 2000, focused on the resurgence area first seen in 1990-91. After some effort and many climbs, a connection was made between the Xalltegoxtli resurgence and Ehecatl; a traverse of 756 m depth with total surveyed length of over 13 km. One peculiar feature of Xalltegoxtli is the fact that the resurgence is not the lowest point in the cave. Indeed, modern water escapes the main passage to connect to a surface valley that is clearly much younger that the main, dry, trunk passage that keeps going slowly down, to the northwest.

Two more important connections were to come in 2002 (Mexpé X) where Sistema Tepepa was created at 26.5 km length and 899 m deep. Gimnastica Selvatica was also discovered close to camp that had been (finally) established in the big sinkhole that drew the very first expedition to the area, called by some locals "Hoya Grande". This camp has been reused for most expeditions since. 2002 was also the year where the once remote village of Tepepa was first accessible by regular passenger cars. It is also that year that electricity was to reach the village. Raising the posts was done by hand through communal chores to which we participated.

2003 (Mexpé XI) brought new entrances to Gimnastica Selvatica and La Ciudad and more overall knowledge of Hoya Grande.

For a change, Mexpé XII in 2005 saw a small team opted to reckon the nearby summit of Cerro Zizinteptl, culminating at 3250 m in a rather harsh environment. The karst is so well developed there that any rain finds itself underground within centimeters of where it hit the ground. This is not good, as it doesn't provide enough water in one place to create large passages. Countless blind pits were descended but a single significant cave was found. The karst being continuous for some 3000 m down, this area will likely see more exploration in the future. A reckon was also done to the villages of Buenavista and Tequixtepec to the south, where promising entrances were found, one of them with a 100 m entrance pit was named Tres Quimeras.

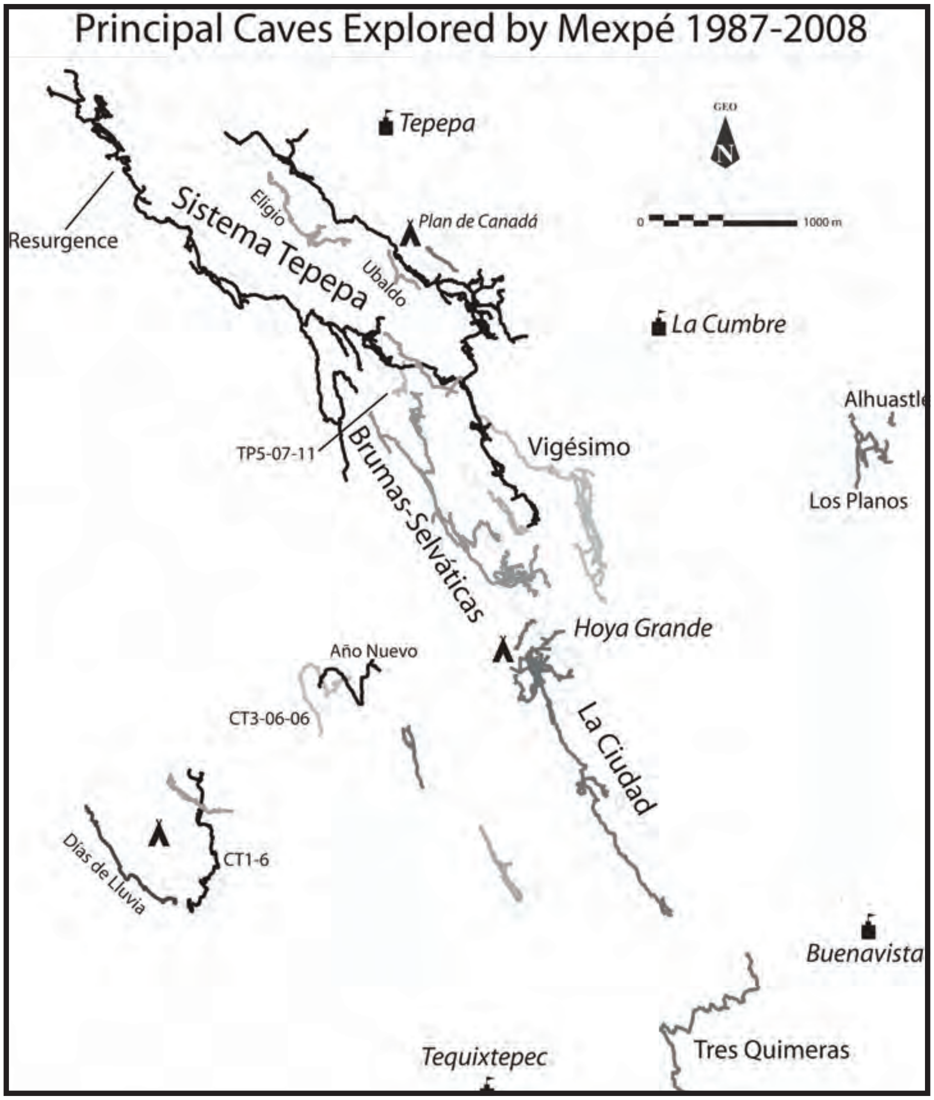

Figure 2: Principal caves explored by Mexpé, 1987–2008.

2006 saw a return to Hoya Grande where yet more entrances to La Ciudad were discovered, one of which allowing us to extend the trunk passage over one kilometer to the south. Sistema Tepepa was also extended to the south, extending to Hoya Grande. Also, an epic connection was made between Gimnastica Selvatica and Las Brumas.

The 20th anniversary of Mexpé in 2007 drew together a very motivated group for Mexpé XIV. One objective was to continue in the trunk passage of La Ciudad where exploration had ended the year before. Another kilometer of trunk passage was easily surveyed. There was also a return to Tres Quimeras where exploration continued well the entrance pit all the way to -513 m. This cave shows no sign of ending and will be the main focus of the 2009 expedition. A major resurgence in a valley about 800 m lower than the entrance might be where it will end. A major new discovery, Cueva del Vigésimo, which was getting close to Sistema Tepepa, gave us hope of a connection to yield the magical -1000 depth, but that was not to be.

Mexpé XV in 2008 doubled the length of Cueva del Vigésimo to over 6 km and -316 m depth. Much time was spent trying to connect Sistema Brumas Selvatica to both Sistema Tepepa and to La Ciudad, but it did not happen. Perhaps another year?

4. Results

Currently, close to 80 km of caves have been surveyed, and there's no end in sight (Fig. 2, Table 1). Sistema Tepepa, at -899 m and 28.5 km is a significant cave, especially when considering the 769 m traverse, one of the deepest in Mexico. But the fact that other significant caves lie nearby with real potential for connections and extensions makes even more interesting.

No less important than the survey statistics is the friendships and collaboration that has developed over the years between

Caves of the Mexpé project over 1.5 km long or 200 m deep, sorted by length	length	depth
Sistema Tepepa	28,564	899
Sistema Brumas-Selvaticas	8,870	473
Sistema La Ciudad	7,828	299
Cueva del Vigésimo	6,137	334
Las Tres Quimeras	2,306	513
Cueva de Eligio	2,229	237
CT1-6	2,026	244
Sótano de los Planos	1,526	694
Días de Lluvia	1,424	260
CT3-06-06	1,423	383
Sumidero del Año Nuevo	1,173	402
Cueva Ubaldo	828	227
TP5-07-11	703	228
Sótano de Alhuastle	596	410

Table 1: List of caves explored by the Mexpé Project.

some of the 110 participants from 7 countries. For many of these participants, Mexpé was the first important expedition, thus serving as some sort of expedition school. Emerging Quebec cavers have greatly benefited from this access to world-class caving opportunity.

Witnessing the rapid changes in the Sierra over the last 22 years has also been quite educational. From villages previously accessible only by hours of hiking on mule trails where people lived much like they did several hundred years ago, the towns have now been transformed by roads, electricity, telephone, TV, and even high-speed satellite internet.

Mexpé has also been the test bed for high-tech survey gear and software, such as Auriga. This has proven quite helpful in obtaining and managing survey data.

The caves are typically composed of multi-pit entrance sections followed by more horizontal base-level passages, often on multiple levels (Fig. 3). Data obtained to date show that base-level water flow was, and still is in active sections, towards the NNW. There are, of course, a few exceptions, such as Tres Quimeras that looks like it's going to go towards the SSE. This cave is most likely of more recent origin as the water that currently flows through it was probably originally responsible for creation of the upstream (southern) sections of La Ciudad.

Fig. 3

The fact that most caves on the western plateau sump between 300 and 400 m, coupled with the existence of an important regional fault between the two areas (running NNW-SSE) makes us think that the likelihood of connecting that areas with caves of the Tepepa valley is quite slim. Moreover, the only surface water for kilometers around is found at various places, for short stretches, along that fault, likely due to an impermeable layer somewhere between the limestone beds that dip steeply to the ESE. If water can't make it through, it is doubtful that cavers will.

5. Conclusion

While most large sinkholes in the center of the study area have been at least partly visited, there surely remain countless cave entrances waiting to be discovered, as every year we find more where we thought we were done. There are promising leads in several places, but the largest potential now lies on the periphery: the plateau to the west and the flanks of Cerro Zizintepetl, the Tres Quimeras, and Tequixtepec areas to the south, La Cumbre to the east, and the resurgences area to the northwest.

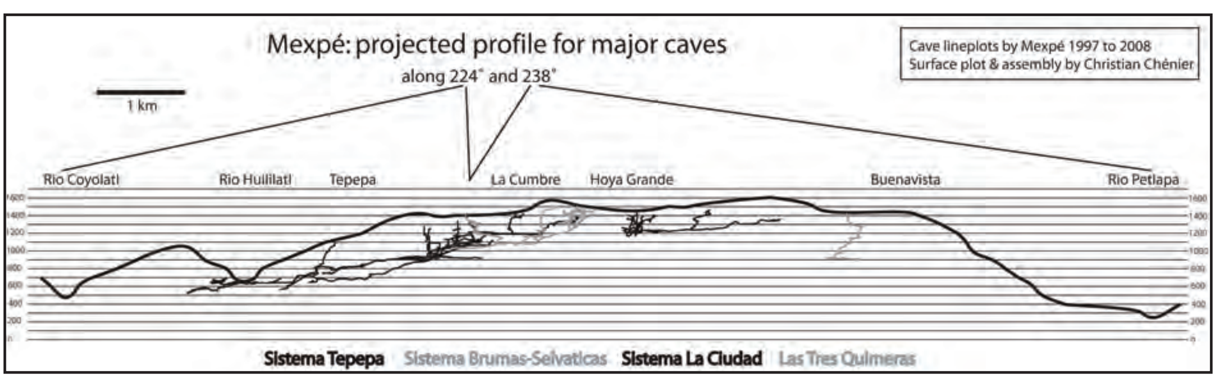

Figure 3: Cross-section of the cave systems.

An expedition is planned for the spring of 2009; it will be a record five years in a row that a Mexpé has been held. The main focus this time will be the southern sections; especially the continuation of Tres Quimeras. Motivation to continue the exploration is as high as the potential for new discoveries.

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RECENT EXPLORATIONS IN THE WHIGPISTLE CAVE SYSTEM: EDMONSON COUNTY, KENTUCKY, USA

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The Whigpistle Cave System in Edmonson County, Kentucky, USA, is a classic central Kentucky cave with complex upper and lower levels that vary from vadose canyons with active streams to grand dry trunks filled with gypsum speleothems. Pits and steep canyons in many locations connect levels. Whigpistle is the 9th longest cave in the USA and has been the site of four caving projects over 30 years. The first three groups had surveyed 51.88 km in the cave since 1977 using three different entrances. Initially in 2005, the fourth group, the "Whigpistle Cave Project" focused on a resurvey of much of the Jackpot section and completing surveys deep in the cave to cartographically integrate the system. From their new work began in Martin Ridge. Continuing passage has been found in several locations including climbs near Screaming Pit, pits in the Dreamland Borehole, muddy streams in lower Quinlan Creek and at upper level Don't Have Kids Crawl (at the end of Petit Hollow). Cavers have primarily been following airflow to make discoveries and continuations have required several wet and dry digs, plenty of rope work, and negotiating a small crawl with eight centimeters of howling wind over water. The past two expeditions have seen trips to the Whigpistle Entrance to a dig lead with air that led to a climb and continuing canyon not far from the entrance. To date 3.6 km have been added to the system. Our group has actively worked to create maps of the cave in a quadrangle format both to give to landowners and for assessing and working leads. Approximately one third of the cave has been drafted in this new format. Future exploration work will focus on climbs, continuing to follow the winds, and more map drafting.

GEOMORPHOLOGY OF THE BOQUERONES CAVE SYSTEM, SANCTI SPIRITUS, CUBA

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The 6.5 km long Boquerones Cave System lies in the Alturas del Nordeste, 30 km inland from Cuba's north coast along the western edge of Sancti Spiritus Province, Cuba. Here, the Río Jatibonica del Norte, on its way to the north coast and through the Alturas, has developed a cave with anastomotic and branchwork mazes, trunk passages, large rooms at passage intersections, and extensive collapsed passages that have left remnant surface canyons. The cave shows an interesting history of parallel passage development, the effects of floods, speleothems and sediments, and strong structural control.

RECENT EXPLORATIONS IN THE ST. PAUL KARST (PALAWAN, PHILIPPINES)

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The Philippine Archipelago hosts several interesting karst areas. One, in particular, is well known because in 1999 it has been included in the UNESCO World Heritage List. The area is located in eastern Palawan, and hosts the Puerto Princesa Subterranean River (former St. Paul Subterranean River). This karst area is located between Ulugan Bay and St. Paul Bay, ~50 km NE of Puerto Princesa, the capital city. The karst covers an area of ~35 km^2 and is made up of a massive to roughly stratified, micritic, light to dark grey colored, lower Miocene limestone showing levels rich with fossils.

The cave, more than 24 km long, is composed of an active level and huge fossil branches; it represents a unique phenomenon, due both to the variety of its ecosystem and to its peculiar hydrodinamic features. Its outflow is about 200 m from the coast line, and tides push their influence as much as 6 km inside the cave, so that its underground river is the site of a huge mixing phenomena between fresh river water and salty sea water. In 1973 the active level of the cave was explored by Balasz, who compared the St. Paul karst to the “Yangshuo type karst” of southern China, featured by extremely steep positive shapes known as “towers”.

The cave, was explored by Australian teams in the early 1980s, and then explored over the course of several expeditions beginning in the late 1980s by the association La Venta and the Italian Speleological Society. In 2007 and 2008, in collaboration with the authorities of the park and the city of Puerto Princesa, La Venta organized two expeditions to this karst area. The project aimed at completing the exploration of the underground river, reaching and exploring some dolines on the NW side of the mountain, surveying the SE part of the area ,and trying to reach the top area of Mount St. Paul (1028 m asl).

In the course of the two expeditions several kilometers of new active and fossil leads were explored and mapped in the Puerto Princesa Subterranean River. Three vertical caves were explored in the NE area, one of which is now the deepest one in the archipelago. Three huge relict through-caves were explored and mapped in the SE portion. In attempting to reach, or even approach, the top of Mount St. Paul, the surveys demonstrated the great difficulties of working in this kind of terrain.

1. Introduction

The Philippine Archipelago hosts several interesting karst areas. One, in particular, is well known because in 1999 it has been included in the UNESCO World Heritage List. The area is located in eastern Palawan, and hosts the Puerto Princesa Subterranean River (PPSR) (Piccini, 2007).

The outflow of the cave has always been known to local people, and the first explorers were probably pushed to enter the cave searching for drinkable water and swallows' nests. Some writings left by visitors in the first part of the cave bear the dates of April 13th, 1937 and June 20th, 1966, but, as far as we know, the first documented exploration of the underground river was carried out by Balasz (1973). Some years later two Australian expeditions (Traditional Explorations and the Sidney Spel. Soc., in 1980, and Environment Studies Ass. of Virginia, in 1982) surveyed the whole length of the main trunk to a second entrance, the so-called “Day-light Hole”. The Australian cavers also discovered a third entrance following a long left affluent. At the end of these expeditions the total length of the cave was 8.2 km.

In 1989, Italian cavers explored the huge gallery levels above the river and some side branches (De Vivo et al., 1990). In the course of the expedition ca. 5.7 km of new passages were explored and the whole cave was re-surveyed. The following year a small group of Italians went back to St. Paul to continue the exploration of the fossil levels. In 1991, besides carrying out geological and biological studies, almost 3 more km of new galleries were explored. These last explorations brought the total development of the system to more than

20 km (Piccini & Rossi, 1994).

In May 2000 La Venta association supported the production of a documentary, "The River of the Swallows", produced by the Italian *Paneikon* together with Italian network RAI 3 and French *La Cinquième*. The documentary was awarded the first prize at the Film Festival of the International Speleological Congress of Brasilia 2001 and the Grand Prix at the Speleovision 2002 Film Festival.

Finally, in 2007 and 2008 the La Venta Esplorazioni Geografiche association reprised the study of the karst system, extending the investigation to the external slopes of the St. Paul ridge. Several caves were discovered and explored testifying the relevant potential of this karst area. Most of these caves are ancient relict caves which indicate a long and complex speleogenetic history (Piccini et al., 2007).

In this paper a short description of recent discoveries is reported

2. Geographical and Geological Overview

The island of Palawan is the fifth most extended island of the Philippine archipelago; it has a long and narrow form and is predominantly mountainous along its entire length. The portion to the NE of Ulugan bay is bordered to the W by a N-S strike-slip fault, which transects the whole island. The karst areas are mainly developed in Cenozoic carbonate formations and are present in the southern part of Palawan as well as in the N, notably in the area of El Nido which has an amazing coastal tower karst.

The Mount St. Paul ridge, 1028 m high, covers a surface of around 35 km^2 and is made up of massive, dark grey micritic limestone of the Late Oligocene - Early Miocene eras. This formation, thicker than 500 m, rests on Oligocene mudstones, sandstones, marls and volcanites. The carbonate outcrop takes the form of a long ridge running NE-SW, bordered by the Babuyan river valley to the E and the Cabayugan river valley to the W. This structure can be approximately described as uniclinal, dipping to the NW, bordered by faults.

On most of the eastern and southern sides, the limit of the calcareous rocks corresponds to the base of rocky cliffs, which can reach 300 m. Such a structure allows the karst system to receive allogenic water only from the W, along the Cabayugan valley, with the exception of the extreme northern part, where small marginal closed basins are drained by swallow-holes on the eastern slope (Fig. 1). The Cabayugan River is absorbed at a height of ~30 m above sea level, and it flows through the St. Paul cave, re-emerging

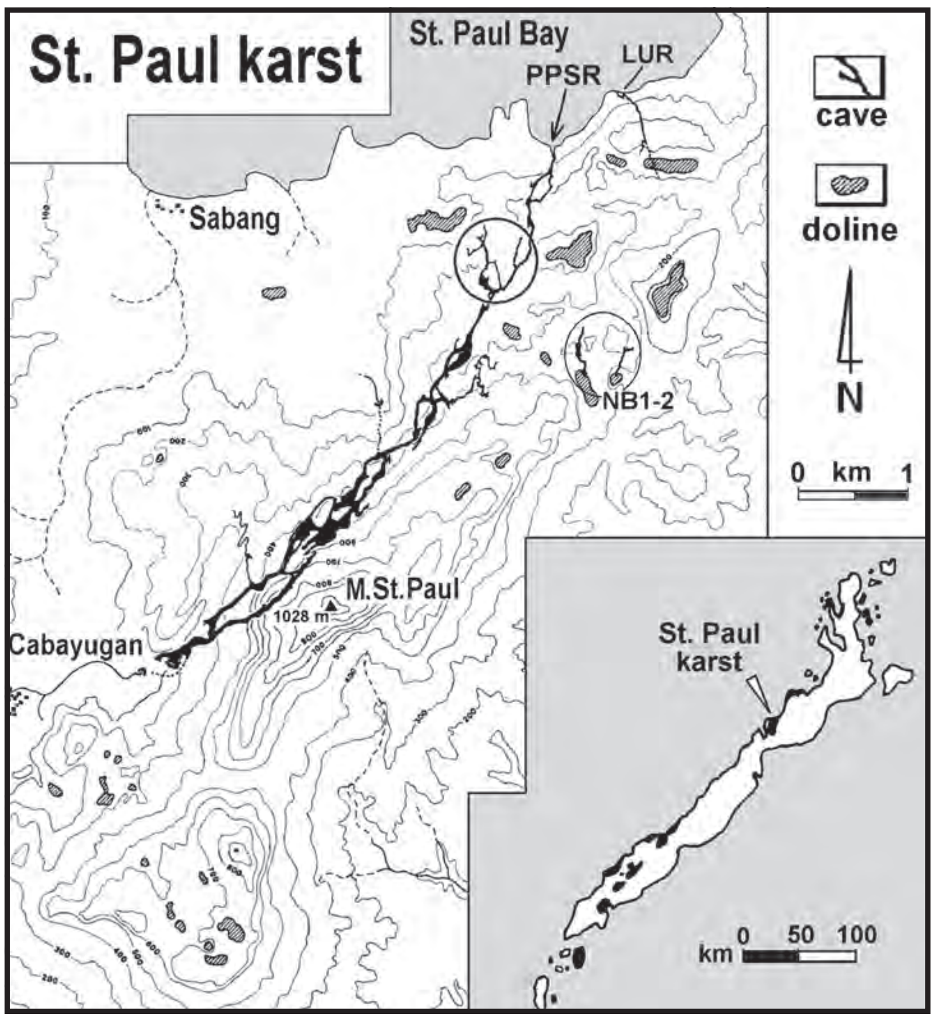

Figure 1: Sketch map of the St. Paul karst area with the location of major caves; circles indicate recent explorations. PPSR – Puerto Princesa Subterranean River, LUR – Little Underground River, NB1-2 – Nagbituka Caves 1 and 2.

on the coast. Beyond the sinking point, the valley is active during the rainy season and shows secondary losses along the edge of the karst. The karst exhibits a typical tower and cockpit landscape.

3. The Puerto Princesa Subterranean River

This large cave system consists of a main axis, which runs NNE-SSW for about 8 km, formed by a large gallery through which the underground river flows, connecting the Cabayugan swallow-hole with the resurgence on the coast. The main gallery has several branches and a few small tributaries, mainly from the left; the main one is the Australian Inlet, which comes from a depressed area slightly to the S of Sabang. On the right side there is only one tributary worth noting, which originates from a brief side passage closed by a sump. The parallel branches extend mainly to the left of the main drain, in its central and southern portions. The largest of these galleries (Cin Gallery) was discovered and explored in 2007. Some of these passages are reactivated during floods, as indicated by the presence of alluvial deposits. In the downstream part of the underground river, some parallel galleries form a sort of ramified network, typical of the estuary's inter-tidal zones.

The main branches are found above the current active course and are segments of an ancient pathway of the underground river, now broken up by collapses or in-fills. The elevation of these galleries, which are generally larger than the current collector, varies from 50 to 100 m a.s.l. Many sections have, however, been affected by collapse, which have increased their size as well as raising the level of floors and ceilings. The largest rock-falls have created a large chamber, called the Italian's Chamber, which is 360 m long, reaches a maximum width of 140 m and a height of 80 m, with an estimated volume of ~2.5 million cubic meters.

One of the most significant hydrodynamic features of the cave is undoubtedly the fact that tides push their influence as much as 6 km inside it, so that it is a site of huge mixing phenomenon between fresh river water and salt sea water. Looking at it in this way, the system may reasonably be considered the world's most classical example of an underground estuary (Forti et al., 1993). From a hydro chemical point of view the St. Paul cave may be subdivided into two different dominions: one, upstream from the Rockpile, characterized by the presence of fresh rain water, showing few, limited mixing effects with salted waters and a constant water flow from upstream to downstream; the other one, from Rockpile to the sea, characterized by mighty mixing effects, by flow direction inversions and by marked vertical variations in salt content (Forti et al., 1993).

4. Recent explorations

4.1 Puerto Princesa subterranean river

Cin Galleries (length 1750 m) - This was the most important discovery made in the PPSR during the 2007 campaign. The main gallery is reached through a flooded branch passage, beginning around 1.5 km from the entrance on the left hydrographic side of the main tunnel. The flooded tract is a small size gallery, with a short low passage that is completely closed when the tide is high. Beyond this tract, a wide gallery with a sandy floor is reached, which runs parallel to the main collector. To the S, the gallery continues among large concretion deposits and sand and mud in-fills, and finally reaches a chamber connected to the Navigator's Chamber. Towards the N, the gallery continues wide for ~200 m and then splits into two branches.

"Frangose" Galleries (length 300 m) - The gallery starts a few dozen meters downstream from the entrance of the Cin Galleries. After an initial narrow stretch and two short drops, the gallery becomes larger and assumes collapse morphology for 100 m, then reduces in size and finally closes on in-fills.

Old River Gallery (length 400 m, vertical range +98 m) - This branch begins on the hydrographic right, about 700 m from the entrance, in the second chamber upstream along the river. It is reached by climbing the rock wall and its overhanging slope of mud and debris for a total height of 50 meters. At the summit a large room with an alluvial terrace shows the levels deposited by the ancient course of the river. From the edge of the balcony, an ample rectilinear gallery, with a triangular section about twenty meters wide, goes on to the S for 70 meters. A slight ascent gives access to a new section characterized by cemented rockfalls that extends ESE for another 50 m.

4.2 The southern sector of the St. Paul Ridge

The extreme southern part of the Mt. St. Paul ridge is characterized by two polygonal mountains, separated from the main ridge. The two elevations have a summit surface, enlivened by long, deep depressions and great sinkholes, whose average altitude is ~500 m for the westerly one, and ~700 m for the easterly one. The two upper surfaces are bordered by steep slopes and cliffs, up to 300 m high.

The two areas are difficult to access and during the 2007 expedition, only the western high, overlooking the village of Cabayugan, was explored, although the other one had many cave entrances, which were observed from the helicopter. The elevation of the area goes from 40 m, which corresponds to the alluvial plain to the NW, to the peak at 615 m at the

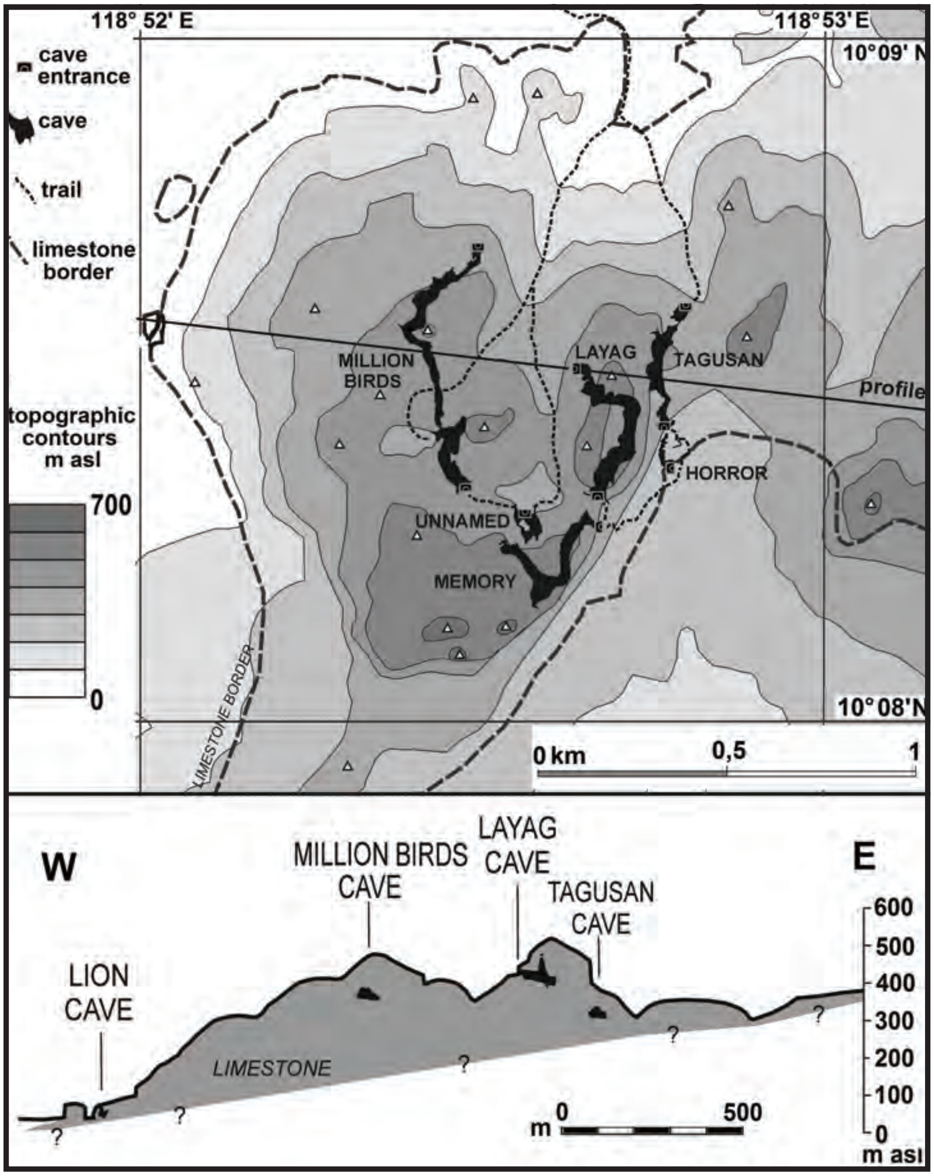

Figure 2: Sketch map of the southern sector of the investigated area, a few kilometers S of Cabayugan, showing the plan development of major caves.

rectangular portal about 20 m wide and 4 m high at the base of the calcareous wall which closes the depression to the NW.

Tagusan Cave (length 515 m, depth - 27 m) - The cave is a natural passage which connects the bottom of two incisions running from S to N under the saddle that separates two cones and its name, "*tagusan*", means "tunnel." The floor of the cave entrance is an accumulation of debris at least 10 m high, beyond which one continues into a gallery 25-40 m wide and 25-30 m high. The gallery contains large and degraded columns and stalagmites.

Memory Cave (length 580 m, depth -38 m) - This cave opens with a portal 15 m high and 25 m wide, on a steep calcareous slope, in the midst of the forest, at an altitude of 360 m. After descending the accumulated debris at the entrance, we intersect a large gallery. The dimensions are impressive, with widths of 25-30 m and heights of 30-40 m. Large blocks, debris, accumulations of guano, columns and stalagmites, which are often heavily corroded, characterize the tunnel. The walls are in places covered with concretions. The gallery seems to extend beneath the narrow valley that separates two karst cones, after about 200 m nearly reaching the surface at the level of a vast depression on the outside. From here, with a sudden 90° turn, the gallery continues for other 180 m, ending with large concretion masses.

Layag Cave (length 550 m, elevation range - 30, +20 m) - A few dozen meters above the entrance of Memory Cave, the gigantic S portal of Layag Cave opens in the right (NE) cliff. The large entrance is raised over an accumulation of collapsed blocks over 15 m high. For more than 400 m

southern extremity of the mountain. In this area six caves were surveyed (Fig. 2). One of these caves, called Horror Cave, is an active swallow-hole that absorbs the waters of a small basin. The other five caves have similar morphological characteristics and consist of large crossing galleries that connect the major depressions, at the centre of the relief, with the external slopes.

Horror Cave (length 220 m, depth: - 64 m) - This is the only cave of the Cabayugan karst area containing an active course of water. The cave is also set apart from all the other known cavities for the smaller size of its conduits and for its morphological features. The entrance is at ~200 m a.s.l., at the bottom of an elongated basin in which Oligocene sandstones appear on the surface, and consists of a the gallery goes on ~40 m wide and ~50 m high, the floor covered with large collapsed blocks. The collapses have deeply modified the conduit giving rise to a huge tunnel with an arched transversal section. After almost 400 m, a pit opens on the right hand wall, which is inhabited by a colony of bats, probably the most numerous of this area. After skirting a large rock pillar, one arrives directly beneath an entrance, situated 70 m above the floor, originating from the progressive collapse of the vault. Further ahead one enters a narrower gallery, which after less than 100 m reaches the outside through a portal about ten meters wide and high, which directly faces out from the cliff towards the Cabayugan plain.

Million Birds Cave (length 1150 m, depth -43 m) - The cave opens at the bottom of a large depression. Once past the usual large accumulation of debris and blocks at the entrance, the gallery reaches a width size of 30-40 m (Fig. 3). 120 m further down it emerges from the slope on the other side of the crest, at the bottom of another karst depression. The gallery continues N for another 700 m, reaching a new exit. The gallery is 20-30 m high and generally ~20 m wide, with walls often covered by the black vertical stripes of oxide crusts, deposited by waters that percolated along the walls. The cave owes its name to the colonies of swallows and bats that populate it, a phenomenon which takes place in all the caves of the Mount Saint Paul area.

Unnamed cave (length 150 m, depth - 36 m) - In the same depression in which Million Birds Cave opens, another large cavern that has no local name is to be found, with a large portal 50 m wide and 25 m high. The entrance floor is the top of a large accumulation of debris at the base of which we reach the floor of the cavern among debris, accumulations of guano, and large collapsed stalagmites. Concretions are generally degraded.

4.3 The northern zone

Steep slopes and calcareous cliffs characterize the eastern side of the St. Paul ridge. Toward the N, the morphology becomes less accentuated and one observes an area characterized by deep depressions that mark the limit of the calcareous outcrop. These depressions, the largest of which is over 2 km wide, have several swallow-holes at their bottom, which are frequently active during the dry season and which feed smaller karst systems parallel to the PPSR. In this area only a rapid survey was made, which has verified the existence of several caves and the exploration of two of them named Nagbituka 1 and Nagbituka 2.

Nagbituka 1 Cave (length 650 m, depth -270 m) - The cave opens inside a small depression furrowed by water and is an active swallow-hole (Fig. 4). The entrance is rather small. After a small collapsed area at the entrance, the cave continues with small jumps, and steep passages along the

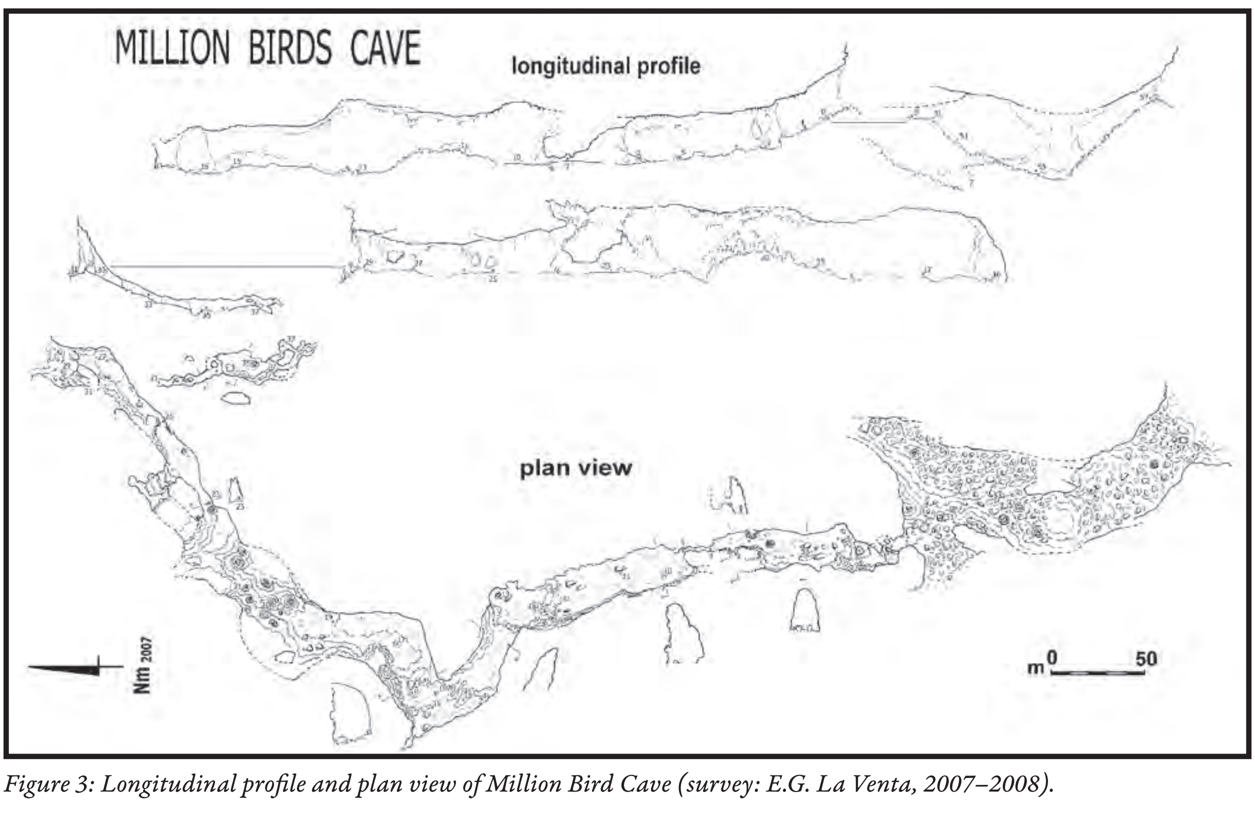

Figure 3: Longitudinal profile and plan view of Million Bird Cave (survey: E.G. La Venta, 2007–2008).

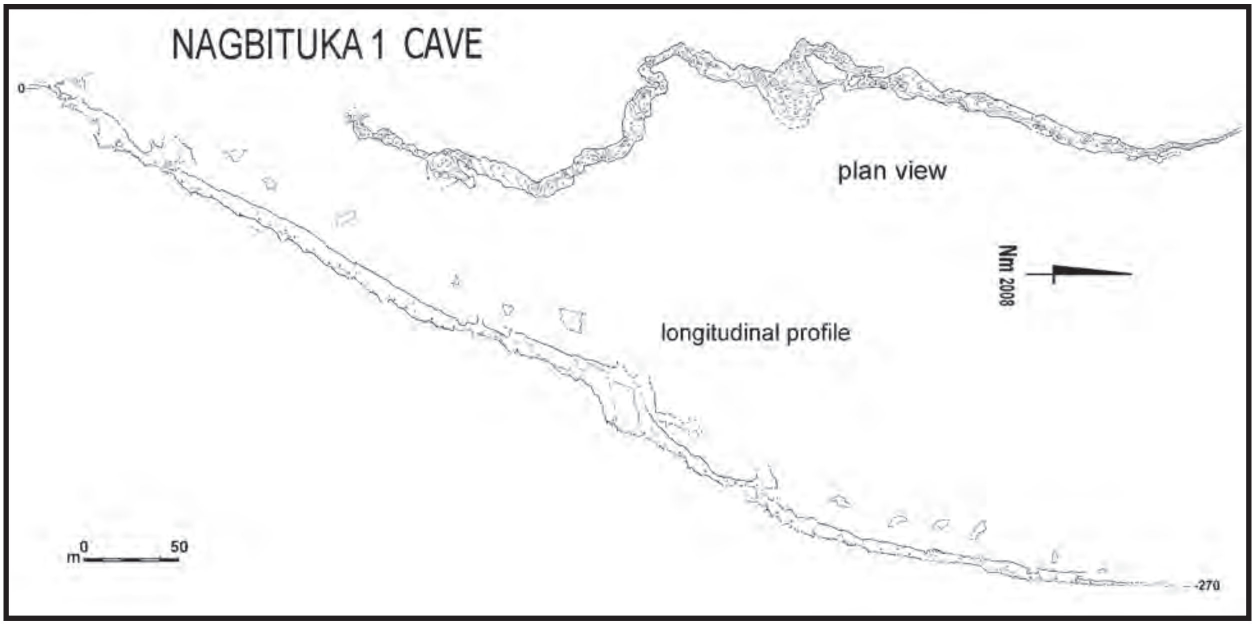

Figure 4: Longitudinal profile and plan view of Nagbituka 1 Cave (survey: E.G. La Venta, 2007–2008).

contact with the sandstone. Continuing for about 30 m meters, a narrow side passage gives way to a large chamber, around 15 m wide. A few meters before this, a small deviation leads to a new fracture, parallel to the first one, which continues descending along the geological contact between limestone and quartz sandstone for a further 100 m. The inclination remains constant, while the water flows in steep passages. Finally, the stream falls down into a large and high chamber with a 40 m waterfall. Descending a steep boulder slope on the left of the chamber we achieved a lower tunnel which continues with minor dip, reducing progressively in dimension. The cave ends with a low and flooded passage just a few meters above the sea level.

Nagbituka 2 Cave (length 500 m depth -132) - The entrance is located some hundreds of meters N of Nagbituka 1, at the bottom of a large doline, and it acts as an active swallow (Fig. 5). After the first small drops, the cave reduces its dimension to a low and narrow passage that is probably completely water filled during the rainy season. A narrow steep passage opens newly on a large descending tunnel, which can be climbed down for ~300 m up to a small pit, which is filled with mud at the bottom. Just a few meters before the rim of the pit, a secondary branch starts with

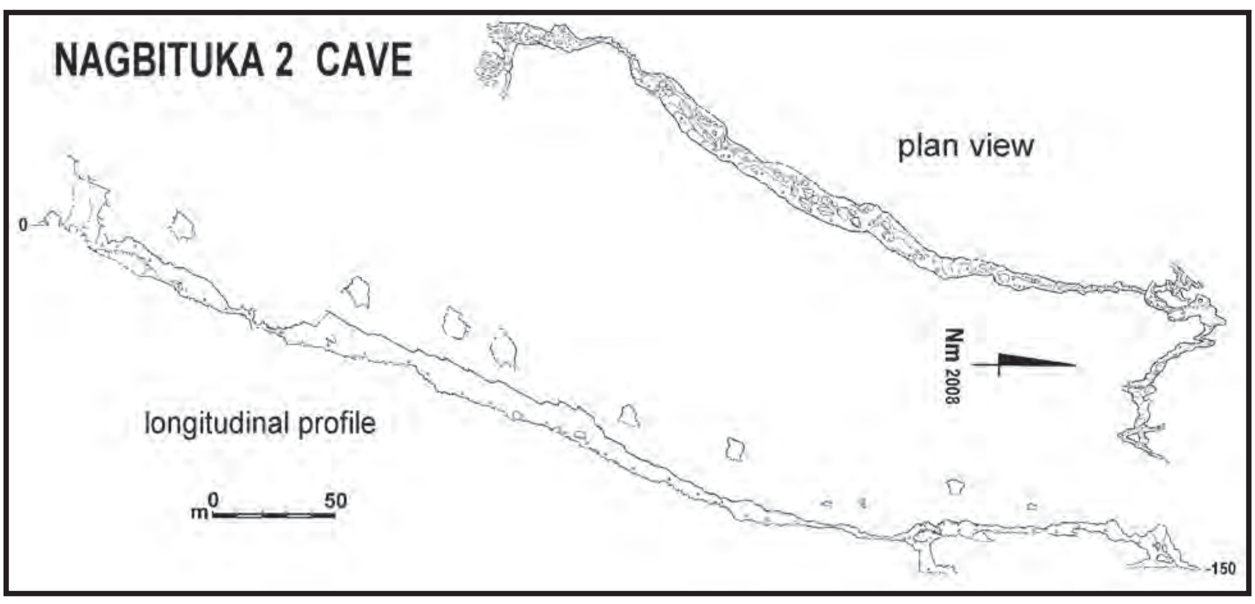

Figure 5: Longitudinal profile and plan view of Nagbituka 2 Cave (survey: E.G. La Venta, 2008).

Name	Elevation m a.s.l.	Vertical range m	Length m
Puerto Princesa Subterranean River	0	+ 100	24000
Little Underground River	0	+ 10	ca. 800
Nagbituka 1 Cave	290	- 270	650
Nagbituka 2 Cave	250	- 132	500
Lion Cave (lower S entrance)	50	+ 15	182
Tagusan Cave (South Entrance)	305	- 12, +15	515
Horror Cave	205	- 64	183
Layag Cave (S entrance)	405	- 40	583
Memory Cave	365	- 38	580
Millionbirds Cave (S entrance)	410	- 43	1150
Unnamed Cave	400	- 35	112

Table 1: Lengths and depths of explored caves.

a dry and beautiful gallery with several concretionary formations. The gallery represents and old phreatic level and reaches again the active pathway after a length of ~100 m. The stream enters a narrow passage that could not be passed due to the presence of much water.

5. Conclusions

St. Paul karst is surely one of the most relevant and still promising speleological areas of the Philippines (Table 1).

The PPSR can be considered as a well explored cave although many minor branches have to be further investigated. The most promising areas are, however, the N and the S sector of the mountain ridge, where many new cave entrances are visible by over-flying the area and on aerial photos. Unfortunately the extreme roughness of the surface, characterised by high and sharp limestone blades, has not yet allowed a complete recognition of the two areas.

Acknowledgements

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(Further information can be found at http://www.laventa.it)

TLÁLOC 2008 EXPLORACIÓN -- MEXICO-ITALIA, HUEYTAMALCO, PUEBLA, MEXICO

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The word Hueytamalco, comes from Náhuatl language: "huey" meaning huge, "temo" for descend, "ahco" for ascent, and together meaning "huge descends and ascents" or "slopest hills." This municipality is located in the northwest part of the state of Puebla in the northern hydrographic slope in 19º 51' 03"N and 20º 12' 42"N and 97º 12' 48"W and 97º 22' 42"W, being contiguous to the north with the state of Veracruz; to the east with San José Acateno and the state of Veracruz; to the south with Teziutlán and the west with Tenampulco and Ayotoxco of Guerrero.

The complicated topography and warm and humid climate strongly influences the vegetation with high perennifolia forest and mesofilic forest in the mountain and varied fauna. An intricate network of cavities in the ubiquitous limestone were partially explored by speleologists in 2005. The karst topography influenced the Pre-Hispanic religion, which has coexisted with Catholicism since the conquest by Spaniards in 1522. This mixture has resulted in a cultural wealth.

The objective of speleological explorations on Hueytamalco from March 10–28, 2008, was to continue exploration conducted in 1998 and 2003, and to evaluate its development, since the topography and the development of some cavities indicated a possible connection of systems. Exploration continued in grottos: Miquizco, Cochinos (Pigs), Cueva del Viento (Wind Cave), and Mama Mia Cave.

The objectives of the exploration were: (a) To cement a relationship between the two countries, México and Italy to develop team work; (b) To evaluate exploration techniques to both complement and improve each other; and, (c) To complete prior explorations which according to underground topography offer the possibility of connections between cave systems.

1. Antecedentes
1.1 . Toponimia
La palabra Hueytamalco, proviene de dos vocablos "huey", grande; "temo", bajar, descender, y "ahco", arriba; formándose el siguiente significado: "Grandes Bajadas, Grandes Subidas" o "Cuestas muy Inclinada".

Localización: Este municipio esta en la parte noroeste

del estado de Puebla. Sus coordenadas geográficas son los paralelos 19º 51' 03" y 20º 12' 42" de latitud Norte y los meridianos 97º 12' 48" y 97º 22' 42" de longitud Occidental. Extensión: El municipio tiene una superficie de 242.38 kilómetros. Colindancias: Norte con el Estado de Veracruz, al Este con San José Acateno y el Estado de Veracruz, al Sur con Teziutlán y al Oeste con Tenampulco y Ayotoxco de Guerrero.

1.2.Orografía
La mayor parte del municipio pertenece a la regiones morfológicas, del declive del Golfo de México, solo el extremo Sur, a partir de la cota 1,000 pertenece a la Sierra Norte.

El declive del Golfo es el declive septentrional de la Sierra Norte hacia la llanura costera del Golfo de México que se caracteriza por sus numerosas chimeneas volcánicas y lomas aisladas; en tanto que la Sierra Norte o Sierra de Puebla esta formada por Sierras más o menos individuales y paralelas, comprimidas las unas a las otras y que suelen formar grandes o pequeñas altiplanicies intermontañas que aparecen frecuentemente escalonadas hacia la costa.

La característica orográfica del municipio es un constante e irregular descenso en dirección Sur-Norte, bastante marcado en la parte austral y que se va suavizando conforme se avanza al Norte, donde ya pierde la característica montañosa inicial. También presenta el declive algunos cerros pequeños aislados; la altura del municipio oscila entre 250 y 1,700 metros sobre el nivel del mar.

1.3. Hidrografía
El municipio se localiza en la vertiente hidrográfica septentrional del estado de Puebla, vertiente constituida por las cuencas parciales de los ríos que desembocan en el Golfo de México, y se caracterizan por sus ríos jóvenes impetuosos; varios de ellos son importantes, en su mayoría bañan el territorio en dirección sur-norte y destacan los siguientes: El río María de la Torre, que por más de 18 kilómetros, baña el Sureste; es uno de los principales formadores del Nautla. El arroyo Puente de Piedra que nace al Norte de la localidad de Hueytamalco; recorre el centro del municipio y se une al Tlacuilolapa formando el Arroyo Soltero, el cual desemboca en una laguna cercana a la costa, al Norte de Nautla, los ríos Xoloatl, Pahuapam y Mazolapa bañan el sureste y se unen formando el río Las Margaritas, que recorre el centro del Municipio hasta unirse al Xoyoquilla, formando el Río Cedro Viejo, que sirve de límite con Acateno. Por último los arroyos Poza Verde, Blanco y Mixiate bañan el Norte y se une al río Cedro Viejo. También cuenta con cantidad de arroyos intermitentes que se unen a los ríos ya mencionados.

1.4. Clima
Dentro del municipio se presenta la transición de los climas templados de la Sierra Norte, a los cálidos del declive del Golfo; se identifican dos climas: Clima semicálido subhúmedo con lluvia todo el año. Es el clima predominante se presenta en la zona Sur del Municipio. Clima Cálido Húmedo, con abundante lluvia en Verano; Se identifica en la zona Norte del Municipio.

Principales ecosistemas: La mayor parte del territorio del municipio está destinado a actividades agropecuarias; existen grandes extensiones de pastizales cultivado de la especie estrella africana, al centro y norte; pastizal inducido, aunque en áreas más reducidas del Sur. Sólo cuenta con áreas reducidas de selva alta perennifolia con vegetación secundaria arbustiva a lo largo del río Cedro Viejo y bosques mesófilos de montaña con especies tales como Jaboncillo, liquidámbar, Pino colorado y encino. Dentro de la fauna, podemos señalar que el municipio existe una gran variedad de aves, de reptiles, así como también existe muy poco venado cola blanca y el temazate. Recursos naturales: Existen piedra caliza, arena y pozos petroleros sin explotar.

1.5. Informe de Exploración
Del 15 al 25 de marzo de 2008 en Atepetaco, Hueytamalco, Puebla, Cuevas "Viento", "Mama mía", "Cochinos" y "Miquizco".

Proyecto compartido: Grupo Mexicano URION e Italianos Sociedad Espeleológica Italiana.

Autoridades y ciudadanos notificados: Presidente Municipal de Hueytamalco, agentes de Turismo y Protección Civil.

Titulares de las propiedades donde se encuentran las cuevas en Atepetaco.

La expedición 2008 Tláloc comenzó a mediados de marzo, con el principal objetivo de continuar las exploraciones ya realizadas anteriormente en el pueblo de Atepetaco, municipio de Hueytamalco, estado de Puebla, México.

Tomaron parte en la expedición espeleológica algunos grupos espeleológicos provenientes de la Lombardia, dos de Sicilia, y varios miembros del grupo URION, el grupo espeleológico de la Ciudad de México, que también da la bienvenida a espeleólogos de otros lugares en México.

El objetivo primordial, se refirió al área principal de investigación encaminada a la localización de la resurgencia de Miquizco una cueva explorada en el 1998 y en el 2002, cuando el agua de un abundante flujo perenne se pierde en grandes salones colapsados al final de la cavidad. Sobre esta referencia es importante decir que fuimos más allá de las expectativas, pues la gruta que marca la resurgencia del sistema no es sólo una, sino dos, y que en última instancia, parecen estar vinculadas en un sistema mucho más complejo.

Después de haber organizado el campamento, de acuerdo con Don Mariano, presidente municipal de Atepetaco, se preparó un panel con las conclusiones de las cuevas ya conocidas y los mapas del lugar, que de inmediato se emplearon de marco para el plan de trabajo.

En primer lugar regresamos hasta el Río Garitta, Para tratar de localizar una llegada desde el lado izquierdo del río, y luego continuar la exploración de Cochinos, cueva también parcialmente exploradas en 2002, con seguimiento tanto aguas arriba como aguas abajo. Fundamental también en la realización de fotografía y vídeo de la cueva principal.

El primer día el grupo en busca de la resurgencia no aporta resultados, mientras se explora la parte río arriba de la cueva Cochinos por unos cientos de metros y se realiza la fotografía y vídeo en la cueva de Miquizco, en particular en la parte del valle, donde el río fluye sobre un plano inclinado.

Se obtienen resultados notables al día siguiente. Algunos de nosotros acompañados de Sergio, entramos en una cavidad parcialmente conocido por los lugareños, como "Viento" por la abundante corriente de aire que se escapa, y se descubre un gran número de galerías que a veces se entrecruzan entre sí.

Pocas horas después, a pocos metros de distancia, detectamos la famosa resurgencia tanto tiempo buscada, que surge a partir de la pendiente entre los cantos rodados. La travesía de los exploradores es de brechas entre rocas y después de unas pocas decenas de metros se ingresa en un túnel de gran tamaño con las paredes tachonada con vieiras (conchas), y la maravilla es tan grande que uno no puede dejar de exclamar "Mama Mía". Y este sería el nombre de la cueva.

En el ínter, exploramos la parte baja de la cueva Cochinos, que ahora parece ser la más difícil, de hecho así después efectuar el descenso del poso 15, continuamos un meandro donde se había detenido la expediciones anterior. El meandro está casi completamente inundado hasta el punto

en que en cierto tramo la profundidad es desconocida, y se recorre casi bajo el agua. Superando este obstáculo la cueva se vuelve bastante amplia, pero después de varias decenas de metros una gran colada de calcita impide continuar, sin embargo en la parte superior de la colada hay motivos de esperanza, y de hecho después de un tiempo para realizar una desobstrucción con los pocos recursos que teníamos logramos avanzar.

La cueva se prolonga durante varios cientos de metros, a un deslizamiento de tierra bloqueando el túnel, encontramos un ramal a la derecha, pero después de haber descendido un poso de 8m proseguimos cerca de 50m y nos detenemos frente a deslizamientos de tierra.

Regresando un poco, examinamos más detenidamente en la galería principal de los deslizamientos de tierra, y podemos encontrar un pasaje entre las rocas que podemos superar.

Exploración referente a los días siguientes. Proseguimos la exploración en la Mama Mía y el Viento con grandes descubrimientos, recorriendo cientos y cientos de metros de las grandes galerías, la topografía se realiza con una extraordinaria rapidez, el entusiasmo es realmente grande.

Durante el descanso se descubren otras cuevas como la Enchonada, un pozo de cerca de 50 metros a la base la cual presenta una galería con un cause de agua que corre tanto hacia arriba como abajo. La Enchonada es la cavidad conocida al este del banco calcáreo de la zona.

Analizando los dato topográficos, descubrimos que la parte superior de Cochinos llega a las inmediaciones del campo cercano y por consiguiente es altamente probablemente localizar otra entrada. Encontramos uno y lo exploramos por cientos de metros, pero sin poder conectarse a Cochinos.

Mientras tanto, las exploraciones de las cuevas Mama Mía y del Viento dar resultados notables, y se continua con la topografía.

Mientras un grupo organiza una sesión fotográfica entrando en la cueva del Viento, en la parte superior se descubre un pequeño lugar entre las rocas colapsadas. Este ascenso permite el acceso al colapso de las grandes bóvedas que primero se elevan y después descienden a un punto en el que se oye corre el agua. Superando un estrecho paso entre las rocas nos encontramos en una galería intersecada por un curso de agua, no parece cierto, pero estamos en Mama Mia!, No creemos haber conectado las dos cuevas tan fácilmente.

En Cochinos continuamos más con la topografía que con la exploración. Habiendo transcurrido el deslizamiento de tierra se abre una galería de un centenar de metros, pero una barrera adicional causada por un denso colado de calcita nos impide seguir adelante. Sólo un pasaje estrecho y angosto donde precipita el curso del agua nos da una esperanza para la futura exploración.

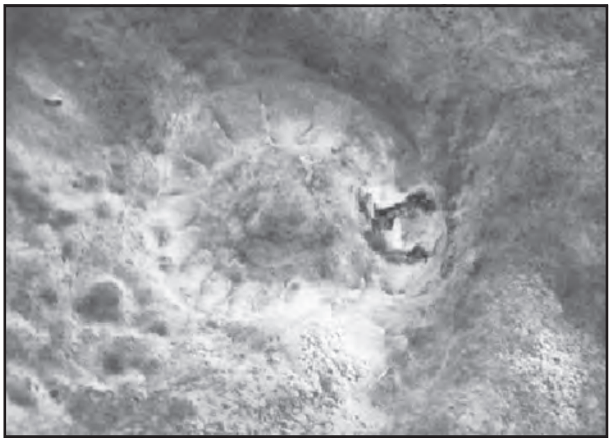
Las salas superiores de Mama Mía es poco probable que continúen, mientras que la galería principal del Viento, como hemos dicho, se conecta con la Mama Mia. Entre los principales ramales que se ven, hay un túnel fósil parcialmente explorado por Giancarlo, y que posteriormente se denomina “Giancrappola”. A través del paso entre las rocas se accede aun conducto con un abundante curso de agua.

Por lo tanto, el último día en el campamento pudimos explorar y topografía ésta zona, extendimos una cuerda de Arianna en la zona de derrumbe, descendimos al conducto que proviene de la montaña y lo proseguimos unos 200 metros, después de lo cual entramos a un deslizamiento de tierras se caracteriza por grandes bloque de otro colapso. Detenemos la topografía y seguimos algunas decenas de metros, pero el paso entre los cantos rodados se convierte cada vez más peligroso y consideramos que si se elevara el nivel de agua en tendríamos el peligro de ser atrapados. Logramos conectar y seguir adelante donde hallamos el tronco, indicación clara de que estamos casi en el lado opuesto del derrumbe. Volviendo abajo sin embargo, el río continúa durante unos 50 metros y a continuación un pequeño lago sifonante bloquea el camino a otros ramales misteriosos.

Ciertamente satisfecho, pero a regañadientes, desmantelamos el campamento y nos movemos desde Puebla a Chiapas. El viaje de considerable longitud, nos permite desarrollar algunos datos sobre la topografía, en el camión descubrimos que la distancia entre la cueva del Viento (zona Giancrappola) y Miquizco es sólo 8m. Por consiguiente a cerca de 5000m de desarrollo del complejo Mama Mia – Viento podrían existir al otro lado más de 1500m de Miquizco, Algunos sugieren volver, pero ahora ya estábamos en la carretera e incluso se había hecho una conexión, habría habido una serie de numerosas posibilidades para la exploración. Será la base para una futura exploración.

2. Resultados:

Se logro la topografía de varias cavidades conocidas por la comunidad como “Miquizco”, “Cochinos”, “Viento” y “Mama Mía” (denominada), obteniendo una exploración y topografía de cerca de 5,200 metros solamente entre Viento y Mama Mía, ubicando tres entradas en Viento y uno por resurgencia en Mama Mía, interconectadas logrando un sistema desarrollado, ubicadas todas con un GPS, con una extensión máxima de 1615 mts, con un desnivel de altura de 68 mtrs; respecto a la hidrología durante todo el trayecto principal de Mama Mía se ubicaron corrientes de agua aún que estamos en la estación seca de primavera, excepto en las galerías de arriba fósiles, en Viento solo habría lodo y chimeneas de escurrimientos secos seguramente por la temporada, en Cochinos y Miquizco se sitúo también corriente acuífera quedando según la topografía muy cercanas a interconectarse con el sistema. Se hallaron restos fósiles, en cuanto a fauna solo se localizaron murciélagos, amplifígidos e insectos.



Análisis Geomorfológico de las cuevas de Hueytamalco, Sierra Norte de Puebla.

Por: Alejandro Torres Cid el Prado.

La Región Karstica de Hueytamalco pertenece a las estribaciones Orientales del gran Macizo Montañoso de la Sierra Norte de Puebla. Existe muy probable la intersección con la Sierra Negra en cuanto a estructura y unidad Geomorfológica se refiere, así estas dos sierras junto con la sierra de Zongolica y la Sierra Mazateca forman la parte de mayor potencial Karstico de la unidad geotectónica mayor es decir la Sierra Madre Oriental.

Es muy probable que debido que debido a dos factores Geotectónicos la región de Hueytamalco sea en la parte inferior de la meseta del mismo nombre la zona de resurgencias y que el karst inicial sea la parte alta de Cuetzalan, Puebla.

3. Propuestas de Análisis:

Propuesta numero uno: Un factor inicial del desarrollo karstico desde Cuetzalan hasta Hueytamalco es la denominada Fuerza de Coriolis que indica que la tierra gira de W Oeste a E Este así siguiendo Hipotéticamente un cauce lineal de estas dos regiones el cauce hidrológico indica que el agua en su patrón mas uniforme viaja en sentido contrario de la rotación terrestre cuando la declinación de la vertiente del Golfo indica que debe de viajar de W a E el flujo de el agua indica lo contrario esta viaja de E a W.

Propuesta numero dos: Los Plegamientos de estas dos Regiones son Geológicamente de etapas similares solo que los Anticlinales de Cuetzalán tienen mayor altura sobre nivel del mar y en su parte superior (entradas de cuevas) presentan un desarrollo karstico mas activo y el tipo de kartstificación en mas desarrollado debido a que la acidez del agua se debe a que esta es mas fría por ser una zona mas alta y por ende una zona con patrones climáticos de menor temperatura; mas fríos que en la región de Hueytamalco los cuales son los últimos afloramientos de un macizo de caliza menos pura la cual presenta contactos Litológicos con roca volcánica en varias de sus cuevas.

En su parte final de las cuevas de Hueytamalco el grado de inclinación de los conductos es muy leve esto indica que el cauce a encontrado su nivel de base así lo indican todas las cuevas exploradas a las cuales se acceso para este estudio desde las resurgencias.

Objeciones a estas Propuestas de Análisis. El análisis de las Cartas Geológicas arroja que el grado afallamiento Geológico es discontinuo es decir la hidrológia entre estas dos regiones es bisectada y posiblemente desviada a otras resurgencias mas locales refiriéndonos a la región baja de Cuetzalan, ahora bien, a menos de 17 km. existe un cañón no del todo conocido que conduce el mayor afluente de agua hacia Hueytamalco es decir esta agua hipotéticamente viene de las resurgencias de Cuetzalan y se interna nuevamente en las cuevas de Hueytamalco siempre y cuando se explore en su totalidad este cañón y se realicen exploraciones buscando esta posible continuidad.

Podemos pensar que las cuevas de Hueytamalco son la parte final de esta unidad Geomorfológica Cuetzalan - Hueytamalco por varios factores:

(1) El grado de escalonamiento en algunas cuevas como (Viento) indican de que siguen un mismo plano de falla esta cueva posee techos planos de poca o casi nula inclinación confirmado por algunos macarrones que señalan esta casi nula inclinación es decir sigue a partir de un mismo estrato rocoso su evolución hacia el interior pero este no varia en su inclinación solo varia su nivel de base y este evolución es de manera moderada es decir la ecorrentia es de tan solo una lamina de agua de 5 a 10 cm de espesor.

(2) Mama Mía es una cueva de poco caudal esto solo durante el estiaje ya que durante las lluvias es obvio el modelado de las paredes ya que en su mayor parte son conductos forzados y donde se ve que el caudal llega hasta los 2.10 metros de altura el volumen por metro cúbico no ha sido precisado. en su parte mas baja la cueva tiene intrusiones señal de antiguos flujos volcánicos previos a la sedimentación de la caliza estas intrusiones son de pedernal con algunos basaltos. En esta cueva cabe señalar la aparición de Turritellas un Gasterópodo de diferentes Épocas del Periodo Cretácico este fósil vivió hace 20 a 65 millones de años lo que habla de un grado de sedimentación relativamente alto.

(3) Dos ojos es una cueva indicativo de una resurgencia con un caudal más constante y que alimenta en el exterior un arroyo de consideración y que es muy probable sea un afluente de la Cueva Mama Mía.

(4) Cochinos este presenta escalonamientos debido a un desarrollo mas activo con presencia de planos de falla y también es parte de la red de afluentes que alimentan la Cueva Mama Mía.

4. Concluciones

1. Esta red de cuevas las cuales están conectadas en su parte media son espeleológicamente hablando parte de un sistema no explorado en su totalidad, ya que es comprobable su conexión pero falta aun la exploración de la meseta alta de Hueytamalco la que comprobaría nuestras propuestas iniciales o refutaría estas mismas, así siendo Mama Mía el conducto principal y las demás son afluentes de segundo y tercer orden; al encontrar su nivel freático a muy poca profundidad estas se asolvan o tienen paso restringido al espeleólogo lo cual lo deja en una interrogante mas, pero al estar a menos de 60 km de la costa y encontrarse esta a 600 msnm señala su muy posible terminación ya que la llanura costera se encuentra muy pronto rumbo hacia Martínez de la Torre donde las cartas geológicas indican la ausencia de sedimentos calizos y la aparición de suelos no sedimentarios y donde el clima posiblemente puede ser un factor favorecedor de procesos de karstificación pero la Litología serie un factor predominante es decir lo volcánico prevalecería sobre lo sedimentario al descender la vertiente hacia el Golfo de México.

2. Afortunadamente la cueva se encuentra en buenas condiciones y sin mucha contaminación de restos orgánicos e inorgánicos (por su ubicación en la serranía y auxiliado por las corrientes de aire), lo que evita que se originen gases pudiendo ser la cueva de bajo riesgo en este aspecto de envenenamiento o asfixia.

3. No se ha concluido la exploración de esta zona pues todavía falta topografíar y verificar en otros puntos que parece que se interconectan de acuerdo a la topografía, si pudiera ser que tuviera continuación este sistema se podrá extender, seguramente la tiene y creemos que este no sea el final.

4. Por último hay que destacar que siempre se debe respetar la idiosincrasia de la comunidad, solicitar permisos por escrito a los dueños, comunidad, autoridades municipales y estatales, trabajar en conjunción con algún grupo local si existe e ir preparados para cualquier situación porque siempre la prioridad debe ser la seguridad de todos.

Aportes especiales:

Ángelo Iemmolo, Giorgio Mario Pannuzzo y Rodrigo Álvarez Rangel en informe de exploración.

Alejandro Torres Cid el Prado (Geólogo Mexicano) en el Estudio Geomorfológico.

Andrea Corna en Fotografía.

URION en la revisión e integración del proyecto.ç

EXPLORATION, GEOLOGY, AND HYDROLOGY OF SUGAR RUN CAVE SYSTEM, VIRGINIA

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Abstract

The Sugar Run Cave System contains 36.2 km of surveyed passages and reaches a depth of 219m. It is the second longest cave system in Virginia and has three entrances. The longest pitch in the cave system is 52 m. The Sugar Run Cave System was explored and surveyed from 1990 to 2002.

The overall layout of the cave can be described as a base level trunk passage carrying a large active stream through the extent of the system. Two somewhat parallel paleo trunks likely indicate ancient flow routes. The first of these has numerous connections with the active stream. The older is more removed and has only a few connections. The active and paleo trunks generally follow the strike at low gradient.

Numerous small infeeders join or intersect the primary passages by flowing down the dip. Typically they form dendritic patterns of complex vadose development. Significant elevation changes are encountered when following them any distance. Throughout the cave many domes and pits have made exploration quite challenging. Minor faulting perpendicular to the strike accounts for several major passage trends and has also posed challenges to exploration by terminating traversable passage at the upstream end of the system.

The Sugar Run Cave System is developed along the northeast facing side of Sugar Run Mountain. This is one of the few mountains that run almost perpendicular to the major SW-NE trend of the valley and ridge province. The orientation of the mountain is related to the Bane Dome structure, cored by exposures of Cambro-Ordovician carbonates, mostly dolomite. The cave is formed in undivided limestones of Middle Ordovician age (Rader and Evans 1993). On the flank of Sugar Run Mountain, this unit is about 300 m thick and has a dip ranging between 20° and 40° degrees into the mountain. Main cave passages lie along the NW-SE strike and along faults trending roughly N-S. All lesser passages follow a strike-dip joint controlled pattern that is common in Virginia's Middle Ordovician caves.

The cave system currently carries the underground flow of the Sugar Run stream, following the strike with a shallow gradient to its resurgence at Wabash Spring 3 km away. Dye studies have confirmed this flow path.

CAVES OF TONGZI, WULONG COUNTY, CHONGQING, CHINA

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Abstract

In April 2007 and 2008 a British and American expedition of the Hong Meigui Cave Exploration Society explored the karst and caves near Tongzi and Jielong in Wulong County, China. The team surveyed 25 km and identified numerous new karst features, caves, and springs.

Highlights of the discoveries include: Lao Chang Dong (Old Factory Cave), a 3,146 m long and 98 m deep cave complex, including old trails and miner's artifacts; Shang Hetao Wan Dong (Upper Walnut Bend Cave), the town dump, which was connected to nearby Leng Dong (Cold Cave), forming a 471 m deep, 8,489 m long system; Quan Kou Dong (Spring Mouth Cave), a 116 m tall entrance with a 3.5 m^3/sec stream and amazing airflow, surveyed to 3,560 m; and Yan Tang Ping Dong, a tortuous cave explored to -154 m with great potential.

Reconnaissance of a several large closed valleys in Jielong township yielded beautifully decorated Xiniu Dong (length – 846 m, depth – 56 m), San Cha Dong, (length – 1,391 m, depth – 74 m), Jiu Gou Ba Shui (length – 553 m, depth – 87m), Long Kou Dong, a major insurgence in the western doline (length – 177m), and many more cave entrances and shafts that were not entered.

The team also continued dye tracing efforts in the Houping/Tongzi/Jielong area to delineate groundwater flow paths. Excellent leads and caves remain to be explored during expeditions planned for spring 2009.

SUB-ALPINE KARST IN NORTHERN NEW MEXICO

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Abstract

Over the past twenty years, cavers from Pajarito Grotto, the club representing northern New Mexico, have been actively studying karst features in San Pedros Parks, a wilderness area set aside by the Santa Fe National Forest. This region of the state is mountainous with elevations of 2400-3000 m asl. The wilderness contains 166 km^2 of high elevation terrain, mostly rolling gentle topography with large wet meadows separated by dense stands of spruce and mixed conifers. The area receives approximately 89 cm of annual precipitation, mostly in the form of snow. Precambrian crystalline rock, namely red granite, is found outcropped on top of San Pedro mountain. Along the northern and northeastern flanks, outcrops of Pennsylvanian strata consist of the Magdalena Group, with Madera limestone as a predominant cave-forming member. Drainage from the wetlands on top of the mountain flows over the Precambrian bedrock, following streams down through this near-alpine karst area to sink and emerge in springs and caves. Because of the snowfall, exploring the region is usually done during summer and fall seasons. Frequent downpours and heavy thunderstorms occur during the afternoons of summer, making interesting backpacking and camping trips. Roads are non-existent in San Pedros Parks, but end just outside the boundaries in the adjacent National Forest areas. Three enterable caves have been explored and mapped. Potential exists for more cave discoveries, as ridge-walking has located springs, small holes and steep canyons paved with limestone.

Gallina Cave is well-known locally and is situated at 2780 m asl. It has about 0.7 km of mapped passage with an active stream throughout. The water temperature is 5.5ºC, and the air is 9ºC. The upstream end has been dived with scuba but the water emerged from a tight hole unable to fit our diver. Bear have been known to hibernate inside the entrance, as evident from their paw prints in the snow. La Cueva de Los Dos Ojos is a fluviokarst system upstream from Gallina Cave, situated at 2970 m elevation. It also has a running stream of similar temperature, and was mapped to be 263 m in length, and about 24 m deep at the downstream end. Because of the difficulty in hiking up canyon through dense undergrowth to this cave, 10 years elapsed (1990-2000) before it was completely explored and mapped. Thunderhole, our most recent discovery (2005), is the most difficult to explore, as it has very little walking passage. Forward progress has been made by digging, moving boulders, and crawling through gaps in the breakdown. It has been surveyed for 475 m to a depth of 35 m so far. The arkosic cap that overlies the cave has caused considerable instability, with collapses and loose breakdown throughout the system. The cave is dangerous due to rock-fall and the potential for flooding during locally-heavy storms. The entrance stream flows throughout the cave, and a second stream is encountered along with an upstream branch of cave. Thunderhole has potential to be much longer, as dye tracing by the Geological Survey in 1953 indicated that the resurgence of the stream is at a spring approximately 130 m lower in elevation and 1.2 km away. These three caves and the surrounding sub-alpine karst are unique for New Mexico.

STUDY OF THE LOCALIZATION OF THE PITS IN THE PLATEAU OF JURD AFQA (MOUNT LEBANON) USING A GEOGRAPHICAL INFORMATION SYSTEM (GIS).

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The Jurd of Afqa (central Mount Lebanon) represents a considerable development of the karstic phenomena, particularly on the surface, in the shape of vast dolines fields that give the landscape its lunar aspect. It is on this desolate plateau that prospecting led by the ALES have enabled on one hand the rectification of the coordinates of the pits known by the Lebanese speleologists, and on the other hand to log the location of the new pits along with their specifications.

The total information collected concerning around thirty pits (position and depth) has led to the creation of a geo referenced database that can be exploited in a Geographical Information System.

We have thus conducted research in order to determine whether or not there is a preferential localization of pits in the karstic mass of Jurd Afqa. As a matter of fact, this area is characterized by a rather homogeneous carbonated layer (formation of Sannine, Cenomanian), around 600m thick and sub horizontally structured. It was a question, in particular, of highlighting the factors behind the placement of the pits using a G.I.S.

1. Introduction

Le Liban, petit pays de la façade orientale de la Méditerranée (Fig. 1) se caractérisé par l'existence de relief élevé, dont le substrat géologique est constitué d'épaisse séries carbonatées

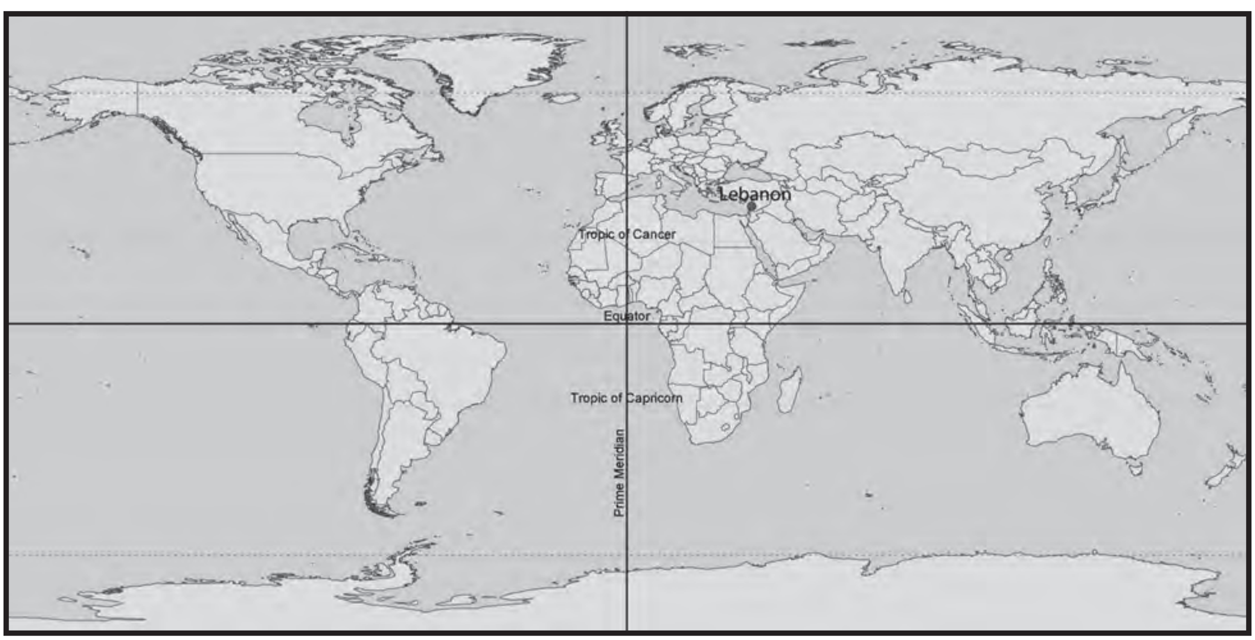

Figure 1 : Carte de localisation du Liban.

dans lesquelles se sont développés d'importants systèmes karstiques. Parmi ces systèmes figure le plateau d'Afqa, situé dans la partie centrale du Mont Liban (Fig. 2). Or, cela fait déjà assez longtemps que les spéléologues libanais parcourent ce secteur à la recherche de cavités à explorer. Dans une première phase 17 puits ont été recensés et documentés.

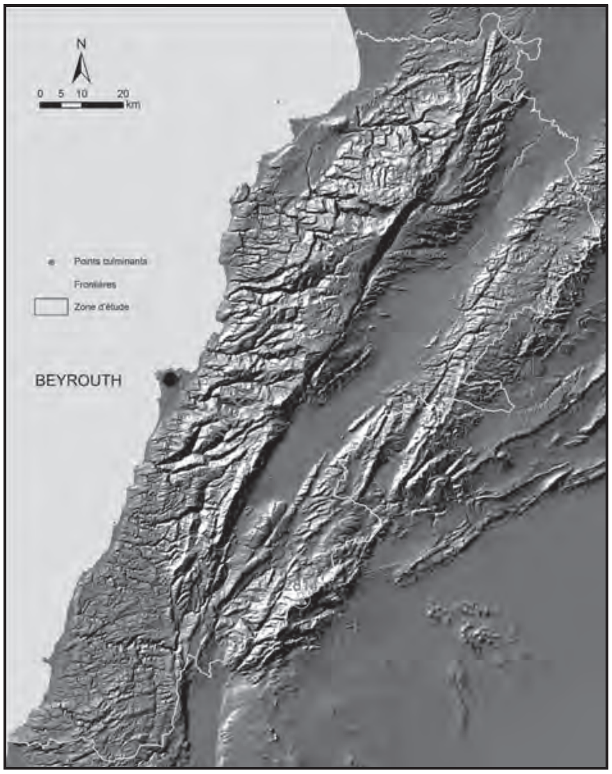

Figure 2 : Carte de localisation de la zone d'étude du plateau d'Afqa par rapport au Liban (Source : CGIAR-CSI SRTM 90m Database (http:// srtm.csi.cgiar.org)).

Comme l'un des spéléologues expérimentés de l'ALES, Christian Akhrass, était intrigué par ce nombre relativement important de cavités présentes dans cette zone d'étendue relativement restreinte, il a mené des investigations plus poussées, notamment afin de contrôler la localisation de ces sites à l'aide d'un GPS. Dès lors, l'ALES a commencé en 2003 une campagne de prospection systématique sur le plateau d'Afqa. Précisons que la présence de champs de mines disséminés sur une partie du secteur a contraint l'extension de la zone d'étude.

Ce travail a permis, d'une part, de rectifier les coordonnées des cavités déjà connues (ABDUL-NOUR, 2004), et d'autre part, de faire de nouvelles découvertes. Le tableau n° 1, ci-dessous, donne la liste des sites relevés :

Vu le nombre relativement élevé de gouffres (37) dans un espace si peu étendu, il a donc été décidé d'exploiter les informations collectées, relatives aux caractéristiques de ces avens, par la création d'une base de données géoréférencées, permettant leur traitement dans un système d'information géographique. Ceci dans le but de déterminer s'il existe une localisation préférentielle ou non de ces gouffres dans le massif karstique du Jurd d'Afqa.

2. Présentation de la Zone d'Étude

DUBERTRET (1951) avait déjà relevé que le plateau d'Afqa forme un ensellement, c'est-à-dire une zone nettement plus basse entre deux secteurs plus élevés : sa surface très régulière se tient autour de 1850 m d'altitude, puis les reliefs s'élèvent de part et d'autre. Vers le N, en direction du Jabal Makmel, où se situe le point culminant du Mont Liban, le Qornet es Saouda (3087 m) ; vers le S, en direction du Jabal Sannine (2628 m). Ce plateau est encadré par des escarpements spectaculaires, mais de commandements inégaux : à

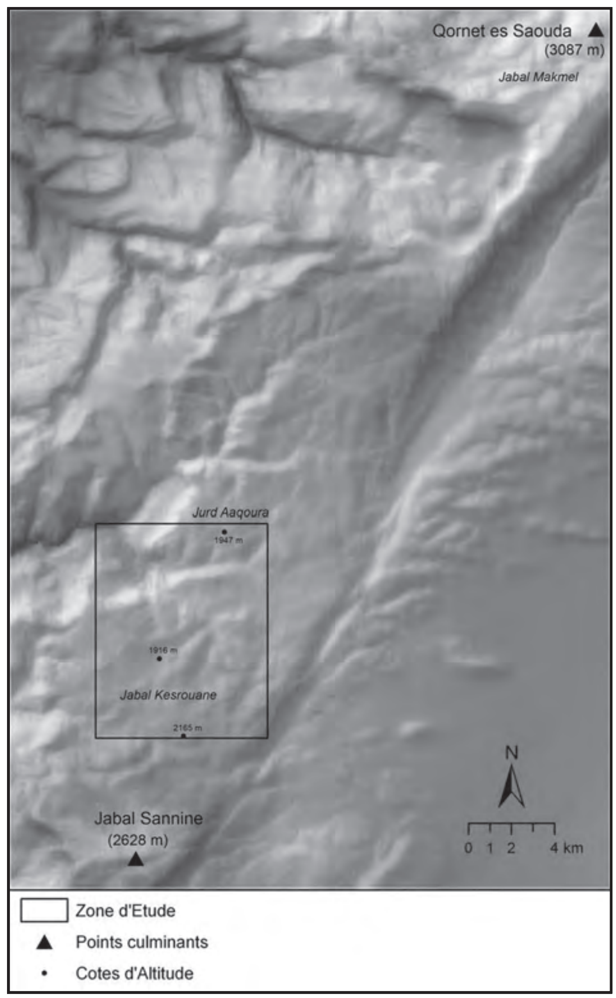

Figure 3 : Contexte topographique du plateau d'Afqa, ensellement entre le Jabal Sannine, au Sud et le Jabal Makmel, au Nord (Source : CGIAR-CSI SRTM 90m Database (http:// srtm.csi.cgiar.org).

N° d'ordre	Dénomination	Altitude (m)	Profondeur (m)
1	Houet Badawiyé	1953	205
2	Houet Jouret al-Houaïyé	1797	130
3	Houet al-Aatoué	1970	126
4	Houet Khachaat al-Midane	1956	90
5	Houet es-Saouda	1792	88
6	Houet ad Daoura	2082	66
7	Houet Fkhit ad Darjé	2000	50
8	Houet al-Dichara	1712	46
9	Houet Akhrass	1967	45
10	Houet Homsaïya	1896	44
11	Houet Ard al-Hamra	2021	42
12	Houet Chafaq Homsaïya	1886	40
13	Houet al-Bahsa	1978	38
14	Houet Chehadé	1977	36
15	Houet Aach al-Hamèmé	1827	34
16	Houet Mohammad Wehbé	1805	33
17	Houet John et Janet	1908	30
18	Houet Ard ech Chaqaa	1966	29
19	Houet Joe	1942	25
20	Houet Jouret al- Barbaris	1980	25
21	Houet Fkhit al-Midane	2022	25
22	Grotte an-Nhailé	2056	20
23	Houet Jacques	1900	20
24	Houet Ouadi es Saqié	1788	20
25	Houet Ariché	2045	17
26	Houet Maqial Jaafar	1847	18
27	Houet Birket el Blata	1924	15
28	Houet al-Bouaïder	1913	10
29	Houet Ard al-Machraa	1883	10
30	Houet Chiaab Semaan Aabboud	1958	10
31	Houet Dahr al-Aqra'a	1790	8
32	Houet al-Lizzèbé	1616	7
33	Houet Jouar Laouandos	1975	6
34	Houet es Sayqa	1904	6
35	Houet Ouadi al-Midane	1990	5
36	Houet Ouadi ed Debb	1912	5
37	Houet Micheal	2031	2

Tableau 1 : Inventaire des gouffres du plateau d'Afqa. Numérotation en fonction du classement des puits selon leur profondeur par ordre décroissant. En italique figurent les cavités connues avant 2003.

l'Est, le talus atteint à peine 200 m de hauteur en face de l'ensellement ; à l'Ouest, l'escarpement bordier domine de 500 m des versants en pente plus douce (vallée du Nahr Ibrahim) (Fig. 3).

Dans le détail, la zone d'étude s'étend sur deux sous-secteurs du plateau d'Afqa : au Nord-Est, le Jurd Aaqoura, connu localement comme le Jurd el Ftouf – Afqa et, au Sud-Ouest, le Jabal Kesrouane. Sur le plan géologique (Fig. 4), le plateau d'Afqa est caractérisé par une série carbonatée assez homogène (formation du Sannine, Cénomanien), épaisse de 600 m environ et de structure subhorizontale (DUBERTRET, 1951). Ces dépôts de calcaires et calcaire marneux sont fortement fracturés et fissurés. La carte géologique de la zone d'étude montre seulement un réseau de fractures principales, à savoir des failles et des linéaments orientés selon deux directions préférentielles : E – W et NE - SW. Précisons que les linéaments portés sur cette carte sont tellement visibles sur le terrain qu'ils ont été figurés sur les cartes topographiques au 1/20.000^{e} du secteur.

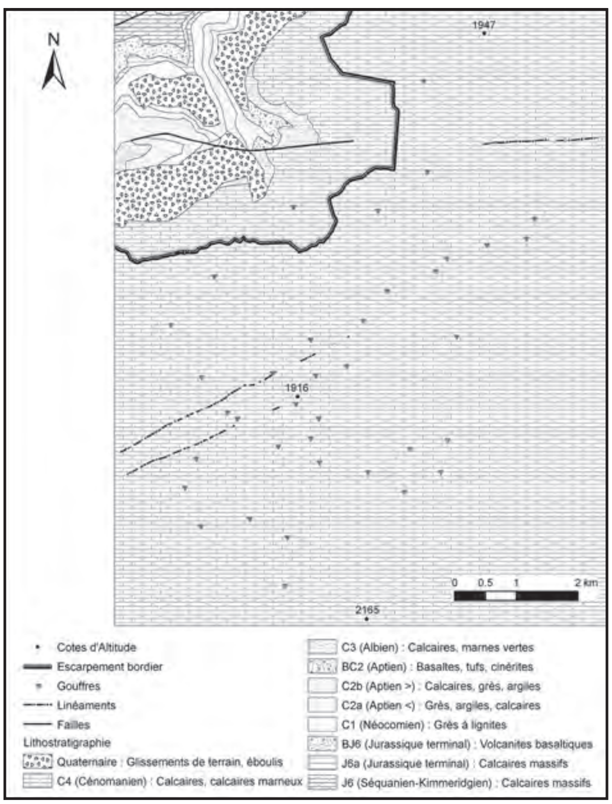

Figure 4 : Carte géologique de la zone d'étude, avec insertion des gouffres localisés sur le plateau d'Afqa (D'après la carte géologique de Qartaba au 1/50.000e (DUBERTRET, 1951)).

En ce qui concerne le karst, ce plateau présente un développement considérable des formes karstiques, notamment de surface, sous la forme de vastes champs de dolines qui donnent un aspect lunaire au paysage (Fig. 5).

Figure 5 : Vue caractéristique du paysage du plateau d'Afqa. Surface topographique défoncée par les champs de dolines. (Prise de vue : Christian Ahkrass)

3. Traitement des Informations et Résultats

Les traitements ont été réalisés grâce au Système d'Information Géographique ArcInfo 9.2. Dans une première étape, ont été entrées dans une base de données géoréférencées les données actualisées relatives aux puits observés sur le plateau d'Afqa :

- coordonnées kilométriques pseudo-Lambert, relevées au GPS,
- altitude (m)
- profondeur (m).

Ces informations ont permis, notamment, d'obtenir un classement des gouffres selon leur profondeur, celle-ci variant entre 2 et 205 m, et de représenter ce classement cartographiquement (Fig. 6). La carte obtenue montre un alignement très net des gouffres les plus profonds sur le plateau d'Afqa.

Dans une seconde étape, nous avons procédé à la digitalisation des champs de dolines à partir des cartes topographiques au 1/20.000^{e} du secteur. En effet, nous sommes partis du principe que l'implantation des dolines est liée au réseau de fractures d'un massif karstique (NICOD, 1967) et du fait que le plateau d'Afqa présente, dans certaines zones, des alignements de dépressions karstiques. Le croisement des couches GIS « classement des puits selon leur profondeur » et « champs de dolines » n'a pas révélé une relation évidente entre localisation des gouffres et densité des champs de dolines. Par contre, les gouffres les plus profonds de la zone d'étude s'alignent nettement selon une direction NE-SW. Lorsqu'on compare la carte du classement des gouffres (Fig 6) à la carte géologique (Fig 4), on se rend compte que cet alignement se situe exactement dans l'axe du faisceau de linéaments d'orientation Nord-Est/Sud-Ouest. Cela laisse supposer que l'implantation des gouffres les plus profonds du secteur est bien liée à l'existence de ce réseau de fractures principales.

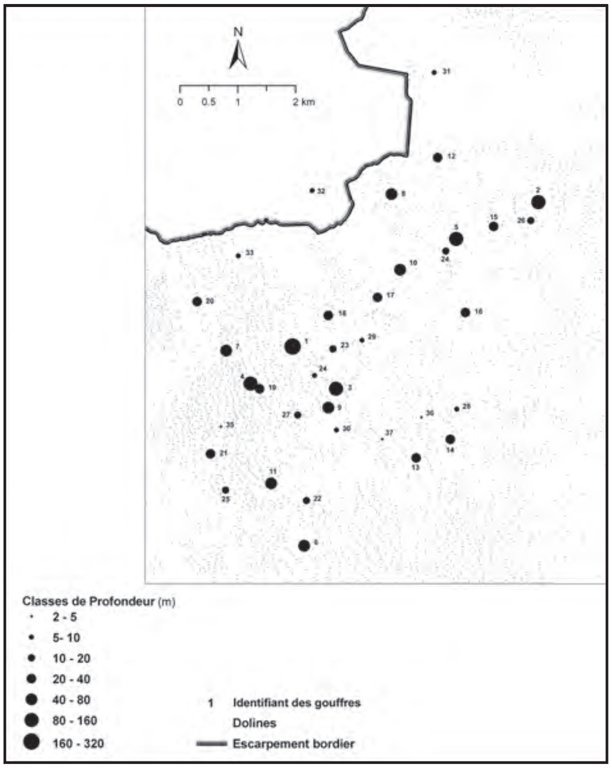

Figure 6. Classement des gouffres du plateau d'Afqa en fonction de leur profondeur et positionnement par rapport aux champs de doline.

4. Conclusion

Cette première approche GIS de l'implantation des gouffres du plateau d'Afqa a permis de mettre en évidence qu'il existe une relation entre la localisation des gouffres les plus importants du secteur et un accident tectonique principal, affectant les couches calcaires de ce haut plateau. Soulignons que ce résultat n'a pu être obtenu que grâce à un relevé systématique sur le terrain des puits. Cependant, nous n'avons pas pu déterminer l'existence de relations aussi flagrantes entre ce réseau de fractures et les autres alignements secondaires de puits.

Ceci implique la nécessité de mener des recherches supplémentaires sur ce plateau, soit pour relever sur le terrain des indices de fracturation, soit de découvrir d'autres avens qui ont échappé à la sagacité des spéléologues. Néanmoins, cette confirmation de la relation « localisation des gouffres-système de fracturation principal » permettra de guider leurs prospections futures dans la région des hauts-plateaux du Mont Liban.

Remerciements

Les auteurs tiennent à remercier tout particulièrement Christian Akhrass, membre de l'ALES passionné par ses investigations sur le plateau d'Afqa, a qui nous devons les informations utilisées dans le cadre de cette recherche, ainsi que tous les spéléologues de l'Association Libanaise d'Etudes Spéléologiques - ALES – qui ont contribué avec leur enthousiasme naturel à ces prospections.

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THE FISSURE CAVES OF NORTH CAROLINA'S MYSTERY MOUNTAIN, RUMBLING BALD

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Rumbling Bald Mountain first attracted worldwide attention in 1874 following a series of earthquakes, which shook this isolated area of western North Carolina. Unknowing residents were convinced that a volcanic eruption was eminent and that the world was indeed coming to an end. Religious revivals were held, and the locals prepared to meet their maker. A large piece of the mountain had become detached from its face, and a number of large fissure caves had formed within the granite gneiss. Residents began wondering if these caves were at all responsible for the mountain's mysterious rumblings. In 1940, an early expedition of the National Speleological Society concluded that sounds of large rocks falling from the cave's lofty ceiling would indeed be amplified by the cave's configuration and be transmitted over the valley. An initial map was prepared during this 1940 trip, but the cavers concluded that certain of the passages were too complex and dangerous to be surveyed. Other partial surveys were made in these granitic fissures during the 1970s and 80s. Unfortunately, however, the fact that the larger nearby Bat Cave System, as well as more interesting limestone caves in neighboring states were beckoning, interest in Rumbling Bald abated. In 2007 North Carolina State Parks acquired part of Rumbling Bald Mountain as they were creating the new Chimney Rock State Park. New surveys of the Rumbling Bald Caves are now being conducted by members of the Flittermouse Grotto of the National Speleological Society. As of November 2008, over 488 m have been resurveyed. With unmapped connections to adjacent caves already confirmed, this may represent just the beginning of our understanding of these world class granitic caves.

Hickory Nut Gorge is one of the most spectacular mountain passes to cut through the Blue Ridge Mountains of western North Carolina. Located primarily in Rutherford and Henderson Counties, this deep, 21 km-long gorge contains some of the most impressive cliffs, waterfalls, and rock monoliths found in the eastern United States. Hickory Nut Falls, for example, is a 122 m cascade, over twice the height of better-known Niagara Falls. Nearby Chimney Rock is a natural stone tower 96 m in height. The top of the Chimney allows a commanding view of the Rocky Broad River, which carved out this remarkable gorge.

Of speleological interest are a series of world-class talus and fissure caves located on both sides of the gorge. The caves are developed in the Henderson granite-gneiss, and are remarkable not only for their lengths, but also for their folklore, histories, and contents. The largest of these is the Bat Cave System with 2 kilometers of surveyed passages. A few hundred meters to the west is the Campbell Cavern-Amazing Bat System with 317 m of passage. Bat Cave and Campbell-Amazing provide homes to 6 different species of bats, two rare salamanders, and several new species of invertebrates. They also contain some remarkable displays of unusual siliceous speleothems. These caves are managed by the North Carolina Nature Conservancy. On the opposite (North) side of the gorge are the mountains known as Round Top and Rumbling Bald. Round Top contains some small caves, and legend has it that a very large cache of gold was buried in one of these in the 1700s. The rumored treasure has yet to be found. Just to the east of Round Top is the mysterious Rumbling Bald Mountain, and its caves which will be the focus of this paper.

Besides Mount Mitchell, the highest peak in the eastern United States, Rumbling Bald received more attention in the nineteenth century than any other mountain in North Carolina. Prior to 1874, the peak was referred to as Bald Mountain or Old Bald. This was soon to change. In the early morning hours of February 10th 1874 a series of earthquakes and tremors shook this rural mountain area. The resultant rumblings and explosive sounds appeared to be centered on Bald Mountain. The terrifying sounds and vibrations were carried throughout the gorge and surrounding countryside. The local residents were frightened beyond belief, and many feared that the world was coming to an end. Religious revivals sprang up overnight, and the mountain folk prepared to meet their maker. Due to the isolation of the region, news about these mysterious rumblings was slow to leak out of the area. By the second week of March, five weeks later, newspaper reporters and numerous scientists began to flock toward Bald Mountain. The news soon spread across the country and even abroad. Even noted French author Jules Verne became fascinated by the reports and later incorporated the mysterious rumblings of this North Carolina peak in his novel Master of the World.

As news began to spread about the rumbling mountain, people started speculating about the causes of the tremors. Many less knowledgeable folk felt that a volcanic eruption was eminent. Other theories included electrical disturbances, burning coal seams, falling rocks, chemical combustion, and explosions. Professor Warren DuPre' of Wofford College, actually managed to be on site to experience some of the tremors first hand. Early in his investigation, DuPre' stated to one of the news reporters on the scene, "The explosive sounds I have heard...are common only to and characteristic of volcanoes." Resultant headlines read "Volcanic Disturbances" and "Our Vesuvius". After further consideration, however, DuPre' felt that the earthquake theory was more plausible. General Thomas L. Clingman as well as F.H. Bradley of East Tennessee University agreed with DuPre' that the explosive noises and rumblings were more than likely due to earthquakes, although the possibility of volcanism wasn't totally dismissed. Joseph Henry, noted physicist and long time director of the Smithsonian Institute, also felt that Dupre' was on the right track. He suggested that the terrain around Bald Mountain was "undergoing a very gradual elevation or depression" producing a tension in the rock strata which would produce a rupture whenever the "limit of elastic cohesion" was exceeded. By June of 1874, the disturbances had subsided, but it was estimated that between February and May somewhere between 75 and 100 tremors had been felt.

After several years without making the headlines, Rumbling Bald gained national attention once again in 1878. Besides experiencing several new tremors, the locals were soon to discover additional clues as to the makeup of this mysterious mountain. In the spring of that year a local farmer, H.F. Alford, made the steep climb up to the summit of Bald Mountain trying to locate some missing cattle he had allowed to graze there. Suddenly, the earth gave way beneath his feet and he immediately grabbed a nearby tree as he watched the dirt disappear down a deep fissure. Alford described the newly formed crack as being 1 to 6 feet (0.3-1.8 m) in width and 150 yards (137.2 m) long. He assumed that his missing cattle had disappeared into this new abyss. Word spread rapidly about this new find and once again, news reporters flocked to the mountain. In May 1878, newspapers across the country received this startling dispatch from the Associated Press: "Bald Mountain has split in twain! Your readers will remember that ... great excitement existed in this section on account of the wonderful and inexplicable noises heard in the bowels of Old Bald. In the past few days the mountain has literally split in twain, leaving a chasm of three hundred feet in length and from eight to ten feet in width. So far as your correspondent can ascertain, the depth is one bottomless abyss." Once again, confusing a crack with a volcanic crater, the report continued, "As yet no smoke or lava has been thrown out from the crater. Great excitement exists, and Bald Mountain bids fair to become the modern Vesuvius."

Additional locals and reporters climbed the mountain to observe the new fissure first hand. During one of these forays, it was found that the original crack had apparently lengthened. More red clay and freshly uprooted trees were noted. Although it was possible to climb part way down the fissure at its western end, most considered it far too dangerous to attempt such a thing. A Mr. Forts decided to explore a bit lower on the mountain in the vicinity of what appeared to be freshly fallen and partially pulverized boulders. Suddenly, Forts noticed a cold blast of air coming out of a crack in the cliff face. By removing some loose pieces of the gneiss, a body-sized opening was soon created. Several of the more adventurous men in the party crawled inside and immediately found themselves in huge walking passage. They reported exploring the giant galleries for 150 yards (137.2 meters) into the mountain before turning back to the surface.

In addition to the local residents and visiting reporters, scientists also returned to the mountain. Professors Frank Clark of the University of Cincinnati and W.C. Kerr from the University of North Carolina each carried out their own investigations of Rumbling Bald in 1878. On July 12, 1878 Clark explored the large crack in the mountain and also located numerous fissure caves lower on the mountain, including the large one which had been first entered by Fort's party a few days earlier. He sent the following description to the New York Weekly Tribune: "Crawling upon our hands and knees through a narrow opening, we found a chamber of rock which I should roughly estimate at twelve feet wide, eighty feet long, and perhaps fifty high. At the end of this a 'window' opened out upon the face of the cliff, from which a magnificent view of the chief rock-masses could be obtained. At right angles to this rocky chamber was another even larger than the first; and at the end of this further progress was barred by a wall about twelve feet high. Beyond this are other spaces, perhaps large, perhaps small, and all soon coming to an end.

The floor of each chamber was covered with fallen rocks. Outside the cave the temperature was 71 degrees, inside 67 degrees: so that the stories about currents of ice-cold air issuing from these caverns have their rise in imagination. There is a constant draft of air through them, but no great lowering of temperature. It should be added, for the sake of completeness, that these caverns contain no water. They are quite dry, and their walls are covered with fine dust, formed by the grinding and crushing of the rocks. Clouds of this dust might easily be mistaken for smoke."

Professor Clark further explained that the rumblings could be attributed to the breaking off of large rock slabs and the numerous caves and fissures acting as resounding chambers, amplifying the sounds and sending them out over the valley. Professor Kerr also felt strongly that Bald Mountain's rumblings could be due to local causes such as rock falls rather volcanic activity or earthquakes. Both these scientists made valuable observations, but their hands were somewhat tied by the limited understanding of earthquake phenomena in those days.

For decades to come, the caves remained quite a local curiosity, and locals would often guide visitors through the passages both at Bat Cave as well as those at Rumbling Bald. One of the most popular and knowledgeable of these guides was Mr. J. M. Flack. Mr. Flack was the proprietor of the Chimney Rock Hotel and later became owner of the popular Mountain View Inn. He loved nothing better than to lead guests through the caves, negotiating the boulder-strewn floors with his walking stick and illuminating the dark passages with his kerosene lantern.

On July 20th 1940, 12 members of the Speleological Society of Washington, D.C., which later became the National Speleological Society, explored and partially mapped the Rumbling Bald Cave. Led by William J. Stephenson, president of the Society, the expedition was sponsored by Miss Ruth Levi who owned the mountain and was curious if the caves had any commercial potential. The group explored and described the main cave as well as two adjacent fissure caves known as the Refrigerator (Ice Cave) and Spring Cave. They concluded that much of the main cave was far too dangerous and unstable to safely explore and survey. The group felt that the rumblings may have been due to contractions and expansions of the fissures experienced during outside temperature extremes and possibly due to the amplification of the sounds of rock falls.

In July 1970, the author and his wife, Susan, accompanied Ed and Nadine Speer on an exploration of the mountain. The entrances of the Rumbling Bald Cave, the Refrigerator, and the Spring Cave were re-located. In addition, two sizeable talus caves, Breakdown and Sliding Rock Caves, were discovered in the large talus field below the previously discovered fissure caves. A year later the author returned to the mountain with Daniel Hudgins, and the two did a survey of Rumbling Bald Cave, Spring Cave, and the two newly found talus caves. Shortly thereafter, the Flittermouse Grotto of the National Speleological Society was chartered. The North Carolina Cave Survey was also established and the local cavers found renewed interest in the caves of Hickory Nut Gorge, including the Bat Caves as well as Rumbling Bald. The 1970s and 80s saw many ridge walks in the area, and dozens of new caves were found. In May of 1980, the author did a solo hike to the upper plateau above the main caves. The large 1878 crack was descended and several cave openings were noted. Due to the lateness of the hour and a long hike back to the car, little exploration was conducted at that time. In 1981, the Subway passage of Rumbling Bald was discovered and mapped. In 1983, the awkward Corkscrew Passage was surveyed. Toward the late 1980s Flittermouse Grotto member, Laurie Adams, took a keen interest in Rumbling Bald and its environs. He, along with several other cavers started a new survey of the main cave and their ridge walks turned up many new caves. These were both fissure and talus in nature. Some were scattered along the side of the mountain and others were discovered on the upper plateau, which the author had briefly visited earlier. Laurie was also successful in connecting Geology Cave with Rumbling Bald Cave.

A lull in activity occurred in the 1990s as the cavers began spending more time in the larger Bat Cave System as well as exploring more in karstic areas. With the North Carolina Nature Conservancy along with Chimney Rock State Park acquiring much of Rumbling Bald Mountain in 2007, there has been a renewed interest in conducting a detailed survey of the caves. Under the direction of Dan Henry, members of the Flittermouse Grotto have once again started a detailed study of the caves. Biological inventories have turned up new species of invertebrates in the caves along with endangered species of bats and salamanders.

Exploration and mapping continues as of this date (Jan-5-2009) with over 549 meters (1800 feet) of passage on paper. A yet-to-be-surveyed physical connection has been made between Rumbling Bald and Spring Cave. The possibility of physical connections to caves of the upper plateau is intriguing, as hydrologic connections have already been determined.

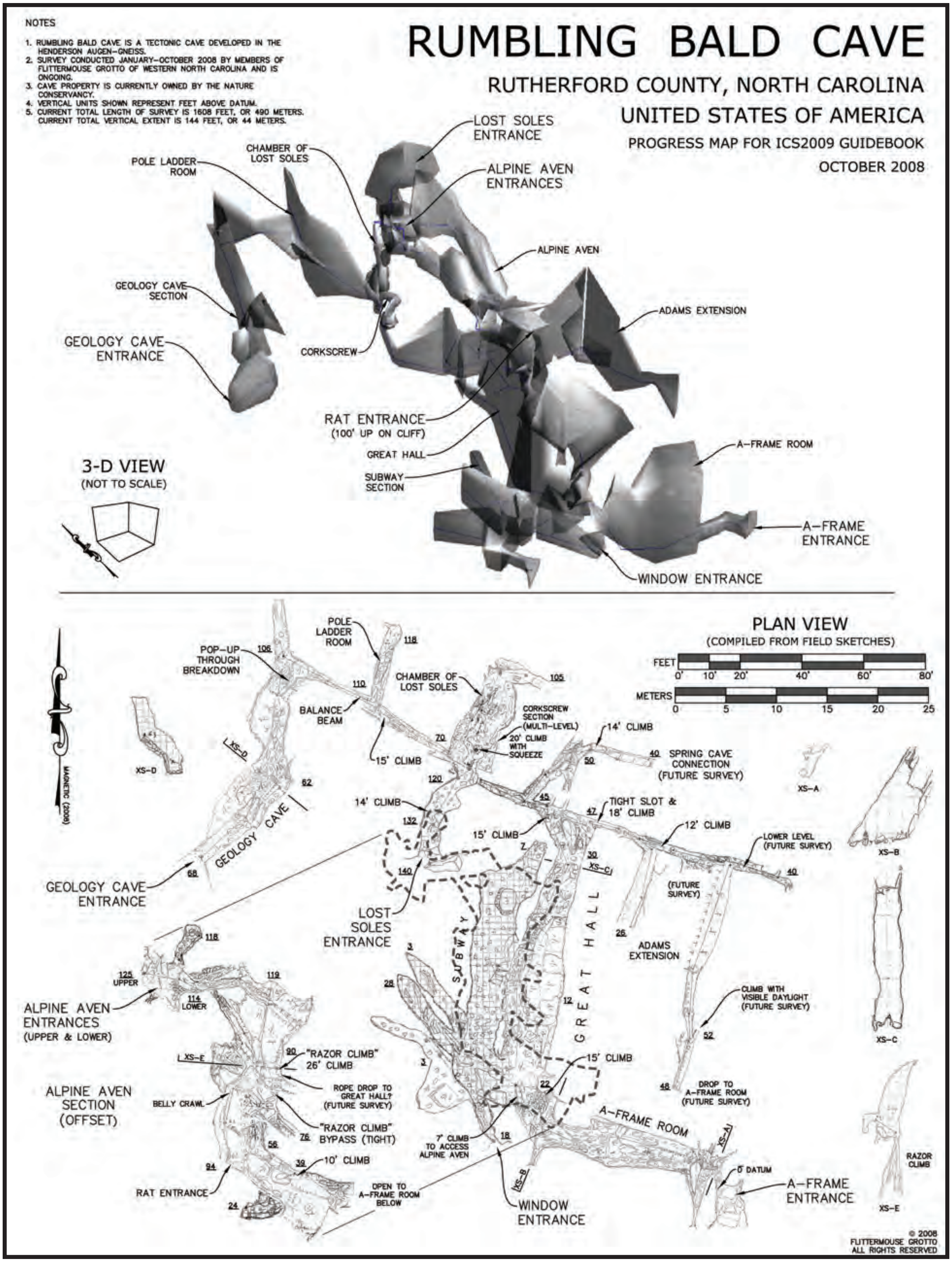

Figure 1: 2008 Progress map of Rumbling Bald Cave. Survey is under the direction of Dan Henry with assistance from Flittermouse Grotto members of the NSS.

In all probability, the mountain's historic rumblings were seismic in origin, with perhaps some local factors contributing as well. It is interesting to note that substantial rockfall occurred in the main entrance of Bat Cave during the winter of 1986 when a 60 ton boulder broke loose from the ceiling. Sarah Laughter, who lives at the base of the mountain, said that over the years she had become accustomed to the sound of ice falling from the cliffs, but the thunderous sound of the massive boulder crashing onto the cave floor was definitely of a far greater magnitude. Then in 1994 a large rock fell from the ceiling of Rumbling Bald, forever changing the contour of its entrance passage. More than likely, we are just now beginning to appreciate the complexities and unravel the mysteries of the caves of Rumbling Bald Mountain (Fig. 1).

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SUCCESSFUL MANAGEMENT OF LONG-TERM SURVEY PROJECTS

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Abstract

In order to be productive, a long-term cave survey project needs to have a tangible goal which is a cave map. To achieve that goal, the project needs to be driven by cartographic objectives and a leadership who is familiar with attaining those objectives. However, there are other important factors that are necessary for the success of a cave project.

The establishment of survey and data collection standards is critical for maintaining consistency in data quality and affords a means of in-cave quality control. Standards should address quality control practices such as back and front sights, level of sketch detail, inclusion of cross sections and profiles, establishment of survey scale, and standard cave symbols. Protocols for marking temporary and permanent stations and for use and selection of survey designations are also important. Data management and archiving are critical components to the long-term cave project. Initial concerns should include selection of data reduction/plotting software, data entry/checking methods, use of loop closures, and blunder detection. In order to sustain a project over a long term, redundant copies of all forms of the data should be maintained in several locations. Survey notes can be kept in hard copy though transforming to digital formats facilitates data/survey note distribution.

An effective survey project is not possible without personnel who are trained in survey techniques and are familiar with all project standards. Training of survey personnel, especially developing sketchers and retaining them is the lifeblood of the project. The project manager or other designated person needs to facilitate the productivity of survey trips by assuring that survey teams are populated with good sketchers and whenever possible individuals who know the route to work areas. They also need to make sure that teams have the equipment, line plots, existing maps and objective lists necessary to make every trip count. Often, large projects have gear and cartographic supply requirements that reach beyond the personal resources of individuals. Having a budget for project gear/supplies becomes an important factor in project sustainability.

Maps are the most important tangible of any cave survey project. A cartographer or team of cartographers is essential to translate the survey/line plot data and sketches into working draft maps and ultimately final products. Establishment of cartographic standards such as symbol sets, map or quadrangle boundaries, final scale, and use of metadata all need to be established

Maintaining positive project morale is essential and one of the best modes to accomplish that is to make all survey data, notes and map drafts available to all project members. And in order to maintain access to the project area, land owner relations are critical to the success of any project.

THAM KHOUN XE OF KHAMMOUANE PROVINCE, LAO PEOPLE'S DEMOCRATIC REPUBLIC (PDR)

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The Xe Bang Fai River originates in the Annam Trung Sun Mountains on the border between Lao PDR and Vietnam and flows across the Nakhai Plateau in Khammouane Province en route to the Mekong River. The river drains through mountainous highlands of granitic and metamorphic rock and across the Nakhai Plateau which is composed of sandstones, silts and shales to the northwest and massive carbonates in the northeast. Of interest to the speleologist is the impressive band of karst formed in the carbonates, because it is here that the river sinks in its surface channel and cuts a subterranean course forming Tham Khoun Xe River Cave. Over 1300 km^2 of drainage disappears into the upstream entrance of what is undoubtedly one of the largest active river cave passages in the world. Stream discharge ranges from a low of 9 m^3/s to an average discharge of 68 m^3/s and maximum of over 600 m^3/s. The cave is well-known to the Lao people, and was first traversed in 1905 by French explorer Paul Macey. However, subsequent documentation and study of the karst and caves of the Nakhai Plateau had been hindered due to war and geographic isolation. In 1995 a team led by Claude Mouret began working in the cave and returned in 2007 and 2008 to continue their project.

In February 2008 an eight-person Canadian/American team of cave explorers fielded an expedition to accurately document this magnificent cave and to determine how its dimensions compared to other documented large river caves of the world. The goal was to produce a detailed map, and photograph the cave and its setting. Surveys documented a massive river trunk averaging 60 meters in width with ceiling heights in excess of 100 meters at passage junctions. The main river passage contains wall-to-wall water punctuated with eight rapids which required portage; so much of the survey was conducted from kayaks. The sheer size of the passages required the use of non-standard cave survey methods and equipment. The same conditions also posed equipment and lighting challenges to the photographic team.

During the eight-day expedition, team members surveyed over 6.5 km of wall-to-wall, deep water passage and an additional 3+ km in side tributaries. The Xe Bang River sinks just outside of the far upstream cave entrance and resurges under the drip line of a massive surface collapse that nears tiankeng dimensions. The underground river flows on a north-south trend through the carbonate massif and finally emerges from a 50-m tall gash in an auspicious carbonate amphitheater. A large lake with a long axis of 240 m formed at the base of the entrance and marks the resumption of surface flow. A total of 11 km of cave were documented during the expedition and the potential exists not only for more extensive cave passages within Tham Khoun Xe Cave, but also for more caves in the surrounding karst. This expedition illustrated it is possible to accurately and efficiently map very large cave passages utilizing long range (>250m) digital survey equipment coupled with detailed in-cave sketching. The team confirmed Tham Khoun Xe is one of the largest sustained river passages in the world, and suggest that a new approach will be needed to survey such caves when they are encountered.

1. Introduction

Tham Khoun Xe or Khoun Xe Cave, an immense, underground segment of the Xe Bang Fai River, is located in a remote corner of Khammoune Province of Lao People's Democratic Republic (PDR). The Xe Bang Fai River originates in the Annam Trung Sun Mountains on the border between Lao PDR and Vietnam and flows across the Nakhai Plateau en route to the Mekong River. The Xe Bang

Fai River drains through mountainous highlands of granitic and metamorphic rock and across the Nakhai Plateau which is composed of sandstones, silts and shales to the northwest and massive carbonates in the northeast. When the river encounters the carbonate bedrock it sinks in its surface channel and cuts a 7 km subterranean course forming Tham Khoun Xe River Cave. Surface drainage from a 1300 km^2 recharge area disappears into the upstream entrance of what is undoubtedly one of the largest active river cave passages in the world. Stream discharge ranges from a low of 9 m^3/s to an average discharge of 68 m^3/s and maximum of over 600 m^3/s.

2. History

Tham Khoun Xe or Khoun Xe Cave is well-known to the Lao people who for centuries have fished in the river that flows from the downstream entrance and with bamboo poles, have scaled its immense walls to harvest birds' nests. European exploration of the cave dates back to 1904 when the French gunboat *La Grandiere* steamed up the river at high water, and raked the lower entrance pool with machine gun fire. In March of the next year (1905), the explorer Paul Macey traversed the active river passage between the two entrances with a bamboo raft that was taken apart at the base of each rapid, and then reassembled above it. Macey's first attempt ended when his small French/Lao party was blown out of the lower entrance by a 1 m flood pulse. Several days later they succeeded making the through-trip after a 21-hour effort.

In 1908 Macey published an account of his trip in *Spelunca* (Macey 1908). However the area remained virtually unknown to Westerners due to its remoteness, WWII and the Indochina war, and its position on the Ho Chi Minh Trail. Claude Mouret visited the cave in 1995 after which the area was closed to foreigners. It was reluctantly reopened to kayakers circa 2005, and a Canadian/American caving team regained access in 2006. Both French and Canadian/American teams are now operating in the area.

3. Expedition Logistics

Khoun Xe Cave lies beyond the end of a dirt track that is impassable during high water and rainstorms. During a reconnaissance trip in 2006, a Canadian/American team managed to push a truck up the track and over fords to the last village and spent several days assessing the logistics of documenting the cave. The team returned in 2008 using small long-tail boats to travel 22 km upriver from the last all-weather road to the downstream entrance. Typically groups operating in the Lao PDR require permits from the National Tourism Administration, NTA-approved guides and local support, so on both occasions the team relied on a local outfitter for camp support.

Two-person, Zebec inflatable kayaks were used to traverse the long stretches of underground river, and two groups of boats were staged above the first and second (of eight) portages to reduce damage to the kayaks. None of the eight rapids required special equipment at low water. Although the flow encountered in 2008 was less than in 2006, battery-powered red flashers were staged above each portage so that the river could be exited under most conditions. In high water this technique would be a life-saver given the huge scale of the passages and the problems that would ensure if a boat was sucked into the rapids.

Two teams were fielded into the cave each day; one dedicated to photodocumenting the immense river passage and the second to surveying it and as many of the side passages that they could get to within the allotted 8-day expedition.

4. Survey Challenges

The initial survey trip during the 2006 reconnaissance documented cave passages that averaged 60 meters in width with a wall-to-wall active river. It became apparent that standard survey equipment and techniques, utilizing hand-held instruments and fiberglass tape (50 m) would not be adequate to map such immense passage. The team did have a Trimble HD150 laser distometer that proved to be an absolute necessity in measuring distances. The sheer size of the passage required a 1:1000 scale in order to fit passage sketches on the width of available paper. Communication was a challenge in the large reverberating river passage and impossible near the rapids. Despite those difficulties the team managed to survey 800 meters of passage.

For the 2008 expedition, the team arrived with a pulse laser device (Impluse 200xl) capable of reliable distance readings to several hundred meters and additional Leica laser distomers. The Impulse 200xl was sealed to military specifications and thus capable of surviving a very wet cave environment. Small FM radios were critical for communication between the survey team.

5. Photographic Logisitcs

The immense river passage with wall-to-wall water also posed challenges for the photography team. The photo team used kayaks as either lighting positions, camera positions, or both. Added to this factor was the difficulty of communication in large passage, the current, and the need to keep everything out of the water.

Many large passage photos were made with flashbulbs and a dozen PF300s. However most of the shots were made with the smaller M5 and M3 bulbs. To enhance light output, flash units with large polished reflectors and clear bulbs were used.

The white balance of the camera was set to color balance the bulbs rather than using filters. To fire the bulbs, vintage and homemade flash units were utilized. The latter were constructed from PVC pipe and designed for wet conditions the vintage units would not tolerate.

In addition to bulbs, four electronic strobes – two Vivitar 283 and two Sunpak 120J bare-tube flashes were used. The latter are some of the most powerful strobes capable of using AA batteries (as opposed to rechargeable battery packs; these units were not an option for this remote expedition location). The large strobes were indispensable for photos shot from a kayak, where bulbs could not be used because of the necessity of setting up a tripod. To synchronize strobes, specially constructed slaves were used. The photographer used a Nikon D70s camera, with a Tokina 12-24 mm f/4.5 lens. He also brought an

f/2.8 Nikkor 24 mm lens specifically for the additional f/stop it afforded. This flexibility was crucial for strobe shots from the kayak.

6. Cave Description

The Xe Bang Fai River sinks in a pile of rock and tree debris 40 meters from the upstream entrance of Khoun Xe Cave. The river reappears in a pool at the entrance and flows through several tens of meters of passage before flowing into a massive breakdown pile which marks the base of a large karst window. The upper edge of the karst window looms 30 meters above the breakdown. Upslope in the breakdown is a massive overflow route that leads to a relatively dry (though sometimes muddy) segment of cave passage that reportedly leads to another entrance of the cave.

Back at the karst window, the river flows south from the base of the breakdown pile where it begins a 7 km underground course before breaching daylight at the downstream entrance. The cathedral-like walls of the river passage reach heights of 100 meters in some places and passage widths average 60 meters though wider sections have been documented. Most of the cave passage is floored with deep water but there are sections where breakdown forms small islands, bends in the river make long beach segments, and boulder piles make 8 distinct rapids. Many large stalagmites, some in excess of 20 meters in height have formed along some the rocky banks of breakdown beaches.

A massive ceiling collapse formed The Oxbow which is the largest room in the cave with dimensions of 220 x 250 meters and containing what may be one of the most extensive gour pools in the world. Truck-sized breakdown blocks litter the floor of the room and the river cuts a big bend on the east side of the room.

A series of east-west trending upper level side passages, which are not river infeeders, have been intersected by the underground course of the Xe Bang Fai River indicating that these passages pre-date the river. Some of the side passages lead to small entrances that are hidden in the jungle high above river level. The largest of these passages, located on the west side of the river, is the Stairway to Heaven; a steeply ascending passage which begins as a wide breakdown room approximately 25 meters above the river and containing a number of immense stalagmites that overlook the river. The passage continues to ascend until it reaches its highest point 160 meters above river level. One of the unnamed eastern side passages contains a small parallel stream passage formed at almost the same elevation of the main river. This sumps upstream and downstream.

The downstream entrance of the cave forms a 50-meter tall gash in the side of an imposing limestone amphitheater. The river resurges into a 240 meter long lake that marks the resumption of surface flow of the Xe Bang Fai River.

7. Expedition Summary

A total of 13.6 km of survey (which includes passage definition shots) was completed during the 8 days of fieldwork. The river traverse has a total length of 7 km and side passages total 2.7 km. An additional 2-3 km of passage remains to be surveyed and the potential exists for more extensive cave passages within Tham Khoun Xe Cave and also for more caves in the surrounding karst. Despite the lighting and equipment challenges inherent to large passage cave photography, the photo documentation effort was successful. This expedition illustrated it is possible to accurately and efficiently map very large cave passages utilizing long range (>250m) digital survey equipment coupled with detailed in-cave sketching. The team confirmed Tham Khoun Xe is one of the largest sustained river passages in the world, and suggest that a new approach will be needed to survey such caves when they are encountered.

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EXPLORATION OF KRUBERA CAVE, THE DEEPEST CAVE IN THE WORLD: TWENTY EIGHT YEARS BENEATH THE ORTOBALAGAN VALLEY, ARABIKA, WESTERN CAUCASUS

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Abstract

Before 1980, there were no caves deeper than 310 m known in Arabika, one of the largest and highest limestone massifs in the Western Caucasus. Established views about regional hydrogeology in that time had ruled out a possibility that caves in the high central sector of Arabika could be hydraulically connected with large springs at the Black Sea shore. Ukrainian cavers have exploring caves in Arabika since 1980, adopting an approach to cave search and exploration that includes detailed investigations in a defined area and systematic testing of cave limits through digging in boulder chokes and enlarging squeezes. A well-shaped glacial Valley named Ortobalagan had been selected for the Ukrainian efforts, located at the crest of an anticline at the forefront of the high sector. This approach, followed in subsequent years by other caving clubs that joined exploration activity in different parts of Arabika, resulted in discovery of many deep caves including five caves deeper than 1000 m and the first cave on Earth deeper than 2000 m. The modern (since 1980) history of cave explorations in Arabika can be divided into two periods: 1) 1980-1992 and 2) 1999-present, separated by the period of the Georgian-Abkhazian ethnic conflict (the war in 1992-1993 and subsequent turmoil). Dye tracing experiments conducted in 1984-1985 established the deepest karst hydrologic system for that time by revealing connection of some caves in the high sector with major springs at the Black Sea shore and the submarine discharge. This greatly motivated further deep exploration efforts. During the first period, the main focus of the Ukrainian expeditions to the Ortobalagan Valley were Kuybyshevskaya Cave (-1110 m) and Genrikhova Bezdna Cave (-956 m) connected into a single system (Arabikskaya) in 1987, as well as Krubera Cave pushed from -95 to -340 m through a series of critically narrow meanders separating vertical shafts. In 1999, the Ukrainian Speleological Association (Ukr.S.A) expedition made a major breakthrough in Krubera Cave by discovering and exploring two branches that stretch in different directions: the Main Branch to -740 m and the Nekuybyshevskaya Branch to -500 m. The Main Branch had been quickly pushed in 2000: in August to -1200 m and September to -1410 m. In January 2001, the Ukr.S.A. expedition explored the cave to -1710 m establishing it as the deepest cave in the world. Subsequent depth records in Krubera were set by the Ukr.S.A. expeditions in August 2004 (-1840 m), October 2004 (-2080 m), September 2006 (-2158 m) and September 2007 (-2191 m). Systematic digging efforts in boulder chokes in the Nekuybyshevskaya Branch resulted in breakthroughs in August 2005 (to -640 m), September 2006 (-1004 m), September 2007 (-1300 m) and September 2008 (-1390 m). The Ukr.S.A. maintains a survey database for the cave consisting of 2210 vectors of the total length of 13,430 m.

The Krubera exploration is a multi-year effort based on team work principles, high standards of personal technical skills, and management of permanent rigging, telephone lines, and camps. The exploration challenges included low temperatures (-1.4 to -7.0° C), great overall depth, multiple siphons in the deep parts, multi-day trips, heavy transport operations, etc. The Ukr.S.A. expeditions to Krubera since 1999 have included over 200 cavers from 10 countries and no serious accidents.

2008 TONGASS CAVE PROJECT EXPEDITIONS IN SOUTH CENTRAL AND SOUTHEAST ALASKA

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During the summer of 2008 the Tongass Cave Project conducted two major expeditions in Alaska. From August 2–16, five cavers inventoried karst features and mapped caves on Prince of Wales and Kosciusko Islands, Tongass National Forest, southeast Alaska with funding from the NSS Exploration and the Dogwood City Grotto grants. Six new caves were mapped on Kosciusko Island with two large remaining leads. Heather's Grotto rivals Goliath Waits Cave for the longest cave mapped on the Island to date. The second destination for this first expedition was the northern end of Prince of Wales Island and Calder Mountain; a peak of Silurian aged Heceta limestone. The weather was rough up on Calder, but the expedition covered over 50 km of ground including hiking over well-developed epikarst to the base of the peak with a mountain of gear. The expedition discovered and mapped five new caves. From August 25th – September 7th three groups of cavers explored the Nizina River, Hidden Valley, and Fosse areas of Wrangell St. Elias National Park. The Tongass Cave Project was granted funding through the National Park Service to inventory areas of carbonate rock within the park for caves and other significant karst features. In the Nizina area, a total of four caves, eight karst features, one frost pocket, one swallet, and nine springs were inventoried. The group in Hidden Valley inventoried 12 caves, five karst features, nine frost pockets, eight springs, and one swallet. The group in the Fosse area inventoried 14 caves, two karst features, nine frost pockets, and no springs or swallets. The Fosse area was almost entirely void of any surface streams, with likely major resurgences under the moraines or ice of the Kennecott Glacier. Information gleaned from these expeditions will prove vital not only to future planned trips in these areas, but also to the local federal land management agencies.

1. Introduction

The Tongass Cave Project (TCP) is an official project of the National Speleological Society (NSS) dedicated to the exploration, survey, study, and conservation of Southeast Alaskan caves. The group is dedicated to protecting and preserving the karst landscape of southeast Alaska from timber harvest through inventory and survey of caves and karst features. The TCP has surveyed several kilometers of passage on Prince of Wales, Heceta, Kosciusko, Coronation, Dall, and Chicagof Islands. During TCP expeditions, the deepest limestone pit in the United States, El Capitan Pit, was mapped to a total drop of 190.5 m, as well as Mossy Abyss at 154 m on Dall Island. In addition TCP expeditions have uncovered significant archaeological and paleontological resources, such as fossil vertebrate bones up to 42,000 years old and in 1996; the oldest known human remains found in North America.

Over the past few years, directors of the TCP Steve Lewis and Kevin Allred began independently exploring karst areas in central Alaska in addition to their work in southeast Alaska, and specifically areas within Wrangell St. Elias National Park. In 2008 the two organized an expedition to Wrangell St. Elias with financial support from the National Park Service (NPS). Previous communication with NPS Chief of Resource Management Eric Veach and Geologist Danny Rosenkrans clarified to the TCP the Park's desire to determine what cave and karst resources were within the Park. Cave survey was a second objective to inventorying karst features on this first expedition. As the inventory progresses in the future, survey and study of the un-surveyed and more extensive caves will be added as needed. The goals of the TCP for this project are to systematically identify caves and significant karst features for the Park, so it can manage these resources accordingly. In order to tackle such a large area of land, the target of the TCP is to evaluate 52 km^2 of karst each year for the next ten years. This year, the park service requested the expedition evaluate the Hidden Valley and upper Nizina River areas first because of significant-looking cave entrances and karst features reported from aerial surveys.

The TCP expedition in southeast Alaska in 2008 occurred on the northern end of Prince of Wales Island and

Kosciusko Island, a smaller island off the coast of Prince of Wales. Work on Kosciusko Island focused on areas that are currently being evaluated as part of the Kosciusko Timber Sale by the USDA Forest Service and were previously inventoried, but the caves were not mapped. Exploration on the northern end of Prince of Wales Island focused on Calder Mountain, a limestone peak that stands at 1030 m and is currently part of a land trade bill proposed by the Sea Alaska Corporation for possible future private harvest. The expedition targeted pits previously located by TCP members in the early 1990s for relocation and survey, and hectares of forest previously unsearched for ridgewalking.

2. Setting

2.1 Wrangell St. Elias National Park and Preserve

Wrangell St. Elias National Park and Preserve is located in south central Alaska and shares a border with Canada's Yukon Territory to the west, the Chugach National Forest to the south and east, and the Tongass National Forest to the southwest. Wrangell St. Elias is the largest unit in the National Park Service, covering over 5.2 million hectares and encompassing some of the highest mountains in North America. Elevations in the park range from sea level at Icy Bay to 5489 m at Mount St Elias, the second highest peak in the United States and Canada. The majority of the Park has an interior continental climate, characterized by long cold winters and warm, dry summers, however the park is so large that it also includes areas of maritime and transitional climate zones (Harris *et al*., 2003). The park is included in a World Heritage Site that expands westward into Canada.

Little is known about karst formation in Wrangell St Elias National Park and Preserve, which was the impetus for this expedition. Karst development discovered in the park to date is found within members of the Wrangellia terrane, a large crustal fragment with a depositional history that spans from the late Paleozoic through the late Jurassic, and completed its accretion by late Cretaceous time (Winkler *et. al* 2000). Thus far, the late Triassic Chitistone and Nizina limestones are the main cave forming units in the Park. These units contain sections of dolomite, chert, and marble and represent a, "shallow to moderately deep marine neritic environment which transitions into an intertidal-supratidal setting" (Richter *et. al*, 2006).

2.2 Tongass National Forest

The Tongass National Forest is the largest forest in the National Forest System, encompassing over 6.9 million hectares covering the islands of the Alexander Archipelago and the narrow band of mainland from Dixon Entrance to Icy Bay (USDA Forest Service, 1991). Prince of Wales Island is the largest island in the Alexander Archipelago at approximately 7,174 km^2 and the third largest island in the United States of America. Elevation ranges from sea level along the coastline to 1218 m at the highest point. Precipitation levels fall into the higher range for southeast Alaska, averaging approximately 4064 mm annually. Prince of Wales Island contains approximately 1,813 km^2 of karst (Baichtal, 2006). These karst areas are concentrated on the north end of the island and surrounding smaller islands, where over 600 caves have been mapped.

Karst development on Prince of Wales and Kosciusko Island is found within members of the Alexander terrane, a large crustal fragment with a depositional history ranging from the late Precambrian to the Early Jurassic (Soja, 1991). The Alexander terrane is partially composed of fossiliferous and largely undeformed or unmetamorphosed interbedded massive carbonate breccias of the Heceta Formation (Baichtal, 2008). The Heceta Formation represents collapsed island shelves as well as reef and shallow water limestones originating in the Northern Hemisphere during the Silurian period (408 – 438 mya) (Aley *et al*., 1993; Soja and Antoshkina, 1997; Freitas *et al*., 1998).

3. Methods

3.1 Wrangell St. Elias National Park and Preserve

The total expedition group of 13 was split into two; one group (numbering six) concentrating their efforts in searching for new caves on the North side of the Hidden Valley area, continuing around the corner and to the north along the Kennecott Glacier until the limestone disappears (totaling approximately 26 km^2 of exposed carbonate). Expedition members who traveled to the Hidden Valley area included: Kevin and Carlene Allred, Benjamin Tobin, Carol Vesely, Bill Farr, and Josiah Hustis. After arriving in the Hidden Valley area, this group further divided into two separate groups, with three members heading out to the Fosse area and the other three remaining in the Hidden Valley area. The other group of seven covered the carbonate area on the west side of the Nizina River from the snout of the Nizina Glacier to the northern part of the Mile High cliffs near the confluence of the Chitistone River (totaling approximately 26 km^2 of exposed carbonate). Expedition members who traveled to the Nizina area included: Steve Lewis, Johanna Kovarik, Dan Nolfi, Jean Krejca, Erin Lynch, Kina Smith, and Rob Cadmus.

Cave and karst features were initially identified via geologic and topographic maps, and then further spotted via aerial reconnaissance by locals, park service employees, and the expedition. Two-sided inventory sheets adapted from sheets developed by the Hong Meigui Cave Exploration Society in China were used for each karst feature or cave, which included GPS coordinates, elevation, information about the feature or cave, and sketches. Entrance and location photographs were also taken of each cave entrance. If possible, some remote or difficult to access caves were surveyed at the time of inventory to avoid having to return at a later date. Cave resource inventory sheets adapted from the Lilburn Cave Project and developed by Carol Vesely were used during cave survey. Caves mapped were mapped using Suunto and tape in feet.

3.2 Tongass National Forest

The total expedition group for Kosciusko and Calder Mountain included five cavers. Cavers split up into groups of two and three to map separate caves or to ridgewalk. Cavers on Koscuisko Island included: Dr. Dan Monteith, Dr. Carl Bern, Andrea Croskrey, Johanna Kovarik, and Dan Nolfi. On Calder Mountain the expedition lost Dr. Dan Monteith and gained Paul Moser. Cave and karst features inventoried on Calder Mountain were first located through aerial photograph and topographic map interpretation. Once located on the ground, a GPS point was taken at each feature for integration into a GIS database. Caves were mapped using Suunto and tape in meters.

4. Results

4.1 Wrangell St. Elias National Park and Preserve

Two years before the expedition, Steve Lewis and Nick Olmsted heard local rumors in Kennecott and McCarthy of some caves in Hidden Valley. The TCP has since discovered that this area has already been partially explored for caves by Jim Nicholls and Curvin Metzler, cavers from Fairbanks and Anchorage respectively. Not much has been learned from them where caves might be found in the Valley. But it was clear they had been exploring a significantly long cave that had been known by some locals since the 1970's. Since they had already been exploring and surveying this cave (Leprechaun Cave) and submitted a report to the Park, the TCP only identified and inventoried the entrance. The expedition hiked many kilometers and checked numerous obvious cave entrances in this area, concluding that Leprechaun Cave is, by far, the largest discovered cave in the area. Numerous unchecked cliff-side holes will require difficult rock climbing or hazardous rappelling to access.

During the 10-day expedition, the group in Hidden Valley inventoried 12 caves, five karst features, nine frost pockets, eight springs, and one swallet. Some entrances checked were not significant enough to be caves as defined by the Federal Cave Resource Protection Act, but still were included in the inventory in order to avoid checking them again in the future. Many entrances that looked like they penetrated deeply turned out to be shallow frost pockets with a dark moss growing on the damp rock. The group checked out the drainage from two small glaciers and found the melt water soon sunk into impenetrable fissures in bedrock or disappeared under extensive moraines almost immediately after leaving the ice.

The group in the Fosse area inventoried 14 caves, two karst features, nine frost pockets, and no springs or swallets. The Fosse area was almost entirely void of any surface streams, with likely major resurgences under the moraines or ice of the Kennecott Glacier. Run-off from one alpine glacier was found to quickly enter the limestone through many small swallets. Another surface stream could be heard beneath talus for a short distance until it presumably sank into the limestone.

In the Nizina area, a total of four caves, eight karst features, one frost pocket, one swallet, and nine springs were inventoried. No large cave systems were found. Many springs in the area are evidence of relatively young hydrologic drainage systems. All the caves found were on the south side of the West Fork, and considerable effort was spent searching the massive deposit of limestone on the north side with only springs and shallow karst sinks located.

4.2 Tongass National Forest

The TCP expedition on the Tongass began under auspicious signs – sunny weather. On the way out to Kosciusko Island, the expedition investigated for sea caves on the coast of Heceta Island, south of Kosciusko. These caves were inventoried with GPS points and noted for future exploration. The expedition then spent five days on Kosciusko Island, and mapped seven new caves totaling in 441 m of new passage. Three going leads were left for future exploration due to a lack of time and proper equipment such as dry suits. One cave on private property has the potential to become the longest mapped cave on the island to date.

5. Dion

5.1 Wrangellscussi St. Elias National Park and Preserve

Although no large cave systems were discovered in the Hidden Valley/Fosse areas during this expedition, there were several caves or karst features judged unique or of special significance. Fill Cave is a horizontal phreatic tube extending only two meters. Although not of significant length, the back of the cave contains a curious rounded bulge, which resembles a glacial varve plug. A gap extends around the sides and top of this plug indicating there has been either preferred dissolution around the plug, or the outer surfaces of the plug itself has been eroded. Closer inspection revealed that the plug is not varves or any other sediment. It is made of a dark-colored limestone (sample tested effervescence by Ben Tobin). This appears to be a paleo cave, which was partly re-formed. Above Leprechaun Cave, a small uvala (approximately six meters by 15 m in extent) was discovered containing at least 10 sinks. Total depth of the uvala is less than three meters. This karst feature appears to have been protected by glacial scouring and subsequent filling by frost shattered debris because of its location on the corner of the major side canyon above Leprechaun Cave.

The expedition investigated some large springs further up the valley. These hold little hope of yielding cave passage as they appear to be quite young. Other smaller springs in the area are also young, and without any accessible passage. The huge spring below Leprechaun Cave was penetrated a few body lengths with a drysuit, but there is a large boulder blocking the way forward. Hibernation Hole above Leprechaun Cave is only some seven meters long, but was used as a bear hibernaculum and contains bear bones. Ben Tobin collected a small bone fragment, which will be dated. Presence of this bone is significant, as it could help us learn more about how long animals have been using the valley.

The Fosse area contains a few caves having many odd, blind hollows and domes without input holes normally accompanying normal mixing corrosion. These caves were not formed through typical water table corrosion, but were created from upwelling geothermal water. None of the caves contained any sign of vadose modification, and the entrances were exposed through glacial scouring or frost shattering without being completely in-filled. Prime examples of geothermal caves are Willow Pit (~ 46 m long), Frosty Cave (~ 46 m long), possibly Comfort Cave (> 46 m long), and Fosse Pothole Cave (> 6 m long). Fosse Pothole Cave is even more extraordinary because the pit complex has formed along a primarily non-carbonate dark-colored breccia, composed predominantly of mudstone. Like the other nearby geothermal caves, Fosse Pothole is a three dimensional vertical maze of "plume"-like passages containing blind pockets and domes. Speleogenesis of these caves will prove complex and fascinating.

Curious areas of small earthen humps were discovered in slightly sloping meadows north of the Fosse airstrip. These had formed in a thin mantle of soil and vegetation atop karst pavement containing sinkholes, grikes and clints. Although obvious to us that these were created through frost action, their positions and orientation seemed controlled by underlying grikes and clints. We set up a five-meter grid and made some preliminary measurements, probing with a ski pole. There is strong evidence that the humps (known on this continent as Cyrogenic Earth Hummocks) do indeed follow the underlying karst forms. Further study is recommended. Other more recently deglaciated pavements without soil development were observed to the north from the air, but were not ground checked.

In the Nizina area, prospects initially seemed good. Information from the Park geologist as well as local pilots told of a large resurgent cave entrance with at least three meters of airspace above the water to the top of the ceiling, in addition to a large pit near the West Fork of the Nizina River with a large waterfall plummeting into its depths. The expedition covered much ground on foot and scrutinized the cliffs with binoculars, but neither of these tantalizing features were discovered. The most exciting discoveries on the Nizina side of the expedition were multiple springs in the area of the West Fork River. Three springs in particular presented a bit of a mystery. Near the confluence of the Nizina and the West Fork, three springs of approximately 280-560 L/s of flow each resurged into a large beaver pond area. The water emanating from these streams had the grayish blue color of the glacial streams. The Nizina group split into two separate groups and scoured the area above the springs even up onto the McCarthy formation, which overlies the Nizina limestone, however no insurgences or major sinkholes were visible. The geologic map of the area suggests that faults could divert water from the West Fork and form a direct conduit over to the springs, however no other evidence of this is visible, except for the glacial color to the spring water. Other explanations include diffuse recharge as opposed to direct point recharge on the broad top of the Nizina limestone cliffs, or point recharge insurgences hidden by the colluvium from the fissile McCarthy formation. Spider Cave contained many small black spiders and gnats of unknown species. Small bones, which may have been from bats, were also noted there.

Towards the end of the expedition, the group finally discovered a handful of caves on the south side of the West Fork River, thanks to the stellar rigging of the Tyrolean of freedom. Three Sheep Cave is the highest cave located during the inventory. It is a phreatic passage that eventually becomes too tight to explore. It contains permanent ice, and may have been covered by glaciations in the past. Crystal Latticework cave is perhaps the prettiest cave discovered by the group, which climbed up to the cave using climbing gear and mapped it to a length of 20 m. Other caves existed near Crystal Latticework cave, however due to time constraints they were left unmapped, and will require climbing gear to reach.

5.2 Tongass National Forest

The most exciting discoveries on the TCP's southeast Alaskan expedition were primarily on Kosciusko Island. A cave mapped on private land turned out to be the largest system mapped and has going potential. Where the team stopped the survey at the end of the main passage, a pinch approximately 50 cm by 50 cm remains, half filled with water. Beyond the pinch, the sound of falling water seems to echo in a larger chamber. In addition, local stories tell of a through trip to the ocean, approximately half a kilometer away. Water resurfaces in multiple springs long the coast in this area along the direction of the main passage. The second cave with a going lead was mapped in a proposed young growth thinning unit on Kosciusko Island. A dig lead was pushed by Dan Nolfi that opened into walking passage below ringed with a thick sediment deposit. The land above My Skirt was harvested in the 1940s, so it could be suggested that this sediment is from the timber harvest of that time, representing a single sedimentation event. If this is true, this cave could present an interesting study for the length of time it takes karst systems on Kosciusko Island to recover from timber harvest impacts.

Calder Mountain proved a damp disappointment in many ways; however the expedition definitely learned where not to look for big pits. Chopper Bopper was not relocated, and contrary to US Forest Service information, appears to be somewhere on the northwest side of the peak as opposed to the southwest side. The deep fissures that looked so tantalizing from aerial reconnaissance trips still had deep snow within them at the time of the expedition. The group hit the area behind the ridge fairly hard the last day, and this appears to have the most promise for future expeditions.

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TEN YEARS UNDERGROUND WITH THE MAYA IN BELIZE, CENTRAL AMERICA

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In February and March each year since 2000, a group named XMET (Xibalba Mapping and Exploration Team) consisting of 15 to 25 National Speleological Society members travels from the United States to Belize to survey caves for the Institute of Archaeology of Belize. Over 8 km of passage, some beautifully decorated, has been mapped in Barton Creek Cave over a period of 5 years. The cave currently ends at a sump 3 km from the entrance. Dye tracing has shown that there is potentially 6 km of passage beyond the sump. Several small caves near the insurgences to the cave were found and mapped. Slate Creek was determined to be the major source of water in the cave, and three other sources of water identified. As part of the mapping process, a cave radio was used to tie the most distant points in Barton Creek Cave to GPS points on the surface.

Many caves in Belize are large river caves that are well decorated in places and frequently contain large quantities of artifacts left by the Maya. Most of the artifacts are between 1200 and 1600 years old.

The lower levels of Chapat Cave are alternately flooded or have insufficient oxygen to permit mapping to take place safely. Access to the lower levels of the cave has been restricted to the rare times when it has been safe to enter. In 2008, during one of those times when it was safe, the skull and leg bones of an ancient Maya male were discovered and subsequently removed for study at the request of the Institute of Archaeology. An intact 22 cm long chert blade was also removed from the cave at the request of the Institute. The blade is similar to one uncovered by Dr. Jaime Awe at Xunantunich, a nearby ceremonial site. Mapping continues in this cave

Offering Cave, which like Barton Creek Cave was used by the Maya 1500 years ago, was mapped in 2002. It has many large vessels more than one meter in diameter and several speleothems that have been modified. Painted Cave, the only cave with painted glyphs known to exist in Belize, and only one of nine caves with painted glyphs known to exist in the Maya world, was photographed and mapped in 2006. Unlike the other caves mapped by the group, it is not much more than a shelter cave.

In 2008, cavers from XMET and a group of 13 local cave guides spent 4 days photographing some of the largest rooms in the Chiquibul Cave System. They also documented a 1.2 m tall speleothem that had grown in a Maya vessel and many other artifacts. Note that the vessel was placed in the cave less than 1300 years ago.

1. Introduction

In February and March each year since 2000, a group named XMET (Xibalba Mapping and Exploration Team) consisting of from 15 to 25 National Speleological Society members travels from the United States to Belize for 2 to 3 weeks to survey and photo document caves for the Institute of Archaeology of Belize. The project began in 2000 in Barton Creek Cave as a three week long mapping project working with archaeology graduate students from the Western Belize Regional Cave Project to document the location, number, and type of Maya artifacts in the cave. XMET has evolved into a continuing project that has mapped and photographed many of the caves in the Cayo District of Belize. Over the last ten years XMET has mapped and photographed small, well known caves such as Rio Frio Cave in the Mountain Pine Ridge and has photographed large sections of Kabal Cave, part of the Chiquibul Cave System, which is the largest cave system in Central America. Work is continuing on mapping more than 30 caves near the Belize Zoo and a major river cave named Haunted Forest Cave east of the Blue Hole National Park. The last trip to Haunted Forest Cave in 2009 found several kilometers of new passage with rooms 100 m wide that have 60 m high ceilings. Two trips are planned for 2010. The first one in March will focus on Haunted Forest Cave; the second one in May will be to Chiquibul Cave System. As part of the project, we are training local cave guides to map and document caves.

2. Cave Descriptions

Painted Cave, the only cave with painted glyphs known to exist in Belize, and only one of nine caves with painted glyphs known to exist in the Maya world, was photographed and mapped. The Jaguar, one of the painted glyphs in the cave, may be meant to be a representation of the "Night Sun" that travels under the earth from west to east to become the "Day Sun" in morning. The two glyphs may be translated as the way or road of the Sun. Unlike most of the other caves mapped by the group, it is not much more than a shelter cave (Fig. 1).

Figure 1: Painted Jaguar on north wall of cave with glyph.

Many caves in Belize are large river caves that have extensive areas of rapidly growing speleothems and frequently contain artifacts left by the Maya. Haunted Forest Cave is a good example of this type of cave. We began the survey of Haunted Forest Cave in 2007 and thought the survey would be complete this year. However, on our last day in the cave in 2009 we discovered thousands of meters of additional upper-level passageway. Each year of the survey, we have discovered additional cave passage.

The lower levels of Chapat Cave are alternately flooded or have insufficient oxygen to permit mapping to take place safely. Access to the lower levels of the cave has been restricted to the rare times when it has been safe to enter. In 2008, during one of those times when it was safe, the skull and leg bones of an ancient Maya male were discovered and removed for study at the request of the Institute of Archaeology. An intact 22 centimeter long chert blade was also removed from the cave at the request of the Institute (Fig. 2). The blade is similar to one uncovered by Dr. Awe at Xunantunich, a nearby ceremonial site. Mapping continues in this cave but unlike Haunted Forest, the survey will be limited by safety considerations rather than by the extent of the cave.

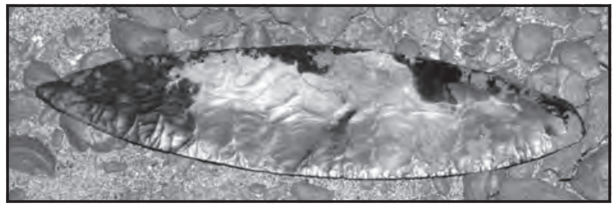

Figure 2: 22 cm long chert blade.

Offering Cave, was used by the Maya 1500 years ago, was mapped in 2002. It has several large vessels over 1 meter in diameter and several speleothems that have modified. Caves were very important in the belief systems of the ancient Maya. They were the entry to the underworld and a portal through which communication with the gods could take place. Ceramic vessels and potsherds are common in the caves. In most cases they were broken at the end of a ritual conducted by the Maya. There are a few intact pots that have

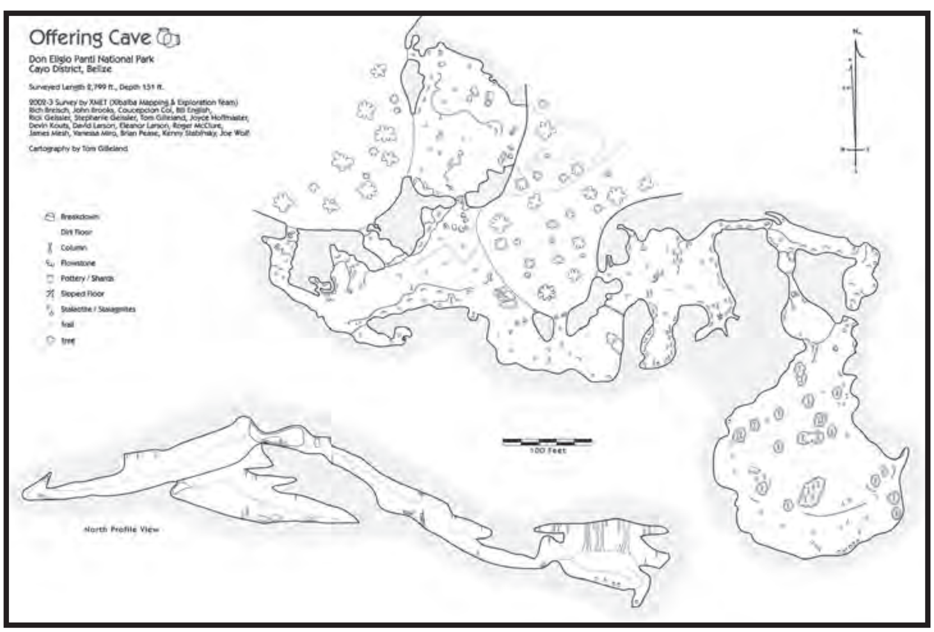

Figure 3: Map of Offering Cave.

been left in place. Some may have been left to collect water. Until we completed the survey of Offering Cave (Fig. 3), we did not understand how the very large pots could have been brought into the cave. They appeared to be larger than the passageways.

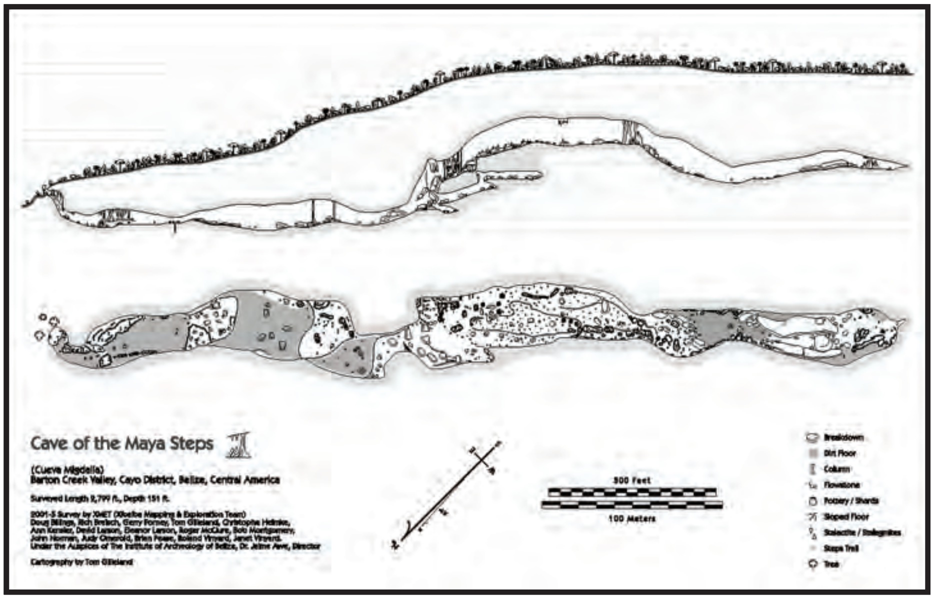

Figure 5: Map of Maya Step Cave.

Over 8 km of passage, have been mapped in Barton Creek Cave over a period of 5 years (Fig. 4). The first 1 km can be seen from a canoe and is used as a show cave. The canoe section ends in a large breakdown pile. The river continues for another 2 km until it vanishes under another breakdown pile at a sump 3 km from the entrance. Dye tracing has shown that there is potentially 6 km of passage beyond the sump. The transit time for the dye was less than 24 hours, indicating free-flowing stream in the, thus far, inaccessible part of the cave. Several small caves near the insurgences to the cave were found and mapped. Slate Creek was determined to be the major source of water in the cave, with three other sources of water identified. Some of the water comes from a stream that enters a cave located 5 km to the south. As part of the mapping process, a cave radio was placed at the end of the cave which we were able to locate on the surface using a loop antenna and a radio receiver. We located the surface point with GPS and used the information to close a survey loop.

We found Maya Step Cave while searching for a back entrance to Barton Creek Cave. It was rumored that there was a cave which connected to Barton Creek which contained a Maya temple. A local person offered to guide us to the cave in 2001. He could not find it but we returned to the area in 2002 and discovered a cave which contained terraced areas constructed of broken formations and stucco. When you climb through the area, there are level places just where you want to place your feet and broken stalagmites where you wish to place your hands (Fig. 5). Climbing gives the feeling of ascending a Maya staircase.

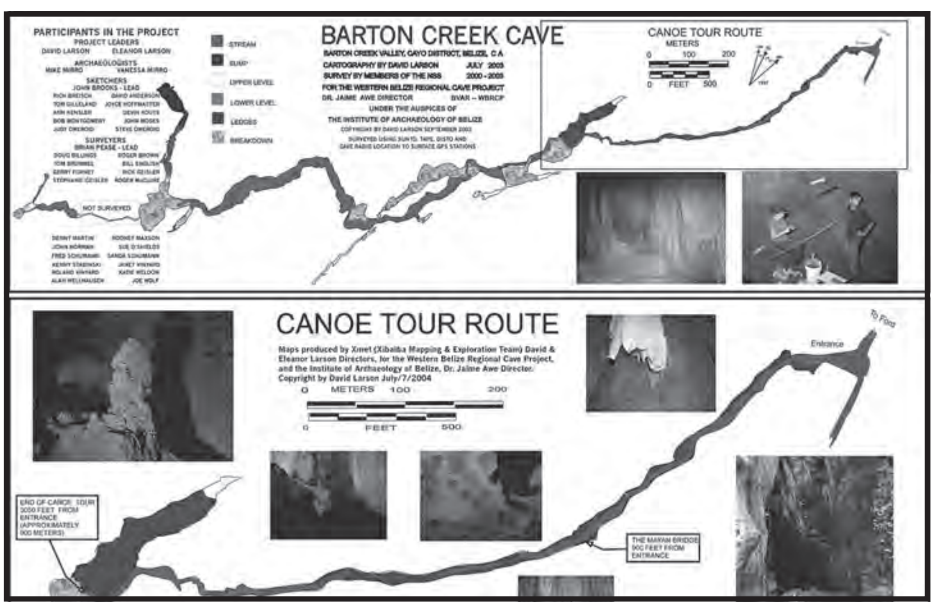

Figure 4: Map of Barton Creek Cave.

In 2008, cavers from XMET and a group of 13 local cave guides spent 4 days photographing some of the largest rooms in the Chiquibul Cave System. The main focus of the trip was to document artifacts including a 1.2 meter tall speleothem that had grown in a Maya vessel and to photograph the 400 meter long Sand Passage and the entrance room of Actun Kabal (Fig. 6, 7). The speleothem was first photographed in the 1980's by George Veni. We established that it is still intact. It should be noted that the vessel was placed in the cave less than 1300 years ago based on dating of the vessel.

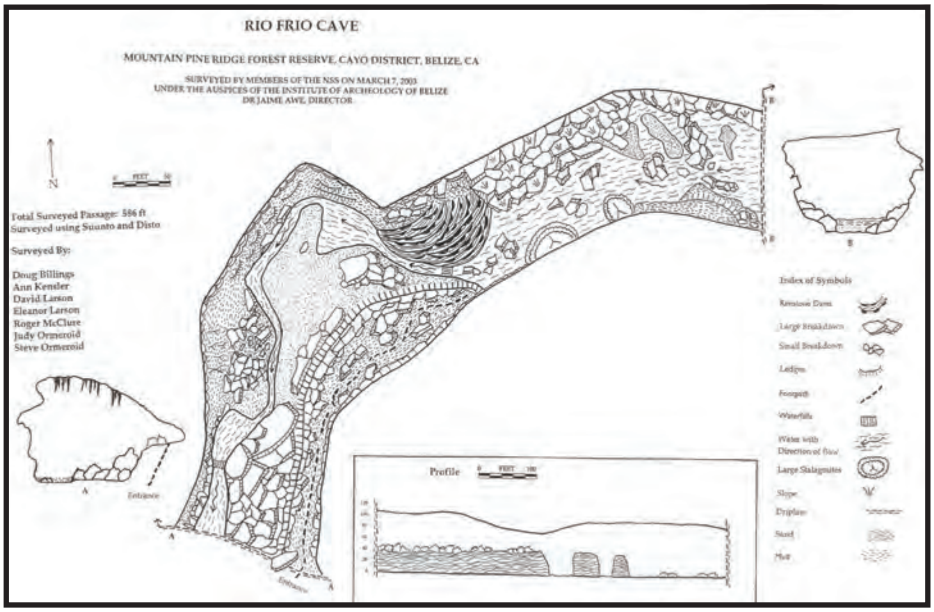

Figure 8: Map of Rio Frio Cave.

One of the first caves the group mapped is Rio Frio Cave (Fig. 8); it is unusual because the cave is on the contact line between granite and limestone layers. It is a popular tourist destination but had never been surveyed before we did so in 2003. The guide books say it is 1 kilometer in length. Our survey measured it as 200 m from entrance to entrance.

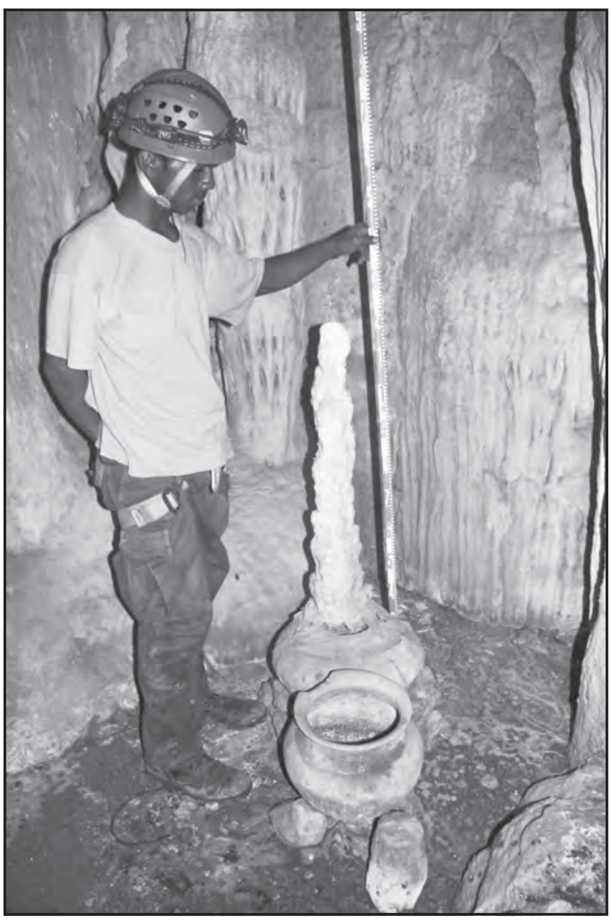
Figure 7: 1.2 meter stalagmite.


Figure 6: Sand Passage Kabal cave.

3. Acknowledgments

The project is under the auspices of the Western Belize Regional Cave Project, directed by Dr. Jaime Awe for the Belize Institute of Archaeology. We wish to acknowledge the continuing support from the Institute of Archaeology of Belize of which Dr. Jaime Awe is the Director.

All photographs and maps courtesy of XMET. Photographers and Cartographers: Doug Billings, Stan Chladek, Tom Gilleland, Ralph Earlandson, Willie Hunt, Ann Kensler, David Larson, Eleanor Burns Larson , James Rice, Don Smith.

CRYSTAL CAVES IN HUNGARY

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Abstract

There are more than 4000 caves in Hungary, most of them normal karstic caves dissolved by non-thermal water. However, crystal caves occur in four different regions of the country and all have hydrothermal origins. Hungary is very rich in thermal springs. The most important area, where their occurrence is considerable, is the Buda region on the west side of the Danube River. The most beautiful and most significant crystal caves are under the homes of Budapest, the Hungarian capital, where seven large and 50 small caves are known. Altogether, they have a length of 40 km.

József-hegyi Cave was discovered in 1984, but last year new and well decorated passages were exposed. This cave is currently 6 km long and 100 m deep. There are chambers 30-70 m in length, in addition to 100 m long by 10 m high passages. On the walls, snow-white popcorn and coraloids can be seen everywhere, sometimes with aragonite needles on top of the popcorn. Gypsum crystals are up to 1 m in length. Gypsum needles, flowers and snakes are spectacular. The most interesting form is needle-grass, similar to human hair in diameter and with lengths up to about 1 m. In many parts of the cave are rafts and raft-formed stalagmites between 1-2 m high. Dissolutional forms (e.g., cupolas, spherical niches) are also wide-spread. The cave is similar to Lechuguilla Cave in New Mexico, U.S.A., but all of speleothems and speleogens are smaller.

Several other important crystal cave discoveries have occurred recently in this area. Pál-völgyi Cave has been known since 1904, but only as 1 km length until 1980 when new parts were discovered. In 1994, passages in the Jubileum section were explored to discover abundant popcorns, cave rafts, and large dripstones. The present length of this cave is more than 14 km. Ferenc-hegyi Cave was discovered in 1933, but the deeper part of the cave was opened up between 2004 and 2007. The cave is 6 km long and the walls are richly decorated with popcorn and barite crystals. Szemlő-hegyi Cave has been known since 1930, but new passages were discovered within the last year. It is a show cave, where the rocks cannot be seen because they are covered by popcorn and gypsum. Citadella Crystal Cave was discovered in 2007. This cave is located on the top of Gellért Hill, which is known as the most popular viewpoint of Budapest. The cave is described as a small jewel box; its length is only 70 m, but is richly decorated with white gypsum crust and aragonite needles. In autumn 2008, cavers worked in the 6-km long Molnár János Cave, which is filled up with thermal water. A new entrance was opened to the Kessler Chamber above the water level. This room is 20 m long and 10 m high above 28,000 m^3 of water. Research has recently revealed St. Lukács Crystal Cave, which is small but rich in spectacular white crystals.

SOAKING WET IN DRY CAVE: THE HISTORY OF EXPLORATION WITH A PROMISE FOR THE FUTURE

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Dry Cave, located in eastern Greenbrier County, West Virginia, is exceptionally well decorated with many striking formations and has unusual characteristics. Developed in the Tonoloway Limestone (Silurian Age), it has a 2.5 km linear extent following a remarkably straight alignment in a northeast direction with 6 km of surveyed passages. It is developed along the eastern flank of the Browns Mountain anticline that forms Beaver Lick Mountain. Dry Cave is not very dry – it contains a stream passage for its entire linear extent. The entrance is located on the bank of Anthony Creek 50 m downstream from a large spring. This spring is the resurgence of the cave stream. At one time, this cave spring was used as a water supply and a concrete dam was constructed which entirely sealed the spring cave entrance. It is now abandoned as a water supply but the concrete dam remains.

The cave is composed of vadose passages that have been carved by the stream flowing along the strike of steeply dipping strata (40°). Although the stream follows a tortuous meandering route for much of its length, the overall trend is unusually straight and, with one exception, only varies 30 m to either side of a straight line for 2.5 km. The one exception is a 122 m offset 1.3 km from the entrance. The upper levels, the highest being 36 m above the stream, are former positions of the stream channel separated by areas of breakdown and flowstone chokes. The gradient of the stream is gentle, scarcely making a sound throughout its length. Although the steeply dipping limestone is thinly bedded, the streambed has a flat cross section about 2 m wide with generally no sediment. There are only a few shallow pools along the otherwise flat streambed. The cave stream has no tributaries and no organic debris such as sticks or leaves has been seen along its length. In August of 1971 an estimated flow of 50L/sec was observed.

The first exploration and survey of the cave was initiated in May of 1971 and continued thru July of 1974 by members of the West Virginia Association for Cave Studies (WVACS). The project was begun again in October of 1986 and continued thru 1987. Formation chokes and the low sloping ceilings along the meandering stream channel make it impossible to stay dry. An "ear-dip" sump proved a formidable obstacle until a by-pass was dug open. Regardless, long wet trips will still test the endurance of exploration teams.

Strong air currents present at the entrance persist throughout the cave and the upper level passage at the upstream end of the cave where the exploration and survey stopped. Walking along the mountainside beyond the known cave has not led to the discovery of other entrances or blowholes. No sinking surface streams have been located. The limestone beds continue northeast along the flank of the anticline for another 23 km but are not exposed for most of this distance. Considering the size of the cave stream, its confinement to a narrow zone along the strike and the northeast extent of the limestone, a much longer cave is conjectured to extend beyond what is presently known.

1. Introduction

In Greenbrier County, West Virginia, Anthony Creek flows southwest for 28 km down the valley between Beaver Lick and Middle Mountain before turning west through a water gap in Beaver Lick Mountain. Approximately 1 km upstream from the water gap along the west bank is a large spring issuing from beneath a concrete dam that was once used to impound the spring for a water supply. Downstream a short distance and 15 m up on a steep hillside is the entrance to a remarkable cave that has a rather inauspicious beginning through a zone of frost shattered rubble. Beyond this collapse, a stream passage is reached that extends in a straight line for 2.5 kilometers along the flank of Beaver Lick Mountain. Prior to the early 1970's the cave was thought to be just a shelter cave. Subsequent exploration has revealed a remarkable cave with unusual features and striking beauty.

2. History

Davies (1958, Caverns of West Virginia), described Alvon Cave as bring small, 92 m long, 2.5 m high, 1.8 m wide having a concrete dam across the entrance supplying water to White Sulphur Springs. In the early 1970's Roger Baroody, representing the West Virginia Speleological Survey, visited the area looking for information about this and other caves that might exist in the area. A local property owner showed him a spring with the concrete dam saying that a cave entrance existed behind the dam (Fig. 1). He said that once, years ago, spring water was piped down to the town of White Sulphur Springs. He explained the cave entrance led to a stream passage that could be entered for a "good ways" prior to the dam's construction. The land owner told of an intense local storm that had occurred in the mountains to the north that caused the spring to run muddy for many days. He said that the spring lost some of its flow to another spring downstream in the Beaver Lick Mountain water gap. Whether his account is accurate is uncertain but, nonetheless, the water supply facilities were moved to the other spring leaving the concrete dam in place across the former entrance. He then pointed to the hillside where an obscure entrance could be seen and said "That's a dry cave up there" – hence the name Dry Cave.

Figure 1: A stream issuing from a cave was formally used as a town's water supply. To create a reservoir a concrete dam was constructed across the cave entrance to impound the stream. The cave stream now flows beneath the abandoned dam.

The initial investigation of the cave found only a rough floored room with a breeze blowing through a collapse zone. Digging through the collapse revealed a much larger cave beyond. The first team surveyed 122 m through a decorated passage to a deep pool of water. A large stream was flowing into the pool from a passage beyond. This pool was just a short distance inside the hill from the concrete dam at Alvon Cave that was apparently still able to dam some part of the stream's flow. Ironically all trips into the cave beyond this point require walking and crawling along the streambed for considerable distances. The first survey of the cave by members of the West Virginia Association for Cave Studies (WVACS) from the Spring of 1971 through July of 1974 accumulated 4.2 km of surveyed passage. The first map showed a remarkably straight-line cave stream passage that extended for nearly 2.5 km. A re-survey of the cave to increase the detail was begun on July 4th, 1986, again by survey teams from WVACS and continued to November 12th, 1988 accumulating 5.9 km of surveyed passages. A new map has been drawn from these two surveys and Figures 6 and 7 are taken from the map.

3. Geology and Description

The cave is developed along the strike in the eastern flank of the Browns Mountain anticline in the Silurian Age, Tonoloway Limestone. The cave parallels Anthony Creek for nearly 2 km before the creeks meanders away to the east. The thinly bedded limestone is dips steeply at about 40 degrees along the length of the cave. Most of the stream passage is a tightly meandering course not varying more than 30 m from side to side and maintaining a horizontal width of about 3 m. In a few places the passage straightens and perfectly follows the strike for as much as 60 m (Fig. 2). The cave seems to have been formed as a single drawdown vadose passage (Fig. 3). Although the meandering stream is cutting back and forth across the thin dipping beds, much of the stream bed is remarkably smooth bedrock with only small amounts of sand, gravel and cobble sediment in the lower section of the cave (Fig. 4). The stream has a gentle gradient, flowing only a few mm deep and rarely having any noisy ripples. The meandering stream passage, perhaps accentuated by the steep dipping beds has low ceilings that curve upwards to former meander bends.

Upper levels start to be encountered about 600 m from the entrance. The further upstream - the larger and more numerous they become, some reaching an elevation of 36 m above the current stream level. Breakdown is also encountered in the upper level passages. The passages interconnect in many places making a complex three dimensional maze. However, it seems clear that all the upper levels are simply segments of the original stream passage whose meanders became separated by collapse, flowstone chokes and sediment fills (Fig. 5). There are many passages

Figure 2: The stream passage alternates between a twisting meandering course and "arrow straight" along the strike.

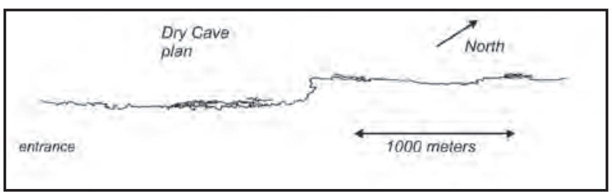

Figure 3: A line drawing plan view shows the linear extent of the cave. About midway there is an offset of 122 m in this alignment. Exactly what causes this is not known.

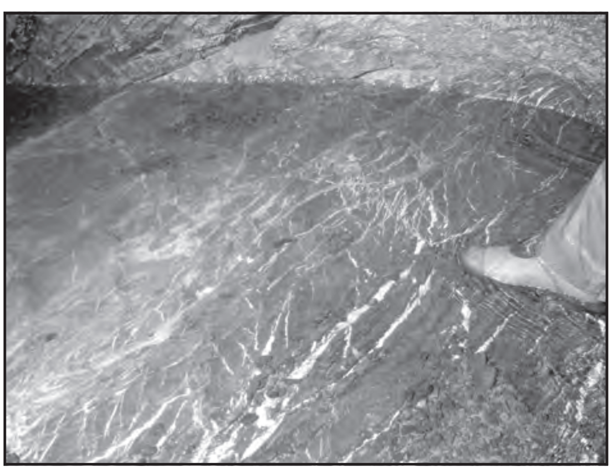

Figure 4: There is a smooth streambed along much of the cave. This image shows the bare rock streambed with gashes of calcite. Notice the caver's boot for scale.

in the upper levels that are unsurveyed and unexplored. Further upstream the passage at stream level becomes larger and larger. In places breakdown fills the passage requiring a detour "up and over" the obstruction. Based on the geologic structure the cave has a potential vertical extent of 150 m.

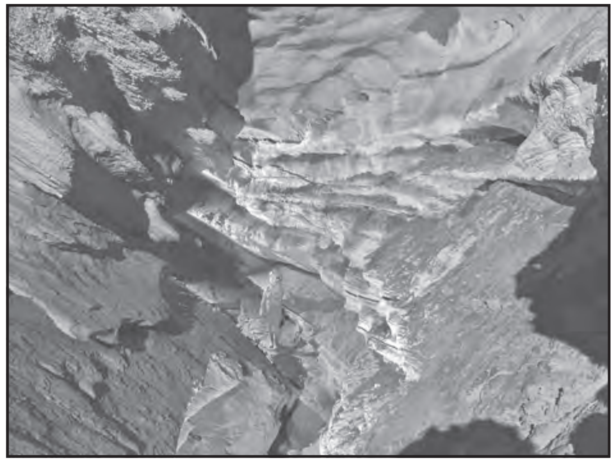

Figure 5: A long sweeping meander in an upper level passage is evidence of the stream's former position.

No infeeder passages have been found, and no stream tributaries are seen entering the cave. The entire cave, as explored, is confined to a narrow zone of about 30 m wide until a point 1.3 km from the entrance (Fig. 6). At that point there is an offset of about 122 m as though the axis of the anticline has been folded. However, it is not known for sure what has caused this offset. In addition, the cave becomes nearly choked with flowstone at this point. Until a blow-hole bypass was enlarged, a 33 m low crawl in the creek was necessary to pass beneath this flowstone encroachment (Fig. 7). With little air space above the creek the survey teams guided their noses through a forest of soda straws while trying to protect their carbide lamp flames from being snuffed out from the strong air currents and waves. Once beyond this point the stream resumes its straight course for another 1.2 km and reaches a gain of 48 m above the

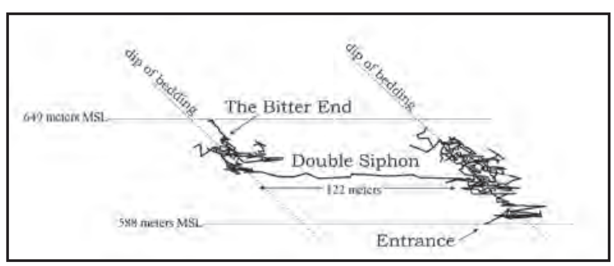

Figure 6: A profile line drawing looking NE along the length of the cave demonstrates how closely the passages are aligned with each other along the strike and the effect of the 122 m offset.

entrance datum. At this point, breakdown at stream level stops forward progress.

Figure 7: Halfway through the cave, the stream flows beneath a flowstone choke. A 33 m crawl in the stream with just inches of airspace was the only route through the choke until a small "blowhole" was opened to allow a bypass.

Flowstone abounds in this cave making it especially interesting to visit and perhaps relieving some of the unpleasantness of being wet. Helictites are especially striking and some astonishing displays of crystals are found in the dry upper levels. In places the amount of flowstone has closed off some passages (Figs. 8, 9).

Figure 8: These antler helictites in an upper level passage are some of the outstanding formations in the cave.

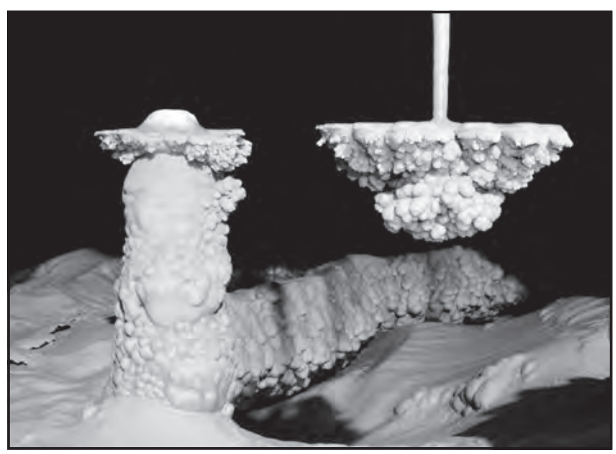

Figure 9: A pair of formations from a drained rimstone pool is a small sampling of the cave's formations.

4. Interesting Aspects and Conclusions

The cave stream has a flow rate of about 50 L/sec. This flow rate seems to be the same volume along the length of the cave. The dipping beds become covered to the northeast along strike and Alvon Spring is the first opportunity for the cave stream to reach the surface along it present gradient. No sinking streams are known along the east flank of Beaver Lick Mountain to the northeast along the strike. No organics are seen along the 2.5 km cave stream course that would indicate surface water finding its way down to the cave carrying organic debris during flooding. Organics do enter the cave from Anthony Creek in the form of hundreds of fish that swim into the cave for shelter during flooding. Many of them subsequently become stranded in the shallow pools just a few cm deep. Accordingly, some survey teams have had to take careful steps traversing the cave stream to keep from stepping on fish.

There is a strong convection air flow that persists throughout the length of the cave. At the upstream terminal breakdown choke the air flow is absent but there are strong air currents in the upper levels just downstream indicating that the cave continues to some unknown upper entrance on the side of the mountain to the north. The Tonoloway Limestone continues along the eastern side of the Brown Mountain anticline for 23 km but remains covered for much of this distance. Field trips to the mountainsides searching for blowholes and sinking streams have not yielded much information thus far. There are many leads in this cave that await the surveyor's instruments. The potential is excellent for a much larger cave to exist beyond the present upstream end but it will require long trips to reach these points.

EIGHT YEARS OF EXPLORATION IN CHINA BY HONGMEIGUI CAVE EXPLORATION SOCIETY

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Since its formation in 2001, Hong Meigui Cave Exploration Society (HMCES) has documented over 315 km of cave and recorded over 1000 entrances throughout south-west China. Expeditions have explored karst areas of Chongqing, Guangxi, Hubei, Hunan, Sichuan, and Yunnan. Highlights include:

- Extensive vertical development in Tianxing, including numerous 200 m+ vertical shafts, the second deepest natural underground vertical drop in the word — a 500 m-deep shaft in Miao Keng, and the two deepest caves in China: Tianxing Dongxue Xitong (35,480 m, −1020 m) and Da Keng (4,273 m, −775 m).
- Over 134 kilometers of complex, multi-level passage in northern Wulong County, including the second and fifth longest caves in China: San Wang Dong (41,221 m, −293 m) and Er Wang Dong (34,778 m, −441 m).
- Over 65 kilometers of cone karst and river caves in Nandan and Leye.
- The 200 m x 300 m Hong Meigui Chamber and some of the largest tiankengs in the world.
- The search for 2,000 m+ depth potential along the deeply-incised Jinsha Jiang (upper Yangtze).
- The longest and deepest conglomerate cave in China, Longmen Dong (13,190 m, −355 m).
- A new species of blind loach, *Triplophysa rosa*, and numerous likely new undescribed species of springtail, millipede, and so on.

With over 100 members from 13 countries, HMCES embraces high documentation standards and openness with regard to data, which is available at http://www.hongmeigui.net.

1. Introduction

Hong Meigui Cave Exploration Society formed in 2001 with three members, with the aim of exploring and documenting caves in China. Since then, more than one hundred people from thirteen countries have taken part in Hong Meigui expeditions throughout southwest China.

2. Wulong County, Chongqing

By far the largest part of HMCES's exploration has been in Chongqing's Wulong County. This has been greatly facilitated by good relations with the local government whose support has been invaluable, by constantly improving transport links within the county and to the rest of China, and by the area's spectacular karst which provides a constant impetus for further exploration. Cave exploration in Wulong county has seen the discovery of China's first 1,000 m deep cave, three systems in excess of 30 km in length, and two shafts of more than 500 m in vertical extent. Exploration has mostly been concentrated in Tianxing village in eastern Wulong, and areas of Wulong north of the Wu River, including Tongzi, San Qiao, and Jielong. Tianxing, San Qiao, and the Er Wang Dong village area of Tongzi are all part of the Wulong Karst cluster of the South China Karst UNESCO World Natural Heritage sites.

An informal effort has been made to document cave biota in the Wulong area. A new species of blind loach, *Triplophysa rosa*, was collected from caves in both Tianxing and Tongzi. Based on a casual review of the literature, some of the invertebrate specimens collected, particularly psudoscorpions and other obligates, are likely new species.

2.1 Tianxing

Tianxing lies at an elevation of around 1100 m, in an area of what appears to be relict cone karst, on the margins of which the ground slopes steeply down into the deeply incised valleys of the Wu and Furong rivers. It is part of the Furong Cave core area of the Wulong Karst World Natural Heritage site.

The caves of Tianxing were first investigated by members of the China Caves Project (CCP) in 1994 and 1996, along with members of the Institute of Karst Geology, Guilin. In 2001, a joint HMCES/CCP expedition visited Tianxing. Among other discoveries, the first pitch of Qikeng Dong was descended. A small Hong Meigui expedition in the spring of 2002 reached −520 m in Qikeng Dong, followed by a second joint expedition which reached −776 m. In a rush for exploration before the lower reaches of the cave were flooded by the completion of a dam on the nearby Furong river, the first of a series of yearly HMCES Tianxing expeditions was held, pushing Qikeng's 0.5 m^3/s streamway to a sump at −920 m while exploration of Dongba Dong reached a sump at −649 m.

In succeeding years, a number of other caves in the area were pushed, including a number of spectacular shafts. Miao Keng includes a 500 m shaft, the second largest vertical extent of any natural underground shaft the world. Da Keng (48H-I12-4)'s entrance shaft is 518 m deep, broken by a ledge 284 m down. Da Keng was pushed downstream to 775 m, making it the second deepest cave in China. In Liuchi Aokou Xia, where the stream breaks through a layer of shale into the underlying limestone, there is a 220 m deep shaft.

In 2006 and 2007, a flurry of connections united Miao Keng, Qikeng Dong, Dongba Dong, Miao Keng II, Lanmushu Dong, Liuchi Aokou Xia Dong, and Xiaoguchiwan Dong to form Tianxing Dongxuexitong (48H-I12-10, Tianxing System) which now stands at 1020 m deep and 35,480 m long – the deepest and fourth longest cave in China (Fig. 1).

2.2 Er Wang Dong area

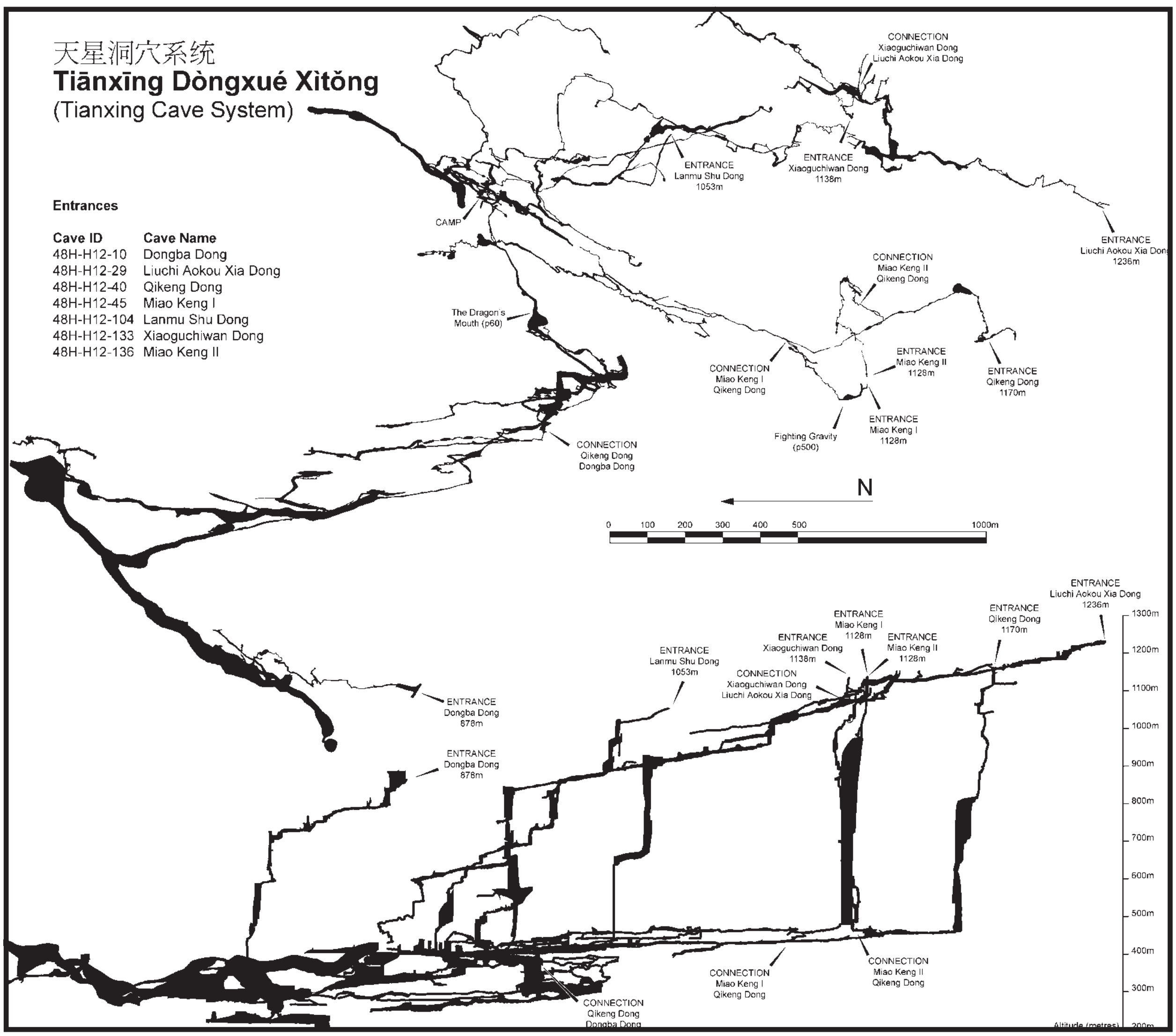

Figure 1: Plan and projected elevation (facing east) of the 1,020 m deep Tianxing Cave System, Wulong County, Chongqing.

The largest caves discovered to date in Wulong County are Er Wang Dong (48H-H12-2) and San Wang Dong (48H-H12-1). They are located in Tongzi, near Er Wang Dong village, and some of the cave passages lie within the Qingkou Tiankeng core area of the Wulong Karst World Natural Heritage site.

Hong Meigui members first visited Er Wang Dong and San

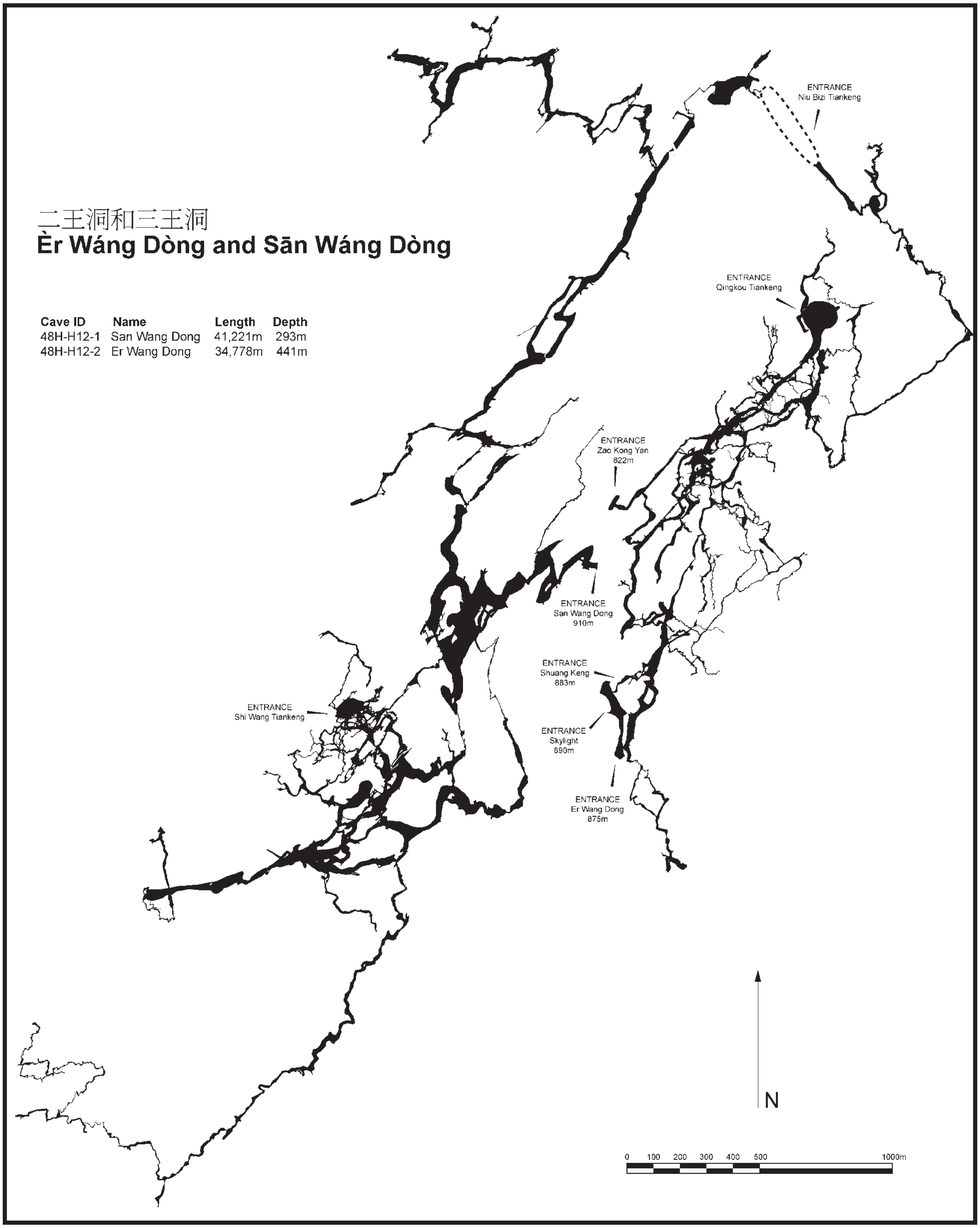

Figure 2: Plan of Er Wang Dong and San Wang Dong, Wulong County, Chongqing.

Wang Dong in 2001. In two days the team documented over 5km of large passage, finding ample evidence that local people have been exploring these caves for a long time, in search of nitrate deposits. Return visits in 2002 made significant advances into new territory which had not been visited by the nitrate miners; a major abandoned trunk passage in San Wang Dong was found that eventually reached a pitch down into a 10,220 m^2 chamber, where once more there was evidence of prior visits by nitrate miners. Following the draught, a shaft to the surface was found, but could not be climbed; it is believed to lie in the bottom of Niu Bizi Tiankeng.

Further small expeditions in 2004 added more length to both caves, finding a series of passages running parallel to the main passage in Er Wang Dong, and a new extension westwards from San Wang Dong. In 2005 a major advance was made in San Wang Dong, when a series of strongly draughting passages with undisturbed sediments on the floor was explored into large abandoned trunk passage with mining artifacts and footpaths; by following the old miners' paths a way was found out to a ledge in the side of Shi Wang Tiankeng. Expeditions in 2006 followed seasonally active drainage routes to find a lower level of development in both Er Wang Dong and San Wang Dong. Niu Bizi Tiankeng was descended and the watercourse followed downstream to connect with the lower level of Er Wang Dong. With this connection, both Er Wang Dong and San Wang Dong have entrances in Niu Bizi Tiankeng.

Throughout much of 2007 and early 2008, exploration focused on San Wang Dong. The area around Shi Wang Tiankeng was found to be extremely complicated with development on at least five levels, and significant progress was made in the west, extending San Wang Dong to 41,221 m long, 293 m deep. More recently a number of higher entrances have been connected to Er Wang Dong, and the cave has been extended on two upper levels, bringing it to 34,778 m long, 441 m deep (Fig. 2).

2.3 Tongzi and Jielong

In April 2007 and 2008 expeditions explored the karst and caves near Tongzi and Jielong in Wulong County. The team explored 25 km and identified numerous new karst features, caves, and springs. Highlights include: Lao Chang Dong (48H-H12-150), a 3,146 m long and 98 m deep cave complex, including old trails and miner's artifacts; Shang Hetao Wan Dong (48H-H12-121), the town dump, which was connected to nearby Leng Dong, forming a 471 m deep, 8,489 m long system; Quan Kou Dong (48H-H12-153), a 116 m-tall entrance with a 3.5 m^3/s stream and amazing airflow, pushed to 3,560 m; and Yan Tang Ping Dong (48H-H12-127), a tortuous cave explored to −154 m with great potential. Reconnaissance of a several large closed valleys in Jielong township yielded the beautifully decorated 846 m-long Xiniu Dong (48H-H12-118), 1391 m-long San Cha Dong (48H-H12-144), and many more cave entrances and shafts that were not entered.

2.4 San Qiao (Three Natural Bridges)

San Qiao is the third, and perhaps most spectacular, core area of the Wulong Karst World Natural Heritage site. San Qiao's landscape is dominated by three natural bridges, each over 100 m tall. While this area was obviously once the site of a sizeable cave system, present day exploration has yielded only a small number of caves, the longest of which is the seasonally-active Xianren Dong, which extends for over 4.5 km.

3. Wuxi County, Chongqing

Wuxi is part of the Dabashan Mountain Range comprised of Triassic limestones overlain by Permian shales. The limestone extends to an altitude of 2500 m, with known resurgences at 500 m. This gives an approximate depth potential of 2000 m. There have been several small-scale expeditions to Wuxi by the CCP and others. In 2002 HMCES undertook a 20 day expedition to Hongchiba village with four people. The expedition explored 3.9 km and confirmed that the area has significant horizontal and vertical cave development. Six caves more than 150 m deep were descended, the deepest being Xiao Shui Dong (49H-A3-16) at 276 m deep and Stemple Cave (49H-A3-5) at 261 m deep. Three caves more than 500 m long were explored, the longest Bai Yan Dong (49H-B3-6) at 1.7 km. In 2006 a team returned to focused on the mid-levels near the town of Wenfeng, exploring a total of 7 km, including a 2178 m-long river cave, 49H-B3-69.

4. Leye County, Guangxi

Leye County is a 50 km^2 area of cone karst with extensive cave development. It is best known for the Dashiwei Tiankeng Group, a cluster of tiankengs (dolines over 100 m deep and 100 m wide). In 2001 HMCES assisted scientists from the Institute of Karst Geology in their investigations of the tiankengs in support of the area's successful application for Chinese National Geopark status. Exploration of Bai Dong (48G-J10-1) led to 5,019 m of passage with a vertical range of 368 m, featured a skylight entrance with a 260 m free-hang into a 100 m-diameter daylight chamber. Dacao Tiankeng (48G-J10-2) which was pushed to 9,461 m long, 203 m deep, including the 200 m x 300 m Hong Meigui

Chamber.

5. Nandan County, Guangxi

Located to the northeast of the caving areas Fengshan and Leye, Nandan is a region of cone karst best known for a 2001 mine collapse. The area was first explored by HMCES in collaboration with scientists from the Institute of Karst Geology. To date there have been four HMCES expedition to Nandan County.

Work in Nandan has concentrated on the course of the area's major underground river which first sinks in La Gan Dong (explored by the Italian group CIRS Ragusa). It resurges in Liang Feng Dong (48G-I12-2), a 6,996 m-long, 128 m-deep river cave which features a 94 m free-hang from a skylight which illuminates two huge stalagmites, one over 44 m high. Downstream, the river sinks in Gan He Dong (48G-I12-1), a 4,991 m-long cave which has been developed for tourists. The river resurges again before sinking in Gan Tian Ba Dong (48-I12-8) which was explored for over 1km to a sump which leads to the 3,962 m-long Jiejie - Xiniu Dong system. The river is next seen in Smoking Yao (48G-I12-60), an entrance shaft which intersects a stream passage for a total of 3,995 m of passage.

Other significant finds in the area include: the 2116 m-long Heni Dong (48G-I12-40), a complicated horizontal cave with 14 entrances. Drum Cave (1015m), this cave features a 85 x 60 35 m room. Shui Yan Dong (1102m), a 50 m diameter entrance shaft leading to sizeable horizontal passage. Wang Shang Dong (48G-I12-65), a well-decorated 1387 m-long horizontal through-trip with thousands of cave pearls on the floor. Wu Dong (48G-I12-73), an unassuming 1m-diameter hole which was pushed to –211 m, including a 189 m shaft.. Bai Dong (48G-I12-128), which had 60 m-wide passage and massive sparkling formations which were surprisingly well preserved considering the 3,702 m long cave is used as a convenient shortcut between two villages. In total, HMCES has documented 39,943 m of passage and logged 130 caves in Nandan County.

6. Jianshi County, Hubei

During 2006 and 2007 small teams visited Jianshi County in north-western Hubei Province to inventory cave life in the area. Numerous millipedes, crickets, springtails, and other cave biota were collected, and preliminary identifications indicate that several of the species may be new to science. The collection is now housed with Prof. Tian Mingyi at South China Agricultural University, Guangzhou.

7. Zhangjiajie Prefecture, Hunan

Zhangjiajie is best known as a pseudo-karst Wulingyuan World Natural Heritage site, but HMCES exploration has focused on karst sites outside of the park: Tianmen Shan and Xilian. Tianmen Shan is a high karst plateau which rises over 1km above Zhangjiejie town. Only one cave on the plateau broke the 100 m-deep mark, Ying Tao Wan Tianyan (49H-I5-25) which ended in a too-tight crawl at –187 m. Located a few hours north of Zhanjiajie town, Xilian is a karst area featuring Wan Ren Dong (49H-G6-1), a 20 m-tall resurgence with not one, but two streams flowing out of it. It was pushed along a dendritic network of seasonal stream passages which branched repeatedly, heading determinedly north for a total of 4016 m. Also explored were two potholes collectively known as Long San Keng (49H-G6-2), which were pushed for 3.3 km, bringing Xilian's total to 7.3 km.

8. Liangshan Prefecture, Sichuan and Wudu County, Gansu

The Liangshan 2006 expedition investigated three different areas, looking for unrecorded cave entrances. The first two areas were in the Liangshan Yi Autonomous Prefecture of Sichuan Province. An area to the west of the Jinsha Jiang (Yangtze River), between the county towns of Leibo and Meigu, was visited in the first week. This area was generally disappointing as the limestone is not as thick as anticipated and is interbedded with other rock types, including lavas. However, there is karst to be explored there. Reconnaissance of a second area north of Yanyuan revealed an extensive area (~35 x 35 km) of well developed karst. This confirmed the exciting potential of this new area, which has potential for long and deep systems with limestone from some 4,410 to 1,750 m ASL). The area contains shafts, caves, numerous large dolines, and several blind valleys where water sinks.

A small team spent two days near the town of Wudu, which lies to the north of Chengdu. The team reported a very large expanse of limestone. This includes a high karst plateau that lies above a show cave which is over 1 km long, and has passages that are over 50 m-wide. This area also looks very promising and has depth potential of up to 1,500 m.

9. Lushan County, Sichuan

In April and May of 2003 a small Hong Meigui CES expedition to Lushan County near Chengdu explored what is now China's longest and deepest cave in conglomerate. The cave, Longmen Dong (48H-F2-1), is a complex maze including four major streamways and numerous high-level passages (Fig. 3). Thus far it has been explored for 13,190 m and a depth of 365 m, but dozens of leads remain ranging from walking passage to endless crawls over sand.

In addition to leads in and around Longmen Dong, several kilometers west of the furthest extent of the cave there is a 2 km-wide depression where the expedition found several sinks which drain away from Longmen Dong.

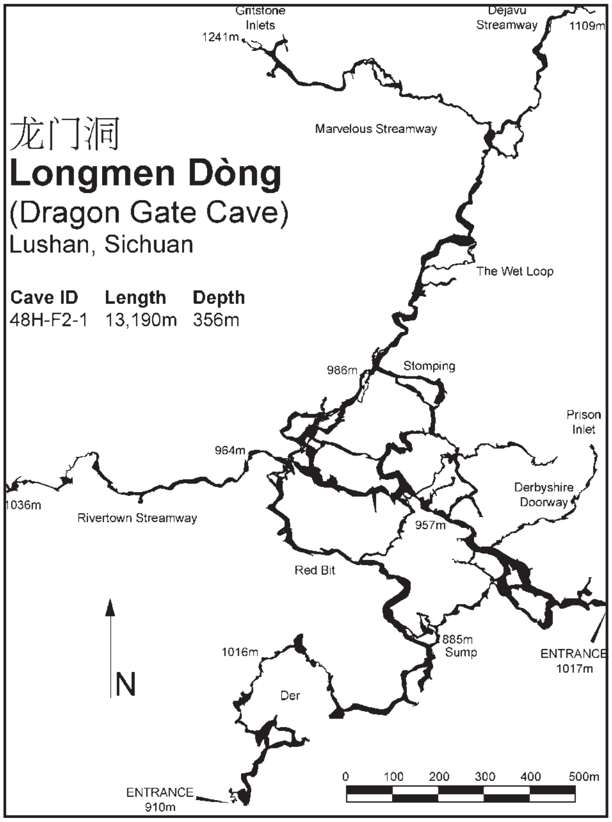

Figure 3: Plan of Longmen Dong, Lushan County, Sichuan.

10. Zhongdian (Shangri-La) County, Yunnan

Zhongdian is a medium-sized, ethnically Tibetan town in the north of Yunnan province. To the west, limestone mountains rise to an altitude of up to 4,550 m before dropping steeply to the Yangtze river, here at 2,000 m ASL. Hong Meigui's interest in the Zhongdian area began in 2002, when a recce noticed the potential for cave systems of up to 2,500 m depth. With limited time, the club found a few entrances at high altitude that year, and came across Shui Lian Dong (47G-B8-6), a resurgence a mere 50 m above the Yangtze.

The search for deep caves in the Zhongdian mountains began in earnest in 2003, when a nine-person expedition, Yunnan 2003, spent five weeks searching for entrances on the plateau at altitudes between 1,900 and 4,350 m ASL. 63 new entrances were logged on this expedition. None 'went' below 70 m, but several undescended shafts remained as enticing exploration prospects for a follow-up expedition. In addition, by this point we thought we had identified the part of the mountain range that seemed to hold the most speleological promise (around the mountain farming hamlet of Ye Kang), and so it was decided to mount a more focused expedition to this part of the mountains in 2004.

2004 marks the high point of Hong Meigui's explorations in Zhongdian to date. A winter dry-season expedition explored the Shui Lian Dong resurgence until its conclusions, some 600m upstream, in three sumps, and discovered a second, much larger resurgence (Ji Ren Shui) some 25 km to the north. In the summer, a 17-person expedition returned to Ye Kang, and spent a further five weeks combing the mountains for entrances. On this trip numerous new entrances were found. Several went below 50 m depth but, the deepest terminated at 110 m and 130 m.

A summer expedition in 2005 attempted to find relict entrances above the known resurgences in the Yangtze valley, and a winter expedition in early 2006 aimed to identify promising high-altitude entrances by looking for holes draughting warm air through snow cover, but unfortunately neither of these expeditions met with much success. A winter expedition in late 2008 hoped to dive the resurgences, but was unable to do so due to delays in getting the requisite diving equipment into the country.

11.Conclusions

During the past eight years, HMCES has explored more than 300 km of caves in China. Even within the confines of

Wulong County where most of the group's activity has been focused huge potential remains for further discoveries. It is likely that cave exploration in China will continue to yield spectacular discoveries for many years to come.

Acknowledgements

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SISTEMA SIMA DE LA CORNISA – TORCA MAGALI (-1507M) (PICOS DE EUROPA, SPAIN)

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Abstract

In the late eighties, a team of French cavers discovered the Sima de la Cornisa in the Picos de Europa, a mountain range in the northwest of Spain. At a depth of -400m, the exploration was halted at the top of an unstable pitch. With no safe way on found, this pitch of over 100m was not descended. In 2001, a team of Belgian and Spanish cavers re-investigating the cave, managed to find a parallel pitch (Pozo Clandestino) and move beyond the unstable part. Throughout the following years, small teams have returned each summer, continuing the exploration. In 2004, another entrance was connected to the system at -500m by Spanish cavers from Matallana, exploring the nearby Torca Magali cave. In 2007, the lowest point so far was reached; a huge master cave ending in a sump, was found at -1507m. Total development of the system is about 6.5 km, with 3 branches going below -1000m. The entrance – the highest one known so far in Picos de Europa – is located at 2540 m. Its expected resurgences, Los Molinos and/or Ferfao, are located at 460 and 350 m respectively.

NEW DISCOVERIES IN THE AMATERSKA CAVE – THE LONGEST CAVE SYSTEM OF THE CZECH REPUBLIC

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Between 2004 and 2008 several important discoveries were realized in the longest cave system in the Czech Republic – Amaterska Cave. In 2005, thanks to a newly opened entrance, faster and safer access to the Sloupsky corridor could start a new period of exploration and documentation in this part of Amaterska Cave. Many small discoveries were made adding one km of new passages. At the end of 2005, 282 years after the first person entered the Macocha Abyss, the last missing connection with a nearby cave was found. So the total length of Amaterska Cave system exceeded 40 km. In 2006 and 2007 several chimneys were climbed and 500 m of new passages with unique eccentricities were found. In 2008 a small, narrow sump in Sosuvsky corridor was passed and 1300 m of new tunnels were discovered and documented. The resurvey and drafting of a new map of some parts of Amasterska Cave have continued.

1. Short History

Amaterska Cave is situated in the northern part of the Moravian Karst – the largest karst area in the Czech Republic. The cave was discovered by members of the Planivy Club in 1969. Exploration between 1970 and 1993 was organized by the Institute of Geography and since 1993, by the Czech Speleological Society, when a new project started. The goal of this project was a detailed exploration, especially in hard-to-access parts, geologic research, and new, more detailed documentation. All activities had occurred in the cave since 1980 as well as description of all the known parts and maps, were summarized and published in 1999 in book "Amaterska Cave - 30 years from the Discovery of the Biggest Cave System in Czech Republic" (MOTYCKA at al., 2000).

Between 2000 and 2004 the greatest achievement were the discoveries in the New Sloup corridor (Fig.1). At the end of 2003 altogether 400 m of new passages were discovered in the barely accessible sections behind four sumps. To continue these explorations it was necessary to find an easier and safer access to these sections. Gradually, several chimneys were climbed and in one of them it was decided to open a new entrance. This happened between 2003 – 2005 by digging a 21 m deep shaft, its stabilization and the installation of permanent ladders to the depth of -70 m.

2. Contemporary Explorations

Since 2005, thanks to this new opened entrance, more detailed exploration of the New Sloup corridor in the northern part of Amaterska Cave could begin. At first, the entire known section of the New Sloup corridor was mapped and all branch lines were explored in detail. This brought a whole range of small discoveries and then the discovery of a new 300 m long area, the so called "Connection to Sosuvka, which bypassed two sumps and interconnected the main tunnel of New Sloup Corridor (Fig. 2) and the Sosuvka branch (Fig.3).

A pumping attempt in a sump that closed the north end of the main tunnel was organized at the end of 2005. The sump was dropped about 6 m, but it has not yet lead to a bypass. But during the next diving attempt, a connection was found between the Amaterska Cave and Sloupsko – Sosuvske Caves. This discovery symbolically crowned the efforts of many generations of explorers, who had tried to discover the connection between Sloup and Macocha abyss for last 300 years. The first man went down into this 138 m deep abyss in 1723!

Between the years 2006 and 2007, the main effort was aimed at chimney climbing in the New Sloup Corridor (Fig.4). A total of eight chimneys were climbed. In the two of them, larger upper floors were found. The first find was at 75m high and a new 200 m long horizontal floor was discovered. Both finds were in the EEK chimney. The end of these new discoveries is only 20 m away from the known Sloupsko-Sosuvske caves, which were discovered more then 100 years ago. If the explorers of that time had continued digging, Amaterska Cave would have been discovered a long time ago.

The next success was made in the Big Chimney. It was climbed up 90 m and there, through a small window, a 600 m long labyrinth of smaller corridors was discovered. Some parts are decorated with excentriques (Fig.5). The highest point of this labyrinth is located at a height of 114m, making it the highest chimney in Amaterska Cave.

In 2008 a diving reattempt in the so called sump No. 8 at

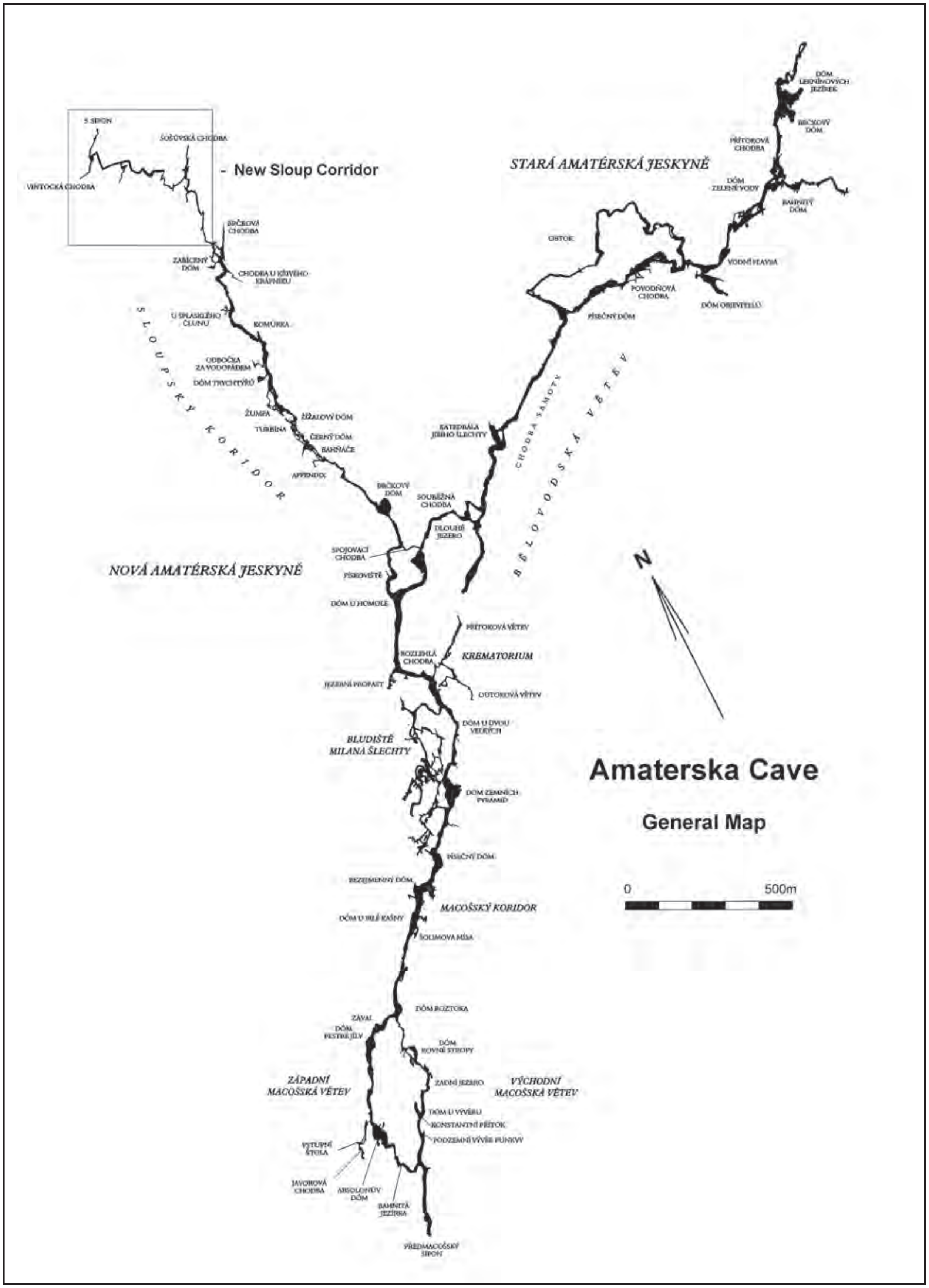

Figure 1: General map of Amaterska Cave.

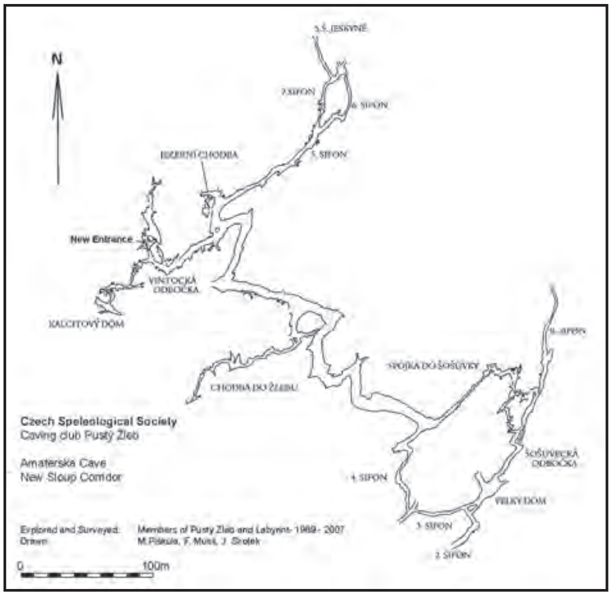

Figure 2: Map of New Sloup Corridor.

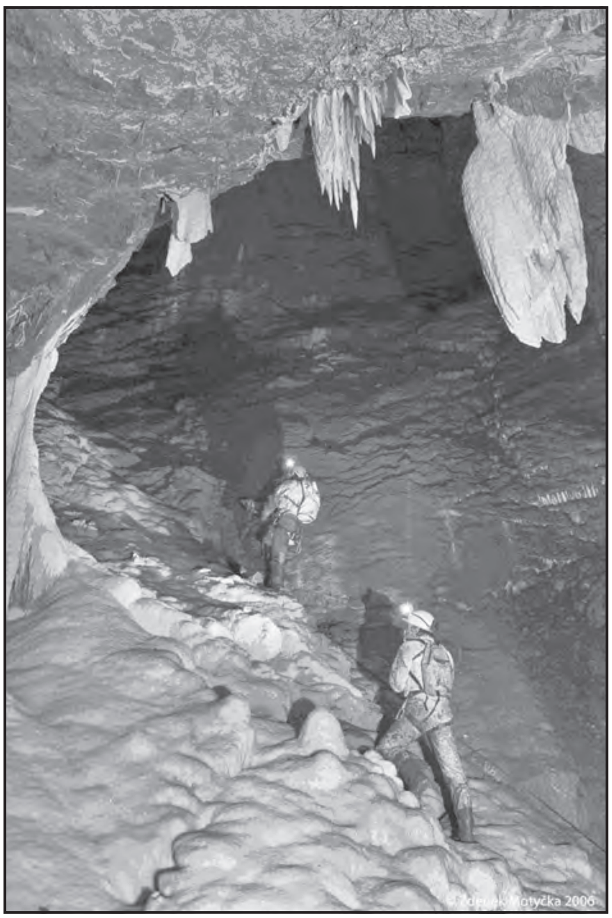

Figure 4: Chimney climbing in the New Sloup Corridor. Photo by: Zdenek Motycka.

the end of Sosuvka branch line was made. During the first attempt in 2000 a depth of 16m was reached, but there was no way to continue. Now a new way on has been found

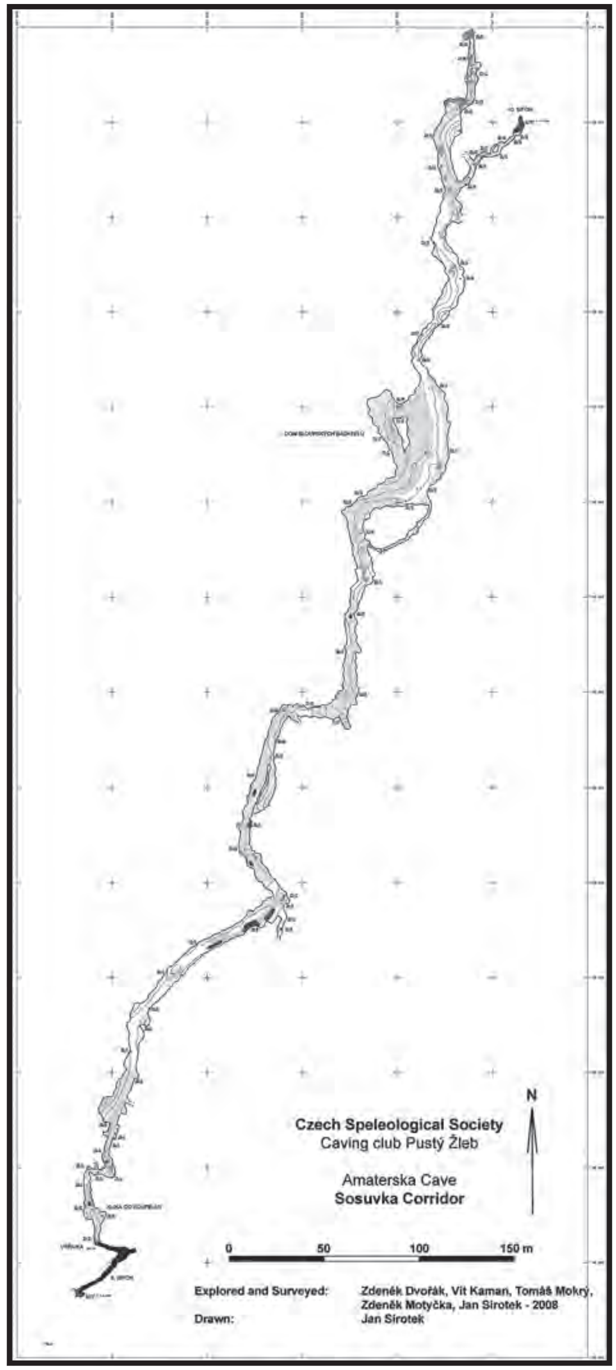

Figure 3: Map of Sosuvsky Corridor.

through a very narrow part underwater after 50 m. Behind the sump, a system of dry narrow passages continues into a huge tunnel, leading to the north almost one km long, to the big hall, 70m long and 40m wide. It is called "Dom Sloupskych Badatelu". There is a cross-road 300m long behind it. First way ends in to big collapse, the second one is finished with a sump, which has not been explored yet (Figs. 3 and 6).

Fig. 6

Figure 5: New discovered parts in New Sloup and Sosuvka Corridor, Amaterska Cave. Photo by: Zdenek Motycka.

Figure 6: New discoveries in the Sosuvka Branch. Photo by: Zdenek Motycka.

At the end of 2008 and thanks to the kindly climate, the shallow sump at the end of the corridor Do Zlebu dried up and behind it about 300m of new spaces were discovered and the exploration still continues.

In the other parts of Amaterska cave several chimneys were climbed in Labyrint of Milan Slechta, but these did not reach higher horizontal cave floors. The diving research of Predmacossky sump was renewed in 2007. Predmacossky sump divides Amaterska Cave and Macocha abyss. This sump was explored only once in 1975. Now, during six diving actions a 311m long and 20m deep sump was surveyed and a new underwater tunnel was discovered. It is 340 m long and 50 m deep and runs parallel with the main sump.

As for the new documentation of the cave there is no positive news. Almost half of the cave is still done in the original, very old, and not very exact maps. Because of this fact it is not possible to confirm the length of the cave – the supposed length is 40 km.

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NEW DISCOVERIES IN UNDERWATER CAVE SYSTEMS IN RIVIERA MAYA, MEXICO

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Between 2005–2008 several new cave systems and new underwater passages were discovered during a cave diving expedition, organized by the Czech Speleological Society, in the Chemuyil area on Riviera Maya – part of eastern coast of Yucatan Peninsula. These expeditions discovered, explored and surveyed 17 km of new passages in the Koo´x Baal cave system, 3 km in Sistema Joolis and a new cave system was created by connecting Cangrejo and Ich Kin cenotes. Several animal skeletons and bones were discovered including the surprising find of an entire skeleton of a new animal species, a type of giant sloth, found in the Koo´x Baal cave system. All caves were surveyed, mapped, and extensively photo documented.

1. 2006

Two thousand six continued the exploration of underwater cave systems in the Mexican Yucatan peninsula during February and March and in October. Ten members of Czech and Slovak Speleological Societies participated in these explorations. The first expedition started with the exploration in cenote Cangrejo, where the way on was first discovered in 2005. The members did several dives during the first week and discovered almost 1000 m of new corridors. During the second week they a found connection with cenote Ich-Kin and leading to the total length of the connected system Cangrejo – Ich Kin of 5131m. The main parts of Cangrejo – Ich Kin are 3 parallel, 1 km long tunnels. Between the southern and middle tunnel there was discovered a labyrinth of spread corridors while between middle and north tunnel there is only one corridor. (Fig.1)

After these finds the main effort was focused back to the Sistema Joolis, found in 2004 with the length of 3.5 km. It was decided to re-explore some sections and finish documentation of the system. After several dives, 700 m of new corridors were discovered and surveyed in part of Hoyt, 1.3 km of corridors in part of Polo. So the total length of Joolis was now is 5.3 km. Sistema Joolis has no general direction and is typically created as a labyrinth of big and small corridors.

The last two weeks expedition moved to the cenote K´oox Baal, explored between 2002 and 2004 by the members of Quintana Roo Speleological Survey (QRSS). During several dives a huge tunnel with the height up to 6 m and width up to 40m was discovered and 3 km of new passages was discovered! Bil Phillips from QRSS continued the exploration after we had to leave and discovered another kilometer of corridors and also big bones of a prehistoric mastodon.

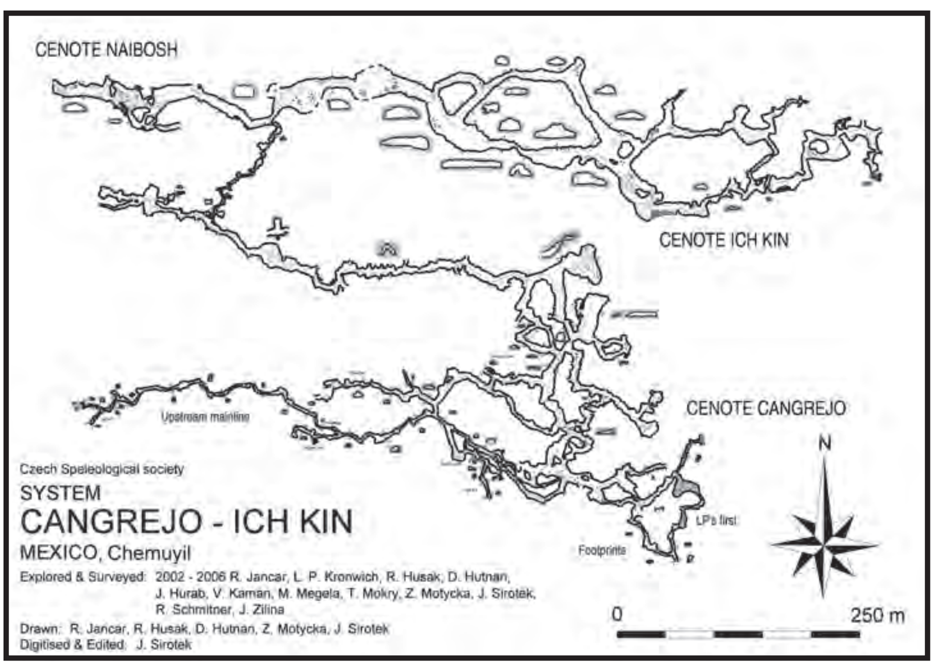

Figure 1: Map of Cangrejo – Ich Kin System, Quintana Roo, Mexico.

In October another expedition started in a couple of southern entrances. In cenote Castillo more than 1 km of new tunnels were explored. After managing to obtain permission to enter the main entrance of K'oox

Baal, exploration of its north part continued. At first the documentation of mastodon bones was made and then another kilometer of new passages were discovered. The total length of system K´oox Ball at the end of 2006 was 9.8 km (Fig.2).

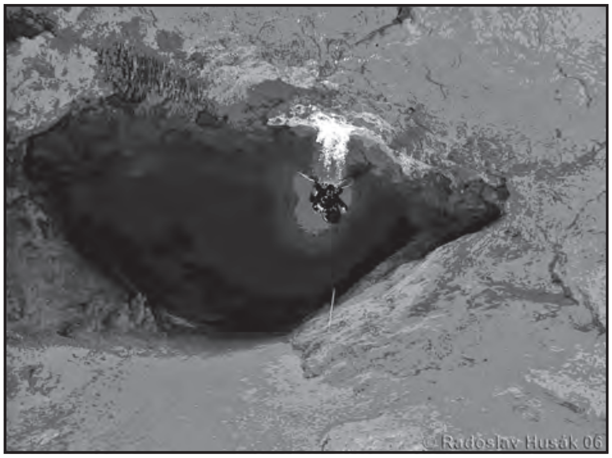

Figure 2: New discovered tunnel in K´oox Baal System, Quintana Roo, Mexico. Photo by: Radoslav Husak.

2. 2007

In 2007 the main effort was focused on exploration of K´oox Baal. The exploration began in the west part, where already the third tunnel, leading to NE-SW, was found. The most western parts are created by the labyrinth of joined corridors and all attempts for another prolongation ended in low profiles. Another advance was also possible only in the SW direction where the 3rd tunnel approximate to the 2nd joined at the end. Also in this section, the originally huge dimensions of the central tunnels branched out and became smaller to limit access. In spite of this fact, 7 km of new corridors were found in the western and southern part of the cave. Besides the new passages found, animal skeletal remains a distance of 1 km from the entrance were found (Fig.3).

In the second part of the expedition, after the evaluation of the discoveries in the western part, we estimated that the similar situation could exist to the east from the main tunnel as well. Then, there was discovered an access hole in the E wall of the main tunnel. We were successful in penetrating this into another parallel tunnel, again following the NE-SW direction, this time however to the east. The width of the tunnel was more than 30 m and the height 6 m. At the NE end of the tunnel there is the huge collapse while the SW leads to the new large cenote. The following exploration discovered the continuation to the east and other corridors leading to NE and SW, but just small sizes. One of them leads to the same cenote as the previous huge tunnel. At the end of the expedition we discovered, in this part of the cave, 3 km of new corridors and the total length of the system K´oox Ball had reached respectable 19.178 m (Fig.4).

3. 2008

At the turn of February into March another expedition to the Mexican Yucatan peninsula was organized, focused again on the exploration of underwater cave systems. After the last successful expeditions in 2007, when we discovered a new continuation for almost 10 km in K`oox Baal system, this year we wanted to be more focused on a possible connection of the system with the system Joolis, because the known parts of the both caves are only a few tens meters away from each other. Several exploration into the north part of K`oox Baal followed, but here the continuation was not found. Even an exploration in the most western parts of the system did not bring discovers of new sizeable corridors. Nevertheless we managed to extend the length of the caves by almost one kilometer to the current 20.087 m.

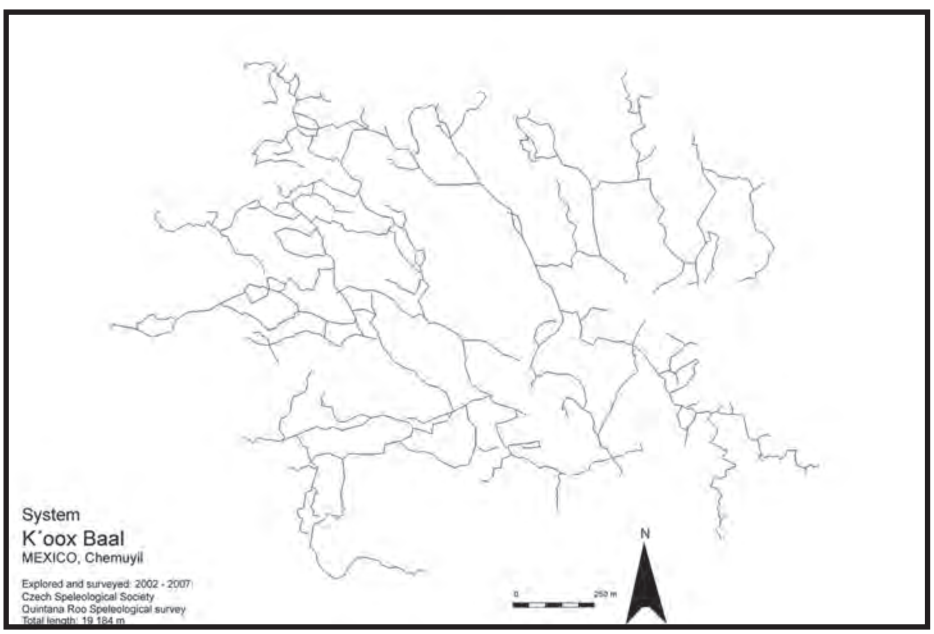

Figure 3: Map of K´oox Baal System, Quintana Roo, Mexico.

During one dive we discovered an animal skeleton of large

Figure 4: Huge tunnel in K´oox Baal system, Quintana Roo, Mexico. Photo by: Radoslav Husak.

proportions. This happened during the detail corridor's survey in the course of one of the last dives into the western parts. It is almost the whole skeleton with a skull 35 cm long lying on its hip in an almost physiological position. The skull has also marked teeth. The length of the spine is 2.5 meters and the animal had to be almost 1.5 meters tall. All of the parts are covered with a thin lay of sinter. It probably protected the skeleton against massive damage as a consequence passage flooding. We can also say the age of the animal thanks to sinter layer. The animal had to live during the time when the local caves were dry, so before flooding which happened during the last sea transgression about 18,000 years ago (Fig.5).

The most interesting thing about the skeleton came

Figure 5: Skeleton of unknown animal species. Photo by: Miroslav Manhart.

after experts examined the find. On the basis of the first statement of Prof. Dr. Oldřich Fejfar, from the Faculty of Scientific of The Charles University in the Prague, the skeleton is a kind of an extinct sloth from the family Megalonychidae. But according to consultation with Dr. Greg McDonald – senior consultant of Natural History from the Park Museum Management Program of US National Park Service, it is a new animal genus, undescribed by science till this time!

Also one new cenote was found. The entrance serves its land owners as a water source. With their permission we made the first dive into this cenote, which was called Aqua Guadalupana by the owners. After 20 meters we got into larger places through a narrow, almost vertical, drift. Step by step we discovered 650 meters in the next days and connected it to Sistema Joolis, whitch is now 5908 metres long.

4. Summary:

Between 2006 and 2008 Czech Speleological Society organized four expeditions to the area. During these expeditions 11 participants spent 14 weeks in the Yucatan and discovered and surveyed 25 km of new underwater passages.

Participants: Jiri Hurab, Radek Husak, Daniel Hutnan, Radek Jancar, Vit Kaman, Michal Megela,Tomas Mokry, Zdenek Motycka, Jan Sirotek, Kamila Svobodova, Jan Zilina.

Acknowledgement:

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2005 TO 2008 SPELEOLOGICAL DISCOVERIES IN CAVES OF KHAMMOUANE, LAOS

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Since 1992, yearly caving expeditions in Khammouane have mapped over 160 km of cave. In Phiseua Cave, a height of +465 m was reached. The "Hidden Chamber" is 215 x 140 x ca 35 m.

The Xé Bang Fai Cave was explored in 1995 (9+ km), then access was forbidden. In 2007 access was again obtained and the upstream end yielded large fossil passages; this added 2+ km. In 2008, side passages were explored, leading to 13 km of cumulative length. This world-class cave is traversed by a 30 m wide allochtonous stream. Floods at the stream inlet reach 40 m above the low water level. During peak rains, downstream of the cave's outlet, a large flood plain is covered by a several meter-deep water layer. At this outlet, a 300 m long, deep, lake results from huge floods. Giant stalagmites and tens of meters long rimstone dam systems have been discovered along with black circles on the floor. In this same area, Tham Ene Cave, (1+ km long, 30 to 50 m large and 10 to 25 high) displays more than 50 such black circles that have been quantitatively studied.

The Tham Koun Dôn-Tham Houay Sai system is now more than 12 km long. This complicated maze cave shows rims, hollow stalagmites and moon milk in significant quantities. A part of the cave shows sub-horizontal passages, and another one, sloppy galleries. The phreatic part is a maze accessible by diving (1998 and 2006). The major Nam Dôn stream flows out of it. Cave outlets have also been discovered in upstream fossil sections.

Tham Phiseua, now more than 13 km, is a complicated phreatic, hypogenic maze cave. Six upper outlets (up to +465 m) are known. The entrance stream in the lower passages has been explored inward, into the limestone massif. Tham Phiseua shows similar development, with its sloppy passages (not so common in Khammouane), hollow stalagmites and rims.

In the polje of Ban Vieng, Tham Lô has been further mapped on two separate levels (now 7+ km). Near Ban That, giant karst lakes (Nong Bet) surrounded by cliffs and steep slopes, can be reached through Tham Lom Cave. Cave diving brought new insights there, as has cave diving around Nhommalat.

In the Nam Non (25+ km) and Nam Hin Boun Caves (13+ km) area, new passages have been explored, above and below water. Complex systems of sunken passages have been discovered.

Every year, geological, karst and biospeological research has been conducted, leading to major discoveries. Cave art, related to both prehistory time and Buddhist monks is present at Ban That. We continue exploring and studying the Khammouane caves and we will return there early in 2009.

1. Introduction

The karst of Khammouane (Fig. 1) has been explored by our team since 1991, especially by the two first authors, who went there nearly every year. Seventeen exploration campaigns followed 3 reconnaissance periods. At the end of the 2008 campaign, the cumulative length of explored and mapped cave passages is 160 km. A positive elevation of +465m was reached in Tham Phiseua ("Tham" means Cave in the Lao language). The longest cave explored is Nam Non, with more than 25 km of passage mapped.

We present here below the original results obtained during the 2005 to 2008 campaigns. We have continued the exploration and mapping of major caves that we investigate regularly.

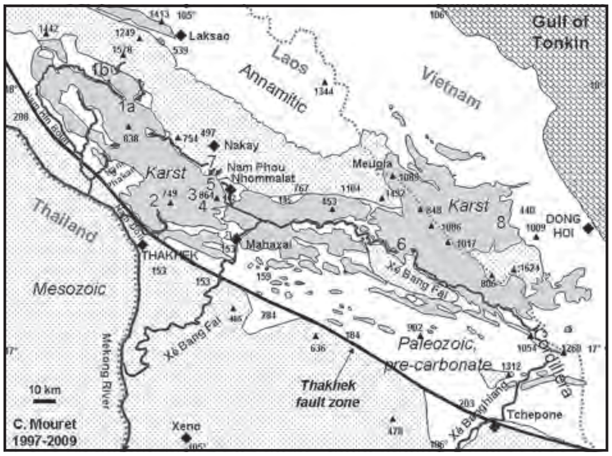

Figure 1: Location map. 1a: Nam Hin Boun area; 1b: Nam Non area; 2: Nam Dôn area; 3: Polje of Ban Vieng; 4: Ban Tat area; 5: Nhommalat-Ban Tathot area; 6: Xé Bang Fai area; 7: Border polje of Ban Mouang Louang; 8: Phongna area (Vietnam).

2. Outlines on the Karst of Khammouane

The karst of Khammouane (Fig. 1) is the largest in Laos, being 290 km long and 40 km wide. It continues into Central Vietnam (Phongna Cave area). The mainly Permo-Carboniferous, 1100 m thick, carbonate body (Fig. 2) is an anticlinorium sliced by longitudinal wrench faults. It is a virgated body, trending NW-SE in the NW part, WNW-ESE in the central part, then NW-SE in the eastern part which is along central Vietnam. The carbonate area is bounded to the SW by the major Thakhek wrench fault system, which separates Devono-carboniferous formations to the NE (with the karst area) from Cretaceous formations to the West. To the NE, the carbonate formations overlap Devonian to Lowermost Palaeozoic strata and metamorphics and Precambrian metamorphics and igneous rocks forming the heights of the Annamitic Cordillera (followed by the boarder between Laos and Vietnam at the crest). The karst of Khammouane is drained towards the Mekong River, by the Xé Banghiang (near the SE tip of the karst area), the Xé Bang Fai, the Nam Dôn, the Nam Phakan and the Nam Hin Boun Rivers (Xé and Nam meaning River in Lao language). The Mekong River is the base level for the whole Laotian part of the karst massif, at some 145 m a.s.l. The karst plains are around 155 to 180 m a.s.l., while the top of the karst reaches commonly 600 m and even 800 m and more. Except along the Vietnamese boarder, the karst is bounded by a marginal depression with border poljes, at the bottom of a cuesta. This cuesta is bounding to the SW Mesozoic, mainly continental, silici-clastic deposits, which unconformably overly the Paleozoic formations.

The climate follows a two-season dry tropical regime, with a yearly mean rainfall depth around 2 to 3 m. The dry season is from November to the end of April/beginning of May and the rest of the year is the rainy season, with a peak in July and August. The hottest months are from mid-March to mid-May, just before the cloudiness and the first rains cool the atmosphere down. It may rain occasionally in the middle part of the dry season. In addition, the hydrological regime of the Xé Bang Fai is influenced by the weather of Vietnam which is different and significant floods may occur during the Laotian dry season.

3. Main Parts of the Karst Explored

We will describe these areas from the NW, close to the Mekong River, towards the SE close to Vietnam.

3.1 The Nam Hin Boun and tributaries area

This area includes two main caves, the Nam Hin Boun Cave, longer than 12 km, and the Nam Non Cave, longer than 25 km. Tham Songdang is 4.5 km long and is the swallow hole of the temporary stream leading to the Nam Non temporary spring cave.

The Nam Hin Boun through Cave, mapped by us mainly in 1994, is now a world-famous cave. Its river is fully crosses the mountain and it can be followed all along by motorized canoes. Some additional mapping was performed in 2006. In the Nam Non area, we continued trying to find the upper way out from the cave. The connection with Tham Songdang could not be made, due to sumps full of big trees (up to more than 10 m long for one tree). Systematic prospecting of the remote upstream side of the karst area, next to Mesozoic sandstone and shale brought us only small caves. We will continue in February 2009. Such prospecting has been fruitful in the sense that a number of interesting caves, despite being shorter (as Nameless Cave on the southern side of the massif) were discovered and mapped.

One sump in Tham Phué Phou and one in Tham Pessong were dived in two caves, both discovered in 1997.

3.2 The Nam Dôn area

The Nam Dôn area (Fig. 2) includes two main caves: Tham Phiseua, now around 13 km long and Tham Houay Sai-Tham Koun Dôn, now about 12 km.

Tham Phiseua is mainly a sloppy cave rising progressively to the relative elevation of +465 m. mainly along a few stratification surfaces. It is a hypogenic cave which shows thousands of cupolas, fine-grained sediments and original mineralogy (Mouret, 2008). New passage mapping has been made in several parts of the cave in 2005 and in the

Figure 2: Fengcong landscape in the Nam Dôn area. Photo C. Mouret.

central maze part and uppermost part in 2006. In addition, a vadose, temporary flowing passage behind the lower entrance has been mapped over more than 1 km beyond the former end sump, thanks to the divers of our team. This passage leads right into the heart of the massif and has nothing to do with the fossil hypogenic part. We continue working on this cave. In 2005, environment-respectful rock sampling was made, in order to analyze many of the unusual mineral deposits present in the cave.

In Tham Houay Sai-Tham Koun Dôn, many passages were surveyed, in order to refine the knowledge of the passage pattern in the western part of the cave (the occasionally flowing Tham Koun Dôn), and to continue both the central part and upstream part (from Tham Houay Sai opening, flowing during floods), towards Tham Houai Sai (another cave, receiving a temporary-flowing, sinking stream from the polje of Bang Vieng, Fig. 1). The permanent water outlet of the system is the large spring of the Nam Dôn. Passage sizes of 30 x 20 m are common in this cave, but not all of them are so large. Passages display a complex pattern.

In terms of relative elevation, the lowest are sunk passages, sunk maze parts, short sumps, deep lakes (down to -35m or more below the water "table"), shallow lakes, temporary flowing passages with lateral sumps or temporary flowing small to average-size passages, large chambers (the "Hidden Chamber" is 215 x 140 x ca 35 m), fossil horizontal passages (two to three levels), fossil sloppy passages (to the West) to sloppy fossil mazes (central part mainly). Three of the sloppy passages have led to upper entrances on cliffs or hill slopes, which proves that the cave has been truncated by external erosion.

There is a geometric similarity between Tham Phiseua and Tham Koun Dôn-Tham Houay Sai: both show a subhorizontal part near the downstream edge-cliff of the massif and fossil sloppy passages beyond. This is related to the structural dip for sloppy parts and bedding or fractures for the subhorizontal parts.

The sloppy parts (mazes and "normal" passages) show a vertical distribution along bedding planes or sets of bedding planes. The upper ones formed first, at least during the late general phase of relative base level fall.

Hollow stalagmites and rims have been discovered by the main author, first in Tham Phiseua (in 2002), then in Tham Koun Dôn (both sampled for lab studies, in 2005), i.e. the closest part of the system to Tham Phiseua. This obviously suggests a comparable or similar origin and both caves may have possibly been one, before truncation of the whole system by a deep karst valley. However, a "speleological" connection of the two caves is not likely, though not fully impossible.

3.3 The polje of Ban Vieng

The polje of Ban Vieng has been studied by us since 1996. The main cave, Tham Houai Sai, is a temporarily flowing swallow hole cave connected with lateral subfossil to fossil passages and a few large chambers. Its mapped length is around 10 km. Its end sump is not very far from the upstream end of the Tham Koun Dôn-Tham Houay Sai. As already explained (Mouret, 1998), we have here a part of a very long cave network, the elements of which remain to be connected, which is our goal. Several springs and ponors in the polje were dived in 2006, but no long cave could be found.

In a branch of the polje, to the Southeast, Tham Lô lies nearly 100 m above the polje level. It has been mapped over for more than 7 km. Tham Lô has two levels. The upper main passages are mainly subhorizontal; transverse, smaller, passages dip along the strata. The current end is the bottom of a shaft in friable sediments. The main passage continues on the other side at the top of the shaft. The lower level is nearly 80 m lower in elevation. Its passages are smaller and broadly follow those of the upper level. Tham Lô shows hollow stalagmites and rims.

3.4 The Ban Tat area

The Ban Tat area is located just next to the end of the SE arm (where Tham Lô is located) of the polje of Ban Vieng. Both are separated only by a limestone saddle around 100 m high and 600 to 800 m long. The Ban Tat area is the end of an arm of a karst plain. A branch of it towards the West bears two caves; one of them was dived over several hundred meters. At the beginning of this branch, a Buddha cave is present, close and broadly parallel to a stream coming from the dived cave. The Buddha Cave and other minor caves along the cliff show a large number of small (around 10 cm long each, or less) schematic anthropomorphs which have a likely prehistoric, BC origin. More recent cave paintings, including lotus flowers, are the work of Buddhist monks.

Around 5 km to the South of Ban That, Tham Lom is the temporarily flowing water outlet of a through cave, which was partly explored in 2005 and fully mapped in 2006. The upstream end of the cave opens near a large karst lake, which is entirely surrounded by high cliffs (up to 200m and more) or steep slopes. The Nong Bet lakes were previously reached by overland crossing (also in 2006) by the first author and several members of the team. It is a taboo place, which can be reached only after the sacrifice of a pig and several chickens. The main lake we reached is nearly 1 km in diameter and surrounded by high cliffs and steep slopes. It is partly filled up with sediments and bears rich flora and fauna. It is an exceptional place. To the West, at the lake level, the opening of a partly water filled cave is directed towards the interior of the karst. One of our cave divers (Richard Huttler) tried his best to find an outlet of the lake, but none could be encountered. The long trip through the jungle above the karst, here easy (for the Khammouane) showed us many interesting features, such as shafts, large dolines, small dry valleys, pavement features, tsingys, etc.

3.5 The Nhommalat area

The town of Nhommalat (Fig. 1) is located close to the contact of the karst with Mesozoic sediments. North of Nhommalat and a small village called Ban Tathot. At the time south of the border polje of Ban Mouang Louang, a number of streams (including the Nam Phou) and tributary streamlets enter the karst either directly into the bordering carbonate cliff or via a succession of shorter and longer tunnels. The sinking areas, already partly studied in 2002, 2003, and 2004, were continued exploring in 2008: several tunnels, temporary sinking streams, horizontal outlets and vauclusian springs were discovered. Three swallow holes and one outlet were mapped, between 100 and 500 m long each; the 100 m one could not be pursued due to quick sands. All these streams converge, probably with a complex pattern, towards the Ban Tathot springs. From the first sinking streams and short tunnels, on the way towards the springs, there is first Tham Deua, a nearly 2 km long river cave explored in 2003, then Tham Khamouk (2003), a nearly dry cave with a sump (dived in 2006 over nearly 500 m) in a lower passage, from which a large stream comes out at surface. This surface stream is 200 m long, and then it enters a short cave separated by a sump from Marie Cassan Cave (re-mapped by us in 2003, after Henri Cassan in 1948 and 1953). The cave water connects at least one of the two springs in Ban Tathot. We are not yet sure whether there is only one or two underground streams or simply a diffluence.

Clearly, in this part of the karst, underground flows are nearly parallel to the karst edge and not transverse. Further downstream along the edge of the karst, another large, permanent, karst spring is likely the outlet of one of the sunk streams further North than the Nam Phou. Further South, two temporarily flowing outlets were also recognized. A cave near a Buddhist temple bombed during the Second Vietnam War was mapped in this area.

3.6 The Xé Bang Fai area

After our exploration in 1995 (C. Mouret, J.F. Vacquié, B. Collignon & C. Lagarde), during which we mapped in detail the Xé Bang Fai underground through river, a world-class cave (Fig. 3), logistic problems prevented us to reach it again in 1996. After that, the whole area was strictly forbidden by the authorities. We tried every year to obtain a new permission with no success. In 1986, the situation changed and new expeditions could be organized in 2007 and 2008. (In 2005, we had approached the area with success near the Meugia saddle (Fig. 1) at the Vietnamese border, where we could make interesting observations on the geology and the karst. This helped us in changing the situation in the area, by progressive approach (Fig. 4).

In 1995, a large temporary flowing side passage was discovered and mapped in the upstream part of the cave: Cave of the Clouds, so called due to clouds in the cave, especially near the entrance. Large fossil passages had been reached in that part (“T” on Fig. 3). Cave of the Clouds is in reality an abandoned upstream, sinuous, part of the Xé Bang Fai. It has been isolated by an autocapture of the stream, between the former sinking point and a sharp curve of the underground passage which was not so far from the outside. The former sinking entrances collapsed, as did the area around the autocapture. The remaining part of the hydraulic “short-circuit” (the most upstream underground 100 m of the present day river) is still a much smaller passage than the rest of the cave.

The fossil passages were finished mapping in 2007. A small outlet to the outside was found. A fossil opening spotted in 1995 above the cave outlet was explored and mapped. It connects the main river passage at a nearly 100 m high relative elevation. Two side passages were spotted along the underground river.

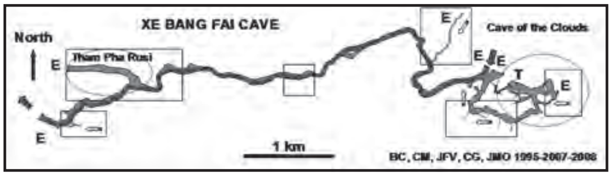

Figure 3: Sketch-map of the Xé Bang Fai Cave (a very detailed one will be published in the future). Ellipsoids: 2007 investigations; rectangles: 2008; darks arrows: main flow; empty smaller arrows: temporary flows; E: entrances; T: terminus in 1995.

Figure 4: The outlet of Xé Bang Fai Cave. Canoe for scale. Photo C. Ghommhid.

In 2008, the mapping of the Cave of the Clouds was refined and a dozen of side passages were surveyed along the abandoned loop: these are temporarily flowing streams during floods ; they behave as temporary vauclusian springs during water rising and probably as sinking points at the end of the floods. Fine-grained sediments (silts) have been deposited in this part of the cave: during floods, the water rises at least 40 m above the normal level of the Xé Bang Fai. Indeed, much complex sedimentation patterns occur there.

At the junction of the underground river and of the Cave of the Clouds, there is a strong water input from below and from the bank: it explains the increase of flow yield from that point. Further downstream, on the right bank, a tributary passage to the outside was noticed by an American team and mapped by us. Several climbs up to 100 m high gave us a much better appreciation of the elevation of the vault above the river. Finally, a left bank tributary was discovered near the cave downstream exit.

A cave located on the left bank of the Xé Bang Fai, Tham Ney, located a few kilometers upstream of the sinking point, was also mapped. It may be a remaining part of a paleo-Xé Bang Fai Cave. Around 5 km to the Northwest of the Xé Bang Fai cave outlet, in the polje of Tham Ene, a fossil cave was explored over nearly 1.5 km : Tham Ene. This 50 m wide and in average 15 to 25 m high passage shows more than 50 black circles on the floor, up to more than 5m in diameter each (Fig. 5). These circles are related to the fall of water from the ceiling, but they obey a complex genesis, which will not be detailed here. Other fossil caves, all shorter than 1 km, were explored in the area in 2007 and 2008.

4. Other aspects and Conclusion

Over the last four years, great progress was made in the study of the karst of Khammouane. In hydrogeology, we

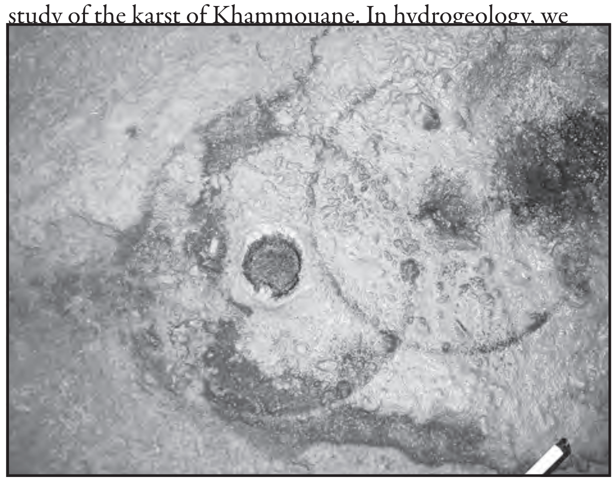

Figure 5: Two secant "black circles" in Tham Ene Cave. Pen for scale. Photo C. Mouret.

now more on the flows through the karst (Ban Tathot and Nhommalat area, Xé Bang Fai...), on underground lakes (up to 35 m deep or more), on the structure of the karst aquifer (by cave diving). About cave formation, we have learned a lot on the 3D evolution of the karst (Tham Phiseua and Tham Koun Dôn-Tham Houay Sai, Tham Lô), on the major guiding role of stratification planes on underground flows, especially in hypogenic caves, on speleothems and related topics (black circles rich in molybdenum, hollow stalagmites, rims, cave minerals, etc.). Further prehistoric anthropomorphs and Buddhist wall paintings have been discovered, Biospeology by H. Steiner has brought up rich discoveries, including a number of unknown species and genera.

All the material collected since 1991will be the matter of a comprehensive book and we actively continue our explorations and studies on the karst of Khammouane.

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Many thanks, of course, to the Lao Administration for permits to explore and to the so many villagers who always welcome us in the warmest way.

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THE INTERNATIONAL SPELEOLOGICAL EXPEDITION TO IRAN (2008)

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The International Speleological Expedition to Iran (ISEI 2008) took place between 23 September and 7 October 2008 in the regions north and southeast of Tehran (capital of Iran). This expedition is under the auspices of the International Union of Speleology (UIS) and aims to help cavers in countries with less developed speleological activities. Fifteen cavers from five different countries trained some 38 Iranian cavers (from 12 clubs from different cities) and explored five outstanding caves (Bournic, Gol Zard, Danial, Yakh Morad, Ghale Kord). Training covered: exploration (surface and subsurface), technical review (SRT and basic self-rescue), cave surveying, and cave photography and filming. Bournic and Ghale Kord caves were surveyed with the discovery of two new caves (one of historical importance) and overall 1000 m of surveyed galleries. Evening movies and presentations on various topics were organized (cave-rescue, cave diving, caving in other countries, international congresses of speleology). The publication of the Expedition Report in the form of an illustrated book and a documentary film are expected for July 2009.

1. Introduction

A first international expedition under the auspices of the International Union of Speleology (UIS) dedicated to help and support local cavers in a speleologically developing country took place in Tanzania (December 2004 to April 2005). This project was called ISET 2004-2005 (International Speleological Expedition to Tanzania) and a comprehensive expedition report was published (a UIS publication; NADER, 2005). Cavers from Belgium, Germany, Japan, Lebanon and Spain, together with Tanzanian members, participated in this expedition. The ISET resulted in exploring caves in Tanzania by an international and local team of cavers, meeting and encouraging local Tanzanian cavers, supporting local cavers by training and equipment donation, meeting administration officers and promoting speleology and karst protection. The immediate conclusion after the success of the ISET 2004-2005, was to organize a second episode of the International Speleological Expedition. Circumstances made Iran the next choice and consequently the International Speleological Expedition to Iran (ISEI) took place from September 23 to October 7, 2008. This contribution reports the activities of the ISEI 2008, which was also a UIS initiative.

The pre-expedition activities of organization and preparation were the key for the success of the ISEI 2008. These included: several meetings, a scouting trip just before the expedition, an expedition website with a forum for the participants, and documents (e.g., "Cave Directory Iran"; RAEISI AND LAUMANNS, 2003). The participants were 38 Iranian cavers from 12 different cities (Damavand Mountaineering and Skiing Club co-organized the expedition and Javad Nezamdoost from the Alpine Club of Iran was the Iranian leader of the ISEI 2008) together with nine Croatian, three Lebanese, one Belgian, one Swiss, and one English cavers.

2. Objectives and Schedule

The ISEI 2008 (International Expedition to Iran 2008) has been designed to exchange caving techniques with Iranian cavers and to tie friendship bonds between cavers from all over the world with cavers from Iran. After four expedition organizing meetings (two held in Belgium, one in Iran and one in Switzerland), the ISEI 2008 objectives were set as follows:

- Technical review and cave-rescue training
- Cave surveying/ topo-training
- Cave photography training

- Cave exploration (surface and subsurface).

Four northern provinces in Iran were visited during the ISEI 2008 (Tehran, Mazandaran, Gilan, and Qazvin). A total of six caves were explored, one of which was newly discovered by the ISEI team. The schedule was relatively compacted and intensive as many locations are far from each others; the team stayed only a few days in each location. The expedition's program was as follows:

- September 23-24, 2008: Arrival of ISEI 2008 foreign members to Imam Khoumeini International Airport, /Lela Hotel.
- Wednesday September 24, 2008: [Morning] visit of Tehran (Carpet Museum)
  [Afternoon] visit of Damavand Mountaineering Club and kick-off meeting of the ISEI 2008
  [Evening] arrival to Harandeh Village (together first group of trainees).
- Thursday September 25, 2008: [Bournic Cave]
- Friday September 26, 2008: [Bournic Cave]
  Evening traveling to Polur town
- Saturday September 27, 2008: [GoleZard Cave]
- Sunday September 28, 2008: [GoleZard Cave]
- Monday September 29, 2008: Traveling to the Caspian Sea (sight seeing and beach visit – the ISEI trainers slept at Mr. Ahmed Rafei's villa near Chalous)
- Tuesday September 30, 2008: [Danial Cave]
  Afternoon traveling to Kohnedeh
- Wednesday October 1, 2008: [YakhMorad Cave]
  Group B of Trainees arrives to Kohnedeh
- Thursday October 2, 2008: [YakhMorad Cave]
- Friday October 3, 2008: Travelling to GhaleKord
- Saturday October 4, 2008: [GhaleKord Cave]
- Sunday October 5, 2008: [GhaleKord Cave]
- Monday October 6, 2008: Return to Tehran
  [Afternoon] Closing ceremony of the ISEI Expedition
- Tuesday October 7, 2008: ISEI 2008 trainers return to home countries

3. Some Results

The first cave that was explored was the Bournic cave near Harandeh village (Province of Tehran; Fig. 1A). An original map was made available by Austrian cavers who were working in this cave (GEYER, 2007). The cave was reported by Ernest Geyer to have an underground development of 517 m and consists of two separate parts (a smaller upper gallery overlying the main lower development). Other than training exercises (e.g. surveying, photography, SRT – on nearby cliff), the ISEI team surveyed a few previously unmapped galleries (with breathtaking speleothems) and succeeded in linking the two major developments of the cave. A new cave (about 100m long) was found close to the entrance of Bournic Cave. Ghar Golezard Cave (also located in the Province of Tehran; near Polur village; Fig. 1B), which is hosted in Quaternary deposits and contain a water channel, was the second cave visited. This almost horizontal cave is reported to be 560 m long (RAEISI AND LAUMANNS, 2003) was only for training and it was followed by a long trip to the Caspian Sea, where a part of the ISEI team visited the Danial Cave (Fig. 1C); which is an active aquatic cave close to the coast of the Caspian Sea (near Chalus town).

Then, the team went southward and stopped by Yakhmorad cave, which hosts ice cascade and a few ice speleothems. This cave (about 400 m of underground galleries) was the subject of remapping activities led by cavers from the Damavand Mountaineering and Skiing Club and Simon Brooks. Important rigging work has been achieved in Yakhmorad cave and the survey was checked and slightly modified. The GhaleKord cave was the last station (Figure 1D). Here, significant mapping activities took place in this huge phreatic-style cave. More than 400 m of underground galleries were surveyed (Fig. 2). Surface exploration also resulted in another new cave (about 50m long), with signs of historical (and maybe prehistorical) occupation (see Fig. 3).

One important fact that must be reported about the

Figure 1: (A) Entrance of Bournic Cave (Harandeh; Province of Tehran; Photo by Johnny Tawk). (B) Entrance to Ghar Golezard (near Polur village; Province of Tehran; Photo by Mladen Garasic). (C) Near the entrance of Danial Cave (on the Caspian Sea; Photo by Afshin Yousefi). (D) Entrance of Ghalekord Cave (Ghalekord village; Province of Qazvin; Photo by Fadi Nader).

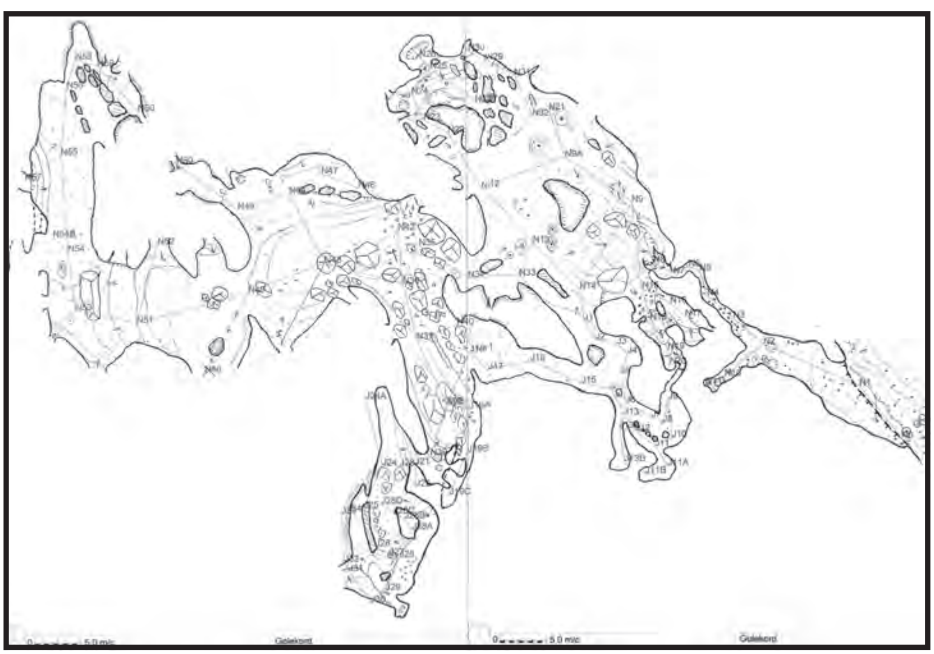

Figure 2: Survey of the Ghale Kord cave (surveyed by the ISEI 2008 team; drawn by Neven Bocic). More than 400 m of underground galleries are surveyed, but the cave is only partially surveyed so far.

kindness of the Iranian people in general and particularly the people of Ghalekord village, is that they hosted the ISEI cavers in the village mosque. This gesture will be never forgotten by the ISEI international members who were received in the most sacred place in that village. Another surprise was the huge closing ceremony that our Iranian colleagues had prepared for us on the last day in a big amphitheatre, where the invited speakers (Government Officials), guests (Ambassadors of Switzerland and Croatia among other officers), and media (national and international) showed the importance given for caves and karst. Once again, our Iranian friends showed us that in terms of hospitality, they are second to none (Fig. 4).

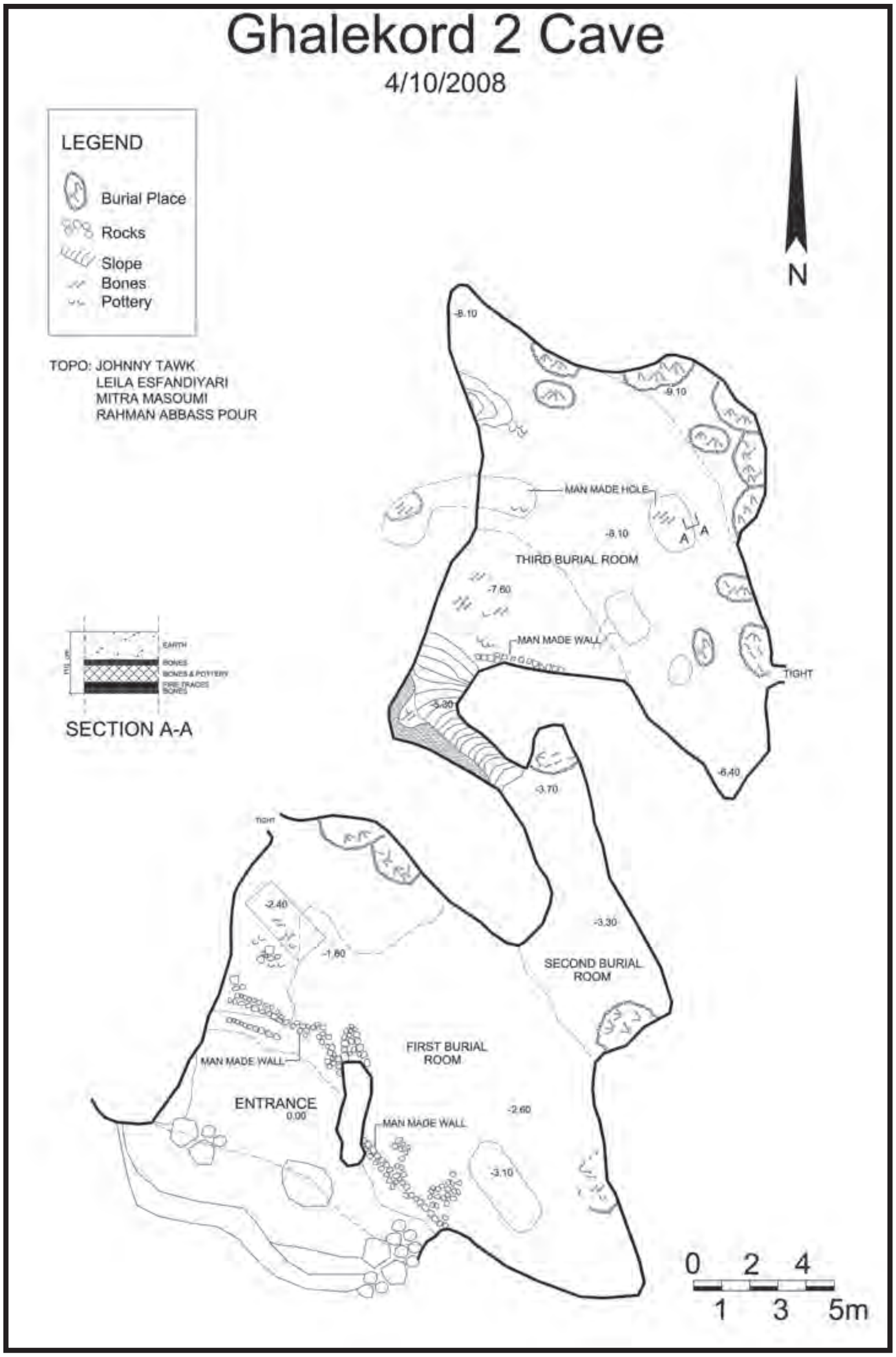

Figure 3: Survey of the new cave found near Ghale Kord (surveyed by the ISEI 2008 team; drawn by Johnny Tawk).

4. Conclusions

Other than establishing tight friendly bonds that link the ISEI foreign members and the Iranian cavers, the results of the ISEI 2008 are the followings:

- 11 days of training of about 38 Iranian Cavers from more than 12 different clubs and organizations from different cities in Iran.
- Training covered: exploration (surface and subsurface), technical review (SRT and basic self-rescue), cave surveying, and cave photography and filming.
- Bournic and Ghale Kord surveyed with the discovery of two new caves and overall 1000 m of surveyed galleries.
- Evening movies on various topics (cave-rescue, cave diving, caving in other countries, international congresses of speleology).
- Evening Sessions on caving equipments, cave surveying, speleo-techniques, the UIS, national organization of caving in different countries, among other topics.
- Post Expedition achievements:
  - Publication of the Expedition Report and Results in the form of high quality book.
  - Documentary Film on the ISEI2008.

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Figure 4: ISEI 2008 members with Mr Maziar Niazmand head of the Iranian Ecotourism Planning Bureau at the closing ceremony in Tehran (Monday October 6, 2008). Standing raw from left to right: Mladen Garasic (Croatia), Saeed Hasheminezhad (Iran), Ivan Drnic (Croatia) Tomislav Gospodinovic (Croatia), Kresimir Pogacic (Croatia), Ivan Kripna (Croatia), Jean-Pierre Bartholeyns (Belgium), Maziar Niazmand (Iran), René Scherrer (Switzerland), Neven Bocic (Croatia), Old Iranian Caver, Boris Watz (Croatia). Front raw: Fadi Nader (Lebanon), Habib Helou (Lebanon), Johnny Tawk (Lebanon), Igor Jelinic (Croatia) and Davor Garasic (Croatia).

EXPLORATION AND MAPPING OF SUNNYBROOK BLOWING CAVE, WAYNE COUNTY, KENTUCKY, USA

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Abstract

Blowing Cave lies just north of the Tennessee/Kentucky border along the Cumberland Escarpment, and is formed in Mississippian age limestones along the eastern flank of the gently dipping Sunnybrook Anticline. The cave has three main levels, likely corresponding to stable climate periods. High, narrow canyons connect the different levels to form a complicated network of stacked passages.

Serious exploration of the cave by NSS cavers began in 1955, when a group from Louisville first entered the lower entrance. Over two subsequent years, the cavers traversed the main passages to make the first connection to Chestnut Grove Sinking Cave, far up the valley. The cave was largely forgotten until the 1970s, when Charles Gibbs (of Gibbs Ascenders fame) bought the property after being told "there's a big cave there"!

A quick survey from entrance to entrance was accomplished in 1974, yielding 3 km. The exploration was not picked up again until 2002, when we took a wrong turn down a crawlway near the back entrance and discovered nearly 2 km of virgin cave heading further up the valley. The survey is ongoing, and is now at 6.5 km, with a vertical extent of 55 m. New discoveries are being made on nearly every trip. The latest discoveries are of two sections of high level trunk, one of them containing the largest single room in the cave, 100 m long and 30 m wide. At least 4 to 5 km of known passage remain to be surveyed, so Blowing Cave may become the longest mapped cave in the area.

THE CENTRE-TERRE EXPEDITIONS TO PATAGONIAN KARST ISLANDS : AN HISTORIC OVERVIEW

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The karst areas of Chilean Patagonia have long remained unexplored because of their remoteness, difficult access and very inhospitable cold, wet, and windy climate. Centre-Terre's first reconnaissance was made in 1995 by a four-caver team aboard a tiny fishing boat. The aim was to verify the presence of karst and possible cave systems on some of the isolated islands at Lat 50° to 52° S. Three epic days of risky navigation allowed a brief incursion on Diego de Almagro Island, where many shafts were located among huge barren lapis, in a region later named the "Marble Glaciers."

Our 1997 journey was the first national French expedition. The 10-caver team confirmed the caving potential of Diego de Almagro by exploring the impressive Perte de l'Avenir to a depth of –96m, as well as several minor caves. The second objective, Madre de Dios Island, was reached but its breathtakingly steep, promising karst could only be scanned with binoculars from the boat that year.

1. Introduction

Centre-Terre's Ultima Patagonia 2000 fielded a major caving expedition. The French Federation of Speleology, National Geographic Society, and the Rolex Awards for Enterprise contributed to its success. The international team, including Chilean geologists, was able to explore Perte du Futur (-376m) and Perte du Temps (>2.500m long). Other smaller caves totaled 8.400m. The discovery of human remains and paint in Cueva Ayayema and Cueva de la Cruz confirmed the archeological potential. Scientists in the team gathered data for various fields of investigation, including the unique "rock comets" (wind-oriented solution features).

Centre-Terre returned to Madre de Dios six years later in the first French-Chilean expedition. The Guarello Quarry was used as safer base camp, from which exploration produced 8000m of new caves, including Gouffre de la Détente (276m) and Finistère Cave (1.085m long). Unexpected prehistoric paintings were discovered in the Pacific Cave and six whale skulls in Whale Cave. In 2008, an international Centre-Terre expedition explored some 70 new caves totaling 8.500m. Owing to bad weather, the Gouffre de la Détente could not be descended further, but Abrigo del Viento (–197m) and Cueva Là-bas (–233m) were successfully explored and mapped. Diving a sump in "Beach Spring" (200m/–28m) led to an unexplored water-free gallery. The presence of whale bones at +37m above sea level in Whale Cave is still mysterious, and new zones for future exploration were found in the even-more-promising northern part of the island.

Centre-Terre's Ultima Patagonia 2010 will involve a two-month 25-person camp. The islands of Patagonia may not reveal record deep caves, but they remain one of the most challenging karst regions for surface and underground investigation. Centre-Terre's nomination of this unique area for a UNESCO World Heritage Site is underway.

2. Geographical and Geological Context

The karst areas of Chilean Patagonia are mainly located in two islands, Diego de Almagro and Madre de Dios, between Lat 52° and 50° South in the Magallanes channels (12th region: Magallanes and Antartica Chilena). The climate is oceanic sub-polar, very stormy and wet (7-8 m/year). The average elevation is 900 m asl. These islands are constituted of several kinds of rocks from two main periods: Permian-carboniferous rocks belong to the old basement of the Andean mountain range, located on the ridge of the Gondwana paleo-continent. They include limestone and marble belonging to a corallian paleo-reef about 300 MA old. These limestones are called Pelantaro Formation in Diego de Almagro and Tarlton Limestone in Madre de Dios. They are both in contact with other non-carbonate rocks (volcano-sedimentary etc…), often inserted in marbles as intrusive dykes. All these old rocks are now in contact with younger granites belonging to the Mesozoic Patagonian batholith about 130 MA old, located on the eastern part of the islands. The distribution and coexistence between carbonate and non-carbonate rocks is very important to understanding the karstification in these islands. Moreover, the conjunction between this geological context and the stormy, windy hyper-humid climate, but also with the paleo-climate influence (glacial periods, sea level fluctuations), explain that we can observe one of the most spectacular karstic landscape in the world, due to record values of dissolution rate in bare surface karst (about 100 mm/ky): Giant karren (1 to 4 meters wide), hydro-eolian, (shaped by rain and wind) features like flat pavements, "rock comets" and incredible "ram" (oblique lapis- table), marine corrosion notches recording the sea level variations since the last deglaciation and the isostatic recovery of the islands.

Figure 1: The "Rock Comets": wind and rain work together to carve residual crests behind insoluble erratic blocks. Photo Richard Maire.

Figure 2: Hazardous prospect on the "Marble Glaciers", photo L.-H. Fage.

3. 1995: First Steps on the "Marble Glaciers"

Back in 1994, J.-N. Salomon and R. Maire brought back from a trip to Chile an article untitled "El fenomeno carstico en Chile" in which G. Ceccioni (1982) mentioned the presence of limestone and visible shaft entrances in the Diego de Almagro and Madre de Dios islands. These observations have been noted in an unpublished report (1945) of the German geologist W. Biese as well as in various confidential notes (1956/57). Curiously the Guarello quarry was exploiting the precious, almost pure limestone since1946 and never drew the attention of scientists or cavers.

On March 11th, the four of us (M. Letrône, R. Maire, J.-F. Pernette, J. Sautereau) were just pacing up and down on windy Puerto Natales wharf, asking for a lift to the first limestone-like island. We eventually found Edgardo and son, skippers of the Katita, a 14 meter long fishing boat, who accepted to take us. A week was necessary then to have the boat ready and obtain special authorization. Three more days and nights of navigation, including a risky U-turn in the middle of furious Union Canal and we finally reached Diego de Almagro. Captain Edgardo stared at us and asked about 3 times: "Do you really want to disembark?" Sure we did and finally spent a few hours on solid ground, more exactly on dense vegetation and at last barren lapies: stunning landscape with tens of crevices and shafts entrances obviously unexplored... We had no gear, no time, but were lucky to get 2 hours of sun (the only ones in the week) just enough for a short video and a few pictures of the extraordinary "Marble glaciers". Figures 1 and 2 are later photos.

These very pictures were to be decisive for planning a new expedition and later on for obtaining a National Geographic Society grant and a Rolex Award for Enterprise.

4. 1997: First Cave Explorations

Two years were necessary to prepare a real expedition. Without any financial support, the budget for renting a larger boat, the "Explorador", is divided by the ten of us: maximum time allowed then will be only 20 days.

January 4th: We reach Punta Arenas. Wind is blowing at 130 km per hour. Welcome to Patagonia! Four days later we are back on "our" lapies. Four disembark to set a camp and the boat drops six for a first prospect on the other side of the plateau. After a 2 hour climb, we are in trouble: A hail storm with a 100km/h wind replaces the almost sunny morning calm. The boat disappeared for a safer place 20 km away and fortunately was able to be back for a marines-type rescue just in time before night and a second storm. The campers were to spend one more memorable night before we could reach them. The lesson was good: from now on, we would use the boat as base camp in a secure mooring, if any. Captain Conrado decided to go to Abraham fjord, where karst is visible about 2 hours up through the magellanic bush... We didn't know but the Perte de l'Avenir was to be discovered right above the cliffs.

The entrance is quite impressive: the overflow (200L/s) of two glacier lakes falls into a 50 meter deep shaft. The descent is made on the opposite side of the waterfall but the last ten meters are quite wet (Fig. 3). At the bottom the underground stream runs calmly for 150 m in a wide and high gallery to a sump. There are no traces at all of flood level. How can we know the importance and speed of floods in Patagonian caves? This one is the first explored ever. A dry passageway continues above the sump and after a 17m pit, we're back in the stream. The tunnel is 4m wide now and the wind is strong enough to blow off a sheet of the mapping

Figure 3: Richard Maire starts abseiling the 50 meter deep entrance pit of the "Perte de l'Avenir." Photo Jean-François Pernette.

note book. Deep pools need long wall rigging and the exploration is very technical.

At the same time, after abseiling 70m into the canyon above, R. Maire was able to reach the underground stream and explore some 30 meters upstream, setting a cairn that the entrance team found a few hours later. The first cave (and through-trip as well) in Chile was discovered (300m/-96m). Mapping, photos, film and de-rigging the cave, plus one last prospect in the foggy higher plateau, completed the 1997 expedition fieldwork on Jan 18th. We headed then towards the fully equipped Guarello quarry base, and after one full day waiting for better conditions of navigation, we have to go back without disembarking on Madre de Dios.

5. 2000: First Expedition to Madre de Dios

The choice for boats to hire is limited in Chilean Patagonia. We eventually found the Puerto Natales Primero, large enough (34m) for our 25-people team plus 9 crew members. Unfortunately our journey was disturbed by major mechanical problems. Heading South from Puerto Montt via Puerto Eden, we finally reach the Guarello base on Jan 29th after a 6 day journey. Like in 1997, the people are very welcoming and the temptation to stay in such comfortable accommodations is strong, but we decide to look for a mooring closer to our objectives: the Eleutorio fjord.

Cueva Mañana and Lobos resurgences are explored and mapped. But on Feb 2nd, the news that comes in is like a cold shower: our ship is taking on water! We really have to go back to Guarello. The only way is to fill the leak with cement and find an extra pump. We'll have one shipped by ferry somewhere in the middle of Concepcion canal. At 2 a.m. our inflatable boat approaches the huge (over 100-meter long) "Navimag" which doesn't even stop. The pump is lowered from the deck with a rope into the dinghy and the big ship disappears in the night. Our forced stay in Guarello will permit the discovery of Cueva Ayayema. A small entrance about 20 meters above water is reached after an 8m climb. A human burial site containing an almost complete human body is discovered inside (Fig. 4). This means that the Alakaluf Indians also used caves. After repairs, we head for a new mooring: the Seno Soplador, well sheltered from storms and which proved to be a better base camp for reaching the many caves in the Soublette and Roberto sectors. From February 7th to 16th activities are oriented around 3 objectives:

The Perte du Temps: it turns out to be the largest cave in the area. After installing a surface camp in a thicket of trees not far from the entrance, over a dozen trips allowed us to explore over 2,500 meters to a depth of 200m. The surface river flows down into a bowl-shaped doline 10 m deep. The water falls into a magnificent underground canyon about 30m high. Progress in the narrowest section, over 20 meters above the tumbling water is really impressive. The cave continues downwards with tributary passages, semi-active levels and sumps. From the surface, several large entrance pits descend vertically to the underground stream (four entrances found). The end of the system, a sump, is extremely close to sea level.

The Perte du Futur is a magnificent cavern. The entrance is a huge, complex pothole with rocky arches that collects water from several cascading torrents. The first pit is 50 m deep from which 40m constitute a single drop. The active passage

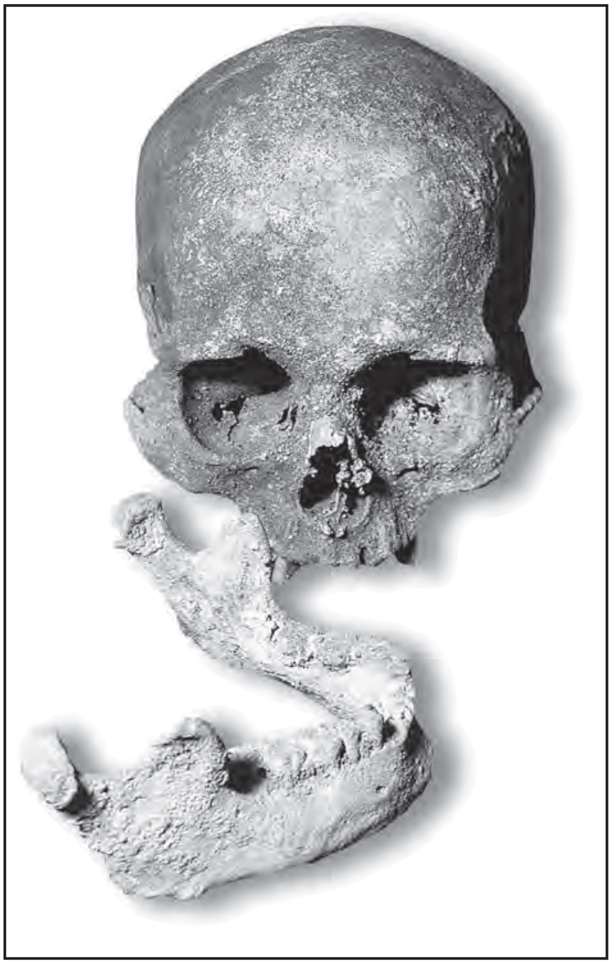

Figure 4: Skull of Cueva Ayayema, dated 4500 BP, photo Luc-Henri Fage.

then plunges through a broken slope with some down-climbs and waterfalls over a huge landslide of sandstone blocks and tree trunks on the ground. Then, the profile becomes more and more vertical to reach a canyon followed by a series of large pitches of which a final pit of 70m allows us to set foot once again in the collector. The cave ends in a superb sump at a depth of -376 m, the deepest known in Chile (Fig. 5).

The Cueva de la Cruz reveals a new Alakaluf burial site with human remains, no doubt re-organized by Chilean fishermen who have erected a cross at its entrance, visible from the fjord. The site contains numerous objects of jewelry made from shells and even wall paintings, mainly in red pigments similar to those from Cueva Ayayema.

February 15th: A miracle of the kind that happens only a few days a year in this part of maritime Patagonia takes place. There's no cloud in the sky and no wind at all. Two dinghies are equipped for a reconnaissance trip to the pacific coast of the island. After passing the southernmost point

Figure 5: The 100-meter-deep "Al Tiro" pit, in the "Perte du Futur." Photo Bernard Tourte.

of Madre de Dios, we head north with a crosscurrent that pushes us towards the shore. We have to move in carefully among the reefs, sharp as razors and barely visible between waves that are now over two meters high. There's no real hope of disembarking and even less of launching the boat under such conditions. We're about to turn around when we spot a huge entrance in the 300m high cliff, at least 70 meters high and 50m wide... It's now or never, two members of the team make a commando style jump and run exploring 200 meters of a large, tubular passage with a diameter of 20 to 30 meters. In the entrance zone, 100 meters from the sea, the skeleton of a whale lies on clayey ground. On the following day heavy rain and violent wind were back. It was time to go anyway. For safety reasons, we head South towards the closest real harbor: Puerto Natales... We'll be back soon!

6. 2006: First French-Chilean Expedition

Six years later, Centre Terre is back to Patagonia. Thanks to our past contacts, base camp will be in Guarello quarry. Our Chilean hosts greet us warmly. They will look after us for two months, lodge us, feed us, without once losing their patience or good humor despite the complications and risks that inevitably come with a band of cavers on expedition: indecent hours, last minute changes to plans, unavoidable noise that's hardly compatible with workers on night shift.

January 16th: One group makes a reconnaissance trip to Isla Tarlton, another limestone island to the South of Madre de Dios. Another group checks objectives that we couldn't visit in 2000. The third group take advantage of the calm to begin the exploration of the Southern part of the island between Senos Soplador and Eleuterio. They install two "altitude" camps in promising zones, one at 400 m and the other at

600 m. The first caves are found and explorations begin. On Jan 21st, while trying to reach Whale cave by following ledges on the limestone cliffs, we made an unexpected find: a small cave with two entrances and plenty of light. Covering the floor were thousands of shells and the remains of fireplaces, clear evidence of human habitation. Suddenly ochre paintings and traces of charcoal came into view on the black wall: more than 40 paintings of a form previously unknown amongst the Alakaluf Indians! (Fig. 6

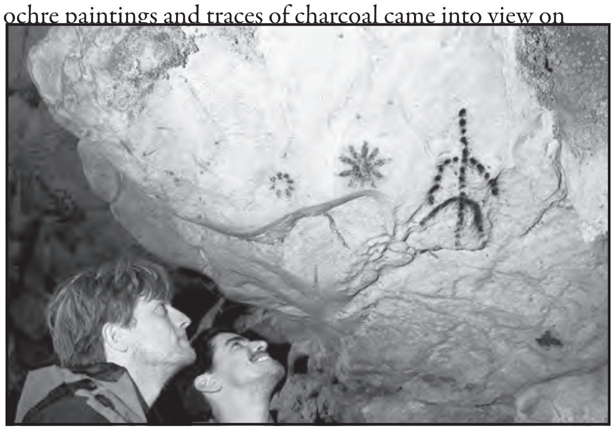

Figure 6: Wall paintings in Pacific Cave: the first artistic traces of the almost vanished Kawésqar Indians. Photo Luc-Henri Fage.

Despite the archeological reorientation imposed by events we also continued with cave explorations. We resumed scientific studies in Moraine cave, discovered on the NW coast of Guarello Island in 2000. It has impressive 20 m thick moraine deposits and finely layered "varve" deposits (formed from glacial rock dust), in a side passage. It is a veritable climatic archive that demands to be studied.

On Jan 29th we installed a more remote base camp at the very end of Seno Conteras with the aim of reaching Seno Barros Luco. This camp "at the end of the earth" would be occupied almost continuously until the end of February by teams on rotations. Three Alakaluf burials caves were discovered and mapped on Isla Ramon. At the same time we installed another five-day camp on the Southern slope of Mt Roberto. Here, during the 2000 expedition, we found several important caves, among those, the Perte du Futur, the deepest cave in Chile, at -376 m. We found several new caves, four of which exceeded -70 m deep and one -120 m deep. We also explored 150 m and mapped to -45 m in Hourglass sink.

On the 7th of February, 9 "Februarians" were unloaded to relieve nine "Januarians". One team returned to Colander Cave, while another returned to Hourglass Cave and found as well a superb 33 m deep bell-shaped shaft that swallowed a waterfall: Restful cave rapidly reached -100m, then -150 m. On the 15th, Hourglass Cave reached -150 m in an active meander and the divers went to Kawtcho Sink in Seno Soplador and reached – 30 m. On the 16th we completed the exploration of Colander Cave. It ended in a squeeze at -180m so we moved to Huequito Cave, which reached -200 m.

After 4 unsuccessful attempts, on the 19th, with only one meter waves a team of eight took to the Pacific. The enormous Whale Cave held even more remains than expected: five more whale skulls and bones. On the 21st, Hourglass Sink reached -271 m. A narrow sump left no hope: the final chamber carried flood marks five meters up the walls… The countdown had begun, we made our last attack on Restful Cave and continued exploration and mapping until the 23rd without reaching the end. The deepest point we reached was estimated to be -305 m. After one last visit to Finistere Cave and a last dive, the expedition left on March 2nd.

7. 2008: First Step Towards Conservation

The expedition shows a new collaboration between Centre-Terre and several Chilean/French universities, research institutions and even government of Chile. This took place at the moment in which Chile voted an official status of protection of Madre de Dios. After some training in 2007, it is during this expedition that the first Franco-Chilean cave explorations, including rigging, mapping and sampling really started. All together 8.500 meters of underground passages have been explored and mapped in no less than 70 caverns. The Gouffre de la Détente could not be descended further, but Abrigo del Viento (-197m) and Cueva Là-bas (-233m) were successfully explored and mapped. Diving "Beach Spring" (200m/-28m) led to an unexplored water-free gallery.

What we all feared since our first steps on the islands, a serious (surface) accident occurred on January 21st. One caver fell six meters into a crevice masked by vegetation and suffered a broken foot and humerus. Fortunately the injured was able, with the help of the team and some strong medication, to get back to the boat in one memorable long day.

On February 5th, thanks to the logistic help of the Compania de los Aceros del Pacifico that put to our disposition the "Del-Mar II" sea-boat, a team was able to explore the Northern part of Madre de Dios during eight full days. This same boat was then used as base camp for another team in Seno Barros Luco sector. They were forced to wait three days because of a tempest with 8m high waves! These two missions allowed us to discover two new sites of Kawesqar Indians occupation. It provided evidence for the existence of an inland route used by the Kawesqar between the Seno Soplador and Whale Beach. They used the following shelters and caves: Cueva de la Cruz, shelters near the Perte du Temps and Soublette lake, and finally the whale bones Hut burial (910 BP). Anthropologic inspection of the bones has confirmed morphological characters typically mongoloids.

Giant Whale Cave revealed a new surprise with the discovery of whale bones on a ledge at +37m (2.600 BP). A post-glacial marine level at this altitude being excluded, it is probably due to a tsunami.

For the first time, a station has been installed on the northern end of Tarlton island in order to measure the different hydrologic and meteorological parameters that control the dissolution speed on bare limestone and the evolution of lapis runnels. Five “Luirographes” (measures water pressure + temperature) have been set in four different sites too. This study will permit to know floods frequency and the number of major ones. The expedition ended on March 1st with many objectives to be continued. On the way back to Puerto Natales the brand new “Patagonian Exploradores” almost caught on fire in Canal Concepcion…

Centre-Terre’s Ultima Patagonia 2010 will definitely be oriented on more scientific and archeological researches: installation of a “laboratory cave” equipped with satellite data transmission and detailed studies of reference sites (archeological caves, clear-water fauna, Whale cave…). The islands of Patagonia may not reveal record deep caves, but they remain one of the most challenging karst regions for surface and underground investigation. Centre-Terre’s nomination of this unique area for a UNESCO World Heritage Site is underway.

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PRELIMINARY OVERVIEW ON THE KARST AREAS OF KALAW (MYANMAR)

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Southeast Asia hosts some of the most relevant karst areas in the world, many of which are in the Indochina Peninsula. Due to the severe restrictions of the government, the karst areas of Myanmar (former Burma) are actually those less explored and studied.

In 2005, in collaboration with the Universities of Bologna (Italy) and Yangon (Myanmar), the association La Venta organized a first expedition to Shan State (NE Myanmar) in order to carry out a preliminary investigation on the karst areas. Unfortunately, the present political situation does not allow further investigation in what is probably one of the most interesting karsts of Indochina.

The investigated area lies within a radius of ~70 km around the town of Kalaw and represents the most western branch of a large plateau made of Permian limestone and dolomite, which extends across a great part of central and southern Shan State. The landscape is characterized by a series of rounded ridges, N-S oriented, which share different basins flowing southward.

The area shows many of the typical geomorphic features of tropical countries. In the carbonate areas the relief displays abrupt ridges, conical hills and large closed depressions. Cockpits and blind valleys mainly occur on limestone, whereas, on weathered dolomites we find hills and cone-karst. The same landscape occurs on the Mesozoic carbonate conglomerates.

During the period of field investigation 27 caves were surveyed. Due to the wide extension of carbonate rocks, most of the investigation should be considered as a preliminary survey, aimed at identifying the most interesting areas. Major caves were accurately surveyed, collecting a total length of about 4 km of cave topographies along with zoological sampling and preliminary geological and hydrogeological studies.

1. Introduction

The Indochina Peninsula hosts some of the most relevant karst areas in the world. Due to severe restrictions by the government, the karst areas of Myanmar (formerly Burma) are actually the least explored and studied.

In 2004, the La Venta Association undertook a reconnaissance expedition in Shan State (NE Myanmar) in order to get a preliminary insight of the karst areas. This mission allowed us to pinpoint many interesting areas but finally we decided to focus our researches on the zone south of the town of Taunggyi. The second expedition was carried out in February 2005 (De Vivo et al., 2006). The team, composed of 13 cavers from La Venta and 6 researchers from Yangon University, focused its effort on the area close to Kalaw and on a wide karst area located to the west of the village of Pinlaung, about 70 km to the south (De Vivo and Piccini, 2006). Due to the wide extension of carbonate rocks, most of the investigation should be considered as a preliminary survey, aimed at identifying the most interesting areas for further and more detailed research in future years. Major caves were accurately surveyed, collecting a total length of about 4 km of cave topographies. Photo and video documentation were also carried out, along with a zoological sampling and preliminary geological and hydrogeological studies.

2. Geological and Geomorphologic Overview

The investigated area lies within a radius of about 70 km around the town of Kalaw and represents the most westerly part of a large plateau made of Permian limestone and dolomite. The landscape is characterized by a series of rounded ridges, N-S oriented, which separate different basins flowing southward, the widest of which is the Paung Laung River. The ridges are made up mainly of carbonate rocks where a well-developed karst landscape occurs.

In the area, two different karst units exist. The most important is part of a thick series of dolomites and limestones of Permian-Triassic age ("Plateau Limestone")

(Thura et al., 2002). This carbonate unit is covered by Mesozoic "Red Beds", which are made of shales, mudstones and sandstone (Brown and Sondhi, 1933). The second karst unit consists of thick Cretaceous conglomerate sequences, which lay unevenly on shaly Mesozoic sequences. Fluviatile environment conglomerates are made of well-rounded polygenic elements, mainly from Permo-Triassic carbonates and some red siltstone pebbles, held in a reddish calcareous matrix and inter-bedded with sandstone. On the old geological map, these are known as the "Kalaw Red Beds" and dip at approximately 40 degrees eastward.

The area is characterized by N-S tectonic lineaments, either compressive or extensive. Roughly, the "Limestone Plateau" ridges correspond to anticlines, whereas conglomerates match to wide curvature synclines. W of Pinlaung, the carbonate outcrops consist of parallel ridges due to E-facing thrusts.

The area shows many of the typical geomorphic features of tropical countries. Topography is controlled mainly by lithology: where clastic rocks outcrop, the landscape consists of rounded hills, with a thick cover of soil, conversely, in the carbonate areas the relief displays abrupt ridges, conical hills and large closed depressions. Cockpits and blind valleys mainly occur on limestone; on weathered dolomites we find hills and cone-karst probably due to a more rapid evolution of the landscape. The same landscape occurs on the conglomerates; in this case the formation of cockpits, instead of cones, depends moreover on the morpho-structural setting, with the formation of the former in the low-gradient areas and the development of the latter in the high relief.

3. Description of Studied Areas and Caves

Our investigation tours took places from the village of Kalaw. Due to the number of caves indicated by local people we were obliged to get only a quick look at most of the karst areas of this region. The areas with the most speleological potential are the mountains formed in the Plateau Limestone belonging to the long N-S strip running W of Kalaw (Fig. 1). During the 2005 expedition our efforts were concentrated mainly in some of the areas close to Kalaw and close to the village of Pinlaung, about 80 km further south, which are here described in more detail.

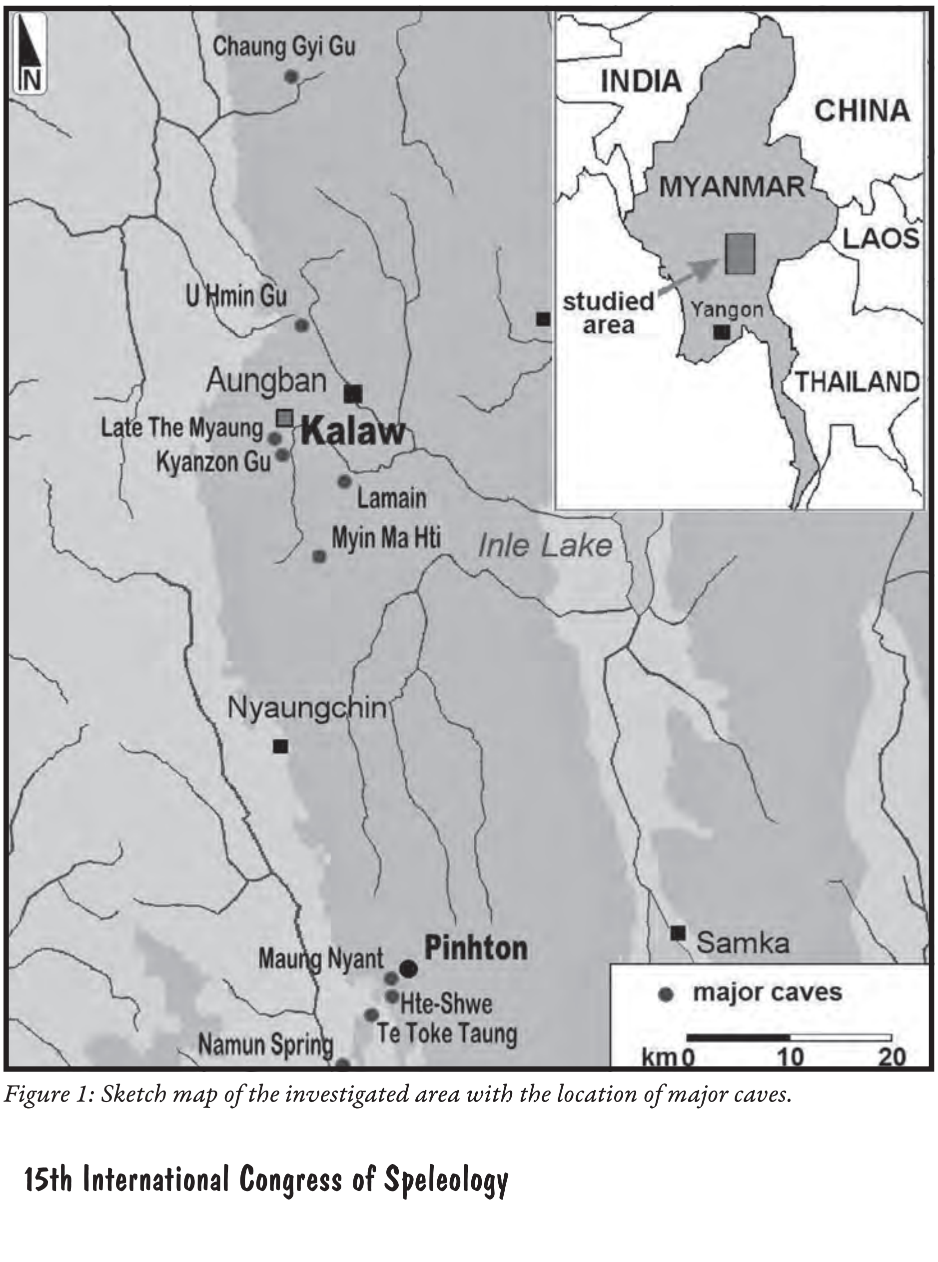

Figure 1: Sketch map of the investigated area with the location of major caves.

3.1. The conglomerate karst in the neighborhood of Kalaw

Just to the west of Kalaw, wide outliers of "Red Beds" conglomerate occur. In the topographically favored areas, we find several closed basins, up to 2-3 km^2 wide, where water flows along blind valleys that feed stream sinks. Minor depressions have variable shapes, ranging from the usual star-like plan of cockpits to the circular plan of dolines. Along the watersheds, we find bare rocks shaped as isolated blocks, pinnacles and rounded karren. The coarse nature of the conglomerates does not allow the development of dissolution sculptures, but the number, and extent, of caves demonstrate that this rock is particularly soluble.

The longest cave explored is the Late Th e Myaung Saint (Dead Tortoise Valley Sink), located about 1 km west of Kalaw (Fig. 2), which represents the present-day sink for the Late The valley. The first part consists of a wide and irregular room affected by rock collapse. Going downwards we can reach an active tubular passage, only a couple of meters wide, which is directed towards the N following a fracture. A meandering route, with several pools, characterizes the middle part of the cave. In the final section, large rooms and active passages lead to the terminal sump.

The Late Th e Myaung Gu (Gu = cave) is located just a few tens of meters above the valley floor. This cave is probably an old swallow-hole. The entrance initially slopes steeply downwards and then levels out before becoming totally choked at the bottom. The cave is used by the ethnic Tibetan community as the site of a religious shrine.

Another interesting cave is the Kyanzon Gu, situated close to the Say Wingabar monastery to the south of the town and consists of two narrow passages that lead to a room with rock fall detritus. The cave follows a main fracture along vadose meanders and epiphreatic passages, with deposits of sand and mud. In the final section, the cave becomes moderately active; here the cave shows parallel fissures and conduits, with sand deposits.

3.2. Areas north of Kalaw

To the north of Kalaw, Permian carbonate rocks outcrop widely, but do not show intense karst features, due to the smooth topography and to the occurrence of thick red soils cover. In some places, limestone residual hills characterize the landscape; in the largest of these, some caves occur, mainly due to lateral infiltration of water.

A typical example is the U Hmin Gu (Fig. 3) that is found in an isolated hillock, formed in the Plateau Limestone, and is of great archaeological and religious importance with hundreds of ancient Buddha images dating back to possibly the 14th-16th century. The cave has two entrances that open onto the first chamber where most of the images are to be found. A side branch leads to the second part of the cave that consists of a maze of tunnels and rooms of different sizes. In the furthest part, a pit of 15 m leads to a lower level characterized by a muddy floor, which ends with high passages.

Further to the north we find Chaung Gyi Gu (Big River Cave). The entrance is large and a terrace of gours spans the passage inside. The passage is around 6 m wide and 10 m high with a highly sculpted floor and continues to a shaft on the right-hand side. Straight ahead the passage becomes

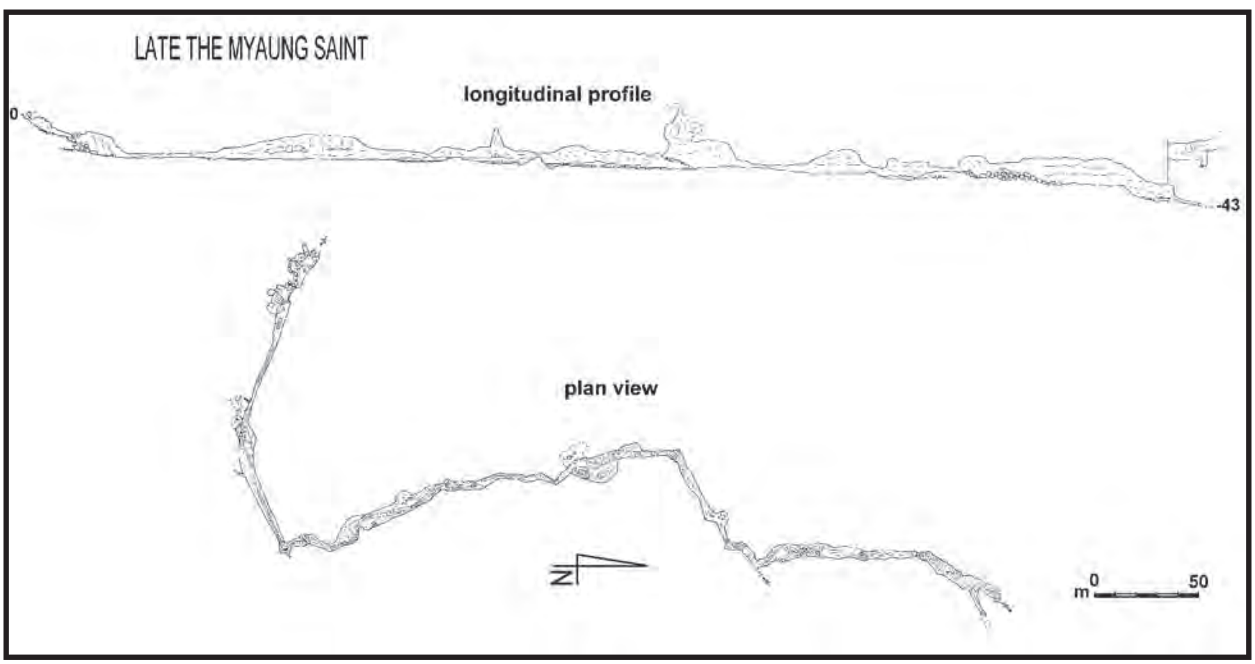

Figure 2: Longitudinal profile and plan view of Late The Myaung Saint Cave (survey: E.G. La Venta, 2005).

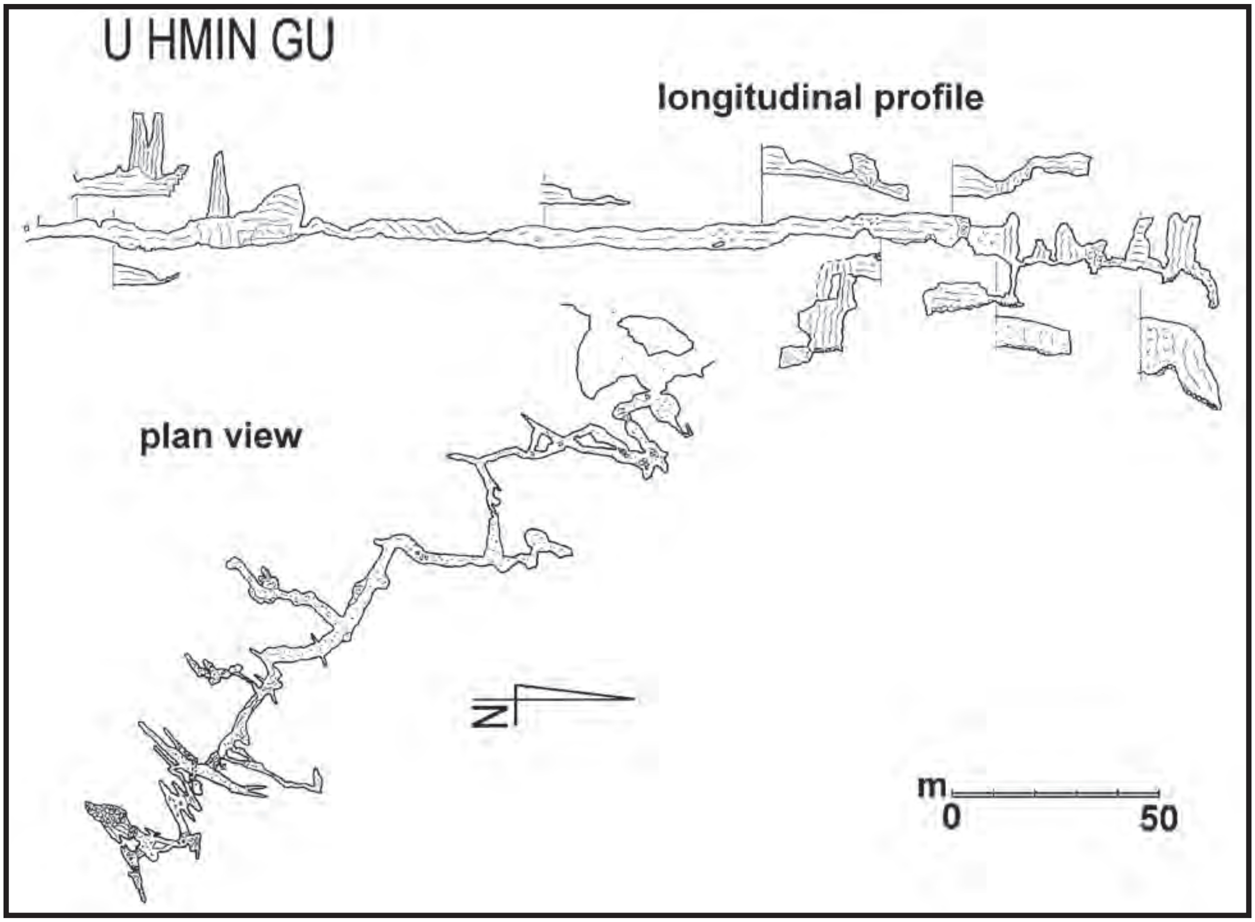

Figure 3: Longitudinal profile and plan view of U Hmin Gu cave (survey: E.G. La Venta, 2005).

narrow and meandering before ending after about 80 meters.

3.3. Areas west of Kalaw

A few kilometers west of Kalaw is an area which shares a similar morphology to that of the area to the west of Pinlaung (see below). In fact it is the northerly continuation of that same dissected ridge with steep slopes that are densely forested and highly karstified. Although time restraints prevented any concentrated efforts in this area two large caves were found. Near the village of Lebyin is a large resurgence cave, Yang-Nyaung Gu. Even in the dry season the issue from this cave is big enough to irrigate a very large cultivation area. The spring itself was not penetrated very far but a huge upper entrance is said to go back down to the water beyond any blockage. Twinn Ii (Bad Smell Cave in the local Palaung language) is another large spring situated near the village of Pinmon, a little further south. It was dry when visited and a large passage (10 m x 7 m) was followed for about 200 meters and the way on is wide open. There is however great potential in both these caves and in other caves nearby.

3.4. Areas south of Kalaw

Towards the south, the limestone ranges display a karst landscape with several promising areas. In all this area we did only a rapid investigation of the most accessible caves.

Lamain Cave is located to the east of the road to Pinlaung, and is a huge open pit that landed in a large daylight chamber with a further pit of around 20 meters. On the rim of the second pit, a wood platform is used to lift the guano from the bottom of the cave. This pit opens into a large chamber hosting a bat colony. From the chamber, two different passages proceed; the first, ascending, contains calcite deposits while the second is accessible through a lateral pit.

Myin Ma Hti Cave is used for religious purposes and is filled with many Buddha images. It is located about 6 km SE of Kalaw. It consists of a karst tunnel, which acted as a phreatic tube in the past, joining some large subterranean rooms. In places, side cavities and short branches may be found. The second part of the cave consists of a wide chamber with different levels. Man has heavily modified the cave and the floor is artificial, and thus it is not easy to recognize its natural morphological features.

3.5. Area SW of Pinlaung (Namun Karst System)

Seventy km to the south of Kalaw and 10 km to the W of Pinlaung village, a broad limestone ridge runs N-S. In the middle part, the ridge is 6-7 km wide and is bounded to the west by the Paung Laung River. Steep slopes, rock walls, and sharp watersheds dividing closed basins characterize the landscape. On the east side, some blind valleys feed stream sinks. In short, it is a typical situation of contact karst, where some rivers, with the upper basin made of impermeable rocks, are forced to cross a carbonate ridge through underground passageways, direct to the Paung Laung valley. The whole karst area is characterized by closed depressions and cockpits, which imply a high development of endokarst. This area belongs to a wide carbonate plateau that is probably divided into different hydro-geological systems flowing towards the SW. The largest among them is located just west of the village of Pinhton and is fed by a basin of about 30 km^2 that converges on a huge swallow hole, along a first narrow carbonate ridge located close to the village of Pinhton (Fig. 4).

The stream, which has here a discharge of about 1 m^3/s in the dry season, passes through a large karst tunnel 270 m long, named Hte Shwe Cave, flowing out in a nearby valley, developed again on the impermeable Cretaceous rocks (Fig. 5). The entrance consists of a large portal, about 40 m high, which continues with a canyon occupied by a lake about 80 m long and closed by a big flowstone. An upper gallery, which enlarges in a room rich with stalactites and gours filled with pisolites, again reaches the stream after a path of about 50 m. After a small descent between large rock blocks, one reaches the exit of the cave. The last chamber, about 40 m long and 20 m high, presents large terraced deposits of sands and gravels, probably formed during the rainy season and eroded in the dry one.

After a path of 5 km southward, the river ends at a second huge swallow hole named Te Toke Taung Cave. The entrance is a portal about 40 m high where the water falls into a large shaft, about 50 m deep. The waterfall jumps into the bottom of the shaft, occupying the whole section of a canyon that continues towards the north.

The river probably resurges at the Namun Spring. Here, just above the upper spring, two small entrances open at the foot of the steep edge of the karst, along the Paung Laung River. From the lower entrance it is possible to reach the first part of a large gallery completely occupied by a lake. The opposite shore of the lake is not visible. Some hundreds of meters downstream, the water rises up diffusely among the blocks of a large rock fall.

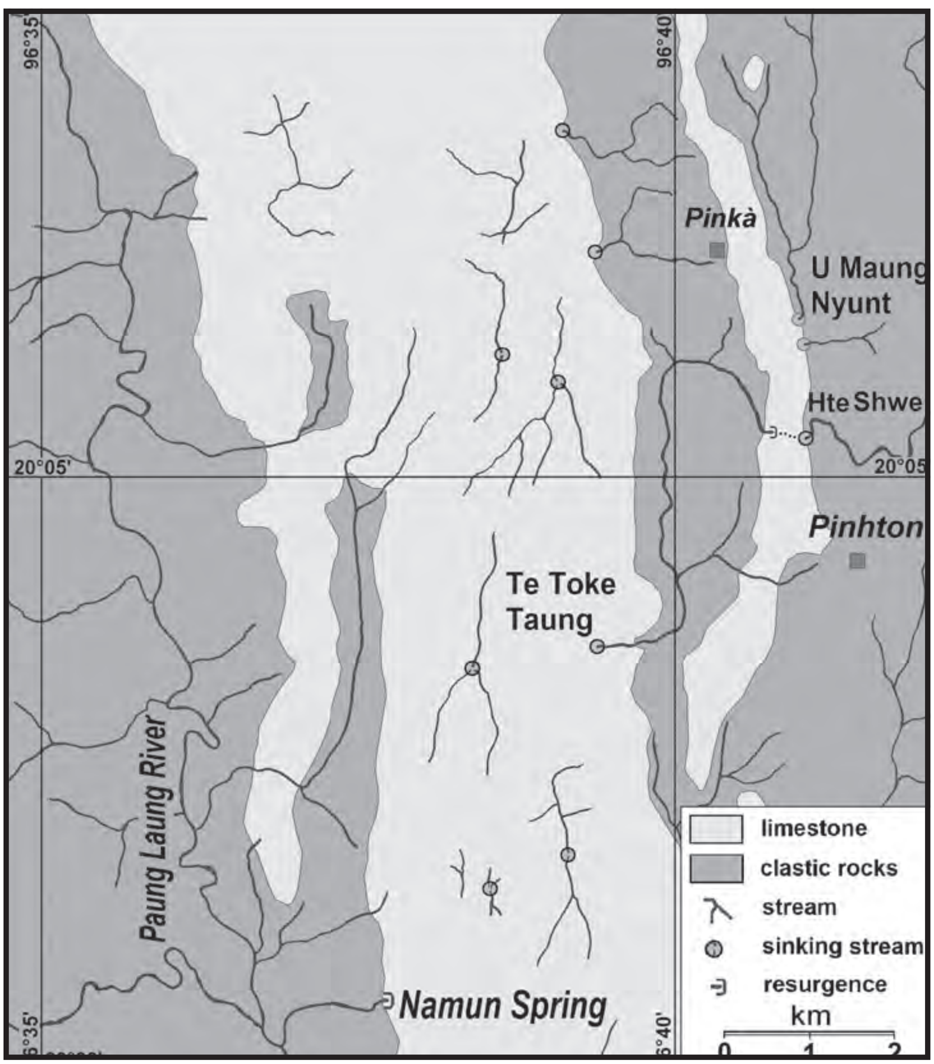

Figure 4: Sketch hydrogeological map of Namun Karst System.

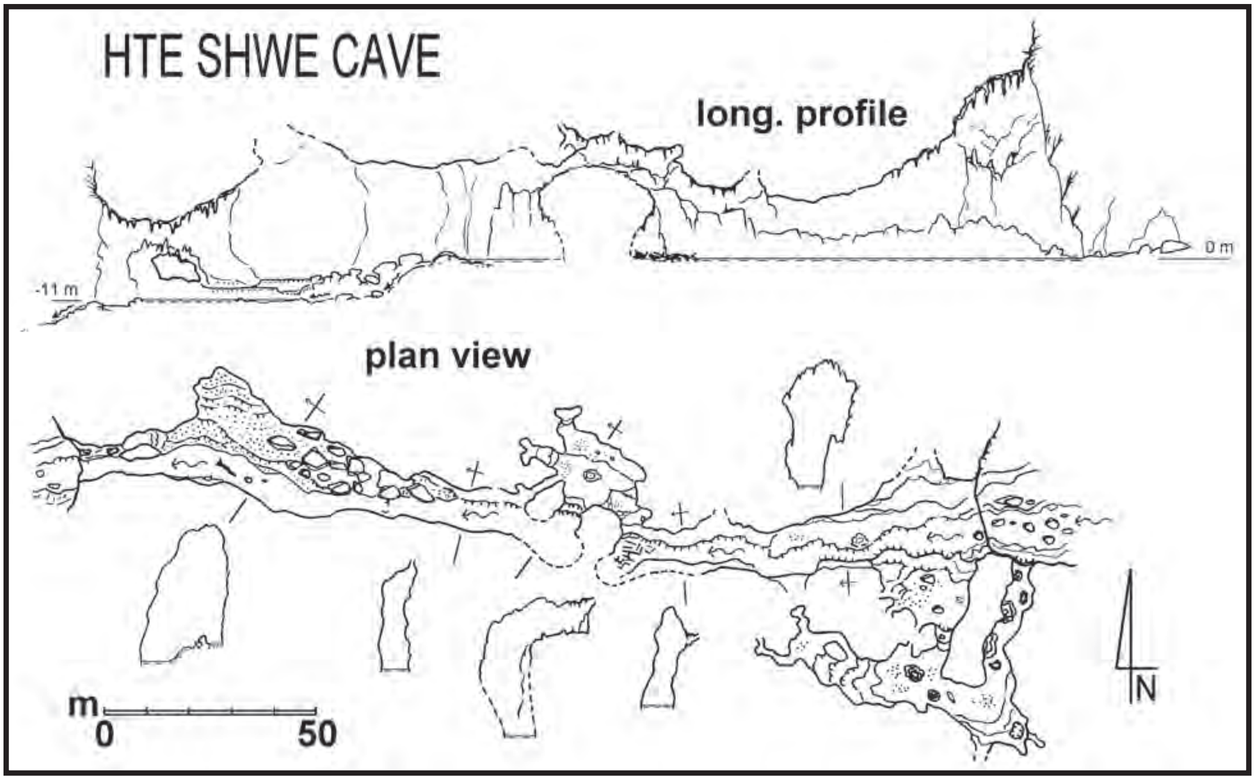

Figure 5: Longitudinal profile and plan view of Hte Shwe Cave (survey: E.G. La Venta, 2005).

The stream so originated receives other secondary tributaries. The spring collects the waters from a wide area, located N and NW, the extension of which, based upon the discharge (3 m^3/s in February 2005), could be estimated around 100-150 km^2. If this is true, during the rainy season the flood discharge of the spring could reach 100 m^3/s or more.

One of the most promising caves of this area is the Maung Nyunt Cave, located about 4 km N of Pinhton (Fig. 6). The entrance absorbs a small creek whose water (about 120 l/s

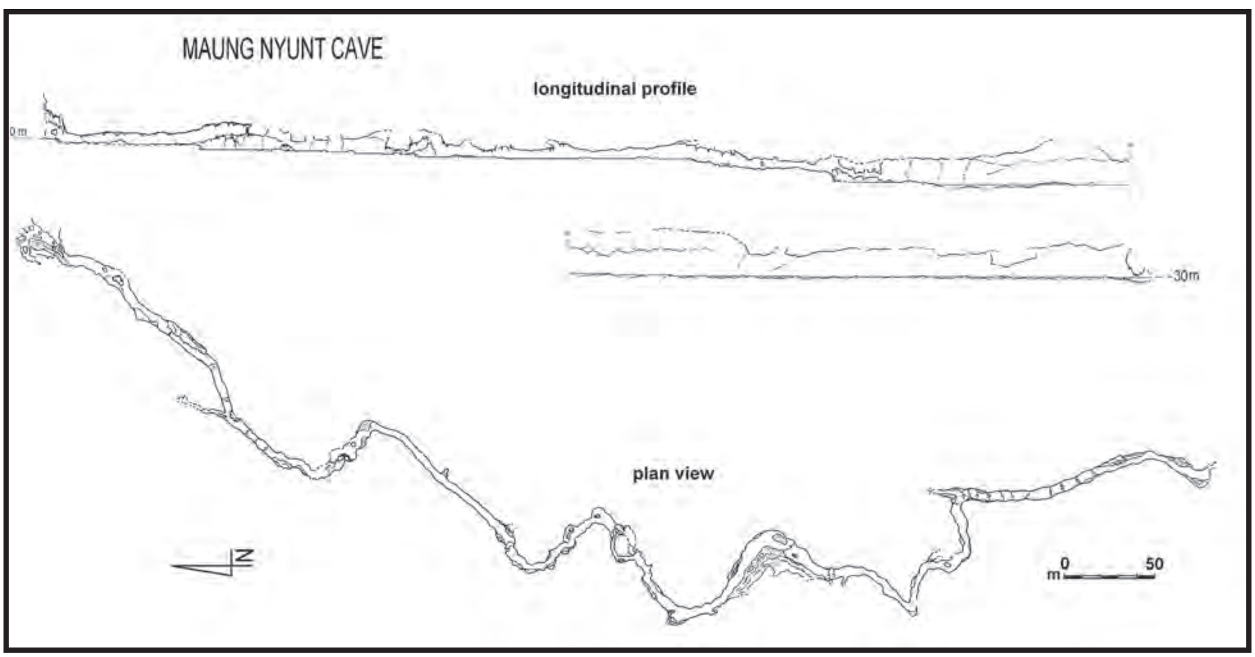

Figure 6: Longitudinal profile and plan view of Maunt Nyung Cave (survey: E.G. La Venta, 2005).

in February 2005) mostly sinks just before the entrance. Beyond the entrance, a regular shaped gallery, 4–5 m wide, goes toward the SSW for about 100 m, followed by a canyon-like tunnel, with local flowstones and stalactites. The canyon proceeds with an angular pattern for a further 150 m. After some passages with small rapids and pools, a tight fissure on the right gives access to the second part of the cave, where the canyon becomes 6-8 m wide and up to 30-35 m high. Deep pools, bounded by gours and sandy banks, form the floor. At about 800 m from the entrance, the cave receives a tributary on the left, not yet explored. Probably this is the connection point with another only partially explored cave, that is located about 500 m S of the entrance. Going downstream, the gallery continues with a regular cross-section and a series of gours and small dams of travertine form the floor. The cave continues with similar features further than the exploration limit.

3.5 Areas around Pinlaung

The village of Pinlaung lies in a plain, N-S elongated, surrounded by karst landscapes. To the west, we find some disrupted karst hills surrounding minor closed basins, whereas, to the east, a wide outcrop of dolomites displays karst towers and small depressions. In this area we have performed just a quick survey of some caves known by local people.

The most promising cave is an active stream sink, named Nanhpa (or Nant-par), which drains a closed plain 3 km NW of Pinlaung. The cave was explored for about 100 m along a canyon-like passage about 5–6 m wide and more than 15 m high. The floor is occupied by water and the airflow can be easily felt.

Name	Altitude m a.s.l.	Vertical range m	Length m
Late The Myaung Gu	1290	- 10	60
Late The Myaung Saint	1275	- 43	650
Myinn Ka Gu (2 entrances)	1507	-50 +14	100
Kyaing Sung Cave	1364	-2 +29	523
U Hmin Gu	1269	-21 +20	625
Myin Ma Hti Cave n° 1	1330	-17 +12	360
Myin Ma Hti Cave n° 2	1343	-19	116
Hte-Shwe Cave	1130	-12 + 30	270
Maung Nyunt Sinkhole	1135	- 28	> 900
Te Toke Taung Cave	870	+14, -50	100
Bat Cave	1070	- 54	180
Namun Spring Cave	370	+2	> 50

Table 1: Location and dimensions of major explored caves.

4. Conclusions

The preliminary investigation of the karst around the town of Kalaw has allowed us to gather initial information which has revealed a really promising potential for further cave exploration. Twenty caves were explored and partially surveyed for about 4 km of passages (Table 1). The major expectative concerns the region S of Kalaw, close to the village of Pinthon, where wide closed basins collect the water towards several sinks which probably belong to a unique karst system feeding the huge spring of Namun. The distance from the major stream sink and the resurgence is more than 6 km in a straight line, which leads us to suppose a complex and ramified subterranean system several tens of kilometers long.

Unfortunately the present political situation in this really "difficult" country has not allowed us to continue the exploration of this fascinating tropical karst of Southeast Asia.

Acknowledgements

The mission benefited from the substantial support of the University of Yangon, formalized in a research agreement between this institution, the University of Bologna and the La Venta group. In particular, we are grateful to Prof. Tin Nwe and Dr.Khin Maung Swe, for their indispensable support during the two expeditions.

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(Further information can be found at http://www.laventa.it).

THE LAVA CAVES OF KHAYBAR, SAUDI ARABIA

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Harrat Khaybar is a lava field ~12,000 km^2 in area, located north of Medina in western Saudi Arabia. Its lavas and volcanoes are mildly alkaline and the age of its flows ranges from five million years old to historic.

No speleological studies are known to have been carried out in Khaybar until Dahl Rumahah, a 208-m-long lava tube, located in northern Khaybar, was mapped in 2003. Rumahah was found to contain large quantities of bones of many kinds along with hyena, wolf and fox coprolites as well as a wooden gouging tool. Because calcite-rich water percolated through ceiling cracks, the cave is decorated with calcite stalactites, curtains and flowstone.

In 2007, explorers found and mapped Umm Jirsan Lava Tube System, consisting of three passages separated by two collapses. This system has a typical ceiling height of 8 to12 m and some passages as wide as 45 m. With a total length of 1481.2 m, it is the largest surveyed cave system in Saudi Arabia and the longest lava-tube system in the entire Arabian Peninsula. It is expected that much longer systems will be discovered in Harrat Khaybar because Umm Jirsan is only one of some 40 strings of collapses mapped by helicopter in the 1980s.

Caches of human and animal bones were found lying on the surface of meter-deep sediment in Umm Jirsan Cave, including a human skull fragment carbon dated at 4040 years BP and an unidentified animal bone 2285 years old.

It is speculated that the surveyed caves may be three million years old, but Harrat Khaybar also has very young lava, such as the flow from Qidr Volcano which is thought to have last erupted in 1800 AD. Numerous cave entrances have been spotted on Qidr and geologists report having observed delicate lava stalactites inside one of them. However, none of these younger caves have yet been mapped.

Because of the large number of lava-cave entrances documented and because of archeologically significant findings in the mapped caves, it is suggested that Harrat Khaybar may be one of the world's most promising sites for vulcanospeleology.

1. Introduction

Vulcanospeleology in Saudi Arabia is a young science which probably began in 2001 (Pint, 2006). Since then, maps of seven volcanic caves have been published (Saudi Cave Unit, 2007; Pint, 2009). Because the country has over 80,000 km^2 of lava fields—most of difficult access—the discovery of which areas might particularly interest speleologists has been a slow process. An assessment of the speleological potential of one lava field, Harrat Khaybar, was presented in 2006 at the XII International Symposium on Vulcanospeleology (Pint, 2008). New discoveries in 2007 confirmed some of the speculations made earlier and a more accurate and complete exposition of the subject is presented below.

2. Harrat Khaybar

Harrat Khaybar is located north of Medina in western Saudi Arabia, between 39° and 41° longitude E and 25°and 26° latitude N (Fig. 1). It has an area of ~12,000 km^2. The lavas and volcanoes in Harrat Khaybar are mildly alkaline with low Na and K content and include alkali olivine basalt (AOB), hawaiite, mugearite, benmoreite, trachyte and comendite. The age of the Khaybar lavas ranges from ~5 million years old to historic.

3. Roobol-Camp Reports

Roobol and Camp (1991) reported the existence of lava-tube caves up to 10 m high on Harrat Khaybar. In one of these caves—located in a flow from Jebel Qidr

Figure 1: Location of Harrat Khaybar Lava Field in Saudi Arabia.

Volcano—delicate lava stalactites were observed. A 100-meter-long lava tube in southern Harrat Khaybar was found to contain a fumarole at its deepest point. In their map, Roobol and Camp also depict at least 40 strings of collapses along whale-back formations found throughout Harrat Khaybar. These strings of collapses are up to 25 km long and in some cases are situated up to 25 km from the source volcanoes. Until recently, it was not known whether intact lava tubes might be found between collapses shown on this map. In 2007, in the case of the Umm Jirsan collapses (described below), the lava tubes not only proved to be intact, but also constituted the longest surveyed lava-tube system on the Arabian Peninsula. Other, much longer strings of collapses shown on the map may house cave systems up to 50 km in length.

4. Dahl Rumahah

Dahl Rumahah (also spelled Romahah) is located in the northern part of Harrat Khaybar. A map of the cave is shown in Pint, 2006. The cave is 208 m long and has a horizontal entrance 1 m high by 1.5 m wide, set in a small depression. Most of the cave is a single, nearly flat, northwest-trending passage from 1.5 to 7 m wide and 2.5 m high. In September of 2003, it was found that dry sediment covered the floor of the southeast part of the cave while mud floored the northwest portion and occurred along part of the eastern wall. Water droplets and cave slime cover the ceiling at the far northwestern end of the cave. A natural bridge 1.5 m thick crosses the passage near its western end. Calcite-rich percolation water leaked through ceiling cracks, producing white stalactites, curtains and flowstone (Fig. 2). There is a large area of mixed bones, along with hyena, wolf and fox coprolites plus hedgehog and porcupine quills. A piece of wood shaped like a gouging tool was found among the bones. The partial skeleton (Fig. 3) of an unknown animal is found in the cave, cemented to the floor by calcitic speleothems.

The highest radon level noted in Saudi caves was found in Rumahah: 119 pCi/L, perhaps due to underlying granite. The cave's temperature was measured at 25° C. Within a period of four hours a change in relative humidity from 68% to 74% was registered at one point in the cave. There is evidence (including construction of a water-retaining wall outside the cave) that this cave has long been used as a water reservoir.

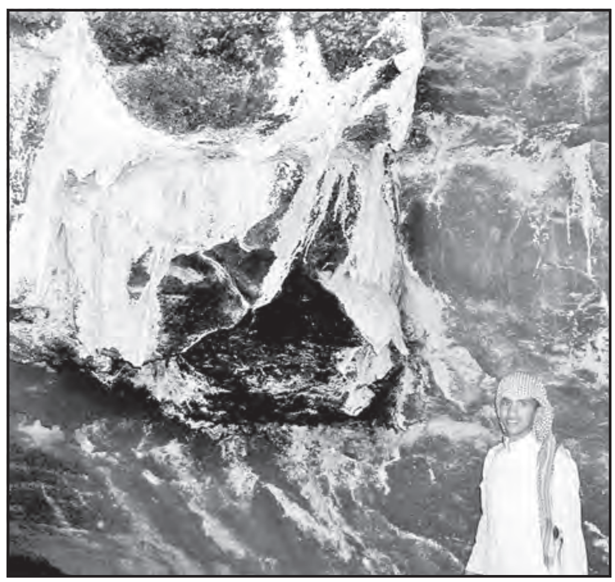

Figure 2: Calcite, flowstone, and stalactites in Dahl Rumahah.

5. Kahf Al Shuwaymis

This cave is located at the south end of Harrat Ithnayn, a small lava field adjacent to Harrat Khaybar and shown in Figure 1. Because of the cave's proximity to Harrat Khaybar, it is briefly mentioned here.

Figure 3: Skeleton Found Cemented to the Floor of Dahl Rumahah, 105 meters from the entrance.

The cave is 530 m long. The entrance (Fig. 4) is a collapse hole, 15 m in diameter, overlooking the floor of a horizontal passage 5 m below. A steep breakdown slope leads to a mostly south-trending passage varying in width from 4 to 15 m. with a typical height of about 10 m. Lava stalactites under 5 cm in length can be seen. There are at least four caches of animal bones (Fig. 5), presumably carried into the cave by hyenas or other animals. A narrow channel of sand runs almost the entire length of the cave, indicating water flow in the past. A map of Kahf Al Shuwaymis is shown in Pint, 2006.

Figure 4: Entrance to Kahf Al Shuwaymis Lava Tube, seen from inside.

6. Umm Jirsan Lava-Tube System

In 2007, Umm Jirsan Lava-Tube System was located and mapped under the auspices of the Saudi Geological Survey. The main passages of the system extend east and west of a collapse 89 m long by 55 m wide with a depth of 13 m. These passages have a maximum height of 12 m with a maximum width of 45 m. Sediment covers the original floor of the cave and was found to be 1.17 m deep at one point. Lava stalactites and lava levees as well as gypsum and calcite formations are found in several parts of the cave and an air

Figure 5: An area covered with mixed bones, found over 250 meters inside Kahf Al Shuwaymis.

temperature of 24° C was recorded. With a total length of 1481.2 m, Umm Jirsan is the largest surveyed cave system in Saudi Arabia and the longest lava-tube system on the Arabian Peninsula. A map of the system is shown in Pint (2009).

Coprolites and guano indicate that wolves, foxes, hyenas, rock doves, bats, sheep or goats and swifts have inhabited the cave at some point in its history. Bats and swifts were seen in the cave and the growls of an animal (perhaps a wolf) were heard. Bones, presumably carried in by predators, were found throughout the cave but were particularly concentrated at the extreme western end of the system. Here fragments of three human skulls and a large animal bone were removed from the cave and radio-carbon-dated. One of the skull fragments was dated at 4040±30 years BP and the still unidentified animal bone was found to be 2285±30 years old. Since these items were found lying on the surface of the sediment, it is speculated that still older human and animal remains might be found at a deeper level.

In one passage, up to 20 fragments of basalt were found lying near one another on the surface. These items either had a point at one end or a sharp edge on at least one side and were of a size and shape which fit comfortably in the human hand.

Several of these fragments are shown in Figure 6. So far, no sign of chipping has been detected in these items, but the concentration of so many fragments usable as tools in one small area, raises the question of whether primitive people without tool-chipping skills may have gathered usefully shaped fragments of basalt (the most common rock in the area) for use as simple tools.

A stone wall and what appear to be the foundations of buildings were found at the eastern end of this cave.

Figure 6: Items found in the east passage of Umm Jirsan System. Foreground: Pointed or sharp-edged basalt fragments. Background: basalt rock with mortar-like form. The pen is 12 cm long.

7. Umm Quradi Cave

In February of 2003, an attempt was made to survey Dahl Umm Quradi, a lava tube located in southern Harrat Khaybar. Just outside the cave entrance, a member of the team was seriously injured and had to be rescued by helicopter, resulting in the cancellation of the survey. However, it was noted that the cave has a walk-in entrance measuring 2 x 3 m and a vertical (collapse) entrance 4 m in diameter and ca. 5 m deep (Fig. 7). A local geologist

Figure 7: Collapse entrance to Dahl Umm Quradi in southern Harrat Khaybar.

estimates the length of this lava tube at 100-200 m and reports seeing entrances to other caves in the area (Pers. com. by Jamal Shawali, 2003).

8. Collapses on Jebel Qidr

Sometime in the late 1990's, German explorer Uwe Hoffman visited the basaltic stratovolcano Jebel Qidr, located near the center of Harrat Khaybar. At the foot of the volcano, he observed and photographed collapses which appear to be in lava tubes, one of which is shown in Figure 8. In 2004, geologist A. Gregory observed and photographed other such collapses on the flanks of the same volcano. According to Roobol et al. (2002), this volcano may have last erupted in 1800 A.D., suggesting that lava caves in this flow may be among the youngest and most pristine in Saudi Arabia.

Figure 8: Entrance to an unnamed volcanic cave in the Jebel Qidr flow. Photo by Uwe Hoffman.

9. Proximity to Archeological Sites and Ancient Trails

The National Geographic Society's Genographic Project is based on evidence that modern human beings are descendants of people who left Africa 50,000 to 70,000 years ago. Some of these emigrants appear to have crossed the Bab Al Mandab at the southern end of the Red Sea and then traveled north on the Arabian Peninsula. These people may have discovered that rain water can drain from lava fields at their edges. This is the case at the western edge of Harrat Khaybar, where a large old step dam was constructed by people living in a nearby ancient settlement. Ruins of this dam, Sadd Qasr al-Bint or Qasaybah, are shown in Figure 9. The settlement, known as Khaybar, is said to have been conquered by the Neo-Babylonian king Nabonidus in 552 BC (Barbor, 1996).

Some of the lava caves in Harrat Khaybar are natural water catchments. One of these is Dahl Rumahah, described above,

Figure 9: River and Part of Qasaybah Dam at the Western Edge of Harrat Khaybar.

whose entrance, even in recent years, was disguised by local people because of its usefulness as a reservoir. If ancient peoples sought these caves in their search for water, it is possible that they also took advantage of them for shelter from the elements, for caching food supplies, or for hiding valuables. A typical year-round cave temperature of 25° C would have offered relief from the unbearable heat of the area in the summer and escape from the strong winds and frigid temperatures of winter. Today, artifacts may lie buried in the sediment which typically covers the original floors of Saudi lava tubes.

A major Neolithic rock-art site with hundreds of petroglyphs (Fig. 10) is found at the northern end of Harrat Khaybar, further supporting the notion that archeologists should visit the area's caves. In addition, it may be mentioned that the western edge of Harrat Khaybar lies alongside the old Nabatean Incense Trail connecting Yemen and Petra (Fig. 11).

10. Conclusions

Figure 10: Ostriches, Camels, and Nabatean Script on a Sandstone Cliff Located 22 km north of Dahl Rumahah.

1. Harrat Khaybar offers excellent possibilities for the discovery of many lava caves in its ancient and recent flows. This lava field may house some of the longest lava caves in the world.

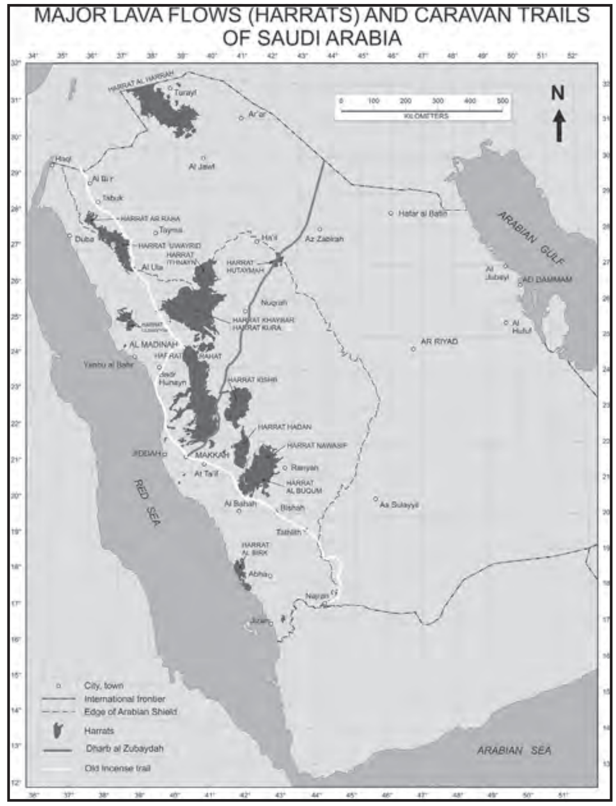

Figure 11: Map showing the major lava fields of Saudi Arabia and two old caravan trails (after Sabir, 1991).

2. Archeological surveys of the caves in Harrat Khaybar should be undertaken because of their proximity to archeological sites and ancient migration and trade routes.

Acknowledgements

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NEW LIGHT ON OLD GUADALUPIAN CAVES: GRAYS CAVE REDISCOVERED AND HAMBLENS CAVE ENTRANCE LOST

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Fieldwork in the Guadalupe Mountains of New Mexico, USA, has recently shed light on two legendary lost caves. Large format images in the Eddy County Historical Society (ECHS) document an excursion, sometime in the 1880s or early 1890s, to a Guadalupian cave identified as Gray's Cave. Surface shots showed a fashionably dressed group out for an outing in a buggy, with women, men carrying shooting pieces, and one young boy. This seemed to limit the distance from town that they might have traveled in what appeared to be a day trip. Rocks shown in the images appear to be tidal-flat dolomites, suggesting the cave could be no further south than the mouth of Walnut Canyon. After some driving around, the skyline shown in some of these images was identified as Carnero Peak, west of the town of Carlsbad, taken from the McGiver Ranch in Little McKittrick Draw. This was near the old road to McKittrick Hill, 12km west of town. Another shot showed a later group (judged by their apparel) at an unidentified cave entrance. Comparison of specific rocks in the image with those at the entrance of McKittrick Cave confirmed the site as the main pit entrance. Known signatures within the cave document visitation to this cave as early as 1894. Early records show that Robert G. Brookshire was living as a hermit the entrance of McKittrick Cave, guiding visitors into the cave and occasionally mining travertine, with which he carved tombstones. Careful scrutiny of one non-published ECHS shot from the same group of photographs, shows what seems to be a roughed out tombstone near the early visitors. Examination of the original print clearly shows diagonal chisel marks covering the face of the stone. This spurred a careful search of McKittrick Cave that resulted in the positive identification of all of the sites shown in the ECHS images, confirming that Gray's Cave is McKittrick Cave. This represents the earliest photo-documentation of tourism to caves in the region. Signatures on the walls shown in the images include Lucy Rush, Jennie Potter, Eva ----, Ada Hogle, J.A. ----, H.L. Potter, Wm. Richards, and Mrs. C.E. Richards. Nymeyer also shows an image of his caving group at small entrance that is identified as Hamblen's Cave. This cave was reported to be in the mouth of Slaughter Canyon, but was supposed to have been buried by gravel during a flood in 1943. This canyon contains some of the most spectacular of Guadalupian caves, so the idea of a lost cave has attracted some attention. However, comparison of the image reproduced in Nymeyer with the entrance of Lair Cave, a small cave in Dark Canyon, reveals unequivocally that they are they same. This does not disprove that Hamblen's Cave exists, nor that it was not covered by the 1943 flood, but if it is found, it will not look like the Nymeyer image.

Introduction

Nothing gets people's attention faster than tales of lost caves, with which oral and written records abound, unless it is a tale of a lost cave found. Recently in the Guadalupe Mountains we are lucky to have written a final chapter in the history of a much-storied cave and to have moved one step closer to understanding another. Rediscovering Gray's Cave was an on-again, off-again effort begun by Michael Queen and successfully concluded by Mark Rosacker. Mark's first-person narrative reads better than any dry third-person account would. Aaron Stockton's story of rediscovering Hamblin's Cave is a logical addition in terms of better understanding the area and on of the principal early area cave explorers. Do we need to continue our search? You be the judge.

Gray's Cave

Large portions of the western United States have been nominally explored, colonized, and settled by Europeans (and their descendents) for at least the past one hundred and fifty years. But, beyond the confines of our many small towns and settlements, the land changes. Beyond our doorsteps, and just beyond the reach of our vision, the land can quickly become unfamiliar and mysterious. Nowhere is this more true than in the vast and unsettled reaches of the northern Chihuahuan Desert. Extending out of Mexico, across west

Texas, and into southern New Mexico, the Chihuahuan Desert represents one of the least known and as yet unexplored areas of the continent. Just beyond the highway lies, the still wild and remote "despoblado", or "unpeopled land". For me, and others like me, this sense of unfamiliarity, wonder, and mystery is exemplified in the dry and rugged, cactus covered slopes and canyons of the Guadalupe Mountains. The range is almost entirely sedimentary, and topographically forms the wings of a giant open "V" or wedge; the point of which extends southward out of New Mexico and into the high reaches of Guadalupe Mountains National Park. Therein lie four of the five highest peaks in Texas. But the peaks are not all you will find there, for concealed among the rocks along remote ridges and in wide desert canyons you will also find caves; many caves, many silent, dark, and beautiful caves. In the dry and boulder strewn foothills south and west of Carlsbad, New Mexico, a roster of these caves will include both Carlsbad Caverns and Lechuguilla. But beyond those that are rightly famous and well known, the mountains and foothills also hide a host of other caves, named and unnamed, known and unknown. And therein lies our particular mystery. The decades long search for a known/unknown, named/unnamed, and ultimately "lost" spot on the map, once known and identified only as "Gray's Cave". My name is Mark Rosacker. My personal interest in Gray's Cave began shortly after I moved to Carlsbad, New Mexico.

However, the first search for Gray's Cave began in 1952, with the death of Carlsbad pioneer Elliott Hendricks. A box of old photographs, was found among his possessions which included at least four photographs depicting a party of early cave visitors utilizing simple white candles as a light source and dressed in Victorian style clothing. Two of the photographs were inscribed, "On Way to Gray's Cave, Carlsbad, New Mexico", while the other two photographs, actually taken inside the cave, were simply inscribed, "Gray's Cave, Carlsbad, New Mexico". These few photographs and the many questions they posed, were passed to a neighbor and photography enthusiast of Hendricks, named Robert "Bob" Nymeyer. Nymeyer, and his friends and relatives in Carlsbad began the original search for Gray's Cave, but the larger caving community only learned of the mystery with the printing of Nymeyer's book, *Carlsbad, Caves, and a Camera*, published in 1978. Inexplicably, in his book Nymeyer published the name of the cave as "Grey's Cave", spelled with an "e", rather than "Gray's Cave", as it is clearly written on the back of the original photographs. In any event, Nymeyer reports that he asked all of the Carlsbad "old timers" he could contact about the location of Gray's Cave, and learned that "none of them had ever heard of Grey's Cave"(sic). None-the-less, he and several of his young friends pursued the mystery as a part of their ongoing interest and activities spent exploring and photographing area caves. Significantly, and as I quote from Carlsbad, Caves, and a Camera; Bob eventually determined, "The countryside in the photographs does not suggest the high mountains. It more nearly resembles the cactus-covered foothills found in the area around McKittrick and Endless Caves. But none of the cave formations pictured in the two flash photographs resemble in any way those seen in early photographs of McKittrick Cave, which was the popular picnic spot of the era". I met Bob Nymeyer in 1977, the same year that I moved to Carlsbad. He invited me to dinner in his home, and I spent the evening somewhat in awe, as he showed me some of his old maps, and regaled me with stories about his experiences as a young man, spent exploring caves in the in the rugged foothills and canyons of the Guadalupe Mountains. It was directly from Bob Nymeyer, that I first heard stories about the mystery of Gray's Cave. Bob was a giant of early caving history and cave photography in the Carlsbad region. In addition to having grown up in Carlsbad, and personally knowing many of the big names in the exploration and development of Carlsbad Caverns, he was also an active and intelligent cave explorer in his own right. Additionally, he was a meticulous and careful writer and photographer, whose record of contribution to the understanding of caves and caving in the Guadalupe Mountains stands unique among his peers. Bob died unexpectedly in 1983, a few years after the publication of his book. I would respectfully dedicate this paper and presentation to his memory.

The second search for Gray's Cave began in 1978. Once a larger group of motivated people became aware of the Elliott Hendricks photographs through *Carlsbad, Caves, and a Camera*, and learned that Gray's Cave actually existed, many people's sense of curiosity was piqued, and some few began to search for it in earnest. Most began by trying to match the two published Hendricks photographs to the known countryside and caves they were familiar with. Others began to pour over the oldest cave photographs of the area that they could find and see whether or not any of them might match the one photograph published from inside the cave. Many people, myself included, became deeply curious, started looking for a time, and stopped, and started sometime later, and then went on to other things. It actually seemed rather hopeless. There is a lot of territory west of Carlsbad where one could begin searching, so the only definitive hope lay in matching the photographs. One published photograph would require matching a particular pattern of closely grouped larger limestone rocks and ledges to the one photograph taken on the way to Gray's Cave, and the other would require matching a particular group of stalactites and other cave formations to the one published photograph taken from inside the cave. I have no real knowledge of how many people were ever either casually or actively looking for Gray's Cave between 1978 and now. But I do suspect that after reading Nymeyer's book and looking at his photographs, a good number of sincere cave enthusiasts started their trucks, pointed them westward, and went out to start ridge-walking at their first opportunity.

One person that I do know was active and persistent in searching for Gray's Cave is Michael Queen. Michael relates that a major break through came one day when he and Carlsbad Museum Director, Virginia Dodier were out southwest of Carlsbad, with vintage photographs in hand, and specifically looking for Gray's Cave. Upon arriving near the ruined walls and corrals of the old McIver family homestead in Little McKittrick Canyon, he noticed and soon confirmed that the contours of Carnero Peak matched one picture they had with them depicting a large group of early cave visitors on their way out to McKittrick Cave in horse drawn buggies. The photograph was a wide view, taken from the flats of Little McKittrick Canyon looking south by southeast, with Carnero Peak in the background. Once it was established that one of the earlier routes to the McKittrick Hill area actually followed a portion of Little McKittrick Canyon, some people, including Jim Goodbar, Michael Queen, and Jim Burke began to concentrate their efforts in that general area. While we could not absolutely rule out that the location of the cave was not in the higher ranges of the Guadalupes, we generally agreed with Nymeyer's assessment that the countryside in the Hendricks photos more closely resembled the lower foothill country just west of Carlsbad. Repeated searches of locations in this general area resulted in wearing out a lot of boot leather, but revealed no new or unknown caverns, or anything else that seemed to match the Hendricks photographs.

Another breakthrough came when Michael Queen invited me to go along with him and Jim Burke on a ridge-walking expedition to the area. Three of us were riding in Burke's old truck and I was riding on the passenger side as we slowly proceeded up Little McKittrick Canyon. Recent heavy rains had left any number of small pot hole tanks in the canyon bottom which we had to negotiate as we headed westward. Just after passing one muddy canyon crossing near such a location, I happened to look out the window and notice some familiar looking rocks. I then jumped out of the vehicle to investigate as the vehicle came to a stop. In my hand I held a Xeroxed copy of the Hendricks photographs. A brief comparison at close range seemed to confirm that this was the location of the "on the way" photograph on page 244 of Nymeyer's book. In a moment, after lining up at least half a dozen points of reference, we all agreed that this was indeed the location of the first photograph. Whether an effect of the camera lens, or just the relative height of the people in the original photograph, we all agreed that this was a purely-by-chance recognition, since the size of the people in the Hendricks photo made the rocks themselves seem at least twice as large as their natural size. This was made even more difficult by the fact that, on the day we located them, the rocks were partially submerged along the edge of one of the previously mentioned rainwater tanks. Needless to say, we pulled off the road and began a thorough search of the surrounding area. While we did find evidence that people had camped in the area many years back, and I even found a portion of the ruffled rim from an old kerosene lamp globe, we did not discover any new cave entrances. On subsequent trips, we climbed the ridges on both sides of the canyon to several promising locations, and did find further evidence in the immediate vicinity that the area had been used for picnics and/or camping, but we did not locate any new caverns. And that is where it stood for a time.

The biggest breakthrough came in Carlsbad quite unexpectedly, when my next door neighbor, Jed Howard knocked on my door one evening and presented me a manila envelope containing the original Hendricks photographs. Appropriately, they had passed from Elliot Hendricks, to Bob Nymeyer, to the Carlsbad Historical Society. Jed Howard is the highly capable archivist for the organization, and he had attended a program that Michael Queen had presented to the Society. Apparently after the program, he and Michael had discussed some of the Gray's Cave material from Nymeyer's book. Jed knew that Michael Queen, myself, and others were working on this project, and he had decided to help. The originals, while small, were much more detailed than the photographs reproduced in Nymeyer's book, and I was very happy to be able to look at them first hand. Also importantly, for the first time, I was able to carefully look at the three non published photographs; the ones Nymeyer or his publisher had not selected for his book. There were actually a total of five original photographs of the same people taken on the same day and the same trip, not four as had been reported by Nymeyer. The first new photograph was of the same group of people(7) having a little picnic, either before or after their cave excursion, the second new photograph was a group(5) of them standing in the bedrock of Little McKittrick Canyon near the same location as the Nymeyer published canyon photograph. But the third thankfully, was another photograph taken inside the cave. It showed a total of eight (8) people; two adult men, five adult women, and a young boy, posing in their finery beside a group of different and larger stalagmites. Nymeyer describes them aptly: "The mode of dress of the people involved would date the pictures to about the turn of the century. The ladies were decked out in long skirts that swept the ground, puffed-sleeve blouses, and neck ribbons. One even sported fancy gloves and a perky straw hat with veil. A little boy about ten years old wore suspenders and baggy pants, a fantastically flowing box tie, and a wilted fedora. The men were elegant in jacket and vest, stiff collars and bow ties, and English caps. One carried what seems to be a 30-30 carbine, and the other toted a double-barreled shotgun. If they expected bears in the cave, they were prepared". Interestingly, and significantly, the outdoor photographs depict six, seven, and five people respectively, while both photographs taken inside of Gray's Cave depict eight people. This raises the question as to who was the photographer? The first three of the outdoor photos of six, seven, and five people, could easily have been taken by any one of the remaining group. But, the two taken inside the cave, showing all eight individuals either implies that there were actually at least nine in the original group, one of whom we have no photographic record; or someone else altogether, perhaps someone already at the cave, or from another group of cave visitors, took the photograph of all eight members of the group on the trip that day.

And there is a likely candidate. As it turns out, there was a hermit who lived on McKittrick Hill around the turn of the century (1900). An apparently well educated, supremely skilled stone mason and tombstone carver named Robert "Bob" Brookshire lived near the entrance to McKittrick Cave. In 1910 and again in 1914 he filed mining claims on McKittrick Cave. In the meantime he survived by carving head stones and other smaller sculptures out of stalagmites and stalactites he found in the cave, and by guiding the occasional curious cave visitor that showed up at his doorstep through the myriad "wonders below". Making his living in this dry and barren landscape, he was known to collect his much needed water supply from cave pools and by placing tin cans under dripping stalactites and soda straws. With no other visible means of support, local ranchers suspected him of occasionally helping himself to one of their cattle, but upon secretly investigating his activities, at least one of them confirmed that this apparently honest man subsisted by trapping and eating woodrats he found living near the cave entrance. Brookshire was also a great friend of the Heiskel Jone's family living on nearby Rocky Arroyo, and one of the earliest stone masons to live in southeastern New Mexico. His exquisite work was in continual demand for decades, as he quietly plied his trade for the growing communities of Seven Rivers, Eddy, and after 1899, Carlsbad.

Having held the photographs in my possession for some time, and spending time looking over them closely with a hand lens, I realized something else interesting in the non published cave photograph. Knowing about Brookshire, I began to unconsciously look at the photographs with a slightly different eye. It was only after I had looked at them for awhile, that I realized one of the cave formations in the photograph had an uncanny resemblance to an upside down headstone. Closer inspection revealed a rope system looped around a nearby natural stalagmite, possibly utilized to assist in removing larger stones from the cave. Moreover, the roughed out "head stone", was literally covered from top to bottom with fresh diagonal chisel marks. Once you see the headstone, it all becomes obvious; but before you make that connection it is not at all apparent. For these reasons, I became firmly convinced that the photograph actually depicts a moment in time, wherein Bob Brookshire was in the process of carving a headstone blank for removal, when he was dropped in upon by a group of early cave visitors, and stopped his work long enough to take a photograph of them. Since Brookshire was also known to have lived in a small shack near the entrance to McKittrick Cave, and to have taken early cave visitors on excursions into McKittrick Cave; McKittrick itself became the prime location to pursue further investigation of Gray's Cave.

A trip to investigate this possibility was arranged and a permit was issued for January 30, 2007. Three of us went on the trip, well armed with the Gray's Cave photographs, as well as a number of other early known or suspected photographs taken from inside McKittrick Cave. One photograph, reproduced from a postcard published by the Star Pharmacy depicts two men in a cave identified only as "Caves of the Whistling Wind". Present to confirm this possibility were, Michael Queen, Patricia Seiser, and myself, Mark O. Rosacker. The results, while solidly confirming our suspicions, were almost anticlimactic. McKittrick Cave was once literally mined for cave formations which were then transported to Carlsbad and White's City to become tourist souvenirs during the early years of development at Carlsbad Caverns. As we worked our way into the heavily damaged cave, by careful observation we were able to confirm precise locations for both Gray's Cave interior photographs. Surprisingly we also found the site for the one identified as Caves of the Whistling Wind as well. Though the area had been significantly damaged and modified, I was first to identify the location where the tombstone photograph had been taken. Pat Seiser was particularly good at noticing small details in the cave ceiling, which helped us to match the photographs correctly. Without her keen eyes and mind, I doubt that the Caves of the Whistling Wind photograph would have ever been identified. When you consider that what we now know as McKittrick Cave, was also commonly known in newspaper articles of the time as Guadalupe Cavern, we can now confirm four known names for the site; Caves of the Whistling Wind, Gray's Cave, Guadalupe Cavern, and McKittrick Cave. The cave itself was never lost. It was only lost in the sense that its name had changed over time, and the people who knew about those changes died without recording their knowledge of the place. Prehistoric ring middens and artifacts at the entrance strongly hint that the cave must have also been know by other names and in other languages now lost to time.

Subsequent, and coincidental investigations in Carlsbad at the former residence of Elliott Hendricks, reveal an earliest possible date for the Gray's Cave photographs. While looking at a piece of real estate offered for sale on 201 North Canal Street in Carlsbad, I realized that it was the old Hendricks residence. Written in pencil in the framing wood of a back closet of what I presume must have been Elliott Hendricks bedroom, and what must have been in Hendricks own hand, I discovered the following inscriptions: E. Hendricks born Oct. 9, 1872, 1928 Built House, Came to Carlsbad May 22, 1894, Married Feb. 1903, Jinnie(sic) born June 21, 1868--wife. Hendricks was married to a Miss Jennie James. I do not know of any extant photographs of Elliott Hendricks as a young man, but if Hendricks can be identified one of the men in the photographs, then the earliest year they could have been taken would be 1894.

The historical mystery of Gray's Cave is far from resolved. In a profound sense, merely finding the cave asks many more questions than it answers. While we can now positively identify it with McKittrick Cave, and pinpoint its precise geographic location on a map; we still do not know why Hendricks and others once knew it as Gray's Cave? We also do not know the identities of any of the eight people in the Hendricks Gray's Cave photographs? Names written in pencil near the tombstone location in the photograph may hint at their identities, but without further research and discovery, they will continue to remain unknown. The fact that a man named Elias "Will" Gray was an early resident of nearby Seven Rivers suggests the possibility that the cave may have been named for him. Eli Gray died in 1879 of an accidentally self-inflicted gunshot wound while acting as Sergeant for the Lincoln County Rifles during the Lincoln County War. It could be as simple as the possibility that Eli Gray discovered the cave. Felix McKittrick is believed to have herded cattle through the area as early as 1867, but by the time of the Lincoln County War, he was "range boss" on the Pecos for cattle baron John Chisum. Headquartered near Seven Rivers, he and his cowboys worked the grazing lands for a considerable distance along both sides of the Pecos River, and included the lands located around McKittrick Hill. It is certain that much of the territory surrounding the cave was long regarded as McKittrick's cattle range. This is attested to by a profusion of local place names, McKittrick's Spring, Little McKittrick's Canyon, McKittrick's Hill, and finally, McKittrick's Cave. As a man of local prominence, it is likely that Gray knew, associated with, or had business dealings with McKittrick in some capacity. If Gray ever told McKittrick or any of his cowboys about locating a cave, it makes sense that these early area residents might well refer to it as "Gray's Cave". Ironically, it is possible that Felix McKittrick himself might have known the location as Gray's Cave. William O. Gray, Eli Gray's only son grew up in the Seven Rivers area, where we know that he spent much of his early life working as a cowboy. It is not beyond the realm of possibility that he may have actually been the one who discovered and named the cave? Interestingly, William was born in 1872, the same year that Elliott Hendricks was born. I cannot discount the possibility that he may have somehow been the one who directed Hendricks or some of his friends to the cave. Neither can I discount the possibility that the cave was named after another person altogether. The earliest known written reference to use of the name McKittrick Cave seems to be a newspaper article which appeared in the June 3, 1893 edition of The Eddy Daily Current. A competing newspaper, The Argus refers to the same area as Guadalupe Cavern or Guadalupe Caves as late as 1895, after which the name McKittrick Cave consistently appears in print. Without further archival research and documentation all such possibilities and assertions remain unknown and subject to speculation. Simply stated, Gray's Cave has been found and identified, but the historical mystery lingers.

Hamblen's Cave

Stories of lost caves are perhaps one of the healthiest prescriptions to get cavers out searching. This is ever so evident with the case of Gray's Cave as outlined above. Years of hard work and historical research are often undertaken when the curiosity of that "lost spot on the map" is strong enough. But sometimes the unraveling of mysteries can occur out of sheer luck and coincidence. This is the story of one such occasion. My name is Aaron Stockton and my story is about another mysteriously lost Guadalupe cave.

As with Gray's Cave, the mystery of Hamblen's Cave also began with the publication of Robert Nymeyer's *Carlsbad, Caves, and a Camera*. Within the book, Nymeyer describes the initial discovery of a small cave which they named Hamblen's Cave. The cave was discovered by one of Nymeyer's regular caving buddies, Glen Hamblen. The story goes that the group of enthusiastic cavers set out on April 29th, 1934 in search of a secret cave in the mouth of Slaughter Canyon, now located in the middle part of Carlsbad Caverns National Park. The location of the cave was given to a member of the group by a former employee of Charlie White, then owner of the popular tourist attraction White's City. The employee had stated that the cave was one that Mr. White had used to collect speleothems to sell at his curio shop. He had kept the location very secret and based on this fact, Nymeyer and his group was sold that this must be a fantastic cave. Nymeyer outlines the directions given to them for finding the cave within his book. So on that April day, they set off to Slaughter Canyon certain they would locate the cave. As with most caving trips, then and now, their good directions quickly developed holes, no pun intended. According to the story, the group was unable to find key landmarks within the directions and soon found themselves wandering aimlessly in the mouth of Slaughter Canyon. It was here that Glen Hamblen stumbled upon a cave entrance located against the hill and almost hidden by boulders, dropping down one meter and continuing as a crawl straight into the hillside. Hamblen was the first to enter the cave and after backing out due to a centipede "the size of his arm" continued in. After 3 meters, they found the cave sloping downward and into a small crawl before opening into a room about four meters square. At this point, the cave was said to have its sole formations, a few large stalactites and a squatty stalagmite beneath. They continued on and found themselves crawling once again before the passage opened into a room twice the size as the one before, but with no formations. In place of formations were several bats and a large pile of guano. The only passage leading out of this room was said to have been blocked by breakdown. It was by this breakdown that Glen Hamblen discovered what Nymeyer describes as a message scratched into the wall by previous visitors. Covering a meter section of the wall were said to be uniform characters carved in the rock. Unable to continue on due to the blocked passage, the group retreated with the curiosity of what lie beyond that pile of rocks and who had left the message on the wall before them. As if this description had not been enough to draw cavers back to the cave, Nymeyer continues on describing how a downpour and subsequent flood of Slaughter Canyon in 1943 had altered the entire course of the drainages and completely covered the location of Hamblen's Cave. At the time of his writing, he stated that he would not even be able to come close to pointing out where the location of Hamblen's Cave was. All that survived from Hamblen's Cave was a picture of its discoverer crawling into the entrance, taken by Robert Nymeyer on the discovery day. The picture was published in Carlsbad, Caves, and a Camera. Another lost cave legend had been born.

Carlsbad, Caves, and a Camera was one of the driving forces that turned me into a caver. Having grown up in Carlsbad, I acquired a copy of the book when I was 12 yrs old. Every spare moment I had was spent staring at the black and white photos included in the publication and picking out landmarks I recognized from my time spent in the Guadalupe foothills. I quickly became fascinated with the idea of Hamblen's Cave and wondered if it had ever been rediscovered. My father, Billy Stockton, drove me out to the mouth of Slaughter Canyon several times where we tried unsuccessfully to follow the directions give to Robert Nymeyer's group for the entrance location of Charlie White's Formation Cave. I hoped in the process I might stumble across Hamblen's Cave. I had hoped that by some chance the same forces that had secluded its entrance might have opened it up once again for another generation to explore. My early caving adventures were much like Robert Nymeyer's. My father and I didn't belong to any caving clubs or organizations and we didn't have any of the correct gear. Armed only with flashlights, we would search out cave locations supplied by local hunters. Once such location was a cave said to be hidden by a large bush, halfway up a hillside located just inside the mouth of Dark Canyon, several kilometers southwest of Carlsbad. With luck, we located the cave on our first search. The entrance was right against the hill, hidden by a large Texas Mountain Laurel, a beautiful native tree that produces light purple flowers and deep green waxy leaves. The entrance dropped down approximately one meter before heading straight into the hillside in a crawlway. On we went. We found ourselves in a crawlway lasting for several meters before the cave began sloping down and opening up a bit. The passage opened into what could be called a room. Just off center of the room was an area that was once adorned with several large stalactites. All that remained was a stubby stalagmite underneath. After 50 meters or so, we were once again in a crawlway that opened into a much larger room- twice the size of the one we had come from. There were no formations in this part of the cave. Only bat staining on the ceiling and a large pile of guano on the floor. There were no other passages heading out of this room. Satisfied with the 100 meters or so of passage we had explored, we exited the cave. On the way out, I snapped a few photos that I would keep in a shoe box full of all my other early cave photos. At the entrance I noticed an aluminum marker that said "Lair Cave, Bureau of Land Management". Lair Cave is was.

I presume that the reader of this paper would notice that entrance and interior descriptions of both Lair Cave and Hamblen's Cave are almost identical. However, the vast difference in the entrance locations (Dark Canyon and Slaughter Canyon) would prevent me from making these connections until just two years ago. While looking at a photo of Hamblen's Cave in the back of *Carlsbad, Caves, and a Camera*, something caught my eye. Although small, in the right frame of the photo, I noticed what appeared to be the leaves from a Texas Mountain Laurel. I noted that it is the same kind of bush growing in the entrance of Lair Cave. I began to notice other similarities as well. The entrances were shaped the same, the bush was on the same side and with Glen Hamblen in the picture for scale, the entrances appeared to be the same size. I hurried to the closet and pulled out that shoebox of cave photographs that contained the ones I had taken of Lair Cave the day I first explored it. With an entrance photo in my hand I quickly noted other features that confirmed what I had just found. Several distinct bedrock fractures were identical between the two photographs. The entrances for Lair Cave and Hamblen's Cave were one and the same. Several local cavers have spent quite a bit of time looking for Hamblen's Cave. Tom Bemis is one of those cavers. Tom, like those that read the discovery story, has focused much on the mouth of Slaughter Canyon. Armed with the evidence, I approached Tom. Acknowledging that the entrances are the same, Tom suggested that possibly Nymeyer mixed up photos or didn't actually have an entrance photo of Hamblen's and used one of what today is called Lair Cave. But if this is the case, why didn't Nymeyer mention the exploration of Lair Cave in his book? And is the almost identical interior descriptions and length of the two caves just coincidental? And if Hamblen's Cave is Lair Cave, why place it in Slaughter Canyon, have it covered by a flood, and what about the breakdown blockage and inscriptions all of which are absent factors in Lair Cave? In my opinion, Lair Cave is Hamblen's Cave. Or it is at least Hamblen's Cave in reality. I believe Bob Nymeyer included those other fantasy details to inspire future cavers to continue the searches that have led to the great cave discoveries of the Guadalupe Mountains. What caver could resist the search for a mysterious cave now covered by a flood? I for one cannot. Even armed with my own evidence, I will continue to search the rolling foothills just outside the mouth of Slaughter Canyon. If I am lucky, the same forces that helped Nymeyer dream up the mysteries of Hamblin's Cave will help me find it.

Reference

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PRIEGO SUBTERRANEAN EXPLORATION GROUP (GESP). 50 YEARS OF SPELEOLOGY IN PRIEGO DE CORDOBA (CORDOBA, SPAIN)

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The origins of GESP can be traced to 1957, in that year a group of youth began sporadic exploration of the caves in the hills around Priego. Little was known of these early explorations as only oral testimonials of speleological activity in Priego could be documented until 2006. In that year, José Martos Espejo donated his historic archives, a written record dating the formation of a Prieguense group of speleology on 1 January 1957, which, through time would evolve to become the current GES Priego. Up until the year 1963 there are very few written records of these activities. There were various speleology groups in Priego until 1970, GEAP, GEP, Murcielago, and SAJUMA. These, eventually converged to become GES de Priego.

In 1969 the Southern Region Speleology Committee (CRSE) was formed, an integral part of Spanish Mountaining Federation. CRSE's first president was a Prieguense from GES Priego, Alfonso Calañas Redondo. He served until 1972 and was very important in structuring the future of Andalusian speleology.

In the 1970s the CRSE organized the IV Regional Speleology Camp in Zagrilla Alta and participated in Operation Hoyos del Pilar in Malaga. There a new attack on the GESM cave was undertaken, leading a depth of 520m. In 1976 the group organized an exposition at the VIII International Symposium of Peninsular pre-history.

In 1980 new techniques for exploration were introduced, namely the Alpine Technique or progression by rope and in that same year the group undertakes two research projects: a study of the "Fuente de la Salud" spring and an audiovisual titled "Subterranean Landscapes." But 1981 the group loses a colleague in Fransisco Padilla García, who dies due to injuries sustained in Fuente Alhama cave.

In 1983 a new generation of people joins the group and in 1984 leads to collaborative studies with the Department of Pre-history and Archaeology of the Faculty of Philosophy and Arts of the University of Cordoba. With 33 members in 1985, GES Priego becomes one of the largest clubs in the province and one of the largest in Andalusia. In that year the club organized the VII Andalusian Week for promoting Speleology.

The club, in 1988, celebrated the commemoration of its XXV Anniversary, basing this on the only documentation available at that time, which established the start of speleological activity by GES Priego as 1963. But in 2006, as noted above, new documentation established the club's start to be 1957, and at the end of 2007 GES Priego celebrated its 50th anniversary.

GRUPO DE EXPLORACIONES SUBTERRÁNEAS DE PRIEGO. 50 AÑOS DE ESPELEOLOGÍA EN PRIEGO DE CÓRDOBA (CÓRDOBA, ESPAÑA).

Los orígenes del GESP se remontan al año 1957, fecha en la cual un grupo de jóvenes comienzan a hacer exploraciones esporádicas a cavidades de nuestras sierras. Del año 1958 solo se tienen testimonios orales de actividad espeleológica en Priego, pero es a partir de una donación de papeles de época por parte de José Martos Espejo, realizada a finales de 2006, cuando se constata por escrito una fecha de constitución de un grupo de espeleología prieguense, el cual con el tiempo irá evolucionando y adaptándose hasta nuestros tiempos en el actual GESPriego; El 1 de enero de 1957. Hasta el año 1963 hay muy pocos datos escritos de estas actividades. Hasta el año 1970 existirán en Priego varios grupos de espeleología, el GEAP, el GEP, Murciélago, SAJUMA, que se unirán -como es lógico- en el GES de Priego.

En 1969 se crea el Comité Regional Sur de la Espeleología (CRSE), integrado en la Federación Española de Montañismo, cuyo primer presidente, y hasta el año 1972 fue un prieguense del GES-Priego, Alfonso Calañas Redondo, su labor como presidente fue importantísima, estructurándose así la espeleología andaluza.

En la década de los 70 se organiza en Zagrilla Alta el IV Campamento Regional de Espeleología, asistimos en Málaga a la Operación Hoyos del Pilar, donde se realizó un nuevo ataque a sima GESM, alcanzando los -520 metros de desnivel. En 1976 realiza una exposición en el VIII Symposium Internacional de Prehistoria Peninsular.

En 1980 se produce un cambio en las técnicas de progresión, introduciéndose la Técnica Alpina, o la progresión por cuerda, y en este mismo año se realizan dos trabajos: un estudio sobre el manantial de la Fuente de la Salud y un audiovisual titulado Paisajes Subterráneos. En 1981 sufrimos el accidente de nuestro compañero Francisco Padilla García, quien fallece poco después a consecuencia de las heridas sufridas en la sima de Fuente Alhama.

En 1983 se produce un nuevo relevo generacional, que se consolida en 1984, colabora con el Departamento de Prehistoria y Arqueología de la Facultad de Filosofía y Letras de la Universidad de Córdoba. En 1985, con 33 miembros el GES de Priego se convierte en el club más numeroso de la provincia y uno de los más numerosos de Andalucía. Organiza en este año la VII Semana Andaluza de Divulgación de la Espeleología.

En 1988 celebra los actos de conmemoración de su XXV Aniversario, basándose en la única documentación escrita que se poseía en esta fecha, y que fijaba el año de comienzo de las actividades espeleológicas del GESPriego en 1963.

En el año 2006, como ya hemos dicho, se produce el conocimiento de nuevos escritos que determinan esta fecha en 1957, por lo que a finales de 2007 el GESPriego celebra los actos de su 50 aniversario.

The first speleological activities undertaken in Priego occurred in 1957 when a group of youths began exploring, on a sporadic basis, some of the caves in our hills. There are oral testimonies (Avelino Siller, Antonio González or Manuel Alcalá-Zamora) that verify that organized expeditions to the caves and climbing practice took place during that year. Following the donation of some historical archives by José Martos Espejo, it was confirmed that the 1st January 1957 was the founding date of the Alonso de Carmona Group, the first name given to the actual GES-Priego. Between the 5th and 9th of April of 1963, specialists from the Spanish Youth Organization came to Priego to give provincial courses in speleological archaeology. These courses, carried out in Murcielaguina cave, Los Mármoles cave, and La Cubé cave, inspired a group of youth from Priego to dedicate their spare time, and sometimes a bit more, in undertaking a new activity that they had newly discovered: speleology. Among this young group of speleological pioneers from Priego we should mention Manuel Alcalá-Zamora Solis, Avelino Siller Calonge, Jaime Álvarez, Alfonso Calañas Redondo, José Antonio Cejas, José Garcia de la Nava, Antonio González Alcalá, Rafael González Vílchez, Miguel Muñoz, Francisco Muñoz Segovia, José Rojas Serrano, José Luis Ruiz, Jesús Zurita and many more.

It is not, however, until 1970 that we can really talk about the evolution of the name GES-Priego as we know it today. Until that year, various independent groups existed. Those that stand out are Alonso de Carmona, GEAP (Alpine Speleological Group of Priego), GEP (Priego Speleological Group), the bat group, and the Marist Brothers group - SAJUMA. Despite this fragmentation of efforts it was a very interesting time as, apart from beginning speleological studies in Priego, the majority of the caves known today were discovered. The first topographical studies began and the archaeological sites in the interiors of the caves were first discovered.

Apart from these first explorations carried out in the local caves of Torrecitas, Siete Cuevas and Tarajal gorge, this first year was interesting in that we collaborated with GEJAM of Córdoba undertaking works in Murcielaguina and Los Mármoles caves.

The following year, in 1964, the Alcaide Hills in the area of Zagrilla were explored. The caves of Peñon Largo and Era del Médico were located and explored for the first time. Due to a lack of equipment, these explorations were also carried out with the assistance of GEJAM. On the 12th of April of that year, one of the most important caves of the area was discovered, Cholones cave. Its exploration was also carried out in collaboration with groups from Córdoba and under the auspices of the pre-historian Javier Fortea. A large area of the cave was explored descending to the grand cavern 100 meters in depth where cave paintings, schematic and medieval, were discovered.

This continuing collaboration with the groups from Córdoba was reflected in 1965 when, in August and September, the Priego group participated in the first provincial camp held in the area of Alcalá la Real and organized by Alonso de Carmona of Priego de Córdoba.

The smooth running of the speleological activities carried out by the groups from Priego in these early years was shattered in March of 1966. It was then when, in Talillas cave with a depth of approximately 80 meters, the speleologist from Granada, Antonio Peinado Arruza, suffered a fall resulting in serious injuries. The rescue was carried out by Priego speleologists, some of whom were involved in the exploration, Alfonso Calañas, Antonio González and Juan and Manuel Alcalá Zamora.

The most notable activities to take place during the following years were camps held in the area around Priego, organized by the GEC and GULMONT groups from Córdoba. At the first camp, in 1968, various speleological groups including those from Priego, explored GEAP and Pelaos caves in Tarajal and Fuente Alhama cave, which at the time was considered to be the deepest in the province with a depth of 210 meters. Various activities were also carried out in Yeso cave, the longest of the province.

In April of 1969, Operation Fuente Alhama II takes place and is a regional camp with groups from Córdoba, Priego, Sevilla, Almería and Granada coming together to undertake topographical surveys of Cholones, Las Latas, Era del Medico, Yeso and Peñón caves. In the same year, another fundamental act took place for Andalucian speleology. The Southern Region Speleological Committee (CRSE) was formed. This organization, integrated at that time with the Spanish Mountaineering Federation, would have its first headquarters in Priego and its first president, Alfonso Calañas Redondo, also from Priego. In effect ,we could say that Priego became the capital of Andalusian speleology until January of 1972 when the next president of the CRSE took office.

In 1970, GES Priego stabilized although its roots date back to 1957. Building on long-term close links between the Priego groups, GEP and GEAP united in March and on the 7th May these two groups united with the remainder of the Priego groups, thus forming GES Priego. In June, the group affiliated with the CRSE, which had its headquarters in Priego. The activities of 1970 mainly took place in the province of Jaén. Three camps lasted several days each in the area of Castillo de Locubín and resulted in the discovery and study of various caverns, some of these with very important archaeological sites, such as Plato cave and Chatarra cave. The archaeological materials excavated during these explorations were presented to Jaén Province Archaeological Museum. Also in Jaén, in Alcón Well, research took place in the La Bolera marsh area sponsored by the Guadalquivir hydrographical confederation. Other relevant activities that year where the attendance at the III Regional Camp in Alhama de Granada and the I National Speleological conference which took place in Barcelona.

In 1971, apart from the various activities conducted by the group in the area around Priego, the most important event was that undertaken during the IV National Camp. This camp, directed by GES Priego member and president of the CRSE, Alfonso Calañas Redondo, took place in Montejaque in the province of Malaga. Various caverns were explored and studied including La Pileta, famous for its cave paintings, and Gato cave which is well known amongst speleologists for its size and beauty, and its dangers at certain times of the year.

As we have said, the Southern Region Speleological Committee (CRSE) was based in Priego for the first three years of its existence and a man from Priego was its president. At the general meeting held in Sevilla on the 16th January of 1972, Federico Ramírez Trillo took over as president and the CRSE offices were moved to Malaga. The work that Alfonso Calañas carried out during his presidency was very important structuring and improving Andalusian speleology. Also in that year an important discovery was made in Cholones cave when in February, Cráneos joint was discovered. Together with GES Sevilla, this zone of the cave was explored and its topography studied. At the base of this joint lies a multiple burial ground completely covered by a thick layer of stalagmites. Extracted are some bones, containers and above all a complete human skull "el agüelo", which after having been studied by specialists from the universities of Sevilla and Madrid is donated to the local historical museum.

During the 1970s, one of the most important events in Priego from a speleological point of view was the IV Regional Camp which took place in Zagrilla Alta in the municipality of Priego. During this camp many of the most important caverns in our zone were explored, Fuente-Alhama cave, Talillas, los Pelaos and Navazuelo caves. As corresponds to a camp of regional importance, speleologists from all over Andalucía took part. Other work carried out by members of the group was assisting in Operation Hoyos del Pilar in Malaga province. During this work, a new attack was made on the GESM cave, reaching nearly 520 meters in depth. (In later years, this cave was to become one of the deepest in the world with a depth of 1080 meters).

The year of 1975 was an important year for GES Priego in that a new young generation of people took the reigns of the group. This new vitality was to be reflected by the activities that took place the following year.

During 1976 in the area around Priego, nearly fifty operations were carried out. Most distinctive must be the camp held in the Sierra de Cabra in the area of Navazuelo. At this camp, a complete geologic study of the sector was carried out and various caverns such as Navazuelo and Sopas were explored and mapped. A complete biological study was carried out in all of these caverns, as well. Besides that members of the group took part in two rescues. One, in Tesoro de Cabra cave, was without fatalities and the other, in Gato cave in Malaga, unfortunately, included one fatal casualty. Also in this year, as part of the VIII International Peninsular Prehistory Symposium, an exhibition was organized of archaeological materials excavated from the caves of Priego. Apart from the people of Priego, this exhibition was visited by numerous Spanish and foreign archaeologists.

The following year the annual camp held by the group took place in Fuente de las Cañas during the month of August with the objective of exploring the area in search of new undiscovered caves. The Sierra Gallinera and Moron Grande de Rute were explored and the results were very positive. Numerous biological, geological and topographical studies were carried out in various caverns -- Palenzuelo cave, Gallinera cave, Tocino cave and Negra cave amongst others. Important archaeological remains were discovered in some of these caves. Also in this year, a topographical study is made of one of the most interesting caves of the area, Talillas cave in the Sierra Horconera. A full topographical study and exploration of Tesoro de Cabra cave is made in collaboration with members from GES and SEM, This cave as mentioned previously is one of the deepest in the province with a depth of 160 meters.

In the following years, 1978 and 1979, as well as highlighting the topography and exploration carried out throughout the year we must mention participating in the Regional Camp which took place in the Motillas complex in the province of Cadiz, organized by GIEX. Together with various other speleologists, we explored and mapped various zones of this karst complex which is several kilometers in length.

The key year of 1980 brought radical changes in the exploration techniques used. Until then, climbing and safety ropes were used to overcome any obstacles, but in this year the group was able to renew the ropes and acquire the apparatus required to use the alpine technique of climbing. This same year two important works were carried out that do not strictly come under the ambit of speleology. The first of these works was a study of the Fuente de Salud spring. The water catchment area was studied where exhaustive microbiological tests were carried out including an attempt to enter the spring using underwater diving teams. The second of these works was a media documentary covering the important caves of Priego and entitled "Subterranean Landscapes". It was released to the public in August and was a great success.

A year of bad memories for the group was 1981. In this year on the 14th of April, an unfortunate accident occurred at around 1815 hrs which cost the life of our colleague Francisco Padilla Garcia, the result of the fracture of an M8 spit which he used whilst exploring a cave that now bears his name. He was hospitalized at 0230 hrs and died on the 21st April due to cardio-respiratory paralysis. On the 7th of March, he would receive a letter of condolence, from which I quote: "Paco, your tragedy has taught all speleologists an important lesson on caution, but we lament with bitterness the fact that we will never see each other again in the caves which you loved and taught us to love. Rest in peace, Paco our friend." Tragic events like these deal a bitter blow to all and as such nearly all speleological activities for the remainder of that year and the next year came to a halt.

This speleological lethargy came to an end at the beginning of 1983. In this year, new members joined the group and consequently introduced a new energy and vitality although most of the activities centered around a period of learning, taking place in the local caves.

In 1984, the new members were well established and the group began to function with vitality. From an administrative point of view it should be mentioned that in this year the group became part of the Priego Sports Committee and was registered in the Register of Associations and Sports Federations of the Superior Council of Sports. This does not mean that before that date the group was not recognized by the sports authorities, simply that there was a bureaucratic change and the Spanish Speleological Federation was founded, independent of the Spanish Federation of Mountaineering. That year the group explored the newly discovered Águila and Tabarrón caves as well as cleared an access to the 1001 Stones Cave in the Albayte Hills, a cave which, although not being very large, contains some interesting formations. On the 1st September a ceremony was carried out in Fuente-Alhama Cave to commemorate our colleague Francisco Padilla. A plaque was placed in the area where the accident occurred and a monolith at the cave entrance. During the month of July, courses were held for youths interested in learning about speleology or mountaineering. Apart from various slide shows and demonstrations of speleological techniques, it is important to highlight the collaboration that the Department of Pre-History and Archaeology of the Faculty of Philosophy and Arts at the University of Cordoba has given the group over the years.

The prestige of the group grew over the years and this was verified in 1985 by the number of notable activities carried out and by the ever growing number of members, as 33 members GES Priego became the largest group in Andalucía. Locally, various explorations took place that year, six new caverns were mapped and some interesting cave paintings were discovered in Palenzuelo cave. During the month of October the group took part in a protest to defend the karst landscape in Sorbas in Almería which thanks to the effort of everyone involved resulted in the protection of this exceptional area. The most important activity organized by the group that year was the VII Andlusian Speleology week. This took place in Priego between the 16th and 22nd September where numerous and varied activities were undertaken including five conferences, two films, and an exploration of Mármoles cave where, as in all the activities, numerous people took part. Also this year, the mountaineering section was formed to further mountaineering and alpine activities.

In 1986, apart from numerous explorations and the discovery of some new caves the most notable activities were as follows: topographical studies of Petronilo, GESP, J1 and Milana caves, this last one being discovered by chance over the spring of the same name. Although it is a small cave, it is interesting because it is flooded by a stream which exits the cave at the spring. The group also prepared a report on a tunnel that appeared during works on a street in Priego. In July some exploration work was carried out in the Jarcas hills and as the area appeared interesting it was decided to set up a camp in the area. This took place in December, in collaboration with the Genil Speleological Society, and fifteen new caves were discovered and some of them mapped. During the month of May exploration took place in the caves of Sorbas in Almería, with the objective of building up an ample library of slides of the areas caves. In the same month the group took part in the first meeting of Andalusian Speleological Rescue and Safety held in Puente Genil.

1987 was an important year as there were various changes in the management of the group. Juan Alcalá-Zamora, who was president of the group since 1970, resigned. A general meeting elected a new management team headed by Fernando Rodriguez Rojas. Of the major events held that year we must highlight a course given by teachers from EADE which some of our members undertook. This course, which began in the Karstic complex of Sorbas in Almería, was completed in Palenzuelo cave (Carcabuey), Soldado cave (Malaga) and Raja Santa cave (Granada). Other notable activities during the year were the biological studies carried out in some caves, the exploration and topography of Amor cave in Almedinilla, Palenzuelo cave and Candil cave. During the month of August, some exploratory work was carried out in Gato cave in Malaga. Antonio Castro García was nominated as a member of honor of GES-Priego for his services to the group.

During 2008, interesting activities were carried out. The topographic works on the cave of La Litrona del Águila (87 meters deep) and the exploration work of Sumidero-Río Zagrilla; this one being specially attractive due to the fact that it is a gypsum cave, unique in Priego and the second of two in the province. We also have been helped on several occasions by members of Seville University. Also, we co-operated with Cordoba Town Hall authorities to organize provincial training courses about speleology. Other activities developed have been: To close the cave "Cholones" counting with the help of the Priego Town Hall authorities in order to protect it; a training course inside the caves; and finally a regional camp in Castril (Granada) has taken place. However, the most remarkable activity during this year has been the celebration of the 25th anniversary of the founding of our group. Due to the absence of any real oral research or written information either, it can be agreed that 1963 was the first year for any speleological records in Priego de Córdoba. It was necessary to wait until 2007 when other oral and written research came to light to consider 1957 as the first year. The majority of the events took place during the last week of October although it might be said that everything started with the publication of the Boletín Interno Pipistrellus XXV Aniversary of the group creation. The events that were organized for the celebration of the 25th anniversary are described as follows: The design of commemorative posters and stickers made by the GES Priego presidents and the Andalusian Speleologist Federation; The showing of five different films were well considered internationally; a show about speleological techniques; several exhibitions with speleological materials; the Museo Andaluz de la Espeleología also organized another exhibition; and eventually an act in honor of previous members of the group.

Acknowledgments

To Andrew Gavin Cockburn and Rafael Rivera Hidalgo for the translation of texts, without them this work had not been possible. To Avelino Siller Calonge, Manuel Alcalá-Zamora Solís, Antonio González Alcalá and Jose Martos Espejo, for so many moments of chat and for the contributed information.

DETAILED SPELEOLOGICAL TOPOGRAPHY ANGEL CAVE (LUCENA, CÓRDOBA, SPAIN)

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Presented are the topographical studies undertaken to develop an artificial access tunnel to Angel Cave within the municipal boundaries of Lucena, in the Córdoba province in Spain. This tunnel will facilitate the paleontological exploration and archaeological studies of the cave.

Using the grade 5 speleological study undertaken in 2002 as a baseline, all local coordinates where extrapolated to UMT, the outline of the cave floors placed on 1:10,000 cartography, and the cartography was enhanced by the insertion of the exterior topography of all affected plots. Locating the tunnel mouth in a fixed area of one of these plots, the necessary parameters where calculated leading to a previously identified zone of the main cavern. The calculation of figures were tested using geographical and geotechnical surveys of the cave, this concluding the assessment.

TOPOGRAFÍA ESPELEOLÓGICA DE PRECISIÓN EN LA SIMA DEL ÁNGEL (LUCENA, CÓRDOBA, ESPAÑA)

Se presentan en este trabajo los estudios topográficos realizados para la construcción de un túnel artificial de acceso a la sima del Ángel, dentro del término municipal de Lucena, en la provincia de Córdoba (España) que facilite su exploración paleontológica y su estudio arqueológico.

Partiendo de la base de una topografía espeleológica de grado 5 realizada en el año 2002, se extrapolan todas las coordenadas locales a UTM, situando la poligonal de las plantas de la cueva en cartografía 1:10.000; complementamos toda la cartografía con el levantamiento topográfico exterior de las parcelas afectadas. Determinando la boquilla del túnel en una zona concreta de estas parcelas, se calculan todos los parámetros necesarios hasta una zona del cavernamiento previamente fijada. Se comprueban todos los cálculos y datos con un reconocimiento geofísico y geotécnico del emplazamiento de la cavidad, dándose por concluido el presente trabajo.

1. Speleological Data

Angel cave is located in the municipal terminus of Lucena, in the province of Cordoba (Spain). The coordinates are UTM XXXX146 YYYY114, in the mountain range of Araceli, 607 m asl. On the UTM reading ED50D data was used. The field work for the topographical study was carried out using the itinerary method, establishing second grade topographical stations along the variations of the established polygon, and closing the scree rubble zone with a closed polygon. The cave has an entrance of 4.12 m height by 2.30 m width, which leads to a hall from where we access the main source of the cave, 21.85 m in length (Fig. 1). In a southeast direction we descend a large and very steep 63.97 m ramp, which leads us to the deepest point of the cave at a depth of 67.4 m. Crossing the scree, there is a path that leads us back to the 63.97 m ramp. The cavern has a total length (D) of 268.14 m, a positive depth (Z) of 3.47 m and a negative depth (-Z) of 65.49 m.

The data were taken using a compass and SUUNTO brand clinometer, a BOSCH brand laser rule, and various tugs. The UTM coordinates of the cave access were attained using a GARMIN Etrex vista GPS using the static positioning mode of the apparatus and an exposure time of 15 minutes.

2. Geologic Setting

The cave is situated 3.5 km south of the town of Lucena, in the Araceli hills within the Subbetica Range (Lias – Dogger) on Jurassic limestone carbonates dating from the Sinemurian to Aalenian age and on a vertical geological joint that runs from NW-SE. The evolution of the cave originates from a small sink hole (Maucci), due to the collapse of the upper

Figure 1. Map of Angel Cave.

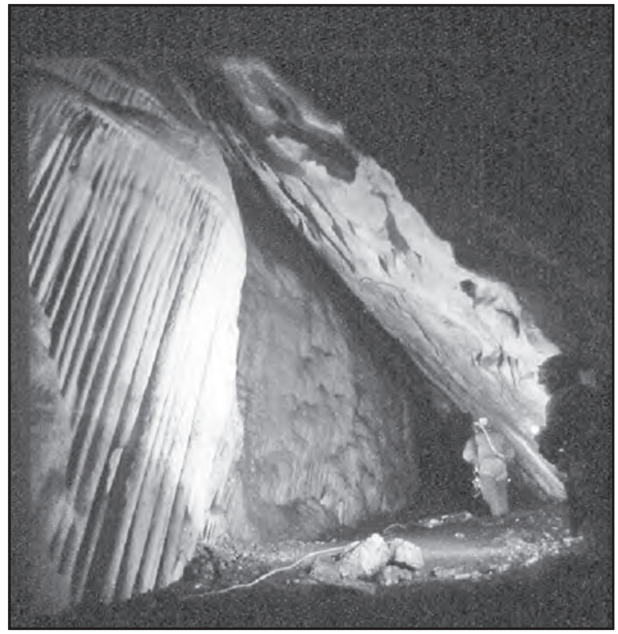

Figure 2. Speleothems in Angel Cave.

levels which now form the central scree slope and debris cone of the endokarstic morphology of the cave.

The geology starts with well stratified light grey limestone, 30 m, and whose age is understood to be from Sinemurian to Domeriense, which can be seen in the Ladera del Cerro, where the cave is located. Over these, grey and ochre limestone tables ranging from Domeriense to Turonian, of not more than 20 m. Over these are tabled limestone with filaments and pellets in banks of 0.5 to 1.0 m, and with abundant silex nodules; whose age is understood to be Aalenian to Bathonian and power of no more than 10 m. The strike of the dip slope is between 15º and 20º to the north.

The lithochemical formations are concentrated on the ramp which reaches the deepest part of the cave, mainly on the SW wall where the common flowstone covers the entire wall, the crusts which cover the main wall of the joint are of particular beauty. Less frequent are stalactites and stalagmites (Fig. 2).

3. Magnetic Declination and Convergence of Meridians

The calculations of convergence of meridians (ω) are based on the elemental quadrant where the cave is located. The figures on annual variation of magnetic declination (Δδ) for the center point of page 98914, as found in map 1:10,000 of the Andalusian Cartographic Institute, on the 1st January 1995 of 7,4' given that there is a difference from the date the co-ordinates of the exterior of the cave were taken (1st April 2006) of 11 years and 90 days, or 11.25 years, therefore -7.4 x 11.25 = -1º23, therefore δ = 3º46' - 1º23' = 2º23', and having the value of ω = 0º 49'.

4. Extrapolation of Magnetic Coordinates to UTM

Taking into account that the polygons in the cave interior refer to a system of local coordinates orientated towards magnetic North, but to test the data obtained in the exterior it is necessary to change these to one universal system of coordinates. If to do this we take a mathematical point of view (GEE, 1986, 324-325) we have:

$X_c = (X_m - X_{vm}) \cos Ø - (Y_m - Y_{vm}) \text{ sen } Ø + X_u$

$Y_c = (Y_m - Y_{vm}) \cos Ø + (X_m - X_{vm}) \text{ sen } Ø + Y_u$ where

X_c, Y_c = UTM coordinates of the projection of topographic station P_x.

X_m, Y_m = Magnetic coordinates of topographic station P_x.

X_{vm}, Y_{vm} = Magnetic coordinates of topographic station P_{39}.

X_u, Y_u = UTM coordinates of topographic station P_{39}.

If Ø = δ - ω = 2º 23' – 0º 49' = 1º 74', assuming that sin Ø = 0.038 y cos Ø = 0.999, with the result expressed in Table 1.

Topographic Station	X Magnetic	Y Magnetic	X UTM	Y UTM
P_{39}	0,00	0,00	XXX164,80	YYYY114,18
P_{38}	-0,54	2,01	XXX164,20	YYYY116,16
P_{36}	-1,70	3,73	XXX162,70	YYYY117,84
P_{35}	-3,78	6,04	XXX160,81	YYYY120,07
P_{33}	-4,19	3,93	XXX160,48	YYYY117,94
P_{31}	-5,89	7,13	XXX158,55	YYYY121,08
P_{30}	-5,89	7,13	XXX158,55	YYYY121,08
P_{29}	-5,89	7,13	XXX158,55	YYYY121,08

Table 1. Topographic coordinates.

	DISTANCE	PROJECTED DISTANCE	COURSE	DECLINE
P_{29}-P_{30}	19,73	0,0000	---	90º
P_{30}-P_{31}	2,12	0,0000	---	90º
P_{31}–P_{33}	4,18	3,6235	151º	30º
P_{33}-P_{35}	2,15	2,1495	10º	0º
P_{35}-P_{36}	3,59	3,1085	137º	30º
P_{36}-P_{38}	2,53	2,0746	145º	35º
P_{38}-P_{39}	2,30	2,0813	164º	25º

Table 2. Polygons with courses, declinations, and distances.

5. Topographic Precision

Basing solely on the parameters of margin of error on mapping (Martinez, 1992: 19-21), the polygon studied is composed of 8 sections, in which is covered 46.3155 meters in the cave. If we want to calculate the average margin of error cubed (E), given the length of cave (r) and the number of sides of the polygon (u), we have: $E = \pm 1/10 \sqrt{r^2/10u + u} = \pm 0.51$ meters. The tolerance would therefore be 2.7. 0,51m = ± 1.37 meters. Taking the precision calculation into account 0.05%

The map of the cave is within the parameters of precision at grade 5, given that the data was taken with light equipment of compass, clinometer, surveyor's poles and measuring rule.

6. Geophysical and Geotechnical Study of the Cave

Among the works carried out in this study are 2 profiles of electrical calicatas using a Sclumberger device, to consolidate the speleological topography of Angel Cave. Over the position of the cave sensitivity values are fixed, through the correspondent limestone – between 4000 and 6000 ohms per meter- finding a major cavity – 18000 and 29000 ohms per meter – which confirms the position of the cave, which extends eastwards from the zone of investigation.

7. Tunnel Calculations

Developing the calculations of an analogical way and graph (CAD), we have that (Fig. 3):

- The topographic station espeleológica that coincides with the exterior is 1-39.
- The topographic station espeleológica that coincides with the point where it he is foreseen that it he finishes the tunnel is 1-29.

The coordinates X, Y, Z, for the point 1-39 they are: X= XXX146,8, Y= YYYY114.18, Z=607.179 The coordinates X, And, Z, for the point 1-29 they are: X = XXX158.55 And = YYYY121.08 Z=579.019.

If the projection of P1-29, it at an altitude of 611.30 m and ZP1-29 = 579,019, then 1-29 inside the cave, it meets at 32.28 m on the projection to the exterior.

7.1. Location of the tunnel mouth

Located 3.30 meters from W boundary. Longitude=8.2692 meters, width=6.6 meters, area= 54.5764 m^2, perímeter=29.7383 meters. UTM Coordinates: x=XXX167.2228 y=YYYY037.8769 z=573.70

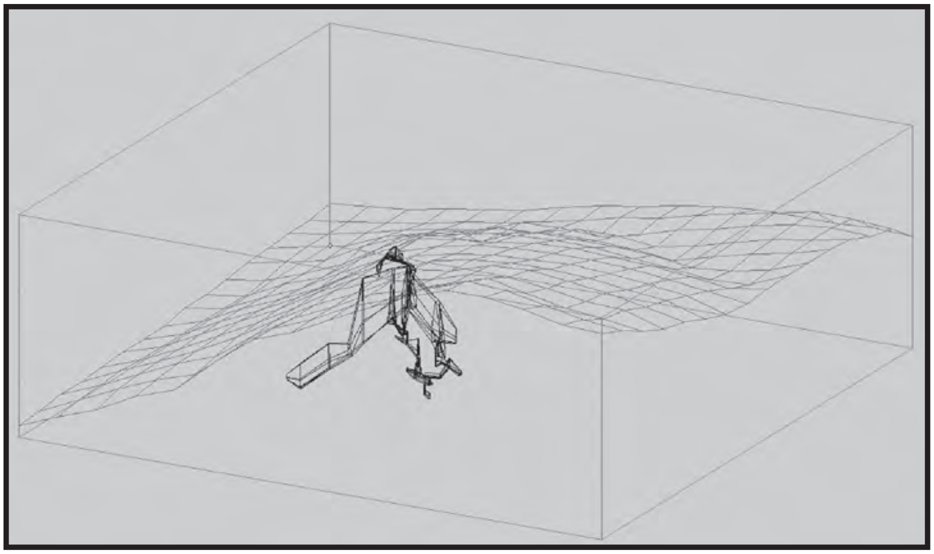

Figure 3. Grid projections on Angel Cave.

These parameters have been calculated taking into account two absolute points:

- The altitude on the map of 573.70 meters, which is where the tunnel begins.
- The western boundary, which is the fixed line that does not overlap the location of the tunnel.

One other variable to take in to account is the map altitude of 578.10 meters, which is where the tunnel mouth reaches a height of 4.4 meters.

x=XXX167.2228 y=YYYY046.1488 z=578.10

7.2. Location of the tunnel

Located with symmetrical axis situated 3.30 meters from west boundary. longitude=68.0335 meters, área=139.6470 m^2, perímeter=140.4658 meters, direction=339º. UTM coordinates:

x=XXX167.2228 y=YYYY046.1488 z=578.10

x=XXX142.7577 y=YYYY109.6311 z=606.41

7.3. Summary of Totals

Total length 76.3027 meters, total area 194.2234 m^2, total perimeter 170.2041 meters.

Acknowledgments

To Andrew Gavin Cockburn and Rafael Rivera Hidalgo for the translation of texts, without them this work had not been possible.

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PRIEGO SUBTERRANEAN EXPLORATION GROUP (GESP). 50 YEARS OF SPELEOLOGY IN PRIEGO DE CORDOBA (CORDOBA, SPAIN)

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The origins of GESP can be traced to 1957, in that year a group of youth began sporadic exploration of the caves in the hills around Priego. Little was known of these early explorations as only oral testimonials of speleological activity in Priego could be documented until 2006. In that year, José Martos Espejo donated his historic archives, a written record dating the formation of a Prieguense group of speleology on 1 January 1957, which, through time would evolve to become the current GES Priego. Up until the year 1963 there are very few written records of these activities. There were various speleology groups in Priego until 1970, GEAP, GEP, Murcielago, and SAJUMA. These, eventually converged to become GES de Priego.

In 1969 the Southern Region Speleology Committee (CRSE) was formed, an integral part of Spanish Mountaining Federation. CRSE's first president was a Prieguense from GES Priego, Alfonso Calañas Redondo. He served until 1972 and was very important in structuring the future of Andalusian speleology.

In the 1970s the CRSE organized the IV Regional Speleology Camp in Zagrilla Alta and participated in Operation Hoyos del Pilar in Malaga. There a new attack on the GESM cave was undertaken, leading a depth of 520m. In 1976 the group organized an exposition at the VIII International Symposium of Peninsular pre-history.

In 1980 new techniques for exploration were introduced, namely the Alpine Technique or progression by rope and in that same year the group undertakes two research projects: a study of the "Fuente de la Salud" spring and an audiovisual titled "Subterranean Landscapes." But 1981 the group loses a colleague in Fransisco Padilla García, who dies due to injuries sustained in Fuente Alhama cave.

In 1983 a new generation of people joins the group and in 1984 leads to collaborative studies with the Department of Pre-history and Archaeology of the Faculty of Philosophy and Arts of the University of Cordoba. With 33 members in 1985, GES Priego becomes one of the largest clubs in the province and one of the largest in Andalusia. In that year the club organized the VII Andalusian Week for promoting Speleology.

The club, in 1988, celebrated the commemoration of its XXV Anniversary, basing this on the only documentation available at that time, which established the start of speleological activity by GES Priego as 1963. But in 2006, as noted above, new documentation established the club's start to be 1957, and at the end of 2007 GES Priego celebrated its 50th anniversary.

GRUPO DE EXPLORACIONES SUBTERRÁNEAS DE PRIEGO. 50 AÑOS DE ESPELEOLOGÍA EN PRIEGO DE CÓRDOBA (CÓRDOBA, ESPAÑA).

Los orígenes del GESP se remontan al año 1957, fecha en la cual un grupo de jóvenes comienzan a hacer exploraciones esporádicas a cavidades de nuestras sierras. Del año 1958 solo se tienen testimonios orales de actividad espeleológica en Priego, pero es a partir de una donación de papeles de época por parte de José Martos Espejo, realizada a finales de 2006, cuando se constata por escrito una fecha de constitución de un grupo de espeleología prieguense, el cual con el tiempo irá evolucionando y adaptándose hasta nuestros tiempos en el actual GESPriego; El 1 de enero de 1957. Hasta el año 1963 hay muy pocos datos escritos de estas actividades. Hasta el año 1970 existirán en Priego varios grupos de espeleología, el GEAP, el GEP, Murciélago, SAJUMA, que se unirán -como es lógico- en el GES de Priego.

En 1969 se crea el Comité Regional Sur de la Espeleología (CRSE), integrado en la Federación Española de Montañismo, cuyo primer presidente, y hasta el año 1972 fue un prieguense del GES-Priego, Alfonso Calañas Redondo, su labor como presidente fue importantísima, estructurándose así la espeleología andaluza.

En la década de los 70 se organiza en Zagrilla Alta el IV Campamento Regional de Espeleología, asistimos en Málaga a la Operación Hoyos del Pilar, donde se realizó un nuevo ataque a sima GESM, alcanzando los -520 metros de desnivel. En 1976 realiza una exposición en el VIII Symposium Internacional de Prehistoria Peninsular.

En 1980 se produce un cambio en las técnicas de progresión, introduciéndose la Técnica Alpina, o la progresión por cuerda, y en este mismo año se realizan dos trabajos: un estudio sobre el manantial de la Fuente de la Salud y un audiovisual titulado Paisajes Subterráneos. En 1981 sufrimos el accidente de nuestro compañero Francisco Padilla García, quien fallece poco después a consecuencia de las heridas sufridas en la sima de Fuente Alhama.

En 1983 se produce un nuevo relevo generacional, que se consolida en 1984, colabora con el Departamento de Prehistoria y Arqueología de la Facultad de Filosofía y Letras de la Universidad de Córdoba. En 1985, con 33 miembros el GES de Priego se convierte en el club más numeroso de la provincia y uno de los más numerosos de Andalucía. Organiza en este año la VII Semana Andaluza de Divulgación de la Espeleología.

En 1988 celebra los actos de conmemoración de su XXV Aniversario, basándose en la única documentación escrita que se poseía en esta fecha, y que fijaba el año de comienzo de las actividades espeleológicas del GESPriego en 1963.

En el año 2006, como ya hemos dicho, se produce el conocimiento de nuevos escritos que determinan esta fecha en 1957, por lo que a finales de 2007 el GESPriego celebra los actos de su 50 aniversario.

The first speleological activities undertaken in Priego occurred in 1957 when a group of youths began exploring, on a sporadic basis, some of the caves in our hills. There are oral testimonies (Avelino Siller, Antonio González or Manuel Alcalá-Zamora) that verify that organized expeditions to the caves and climbing practice took place during that year. Following the donation of some historical archives by José Martos Espejo, it was confirmed that the 1st January 1957 was the founding date of the Alonso de Carmona Group, the first name given to the actual GES-Priego. Between the 5th and 9th of April of 1963, specialists from the Spanish Youth Organization came to Priego to give provincial courses in speleological archaeology. These courses, carried out in Murcielaguina cave, Los Mármoles cave, and La Cubé cave, inspired a group of youth from Priego to dedicate their spare time, and sometimes a bit more, in undertaking a new activity that they had newly discovered: speleology. Among this young group of speleological pioneers from Priego we should mention Manuel Alcalá-Zamora Solis, Avelino Siller Calonge, Jaime Álvarez, Alfonso Calañas Redondo, José Antonio Cejas, José Garcia de la Nava, Antonio González Alcalá, Rafael González Vílchez, Miguel Muñoz, Francisco Muñoz Segovia, José Rojas Serrano, José Luis Ruiz, Jesús Zurita and many more.

It is not, however, until 1970 that we can really talk about the evolution of the name GES-Priego as we know it today. Until that year, various independent groups existed. Those that stand out are Alonso de Carmona, GEAP (Alpine Speleological Group of Priego), GEP (Priego Speleological Group), the bat group, and the Marist Brothers group

- SAJUMA. Despite this fragmentation of efforts it was a very interesting time as, apart from beginning speleological studies in Priego, the majority of the caves known today were discovered. The first topographical studies began and the archaeological sites in the interiors of the caves were first discovered.

Apart from these first explorations carried out in the local caves of Torrecitas, Siete Cuevas and Tarajal gorge, this first year was interesting in that we collaborated with GEJAM of Córdoba undertaking works in Murcielaguina and Los Mármoles caves.

The following year, in 1964, the Alcaide Hills in the area of Zagrilla were explored. The caves of Peñon Largo and Era del Médico were located and explored for the first time. Due to a lack of equipment, these explorations were also carried out with the assistance of GEJAM. On the 12th of April of that year, one of the most important caves of the area was discovered, Cholones cave. Its exploration was also carried out in collaboration with groups from Córdoba and under the auspices of the pre-historian Javier Fortea. A large area of the cave was explored descending to the grand cavern 100 meters in depth where cave paintings, schematic and medieval, were discovered.

This continuing collaboration with the groups from Córdoba was reflected in 1965 when, in August and September, the Priego group participated in the first provincial camp held in the area of Alcalá la Real and organized by Alonso de Carmona of Priego de Córdoba.

The smooth running of the speleological activities carried out by the groups from Priego in these early years was shattered in March of 1966. It was then when, in Talillas cave with a depth of approximately 80 meters, the speleologist from Granada, Antonio Peinado Arruza, suffered a fall resulting in serious injuries. The rescue was carried out by Priego speleologists, some of whom were involved in the exploration, Alfonso Calañas, Antonio González and Juan and Manuel Alcalá Zamora.

The most notable activities to take place during the following years were camps held in the area around Priego, organized by the GEC and GULMONT groups from Córdoba. At the first camp, in 1968, various speleological groups including those from Priego, explored GEAP and Pelaos caves in Tarajal and Fuente Alhama cave, which at the time was considered to be the deepest in the province with a depth of 210 meters. Various activities were also carried out in Yeso cave, the longest of the province.

In April of 1969, Operation Fuente Alhama II takes place and is a regional camp with groups from Córdoba, Priego, Sevilla, Almería and Granada coming together to undertake topographical surveys of Cholones, Las Latas, Era del Medico, Yeso and Peñón caves. In the same year, another fundamental act took place for Andalucian speleology. The Southern Region Speleological Committee (CRSE) was formed. This organization, integrated at that time with the Spanish Mountaineering Federation, would have its first headquarters in Priego and its first president, Alfonso Calañas Redondo, also from Priego. In effect ,we could say that Priego became the capital of Andalusian speleology until January of 1972 when the next president of the CRSE took office.

In 1970, GES Priego stabilized although its roots date back to 1957. Building on long-term close links between the Priego groups, GEP and GEAP united in March and on the 7th of May these two groups united with the remainder of the Priego groups, thus forming GES Priego. In June, the group affiliated with the CRSE, which had its headquarters in Priego. The activities of 1970 mainly took place in the province of Jaén. Three camps lasted several days each in the area of Castillo de Locubín and resulted in the discovery and study of various caverns, some of these with very important archaeological sites, such as Plato cave and Chatarra cave. The archaeological materials excavated during these explorations were presented to Jaén Province Archaeological Museum. Also in Jaén, in Alcón Well, research took place in the La Bolera marsh area sponsored by the Guadalquivir hydrographical confederation. Other relevant activities that year where the attendance at the III Regional Camp in Alhama de Granada and the I National Speleological conference which took place in Barcelona.

In 1971, apart from the various activities conducted by the group in the area around Priego, the most important event was that undertaken during the IV National Camp. This camp, directed by GES Priego member and president of the CRSE, Alfonso Calañas Redondo, took place in Montejaque in the province of Malaga. Various caverns were explored and studied including La Pileta, famous for its cave paintings, and Gato cave which is well known amongst speleologists for its size and beauty, and its dangers at certain times of the year.

As we have said, the Southern Region Speleological Committee (CRSE) was based in Priego for the first three years of its existence and a man from Priego was its president. At the general meeting held in Sevilla on the 16th January of 1972, Federico Ramírez Trillo took over as president and the CRSE offices were moved to Malaga. The work that Alfonso Calañas carried out during his presidency was very important structuring and improving Andalusian speleology. Also in that year an important discovery was made in Cholones cave when in February, Cráneos joint was discovered. Together with GES Sevilla, this zone of the cave was explored and its topography studied. At the base of this joint lies a multiple burial ground completely covered by a thick layer of stalagmites. Extracted are some bones, containers and above all a complete human skull "el agüelo", which after having been studied by specialists from the universities of Sevilla and Madrid is donated to the local historical museum.

During the 1970s, one of the most important events in Priego from a speleological point of view was the IV Regional Camp which took place in Zagrilla Alta in the municipality of Priego. During this camp many of the most important caverns in our zone were explored, Fuente-Alhama cave, Talillas, los Pelaos and Navazuelo caves. As corresponds to a camp of regional importance, speleologists from all over Andalucía took part. Other work carried out by members of the group was assisting in Operation Hoyos del Pilar in Malaga province. During this work, a new attack was made on the GESM cave, reaching nearly 520 meters in depth. (In later years, this cave was to become one of the deepest in the world with a depth of 1080 meters).

The year of 1975 was an important year for GES Priego in that a new young generation of people took the reigns of the group. This new vitality was to be reflected by the activities that took place the following year.

During 1976 in the area around Priego, nearly fifty operations were carried out. Most distinctive must be the camp held in the Sierra de Cabra in the area of Navazuelo. At this camp, a complete geologic study of the sector was carried out and various caverns such as Navazuelo and Sopas were explored and mapped. A complete biological study was carried out in all of these caverns, as well. Besides that members of the group took part in two rescues. One, in Tesoro de Cabra cave, was without fatalities and the other, in Gato cave in Malaga, unfortunately, included one fatal casualty. Also in this year, as part of the VIII International Peninsular Prehistory Symposium, an exhibition was organized of archaeological materials excavated from the caves of Priego. Apart from the people of Priego, this exhibition was visited by numerous Spanish and foreign archaeologists.

The following year the annual camp held by the group took place in Fuente de las Cañas during the month of August with the objective of exploring the area in search of new undiscovered caves. The Sierra Gallinera and Moron Grande de Rute were explored and the results were very positive. Numerous biological, geological and topographical studies were carried out in various caverns -- Palenzuelo cave, Gallinera cave, Tocino cave and Negra cave amongst others. Important archaeological remains were discovered in some of these caves. Also in this year, a topographical study is made of one of the most interesting caves of the area, Talillas cave in the Sierra Horconera. A full topographical study and exploration of Tesoro de Cabra cave is made in collaboration with members from GES and SEM, This cave as mentioned previously is one of the deepest in the province with a depth of 160 meters.

In the following years, 1978 and 1979, as well as highlighting the topography and exploration carried out throughout the year we must mention participating in the Regional Camp which took place in the Motillas complex in the province of Cadiz, organized by GIEX. Together with various other speleologists, we explored and mapped various zones of this karst complex which is several kilometers in length.

The key year of 1980 brought radical changes in the exploration techniques used. Until then, climbing and safety ropes were used to overcome any obstacles, but in this year the group was able to renew the ropes and acquire the apparatus required to use the alpine technique of climbing. This same year two important works were carried out that do not strictly come under the ambit of speleology. The first of these works was a study of the Fuente de Salud spring. The water catchment area was studied where exhaustive microbiological tests were carried out including an attempt to enter the spring using underwater diving teams. The second of these works was a media documentary covering the important caves of Priego and entitled "Subterranean Landscapes". It was released to the public in August and was a great success.

A year of bad memories for the group was 1981. In this year on the 14th of April, an unfortunate accident occurred at around 1815 hrs which cost the life of our colleague Francisco Padilla Garcia, the result of the fracture of an M8 spit which he used whilst exploring a cave that now bears his name. He was hospitalized at 0230 hrs and died on the 21st April due to cardio-respiratory paralysis. On the 7th of March, he would receive a letter of condolence, from which I quote: "Paco, your tragedy has taught all speleologists an important lesson on caution, but we lament with bitterness the fact that we will never see each other again in the caves which you loved and taught us to love. Rest in peace, Paco our friend." Tragic events like these deal a bitter blow to all and as such nearly all speleological activities for the remainder of that year and the next year came to a halt.

This speleological lethargy came to an end at the beginning of 1983. In this year, new members joined the group and consequently introduced a new energy and vitality although most of the activities centered around a period of learning, taking place in the local caves.

In 1984, the new members were well established and the group began to function with vitality. From an administrative point of view it should be mentioned that in this year the group became part of the Priego Sports Committee and was registered in the Register of Associations and Sports Federations of the Superior Council of Sports. This does not mean that before that date the group was not recognized by the sports authorities, simply that there was a bureaucratic change and the Spanish Speleological Federation was founded, independent of the Spanish Federation of Mountaineering. That year the group explored the newly discovered Águila and Tabarrón caves as well as cleared an access to the 1001 Stones Cave in the Albayte Hills, a cave which, although not being very large, contains some interesting formations. On the 1st September a ceremony was carried out in Fuente-Alhama Cave to commemorate our colleague Francisco Padilla. A plaque was placed in the area where the accident occurred and a monolith at the cave entrance. During the month of July, courses were held for youths interested in learning about speleology or mountaineering. Apart from various slide shows and demonstrations of speleological techniques, it is important to highlight the collaboration that the Department of Pre-History and Archaeology of the Faculty of Philosophy and Arts at the University of Cordoba has given the group over the years.

The prestige of the group grew over the years and this was verified in 1985 by the number of notable activities carried out and by the ever growing number of members, as 33 members GES Priego became the largest group in Andalucía. Locally, various explorations took place that year, six new caverns were mapped and some interesting cave paintings were discovered in Palenzuelo cave. During the month of October the group took part in a protest to defend the karst landscape in Sorbas in Almería which thanks to the effort of everyone involved resulted in the protection of this exceptional area. The most important activity organized by the group that year was the VII Andlusian Speleology week. This took place in Priego between the 16th and 22nd September where numerous and varied activities were undertaken including five conferences, two films, and an exploration of Mármoles cave where, as in all the activities, numerous people took part. Also this year, the mountaineering section was formed to further mountaineering and alpine activities.

In 1986, apart from numerous explorations and the discovery of some new caves the most notable activities were as follows: topographical studies of Petronilo, GESP, J1 and Milana caves, this last one being discovered by chance over the spring of the same name. Although it is a small cave, it is interesting because it is flooded by a stream which exits the cave at the spring. The group also prepared a report on a tunnel that appeared during works on a street in Priego. In July some exploration work was carried out in the Jarcas hills and as the area appeared interesting it was decided to set up a camp in the area. This took place in December, in collaboration with the Genil Speleological Society, and fifteen new caves were discovered and some of them mapped. During the month of May exploration took place in the caves of Sorbas in Almería, with the objective of building up an ample library of slides of the areas caves. In the same month the group took part in the first meeting of Andalusian Speleological Rescue and Safety held in Puente Genil.

1987 was an important year as there were various changes in the management of the group. Juan Alcalá-Zamora, who was president of the group since 1970, resigned. A general meeting elected a new management team headed by Fernando Rodriguez Rojas. Of the major events held that year we must highlight a course given by teachers from EADE which some of our members undertook. This course, which began in the Karstic complex of Sorbas in Almería, was completed in Palenzuelo cave (Carcabuey), Soldado cave (Malaga) and Raja Santa cave (Granada). Other notable activities during the year were the biological studies carried out in some caves, the exploration and topography of Amor cave in Almedinilla, Palenzuelo cave and Candil cave. During the month of August, some exploratory work was carried out in Gato cave in Malaga. Antonio Castro García was nominated as a member of honor of GES-Priego for his services to the group.

During 2008, interesting activities were carried out. The topographic works on the cave of La Litrona del Águila (87 meters deep) and the exploration work of Sumidero-Río Zagrilla; this one being specially attractive due to the fact that it is a gypsum cave, unique in Priego and the second of two in the province. We also have been helped on several occasions by members of Seville University. Also, we co-operated with Cordoba Town Hall authorities to organize provincial training courses about speleology. Other activities developed have been: To close the cave “Cholones” counting with the help of the Priego Town Hall authorities in order to protect it; a training course inside the caves; and finally a regional camp in Castril (Granada) has taken place. However, the most remarkable activity during this year has been the celebration of the 25th anniversary of the founding of our group. Due to the absence of any real oral research or written information either, it can be agreed that 1963 was the first year for any speleological records in Priego de Córdoba. It was necessary to wait until 2007 when other oral and written research came to light to consider 1957 as the first year. The majority of the events took place during the last week of October although it might be said that everything started with the publication of the Boletín Interno Pipistrellus XXV Aniversary of the group creation.

The events that were organized for the celebration of the 25th anniversary are described as follows: The design of commemorative posters and stickers made by the GES Priego presidents and the Andalusian Speleologist Federation; The showing of five different films were well considered internationally; a show about speleological techniques; several exhibitions with speleological materials; the Museo Andaluz de la Espeleología also organized another exhibition; and eventually an act in honor of previous members of the group.

Acknowledgments

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HOUET TABET: NEW DISCOVERY APPROACH

GHADA SALEM, JOSEPH TABET, JACK SAFI, LORINE MOUAWAD, SAMER AMHAZ, MAZEN ARZOUNI and CAROLE NEHME

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Among the "*Association Libanaise d'Etudes Spéléologiques*" (ALES) 2007-2008 new discoveries is Houet Tabet. Its entrance is a 3.5 m padding pit that has an extraordinary discovery approach and allows to cavers an exciting experience at all levels:

The enduring negotiation that lasted four years with the land owner to give us the authorization to enter his land.

The excavation techniques used to clean out the contents (soil, blocs, and concrete and sewage disposals).

The most stimulating conjecture is the plausible connection with the second deepest and largest pit in Lebanon, Houet Qattîne Azar (-507 m, more than 6 km long), whereas, the pit of Qattîne Azar was discovered by the cavers of the same association in 1996.

The karst network to which these pits belong developed in the Kesrouane Limestone [Jurassic (J4)], more than 1000 m thick in the area, although only 500 m of the calcareous deposit of sediment are observable as gray-bluish benches.

A simple conversation about a cave, whose entrance was exposed while building the restaurant in 1980s and the land owner who re-closed it for safety reasons, leads to a great discovery. Joseph Tabet, a member in the Assosiation Libanaise d'Etude Spéléologiques – ALES, carried on the negotiations with Mr. Boutros Azar, the land owner, for four years until we got the OK to excavate and re-open the cave entrance.

Why did this specific spot attract our interest so badly?

This location is at an altitude of 1480 m and develops in the carbonated formation of Limestone's of Kesrouane [Jurassic (J4)], exceeding 1000 m thickness in the area, although only 500 m of the calcareous deposit of sediment are observable as grey-bluish benches (DUBERTRET and RENOUARD, 1953). This gives it a great potential and is located near the Qattine Azar pit. Qattine Azar pit was discovered by ALES in 1996 and is the second deepest cave in Lebanon at -512 m and is over 6 km long.

More exploration have been going on in the Qattine Azar pit, especially at the end of a lateral extension the *Galerie des Français*, where ALES members have been working hard with the free climbing techniques. Actually they are exploring the pit from the bottom up and have already climbed up about 50 m.

Our expectations were high for a possible connection of both cavities. The entrance known as Tabet pit is 150 m North of Qattine Azar's entrance and 200 m South West from the escalade area at the *Galerie des Français*.

On 15 September 2007 the excavation work started with a team of ALES members who were extra ready for the hard work. The initial area to excavate was 1.20 m by 0.90 m.

This is probably the first time such an attempt has been taken on a buried unknown cave. We say unknown because we are digging out the soil into the unknown. There are no records of an existing cave at this spot, but we took the chance and put our energy into action.

Among the stories recalled by the land owner and his son is that we have to dig approximately one meter and then it opens horizontally where they blocked it with cement and blocks then with soil. Another clue is that water used to drip endlessly and dive into the earth. Some dissolution traces are obvious on the entrance wall, so another push.

Joseph Tabet, Badr Jabbour-Gedeon, Mazen Arzoni, Samer Amhaz, Lorine Mouawad, Jack Safi, Najji Jabbour, Issam

Hachem, Rita Stephan and I, Ghada Salem was in action, and tools were put to motion. Group work, synchronization and taking turns, what an experience! Each had a role to take part in and did it with utmost energy. Shifts were taken and almost no time to take a rest, lunch breaks were postponed to dinner.

First day (September 16, 2007), 5 hours of digging we descended 1.7 m and still more soil to take out. A Speleo-alpine technique of pulley systems was used to carry the heavy loads out of the pit and the soil was transported to a nearby area with a carriage.

Second day (September 23, 2007) digging and more digging, 5 carriages of soil and 6 blocks until we reached a layer of sand and after emptying 5 carriages from here we came to a sewage pipe. Could this be a sign of a near opening? Enormous work was done and huge quantities were excavated until we reached a concrete surface at approximately three meters depth. Still the sewage pipe was going through the concrete. After breaking it we estimated the thickness of the concrete is about 30 to 35cm. thick. Are we there?

Third day (September 29, 2007 afternoon) we got an air compressor to remove the concrete layer. Set, ready, go. The air compressor worker was in the pit and breaking the hard concrete into peaces. Then some blocks started being exposed and removed. Two hours and a half passed of breaking and removing the concrete and more to go.

Fourth day (September 30, 2007) we installed a metal gate for the safety of the restaurant visitors. We continued removing the concrete but this time manually, with a hammer and chisel. At 5 pm the great news spread, it opened to a very narrow two meter passage. That was a great and indescribable feeling, no words to express our joy and reward. Our efforts have paid off. Wow!

The passage had an obstacle after one meter where it shrinks to a 35 cm width and 26 cm height. Samer was the first to pass after he took off all his speleo-gear and squeezed himself inside. He disappeared for 15 minutes and came back shouting, speaking non stop, singing you name it… He walked into a bedding plane for approximately 100 m length then reached a 10 m opening of a pit. Great news!

Actually, the first part of the pit was used as a sewage discharge for the Azar family's toilet, so when enlarging the passage it smelled very badly… Can you imagine being in such a narrow area with such bad smell!?

The 3.5m entrance pit led to a horizontal narrow passage which has a muddy floor then it opens to a large gallery which seems to be a bedding plane containing lots of speleothems, muddy floors, flowstones, sinter pools, soda straws, and flowing water. Different passages with various height and width opens all along the main axis leading to a 8x8 m wide pit opening and 15 m deep that turns to another pit of 30 m depth. The base of this pit opens to the East into another passage of 20 m height and lots of chimney potentials. The floors of these areas are covered with blocks of different nature and size. The passage is closed at the end with lots of blocks and pebbles on the floor level.

This is probably one of the most beautiful ALES discoveries in 2007. There are still a lot to be explored in the coming years, especially in the chimneys which have a connection potential to Qattine Azar pit. The most significant experience we learn is that it takes a lot of patience to gain the trust of the locals. No Pain No Gain

Reference

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FIVE YEARS OF SPELEOLOGICAL INVESTIGATION IN THE KARST OF SIERRA MIXTECA-ZAPOTECA, SOUTH OF TEHUACÁN, OAXACA, MEXICO

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Since 2002, the Italian team "La Venta" is carrying on a research project that has the aim to investigate the karst systems in the area of Sierra Mixteca-Zapoteca, located south of Tehuacàn. The Sierra consists mainly of Cretaceous limestone, covered by Upper Cretacic marly limestones and Tertiary calcareous conglomerates. The most karstified area is the limestone plateau crossed by the Rio Juquila (or Xiquila) Canyon. Presently, five missions, performed in the years 2002, 2003, 2004, 2006 and 2007 have allowed discovering more than 70 caves. Despite the good karst potential of the area, large underground systems have not been yet discovered. The longest cave is located in the middle part of Juquila Canyon and consists of a large relict phreatic conduit more than one km long. The deepest caves, vadose in origin, are placed in the top area of Cerro Granudo and in the southeast area, between the canyon and the village of Santa Maria di Ixcatlàn. Some of these vertical caves have deep pits, which are clogged at bottom by debris and mud deposits carried in by runoff water. The Cueva de la Laguna Prieta, for instance, which opens as a wide collapse sinkhole at 2490 m of elevation, displays a first shaft of 210 m, whereas the cave is 280 m deep. In the area just northwest of S. Maria, some caves of thermal origin have been surveyed during the 2006 mission. These caves display morphologies due to underwater solution processes, which probably attained during the rise of ipogenic waters. The caves are remnants of old hydrothermal karst system, presently remoulded by seepage waters and filled by deposits.

During the last mission, in November 2007, the higher part of the Juquila Canyon, named Rio Matanzas, was explored. This area is characterized by a very deep gorge more than ten km long whose cliffs present some big caves that represent the relict of an ancient phreatic system. Those caves are filled by speleothemes and re-crystallized calcite deposits. Finally, many caves show ancient traces of human's frequentation, as graffiti, wall paintings and jars, usually close to ruins of pre-hispanic (Ñuiñe culture) settlements.

1. Introduction

The Tehuacán-Cuicatlán valley, in the north of the state of Oaxaca, is a NNW-SSE tectonic basin bordered by the Sierra Mixteca-Zapoteca on the western side and by the Sierra Mazateca, the Sierra de Juarez and the Sierra de Zongolica on the eastern side (Fig. 1). The eastern ridges are made up mainly by Jurassic-Cretaceous limestone and the karst is present with majestic underground systems. The Sierra Juarez-Mazateca hosts the deepest caves of the whole American continent, the Cheve System (-1484 m) and the Huautla System (-1475 m) with tens of kilometers of explored passages. In contrast, the western mountains do not display relevant karst landforms. In order to investigate the sierra located west of Tehuacán, the "La Venta" Geographical Association performed five speleological expeditions from 2002 to 2007 (De Vivo, 2003; Bernabei et al., 2003; Mecchia & Piccini, 2006, Piccini et al., 2008; Sauro, 2008) focused on the central area of the mountain chain. This part is a wide limestone plateau, with mountains passing 2600 m in altitude, crossed by the Rio Juquila (or Xiquila) from SW to NE. The river drains the waters of a wide highland area towards the Rio Salado, in the Cuicatlán valley, a river flowing into the Gulf of Mexico. Limestone outcrops on a surface of about 450 km^2, but field investigation has revealed that karst forms are concentrated in a few limited areas.

2. Geographical Setting

The studied region is a small part of the whole karst area that develops for about 200 km from the west of Tehuacán (Puebla) in the north to the city of Oaxaca in the south. From an administration point of view, the region belongs to the communities of Tepelmeme de Morelos and Santa Maria Ixcatlán and is part of the protected semi-desert area of the Reserva de la Biosfera de Tehuacán -Cuicatlán, world known for its many endemic species of cacti. Geographic and climatic isolation of the valley contribute to a high level of endemism. Mountain ranges surrounding the valley

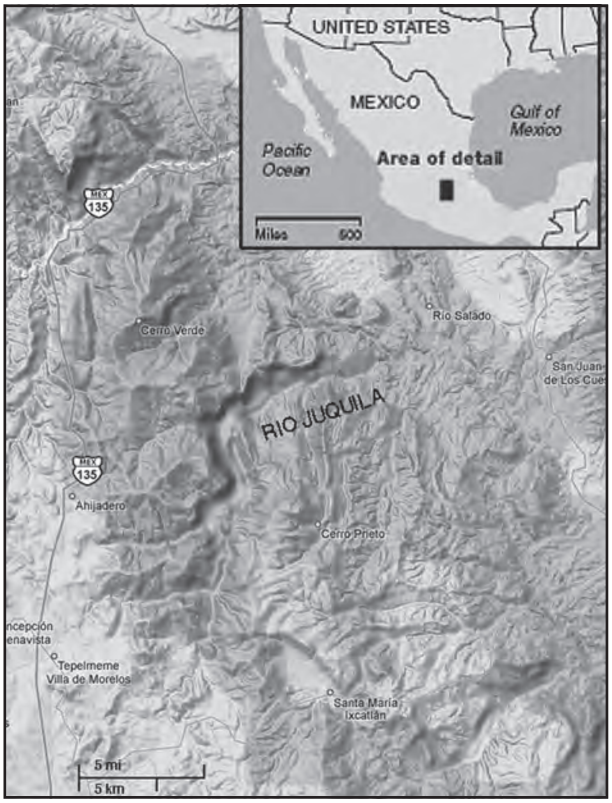

Figure 1: Relief map of the investigated area.

reduce the influx of tropical maritime moisture. Just east of the valley, slopes of the southern Sierra Madre facing the Gulf of Mexico (Sierra Mazateca), receive an annual average precipitation of more than 4000 mm and support tropical rainforest. In contrast, the ranges west of Tehuacán basin are characterised by a semi-arid climate, with rainfalls ranging from 250 to 500 mm, depending on the altitude, concentrated in the months from June to September. Since there are no pluviometric stations, it is not possible to give a reliable evaluation of the rainfall, but on the highland above 2000 m altitude it could reach 500-600 mm per year.

3. Geological Framework

The Late Cretacic Laramide orogenesis produced the main tectonic compressive structures of the Mixteca-Zapoteca range, whereas the Oaxaca normal fault is the regional structure responsible of the neotectonic evolution. The latter is a complex deformation zone that consists of faults having mainly NW-SE directions in the northern segment and N-S directions in the southern one (Nieto-Samaniego et al., 2006). The Mixteca-Zapoteca carbonate range lies west of the fault, which also forms the eastern edge of the Tehuacán valley. At the end of the Paleocene - beginning of the Eocene, an extension phase started, producing the deepening of the Tehuacán valley. This distension phase was accompanied by volcanic activity of andesite type lasting until the Oligocene (Martiny et al., 2000).

The Sierra Mixteca-Zapoteca consists mainly of an Early Cretacic calcareous sequence, about 1000 m thick, characterised by mainly detritic and bioclastic facies, which lies on Cretacic marls and shales.

In the canyon area, and particularly east of it, we found bioclastic calcarenites and calcirudites with decimetric to metric thick beds with megabreccias bodies and frequent horizons enriched with cherts nodules and rare interlayers of yellowish clay. In the western sector of the area we found well stratified limestone, with abundant cherts, often interlayered with marly and shaly beds. In the eastern sectors of this area Upper Cretacic limestone crops out. A Tertiary (Paleocene – Oligocene) terrigenous sequence, consisting mainly of marls and sandstones, overlies calcareous formations in the south-western sectors of the Juquila basin. Beds are moderately westward dipping. The limestone massif is cut by several faults, prevalently NNW-

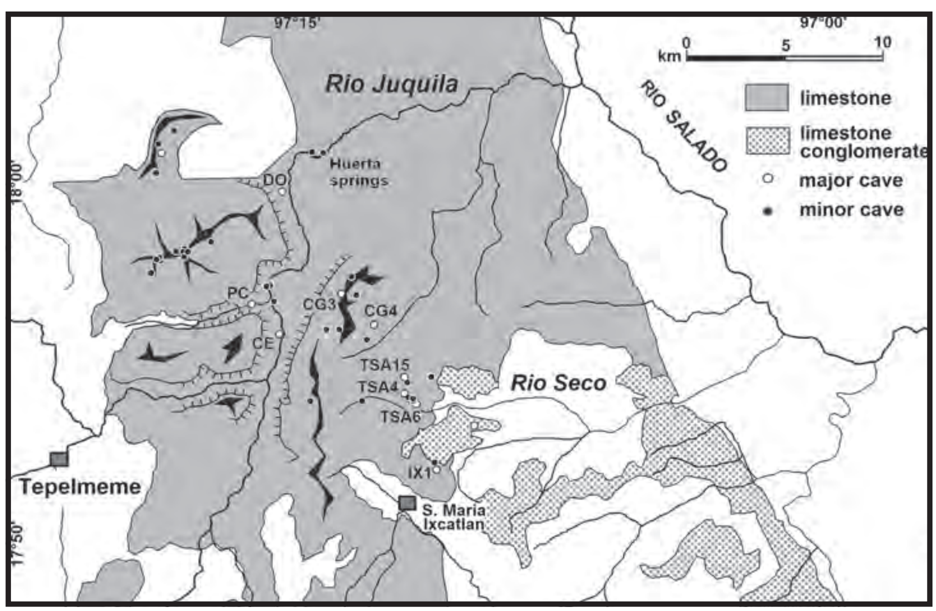

Figure 2: Sketch geological map of the karst area with the entrances of the main explored caves (cave labels are those in Table 1).

SSE oriented, parallel to the master faults of Tehuacán basin. Other faults have an orientation E-W. The river network is mainly developed along faults and it shows an angular pattern.

In many places, wide debris deposits due to the intense physical weathering cover the bedrock. These detritic deposits are responsible for the filling of inner basins. The slope debris forms well-cemented covers, typical of semi-arid mountain environments, which probably hide many ancient karts landforms.

4. Cave Surveying Results

The investigated area may be subdivided into three sectors: 1) Juquila canyon, 2) left hydrographical side highland, 3) right hydrographical side highland (Fig. 2).

4.1 The Juquila canyon

The Juquila canyon is one of the most impressive of the Sierra Mixteca-Zapoteca. Both sides are steep, sometimes forming almost vertical walls up to 500 m high. It starts from the junction between two secondary rivers, Rio Matanza and the Rio Grande de San Miguel, coming from the terrigenous impermeable Triassic sequences that characterises the western sector, toward Tepelmeme, and the southern sector, toward Santa Maria Ixcatlán. Both these rivers, where they meet the Cretacic limestone, at altitudes of about 2100 meters, fall into long and narrow gorges delimited by more than 100 meters high walls. After a dozen of kilometers of lakes and waterfalls, the two rivers flow into each other becoming the river Juquila. The main river flows all the way down for more than 20 kilometers of canyon to the more open sector of La Huerta springs, located at an altitude of approximately 1200 m a.s.l. Several springs flow out from both sides of the riverbed at La Huerta. In this area, in fact, the canyon incision reaches a less permeable layer, which consists of limestone, marl and sandstone, underlying the strongly karstified limestone that forms the walls of the canyon and the plateau. The total discharge of the springs is not known, although it is still a reasonable amount even in the driest periods. According to the available information, there is not much difference between the dry season flow and the wet season one. One of the spring-caves is located on the western side and may be accessed for about 70 m up to a final sump. During winter 2003 its water flow was some 30-40 litres per second.

All along the canyon several cave entrances may be found either close to the riverbed or on its steep slopes. In the upper part of the canyon, from Rio Matanza to the central part, at an altitude between 1950 and 1600 m a.s.l., 12 caves have been explored during the last 2007 expedition. In this sector the caves are prevalently relics of vadose systems, with high inactive meanders and pits cut by the development of the Matanza's gorges, and relict caves in the walls with remarkable concretional deposits. We believe that some parts of this narrow canyon had been a huge cross-cave which was then uncovered by successive collapses of its vault. A similar phenomenon is visible in its majestic form in the central part of Juquila Canyon, after the confluence between Rio Matanza and Rio Grande. A very interesting cave, well known since a very long time, is located in a tributary canyon that cuts down the limestone massif near the village of Puerto Mixteco. This cave is locally renowned as Puente Colosal (PC), and consists of a natural 250 m long tunnel. This impressive gallery, located at the end of a blind valley, is up to 50 m high in the final part and never less than 15 m wide. Nuiñe paintings and inscriptions are present on the gallery walls; the archaeological studies date them between 300 and 800 A.D. (Mautner, 2005; Urcid, 2004). Today the cave is completely dry, except during strong floods.

From Puente Colossal to La Huerta, at altitudes between 1600 and 1400 m a.s.l., nine caves have been explored. These

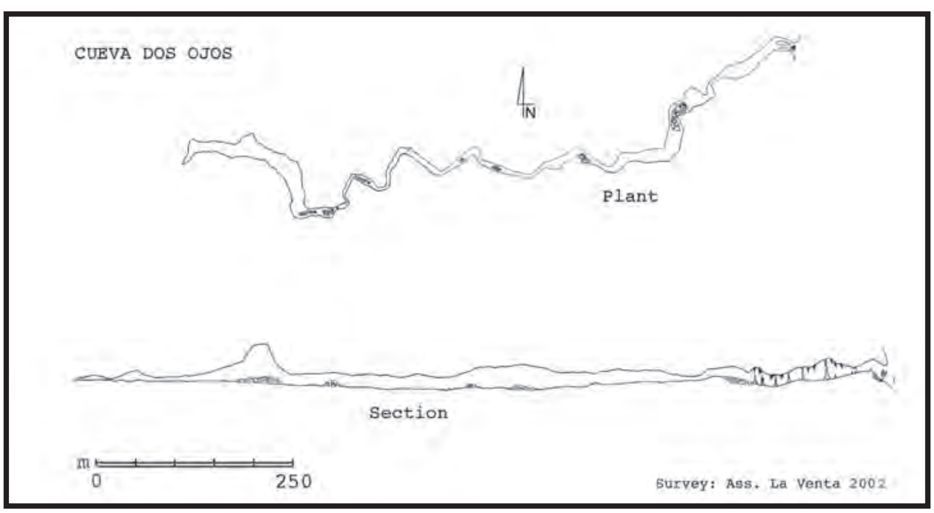

Figure 3: Longitudinal profile and plan view of Cueva Dos Ojos (survey: E.G. La Venta, 2003).

are short segments of old phreatic tubes, up to 10 m in diameter, closed by fluvial deposits, flowstones or rock falls after a few dozens of meters of length. The longest cave is the Cueva Dos Ojos, located on the left side almost 300 m above the active springs (Fig. 3). This is an almost straight dry gallery, about 1 km long, which presents clear phreatic features (Fig. 4)

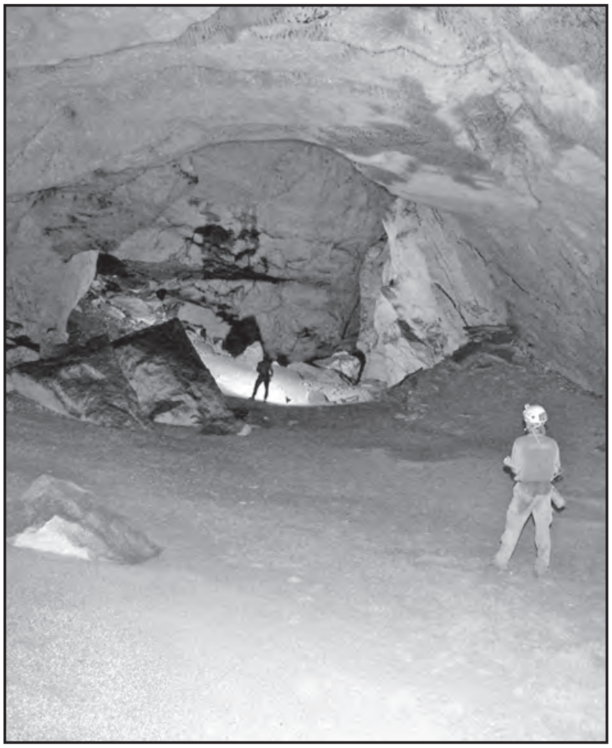

Figure 4: Big paleo-phreatic gallery in the Cueva Dos Ojos (photo: Giuseppe Savino, La Venta).

4.2 Left hydrographical highland

The western section of the limestone range consists of a 15 km long ridge connecting, from south to north, Cerro Tequelite, Cerro Pericon and Cerro Verde, the latter almost 3000 m in altitude. The range presents rounded crests covered by tree-like vegetation, particularly on the north facing sides. The slopes are covered with debris deposits, particularly thick and wide on the lower sides.

The 23 explored caves are concentrated in the upper areas, above the altitude of 2600 m, mostly on low gradient surfaces close to mountain crests. For the most part they are non-active vertical caves, truncated by erosion and showing clear signs of senescence, as the altered stalactite and stalagmite deposits clearly demonstrate. The longest cave is Majada Somiate, at an altitude of 2300 m on the eastern slope of Cerro El Zotol, close to the small village of Mahujzapan. This cave consists of a 210 meters long and 20 meters wide gallery, filled by big stalagmites and speleothems deposits. The deepest cave is Pozo de los Murcielagos, a big system of interconnected pits that reach a depth of 85 meters where the bottom is completely closed by mud and guano (with the assured presence of the dangerous fungus *histoplasma capsulatum*). All the other vertical caves explored in this sector (MZ2 –37/50 m, CV4 –50/60 m, CV5 –60/70 m at an altitude of 2750 m) are filled to the bottom with mud and organic material and are completely dry. Only Cueva El Basulero, a sequence of narrow passages and short pits that opens other La Huerta springs, presents a small stream that flows in a very narrow meander not completely explored. Only in the lower plateau of Mauizapan some caves present a sensible "high entrance" air circulation, while in the higher slopes of Cerro Verde and Cerro Pericon caves have no air circulation and sometimes the presence of CO_2 due to the decomposition of organic material was found.

4.3 Right hydrographical highland

The highland located east of Juquila canyon represents the widest karst area and is characterised by flat areas, different from what may be found on the left hydrographical side, with several wide and shallow dolines and some collapse depressions. The 26 caves surveyed in this zone are concentrated in two areas: Cerro Grande, in the NW (CG zone), in the territory of Tepelmeme, surveyed in 2003, and Llano la Cumbre, in the SE (IX and TSA zone), in the territory of Santa Maria Ixcatlán, surveyed in 2006.

The longest and deepest cave is the Sotano de la Laguna Prieta (CG3) located near the top of Cerro Grande. The entrance consists of a wide collapse doline that opens on a 140 m deep shaft, formed by two joined parallel pits. A hanging terrace made of rock blocks opens on a 40 m vertical drop that gives origin to a high, few meters wide, gorge descending SE. A further 35 m deep pit leads into a chamber with big blocks embedded among the walls. The bottom section is definitely stuck by mud and organic material (Fig. 5). The other relevant cave in Cerro Grande is the Pozo de la Vaca Ladra (CG4), not far from CG3; its entrance, also shaped as a collapse doline, leads into a 12 m deep pit. At its base a detritic slope leads onto a 100 m vertical drop, which consists of a pit with 4 x 6 meters elliptic plan. A narrow side passage, along the generating fracture of the pit, leads into a 7 m drop, closed by mud at the bottom (Fig. 6).

Llano la Cumbre is a wide depression located NW of Santa Maria de Ixcatlán, artificially dammed in order to form a basin for watering livestock. The largest cave of this area is

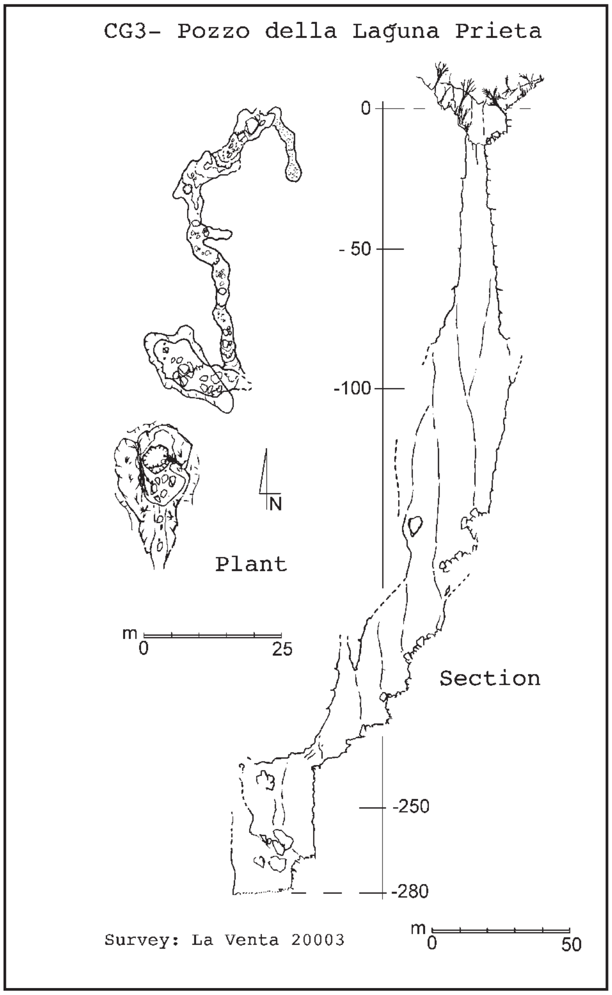

Figure 5: Longitudinal profile and plan view of Pozo de la Laguna Prieta (survey: La Venta E. G., 2003).

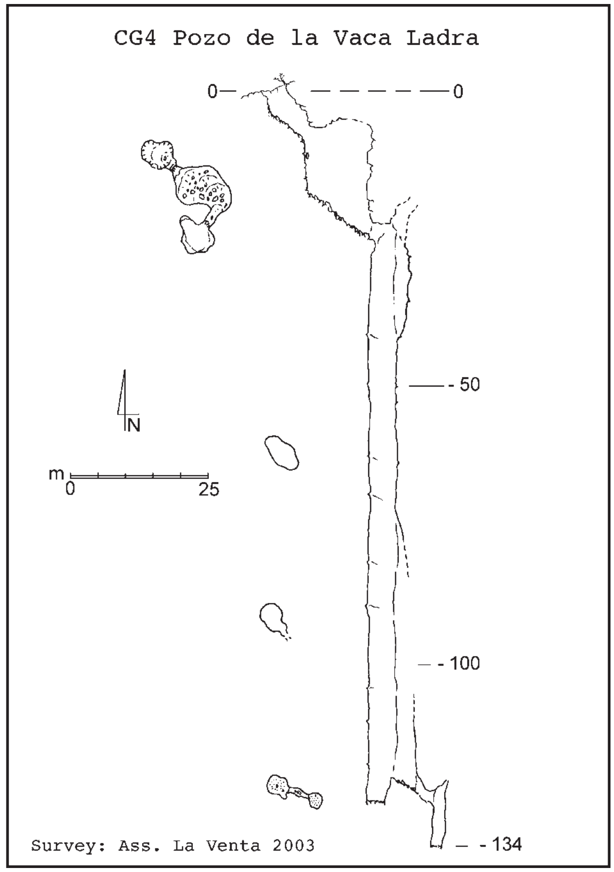

Figure 6: Longitudinal profile and plan view of Pozo de la Vaca Ladra (survey: E.G. La Venta, 2003).

Sotano Rodeo (IX1); it opens with a 10 m large sinkhole. It is composed of three vertical pits of 40, 10 and 75 meters. At the bottom is a small meander, blocked by debris after about twenty meters at a depth of -135 m. For the main part, the other explored caves are in the small valleys of the Terrero San Antonio, 2-3 km north of Llano la Cumbre. Among these caves, the deepest one is Sotano la Calabera (TSA6) consisting of a single 77 m deep shaft.

The main valley is now divided into small blind basins, lined in N-S direction and drained by sinking streams. Probably, before the waters were absorbed underground, they formed a single valley, the left tributary of Rio Seco. At the present time, the runoff rills are active only in the wet season. Following the bottom of the ditches, two sinkholes were discovered and explored for a few tens of meters, Cueva Perfecto 3 (TSA15), upstream, and Sumidero San Antonio (TSA4), downstream. Cueva Perfecto 3 starts with a 20 m pit and continues in a gorge that after a dozen meters ends up in a chamber, where two different conduits may be covered for a maximum of 30 m both upstream and downstream. The latter shows a low gradient, meander-like course and ends up in a shallow water pool (-39 m). Along the same valley line, 700 m downstream TSA15, we find the second sinkhole, Sumidero San Antonio, 100 m long. This cave as well as Cueva el Calacote (TSA10), that opens 2 km further west, is particularly interesting for the understanding of the geological evolution of the area because these caves show solution forms typical of a convective circulation of thermal waters, with calcite crusts covering distinctive dome-shaped voids. This morphology might testify to an ancient phase of karstification produced by uprising hot water, and therefore the two caves might be among the oldest ones in the region. Presently, the surface erosion has exhumed the two caves and in Sumidero San Antonio the hydrothermal forms were locally remoulded by the flow of the rainwater stream sinking into it.

5. Conclusions

The evolution of caves and karst in the area of Juquila Canyon is certainly related to the complex morpho-tectonic history of the Tehuacán basin. The present relief represents

Name (cave label)	Altitude m a.s.l.	Vertical range m	Length m
Puente Colossal (PC)	1760	- 37	255
Cueva Dos Ojos (DO)	1495	-25, +30	1020
Cueva Espinosa (CE)	1529	150	+15
Sotano de la Laguna Prieta (CG-3)	2490	- 280	330
Pozo de la Vaca Ladra (CG-4)	1495	-25, +30	1020
Sumidero San Antonio (TSA4)	2190	-23	100
Sotano la Calavera (TSA6)	2260	-77	100
Cueva Perfecto 3 (TSA15)	2265	-39	172
Sotano Rodeo 1 (IX1)	2200	-135	210

Table 1: Location and dimensions of major explored caves.

what remains of an ancient planned surface that might have formed in the late Cenozoic, during a period of relative tectonic quiescence. During the formation of this surface the karst should not be so developed in extension and depth. The opening of new fractures during the faulting events and the deepening of the canyon, forced the transfer of the flow through underground pathways, with the activation of springs located at lower altitudes. The change of the drainage network implied activating new fractures and widening them to form new caves (Piccini et al., 2008).

At the present time, we observe several phases of karst development. The most ancient caves are located in the southern section of the studied area, and are hypogenic caves elaborated again by percolation waters and intercepted by surface erosion. Such caves might be related to the last phases of the Tertiary magmatic activity that affected the area (Miocene?).

Surface karst dissolution had a relevant role leveling the topographic surface. As a consequence, the first-phase karst forms have not survived, other than as relict and truncated caves. Traces of the progressive lowering of the base level are found in the canyon walls, mainly between 1600 and 1500 m a.s.l.; they are segments of an ancient phreatic network that fed springs deactivated due to the following lowering of the base level. Also the vertical caves explored on the highland may belong to different generations and some of them are still rather active, despite the scarcity of rain feeding the underground network. At present, the decrease in the feeding of the karst network, due to the recent passage to a drier climate, has reduced the entity of karst dissolution and slowed down the development of the underground network. Furthermore, the progressive washing away of the soils present on the top plateau together with the abundant vegetable material, is leading to the obstruction of the karst cavities. This seems to be one of the main reasons that have kept us from reaching the deeper parts of the karst systems.

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PIANI ETERNI: TWENTY YEARS OF EXPLORATIONS IN THE DEEPEST CAVE OF DOLOMITE MOUNTAINS, VENETIAN ALPS, ITALY

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The investigation of the karst area of Piani Eterni, in the Italian Belluno's Dolomites National Park, began in the 1980s. In 1989, the discovery of the main entrances of PE10 and V35, proved the existence of a deep and complex karst system. Since then, 12 km of galleries and shaft to 971 m in depth have been mapped. The Piani Eterni Karst Complex shows a complex pattern of development that derives from the strong interaction between lithological and structural factors. The two abysses developed along a fault surface and are connected by horizontal galleries at 450 and 700 m in depth. The presence of paleophreatic levels in the cave documents the uplift evolution of the area, marking ancient groundwater-table levels.

In summer of 2005, after passing a short sump, a new branch was explored towards the northeast. The next year a pit of 100 m lead the exploration into a huge level of phreatic galleries. Within one year five kilometres of new horizontal passages were mapped. At the same time, a new branch of similar phreatic galleries was found in Isabella Cave, on Val Falcina slope, below the main PE10 system. Now explorations are searching for the connection of the two caves that should realize a complex more than 25 km long.

1. Introduction

The Piani Eterni area is a glacio-karstic high plateau located in the southernmost Dolomites, 15 km NE of the town of Feltre (NE Italy). It presents a huge number of karstic caves (more than 300), coupled with a glacio-karstic landscape of great beauty, protected within the heart of the Dolomiti Bellunesi National Park (Fig. 1).

Inside this plateau, there is one of the deepest caves of Italy, the Piani Eterni Karst Complex, with a total depth of 971 m and more of 17 kilometres of galleries mapped, now the deepest and longest cave explored in Dolomites (Fig. 2). Even though the explorations of this cave was extended over twenty years of researches, still now we don't know exactly the hydrological extension of this complex and we don't know which are the main resurgences of the streams found in the cave. In the last four years, explorations brought new information about the ancient phreatic levels inside the mountain and allowed to suppose unexpected connection with other karstic plateaux of this area. In this work we summarize the main scientific and explorative knowledge about this system in order to develop new researches and explorations for the future.

2. Story of Explorations and Description of the System

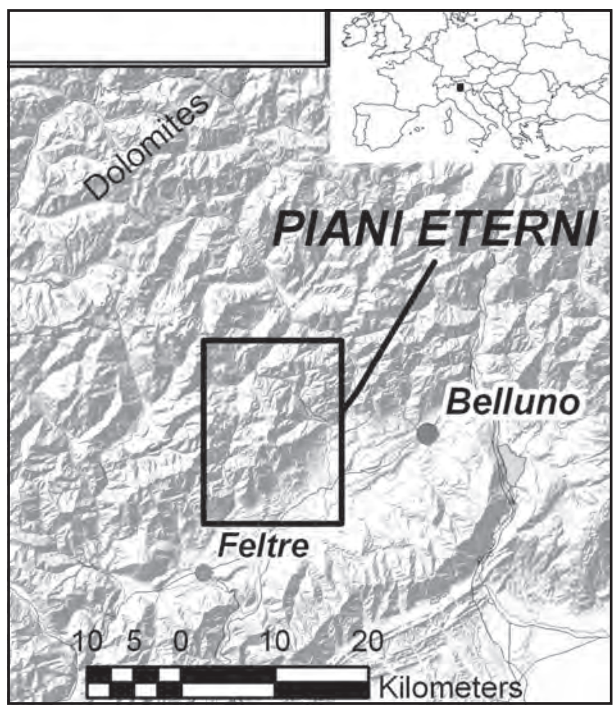

Figure 1: Geographical map of the investigated area in the Belluno's Dolomite National Park.

The Piani Eterni Karst System was discovered in 1989 and since then explorations permitted to map more than 17 km of galleries with a total depth of 971 m (Fig. 3).

Figure 2: The karst system develops mainly under glacio-karstic depressions like this one named White Dolin (photo: Marco Salogni).

Now the cave presents five different entrances, located at altitudes of nearly 1890 m., and goes rapidly downward along deep shafts alternating with galleries marking paleo-phreatic levels (- 40 m, -200 m, -450 m, -560 m, -700 m and -810 m). We can divide the cave in two main sector, the former conditioned by the" PE10-V35 Fault", explored since 1989 to 2007, and the new sector of the –560 paleo-phreatic level, explored since 2007. One other sector of the underground karst, not connected yet with the main system, is Isabella Cave, a big paleo-phreatic gallery that opens on the Val Falcina slopes and develops for about 4 kilometres toward WNW overlapping the new branches of the –560 level of the system.

2.1 The fault PE10-V35 sector

From the entrances to a depth of -100 m, the cave presents big rooms and shafts hosting perennial ice deposits at a temperature near to 0° C. Below -150 m of depth, the temperature stabilizes on 4 °C, inside a complex and evolved system of horizontal galleries and vertical shafts up to 150 m deep. At -270 m, the internal morphology changes totally, due to the passage from limestones to coarse-grained dolomites. Here, the main path intersects "the Fault": it is a NW-SE oriented and NE-dipping fault that controls the cave development until a depth of -900 m. Along the Fault two main streams flow downward, named Vincè and PE10, connected by two paleo-phreatic levels, at –450 and – 700 m, developed along the strike of the Fault. Vincé ends in some narrow passages in the Pisoliti branch at about –870 meters of depth, while PE10 , after -900 m, becomes narrower due to a lithological change and a more pervasive fracturation. At –971 a narrow meander stopped the

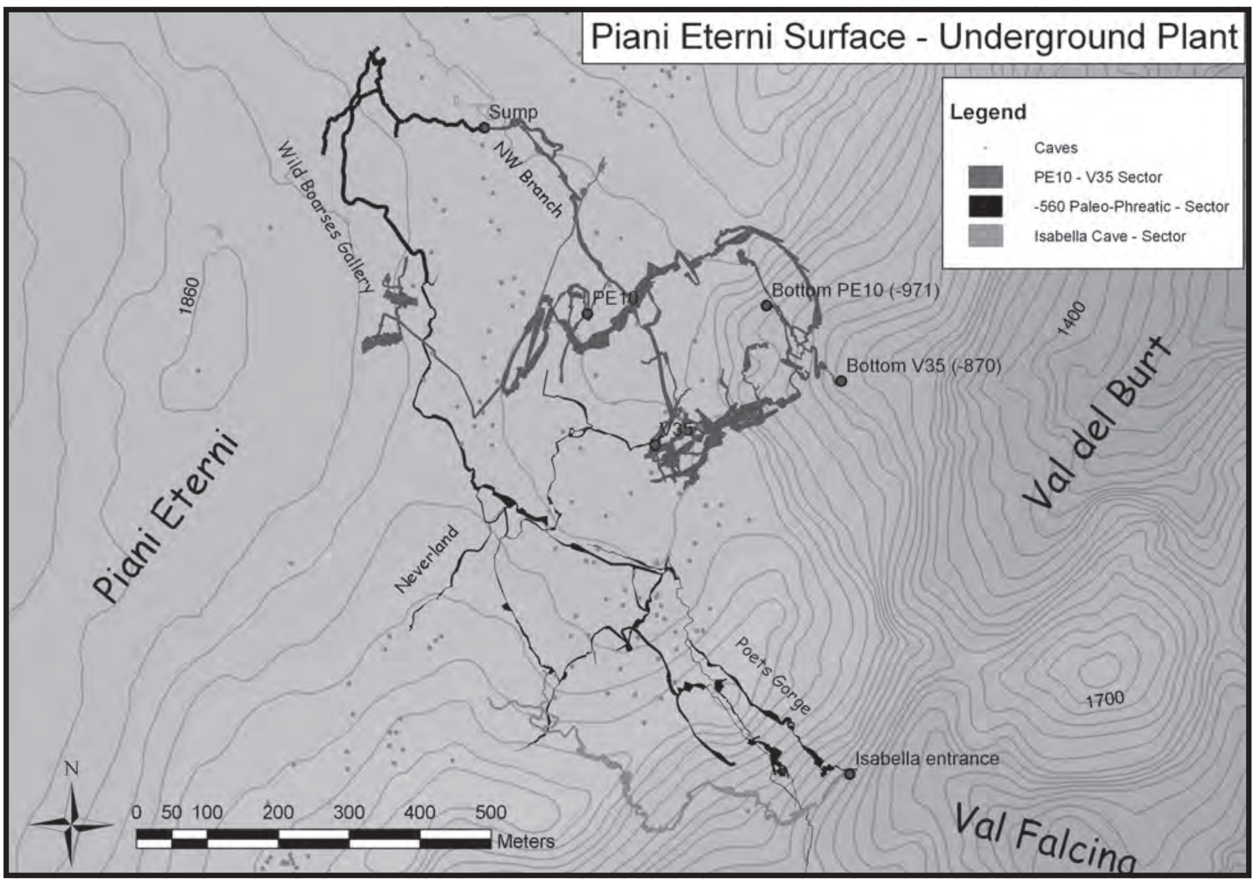

Figure 3: General map of the cave system.

explorations.

2.2 -560 paleo-phreatic level sector

In 1992 a continuation of the Camp Gallery, at a depth of –450, was explored toward NE, encountering a small fragment of an ancient phreatic level cut by the main Fault (Zàpeghe Branch). In order to find new answers about this anomalous sector, in 2005, a new expedition overcame a short semi-open sump leading into a complex system of small active meanders and older inactive ways of half a kilometre of length, almost totally unrelated with the main PE10 Fault. In autumn 2006 a very big pit of more than one hundred meters of depth led into a big paleo-phreatic system situated at 560-590 meters of depth (1300-1330 meters a.s.l.). The main conduit (Wind Gallery and Wild Boarses Galleries) was explored for more than 1.5 kilometres, first toward the S, and then toward SE, doing a very particular route surrounding all the known complex (Fig. 4). To the S of the main conduct, a big system of secondary galleries, related with the bedding planes settlement of the area, was explored for more than 3 km of development and 200 meters of upwards drop. The streams flowing in this sector of the cave run into the Poets Gorge, that descends, joint and strata controlled, to a siphon at a depth of –680 meters. Along this branch one other, smaller, paleo-phreatic level was found at a depth of -600 meters (1390 m a.s.l.), named Happy Tuna Gallery (Fig. 4).

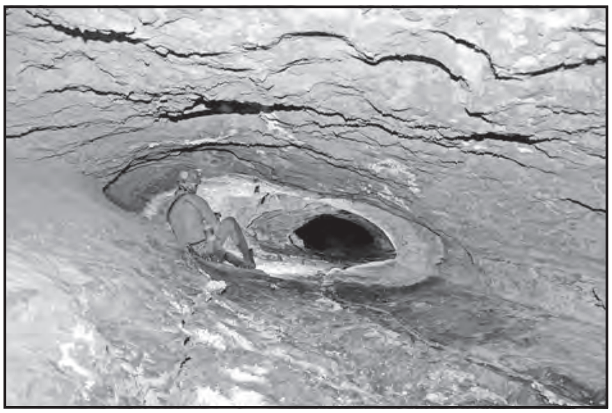

Figure 4: Wind Gallery, the main conduct of the –560 paleo-phreatic level (photo: Marco Baroncini).

Now explorations are concentrated in a new sector of the galleries, Neverland, which develops from the main conduct toward SSW, in a totally unknown zone that could get under the Piazzole-Erera glacio-karstic depression. This sector of the cave is evidently very important from a strategic explorative point of view because, through a labyrinth-form phreatic system, could connect other glacio-karstic depressions situated near the Piani Eterni plateau. The paleo-phreatic level seems to be very few disturbed by tectonics while it is surely controlled by the bedding planes settings with a gentle WNW dipping. Moreover in this zone different blasts of air merge from unknown areas and turn to a hypothetical lower entrance that maybe could be the Isabella Cave (or another still unknown cave).

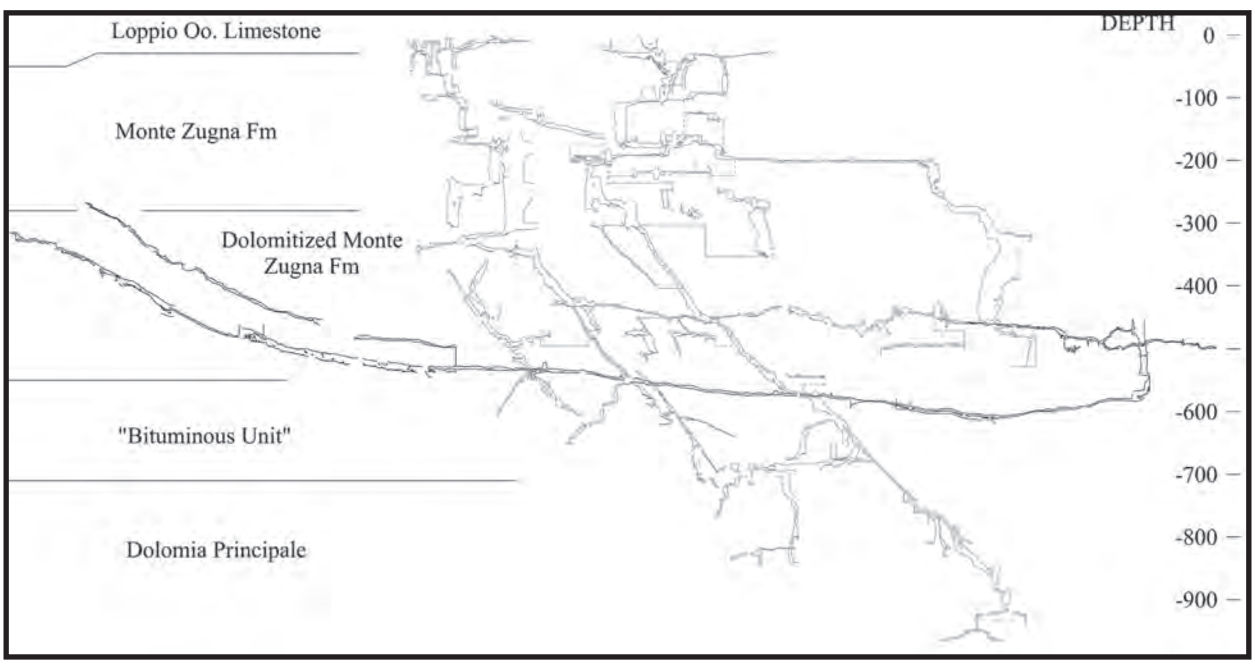

Figure 5: Section of the Piani Eterni karst complex related with the stratigraphy sequence (-560 paleo-phreatic level in evidence).

2.3 Isabella Cave

This cave opens at an altitude of 1640 m a.s.l., on the cliffs of a lateral branch of Val Falcina Valley, in a very wild area of the mountain. It was casually discovered in 1969 by a hunter, Count Miari Sulcis. In fact, the entrance of the cave is not visible from any point of view and need five hours of approach without treaded track. For this fact the cave was explored in its first part only in 1997, and only in summer 2007 a collapse was overcome allowing to explore more than 3 km of new ways.

The cave is characterized by a big paleo-phreatic gallery (Fig. 6), with sections of more than 5x5 m, developing alternatively toward southwest and northwest, gentle dipping according with the bedding planes. Scallops' orientations show that the paleo-phreatic flow was toward the inside of the cave. The gallery is locally cut by tectonics perpendicular discontinuities, corresponding to rockfall zones. Here an important stream has been captured by a younger vadose way flowing inside a deepening gorge. This new way was explored recently to a depth of –340 meters (1300 m a.s.l.), but the connection with the main system, and in particular with the underlying paleo-phreatic level of –560 (1320 m a.s.l.) in PE10, has not been proved yet.

3. The Survey of the System

Since the beginning of the exploration of the Piani Eterni karst system, topographical survey has been carried on. The collected data can be considered very good, if all the closed loops are characterized by very small errors. For instance, when in 1994 the two caves PE10 and V35 were joined the 6 kilometer loop was not closed for only 1,5 meters! Until 2004 the drawn official survey has been digitalized with AutoCAD software and then survey vectorialization has started. In CAD environment, using plan and profile maps, a 1080 station "fictitious shot line" has been built up. The amount of data has been collected and elaborated both with VisualTopo and Compass softwares. Nowadays all the new data are directly digitalized and linked using VisualTopo software.

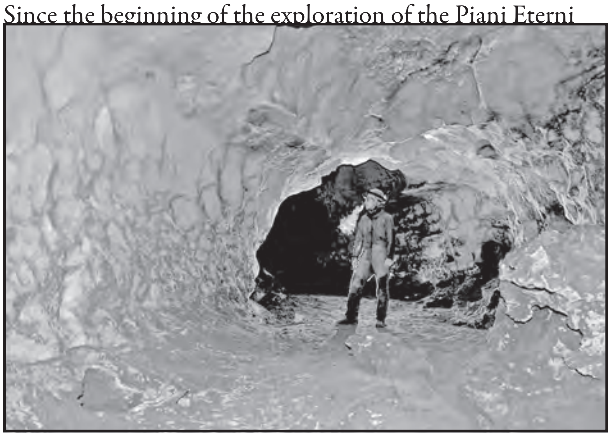

Figure 6: The big paleo-phreatic conduct of Isabella Cave (photo: Cristiano Zoppello).

Vectorialization represents a long step forward in our research activity. It is now possible to create more accurate and up-to-date maps, to compare in real time the external surface with the spatial pattern of the cave, to make 3D-models of the Piani Eterni plateau. At the moment vectorial survey is made of nearly 2000 shots and it is quite complex. The development of the cave system is about 18 kilometers, 6 of which explored in the last 4 years.

Next step is to create an air circulation model using digital maps. We have realized that a really complete approach to the exploration of the paleo-phreatic galleries requires not only the understanding of the shape of the cave but also the comprehension of the air circulation and digital maps can be very useful for this.

4. Geological Investigations

During a three-year scientific research program, about 30 lithological samples have been recovered from the karst complex, allowing to build a detailed stratigraphy (Fig. 5), coupled with a detailed geological mapping of the area (Fig. 7).

The base of the succession is represented by the Dolomia Principale (Carnian-?Rhaetian) Formation, made up of metric-scale dolomitic banks with stromatolitic caps. The unit represents the basement of the Piani Eterni and has been penetrated by the known cave only for 200 m in depth. The overlying unit is here informally called "bituminous unit" because of the uncertain age. The "bituminous unit" is made of white to grey banded coarse- to medium-grained dolomites with decimetric bedding, without fossils and microfossils. The peculiarity of this unit is the very strong fetid smell. The thickness is about 200 m and the age is uncertain due to the lacking of diagnostic fossils. The "bituminous unit" passes rapidly to metric subtidal banks of coarse-grained dolomites representing the dolomitized part of the Monte Zugna Fm (Calcari Grigi Group) Hettangian to Sinemurian in age (Casati and Tomai 1969). The dolomitization is very pervasive and destroyed all the sedimentary features, including the green-clay caps that are common in this unit (Masetti et al. 1998, Barbieri & Grandesso 2007).

The dolomitization front that marks the top of the dolomitized zone is very irregular, with chimneys reaching

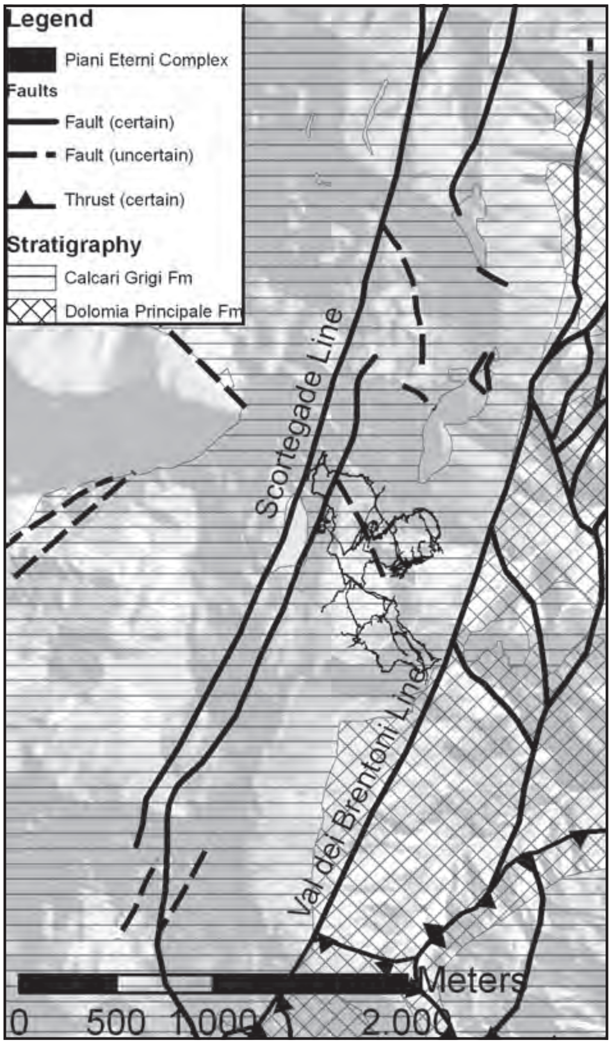

Figure 7: Sketch geological map of the karst area.

also the overlying Loppio Oolitic Limestone. The total thickness of the dolomitized zone is about 430 m. In the cave, the front has been intersected at a depth of -270 m, where the transition to peritidal limestones occurs in about 25 m. The undolomitized part is characterized by supratidal to subtidal cycles of grainstones to packstones, often with stromatolitic caps covered by green clays. This unit presents an abundant microfossil content, but without biostratigraphical relief. Sometimes, some patchy secondary dolomitization occurs. The undolomitized portion of the Mount Zugna Fm is about 250 m thick, passing rapidly to the Loppio Oolitic Limestone. The Loppio Oolitic Limestone represents the uppermost 25 m of the cave, with metric banks of oolitic grainstones, sometimes dolomitized.

From a structural point of view the Piani Eterni area is located in a syncline depression between the Valsugana Line and the Coppolo – Pelf Anticlyne. In the area of Mount Cimia, to the south of Piani Eterni plateau, the syncline shows an asymmetric spoon form that control the development of the –560 m paleo-phreatic level, as it is possible to see in the survey section (Fig. 8). The eastern part of the Piani Eterni presents a swarm of NNE-SSW left strike-slip faults probably reactivating older Mesozoic structures. The main faults of the area are the Scortegade Line (to the West) and the Val dei Brentoni Line (to the East), which are bounding the area where the karst complex develops (Fig. 6). In particular the latter corresponds to the slope of Val Falcina Valley were the paleo-phreatic conduct of Isabella cave is cut, and also controls the higher part of the Poets Gorge, under Cimia Tectonic Plateau. Also in the upper part of the cave, above – 270 m, the speleogenetic evolution seems strongly controlled by the NNE-SSW trending faults and fractures. The so-called "the Fault" in the deep part of the cave represents an antithetic fault related to the dextral movement inside this faults corridor developed between the Scortegade and Val dei Brenoni Lines.

5. Hydrogeological Context and Hypothesis

Piani Eterni karst complex presents active groundwater circulation with a very short response to rainfalls: a flood episode can reach -500 m two hours after the beginning of a summer thunderstorm. There are not quantitative data about the water flowing in the system, and we don't now exactly which is the real drainage area interesting the whole cave system. There are two main springs linked to this area: Bus del Cavron in Val Falcina

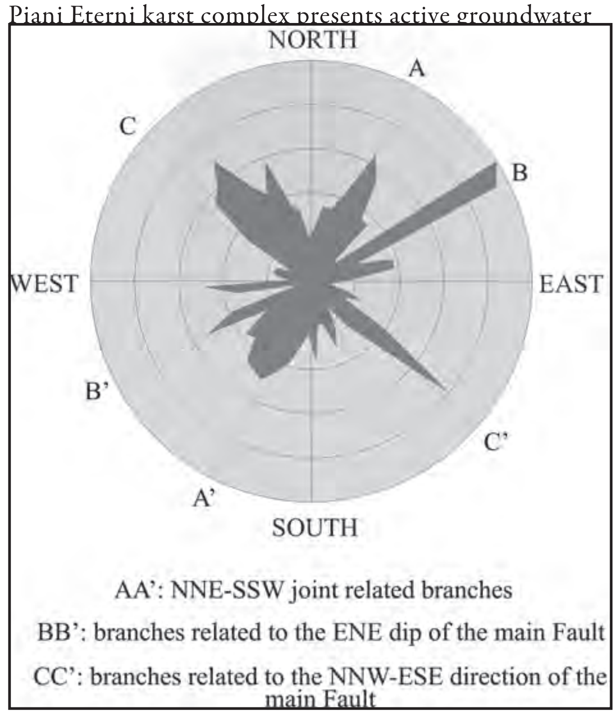

Figure 8: Polar diagram based on the frequency of shot directions in the vectorialized survey of PE10-V35 sector.

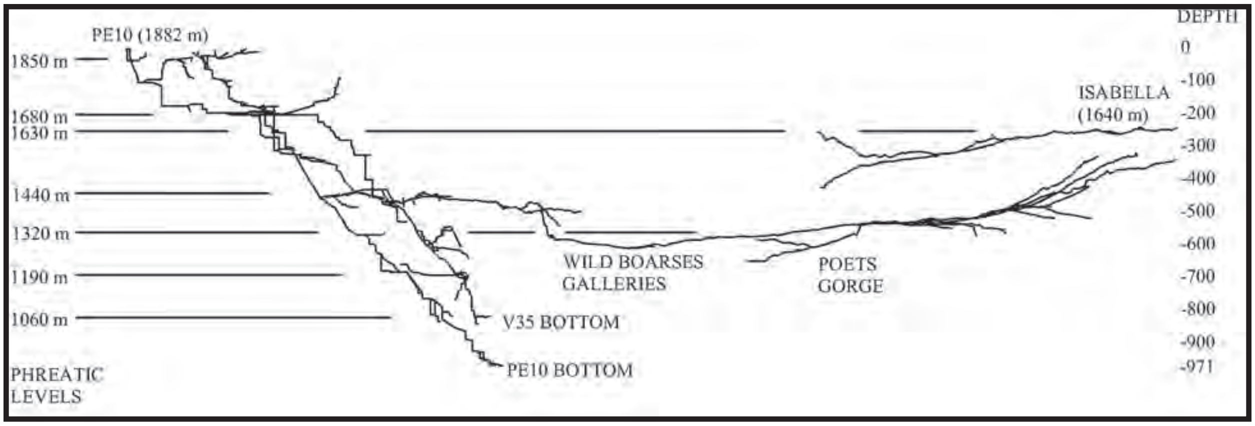

Figure 9: Section of PE10-V35 and Isabella Cave related with the main paleo-phreatic levels.

Valley to the West (745 m a.s.l.), and Fontanon della Stua in Mis Valley to the East (550 m a.s.l.). The former is a valclusian type spring that seems to be related with the Erera tecto-karstic plateau and not directly with the known system. The other one is a spring situated 4,5 km far, by planar distance, from the Piani Eterni Plateau. It presents a minimum flow of 50 l/s, and a maximum of 2 m3/s. The speleo-divers explored it for a total length of 70 m, but the submerged conduct goes on. Fontanon della Stua is situated at the north side of the Scortegade-Val dei Brentoni lines tectonic corridor. As a consequence we suppose that this spring cave is more related with the system than the others. Unfortunately nowadays any tracing experiment has not be performed due to highly restrictive natural protection rules of Dolomiti Bellunesi National Park.

The recent explorations in the system of the paleo-phreatic –560 level allow to suppose that the hydrologic network inside the cave is divided in two main types: bedding plane controlled and joint-faulting controlled. The former is the more ancient, only partially active now, dipping gently to WNW, toward the Erera plateau and Cavron spring. The second one cut the first and is capturing the water in tectonic structures NNE oriented, so toward the Fontanon della Stua spring. This is probably the preferential water flow direction in the system now.

Further investigations to verify this hypothesis will be possible only when low-impact water tracing experiments will be authorized by the National Park for a deeper knowledge on the karstic hydrological system and thus improving the protection of the whole area.

6. Speleogenesis and Paleogeography

The presence of ancient paleo-phreatic levels in the cave seems to be correlated with the tectonic and geomorphologic evolution of the area. The higher levels (at -20 and –200 meters of depth) are probably related with various suspended paleo-water tables controlled by lithological barriers when the vadose network wasn't developed yet. The –450 level (1440 m a.s.l) is the most ancient, in part dismembered by a neotectonic re-activation of the Fault, as it is evident in the short isolated fragment of Zàpeghe Gallery. This level is the most unintelligible, developed on the PE10-V35 fault discontinuity but also along horizontal bedding planes pathways. One other, high level is represented by the big phreatic main gallery of Isabella Cave, between 1640 and 1540 m a.s.l, with a descending trend. These levels are probably both related with the most ancient development step of the system, but we don't have data to formulate hypothesis about the age of their evolution.

However the deeper and more developed level of –560 (1300 m a.s.l.) is certainly related with a period when the Valley of Mis wasn't already deepened by the middle Pleistocene glacial erosion. In origin the Cimia Plateau (at an altitude of 1600 m a.s.l), was probably more extended to the East as a great tecto-karstic plateau representing the hydrologic drainage basin of the system. This model explains the general setting of the phreatic network WNW dipping and the presence in the cave sediments of exotic pebbles, like granitoids, evidently carried by glaciers.

The deepest and most recent levels are both the one of –700 (1250 m a.s.l) in PE10-V35 sector and the small one at the bottom of V35 to a depth of -810 (1070 m. a.s.l.), which are probably correlated with the erosional deepening steps of the Mis Valley.

In future, geochronological datation of speleothems found in the whole paleo-phreatic levels sequence can perhaps give answers to most of the related speleogenetic questions.

7. Conclusions

Only future researches and explorations can better explain history of the largest known karst cave complex in the Dolomite Mountains. The discovery and exploration of this cave has confuted a popular opinion that in these mountains, composed prevalently by dolomite rocks, the formation of great and well developed cave systems is unlikely. Facts demonstrate that this area of the Alps, very wild, with distant plateaux and vertical cliffs, is worth of further speleological investigations, useful to understand the geological and geomorphological evolution of the Dolomites.

Acknowledgements

To all the cavers that have worked in this project, represented by the caving clubs Gruppo Spleoleogico Valdobbiadene, Gruppo Grotte Feltre, Gruppo Speleologico Padovano, Gruppo Grotte "Solve" Belluno. To the Dolomiti Bellunesi National Park that has supported the researches.

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DALOVICA PECINA, MONTENEGRO

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Cavers from the caving club “Pustý Žleb” of the Czech Speleological Society have been organizing expeditions to the Dalovica plateau in Montenegro since 2003. Six expeditions have been focused mainly on exploration of the Dalovica Cave, one of the largest cave system in the Balkans. The Dalovica Cave (also known as Pecina Nad Vrazjim Firovima) was explored in 1980’s by Serbian cavers from Belgrade. Their exploration stopped at the first sump at the end of the cave. They dived through but did not continue further. During our third expedition we successfully passed the second sump and systematically explored the new part of the cave. Several bivouacs were organized and we explored more than 3 km of new corridors. The biggest dome of the cave called the Big Brother Dome (100 x 40 x 20 m) was found as well. Exploration was complicated mainly due to hard logistics connected with transportation of heavy diving equipment through a passage several kilometers long.

Another 500 m long cave in the Dalovica canyon above the emergence of the Bistrica River was explored and named Brno. Two dives were also organized in the emergence called Jurisko Vreljo that reached the distance of 300 m and the depth of 50 m. During the expeditions we were searching for new cave entrances on the Dalovica plateau as well. All the newly explored areas were surveyed and a movie about the expeditions was created. Our expeditions were organized in cooperation with Montenegrin cavers.

1. Beginnings

We made the first trip to Montenegro on invitation of Mr. Izudin Gusmirovic and Mr. Jezdimir Vujcic in 2003. We were asked to take up to the exploration done by Serbian cavers from Belgrade from 1980’s in the Dalovica cave. The Dalovica cave (also known as Pecina Nad Vrazjim Firovima which means Cave over Devil’s Whirlpools) is the longest cave system in the former Yugoslavia (Fig. 1). It is situated on the border between Montenegro and Serbia on the Dalovica plateau at the altitude of 1000 – 1300 m above the sea level and not very far from the town of Bijelo Polje situated at the edge of the Pester Mountains. The plateau and the cave were both named after Dalovic family that has lived here for ages. The cave has been explored since 1987 and when we started with our exploration its length was 13 km (Fig. 2). The Dalovica Cave is very rugged and there exist several floors of different genesis and age.

Figure 1: Entrance of Dalovica cave (photo: Jan Sirotek).

The target of our first expedition was to get beyond the first sump at the end of the cave. Serbian cavers dived through the sump earlier; however, a detailed description of the situation behind the sump was missing. Two divers had to transport 10 bags through the main corridors of the cave 7 km long. In some places it was necessary to use ropes to climb over pitches or to pass over a lake on a traverse (Fig. 3).

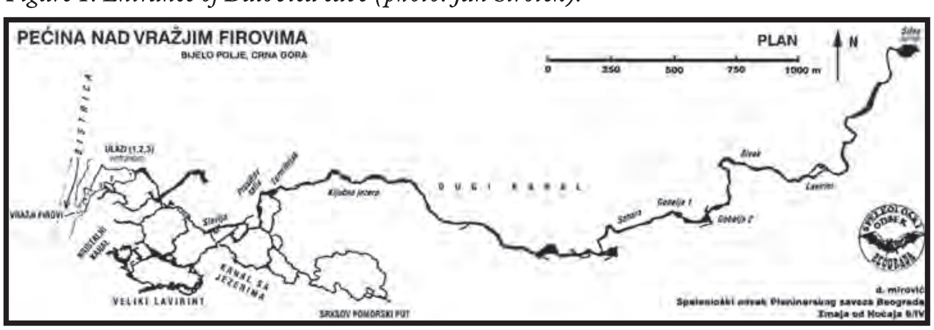

Figure 2: Map of the whole system (map by Planinarski Savez Beograd).

Fortunately, most of the places were equipped with ropes by Serbian explorers.

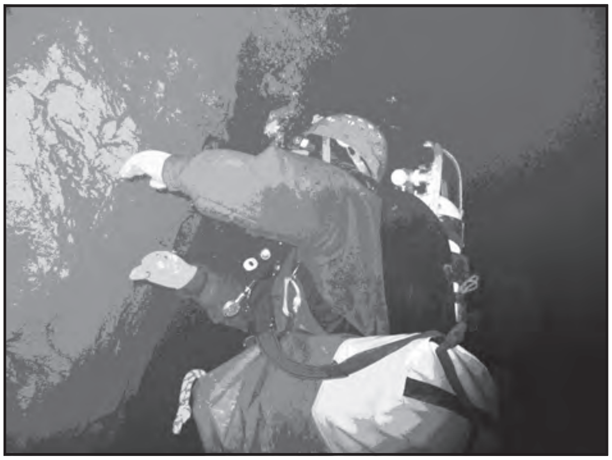

Figure 3: Difficult transport of material through sumps (photo Jan Sirotek).

The first trip to the sump took us more than 10 hours. Several members of the team did not get to this point as they turned back along the way. We admired unique stalactite decorations which lined the whole cave. Especially the 30 m high stalactites in the Cathedral Dome were fascinating. Even if we were very tired after the distressful transport we decided to dive. Without any big problems we passed a 30 m long and 4 m deep sump and continued swimming till the end of a 50 m long lake. We found that the lake was supplied by a small stream. We followed the stream both upstream and downstream. Downstream after crossing another big dome we discovered a second sump. We estimated that the total length of the corridors beyond the sump was one km. As the time was running short, we just made a brief sketch and returned to our friend waiting for us before the first sump. We did not have enough equipment to make another diving attempt and the time of our expedition was limited. Therefore we planned a new expedition in 2004.

We came back to the Dalovica Cave in August 2004. We already knew the conditions in the cave; therefore, we had better equipment for transport of diving equipment. Unfortunately, water level did not allow us to reach the first sump as the lakes in the final corridor were full of water. Tired and frustrated we put the bags back on our shoulders and set for the way back out of the cave. We spent the rest of our expedition exploring the canyon and the plateau. We found and mapped a completely new cave located over the Bistrica emergence that we named the Brno Cave. Total length of the cave is 500 m and it is tied on the underground stream of the Bistrica River.

2. Second Sump Dived in 2005

Our expedition in 2005 was a turning point. We came to the Dalovica plateau again at the end of summer. That year we met one of the Serbian explorers Dejan Vuckovic, who shared with us lot of valuable information. Thanks to a very dry season we got to the first sump without any problems. Equipped with 2 x 7 l tanks we dived through the first sump and crossed the complicated terrain between the first and second sump. Unfortunately while climbing one of the divers ripped his dry suit. As the water was extremely cold (4°C) he decided to stay in front of the second sump and I had to continue on my own. The second sump was 70 m long with the depth of 8 – 10 m. It opened up into a set of lakes. At their end I entered "never ending" gigantic corridors. During the first visit I explored approximately 1.5 km but had to return soon to get back to Martin who was waiting between the sumps freezing.

3. Newly Explored Parts

During our expedition in 2005 we made two more trips behind the second sump where we found and reported almost 2 km of new passages including 2 large domes – 'Porters' Dome' and 'Big Brother Dome'. The latter has the size of 100 x 30 x 30 m and it is definitely the largest one in

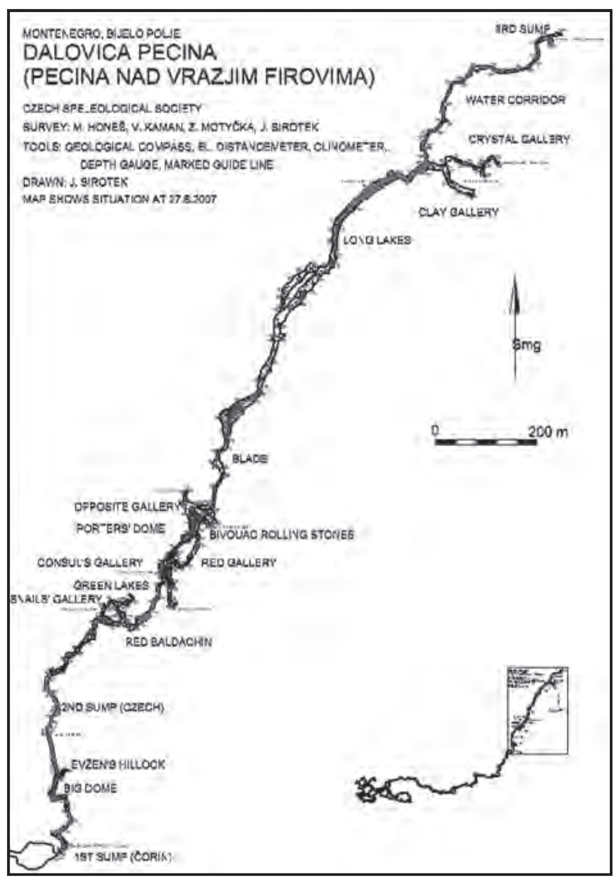

Figure 4: Map of the system beyond the first sump.

Figure 5: Crystal Gallery (photo Zdeněk Motyčka).

the whole cave. We finished our exploration in the middle of a lake 300 m from the Big Brother Dome. It was obvious that without bivouac we did not have many chances to continue with our exploration in this part of the cave.

In 2006 and 2007 we organized other two big expeditions and we stayed a couple of days beyond the second sump. We explored the "Crystal Gallery" at the end of the above mentioned lake behind the Big Brother Dome with unique decorations and large crystals of calcite. In 2007 we found new passages which ended up with another sump where we did not attempt to dive. We explored most of the chimneys and galleries we could safely enter and created a map of the whole (Fig. 4).

Figure 6: Red gallery (photo Zdeněk Motyčka).

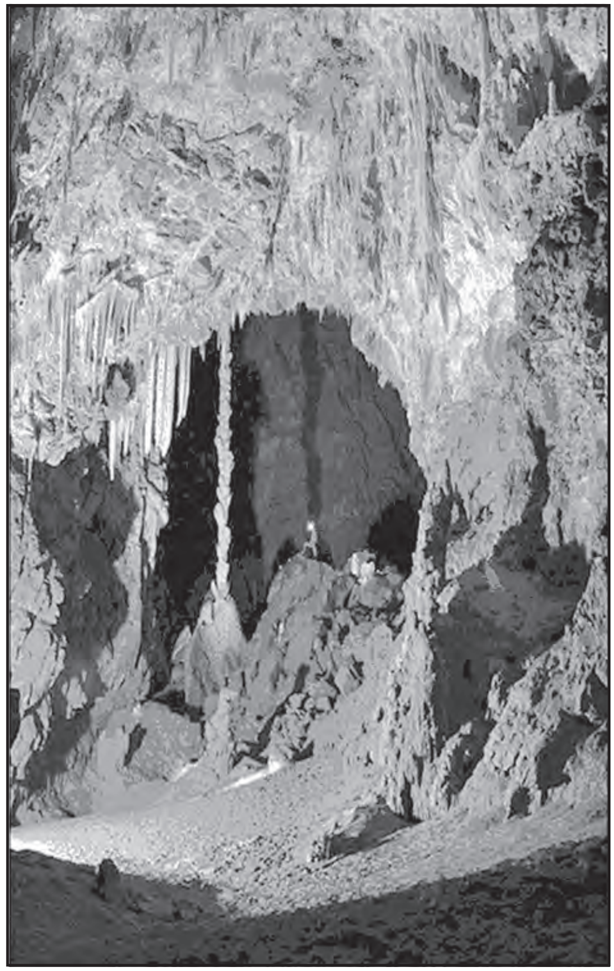

Figure 7: Cathedral (photo Zdeněk Motyčka).

Newly discovered parts have a different character than the parts before the sumps (Figs. 5-7). They are much younger. High corridors bear prints of corrosion. A stream running out from third sump completely follows newly explored passages and in many places creates lakes where it is necessary to swim. Several large domes with many big fallen blocks break the corridors. The cave constantly goes in the NE direction.

4. Other Activities

As mentioned above, in 2004 we discovered the Brno Cave that is tied to the Bistrica River. In 2007 and 2008 we made two diving attempts in the emergence Jurisko Vreljo. We reached the distance of 300 m passing the depth of 50 m. Large underwater corridor continues inside the massive. We did also a lot of surface exploration work and checked several new cave entrances.

There was an entomologist present on two of our expeditions. In 2005 we found a new sub species of beetle *Remyella scaphoides* (Jeannel 1931) at the entrance of the Dalovica Cave.

XILITLA: LOCUS OF MEXICAN CAVING

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The birthplace of Mexican speleology can be considered to be Xilitla, located in the state of San Luis Potosí. The first scientific investigation of the Xilitla caves was led by biologist and Spanish immigrant Dr. Federico Bonet in 1945, and cavers arrived in the area in the summer of 1958. In September 1962 vertical pioneer Bill Cuddington and crew descended the 105 m entrance drop to Sótano de Huitzmolotitla using revolutionary single rope techniques, setting the stage for deep caving all across the country for decades to come. Exploration has continued in Xilitla at a steady pace, and with 292 recorded caves it ranks as the most cave-populated municipality in México.

Despite the density of known caves, new discoveries continue, and since 2004 have revealed some very interesting caves. Sistema Huatecán resulted from the connection of insurgence and resurgence entrances, creating a system 1000 m long and 155 m deep. Sótano de Plan de La Florida captures a large drainage and reaches a depth of 180 m. Other recent finds contain significant archeological remains. Unfortunately the caves of Xilitla are threatened by rampant dumping of trash into pit entrances.

1. Introduction

The first investigation of the caves of Xilitla was led by biologist Dr. Federico Bonet. Bonet emigrated from Spain in 1939, and in 1945 visited Cueva de El Jobo. He and his team mapped a number of caves and collected invertebrate specimens during expeditions in 1950 and 1952, publishing a book on the area in 1953 (Bonet, 1953). Organized caving began in 1960, when Robert W. Mitchell made the first descent of the 105 m entrance drop to Sótano de Huitzmolotitla using a winch and considerable luck. In September 1962 vertical pioneer Bill Cuddington and crew descended this pit using revolutionary single rope techniques, setting the stage for deep caving all across the country for decades to come. Huitzmolotitla was mapped to 1606 m in length and 205 meters depth, making it the deepest known cave in México at the time. Many other deep caves were mapped in Xilitla in the 1960's, largely by Texan cavers, including 454 m deep Sótano de Tlamaya, which became the deepest cave in the hemisphere in January 1966. The deepest known cave in Xilitla was located in December 1977 by Canadian cavers, and after a number of pushes Sótano de Trinidad reached a depth of 834 m. In 1985 a British expedition spent a number of weeks in the area, exploring numerous caves. Little cave exploration took place in Xilitla during the 1990's, but in the following decade three expeditions documented twenty new caves in the municipality.

2. 2004 Explorations

In 2004 a crew of Texas cavers spent a week locating and mapping caves in the area. Nine caves were mapped, and several others located. One of these caves contained significant archeological resources, and three of them were major stream conduits.

2.1 Cueva Tepeatl

This cave is located in a cone karst area east of Peña Blanca. The name means "cave in the hill" in the Nauhua language. The entrance is in the side of a hill, and is 20 m wide and 15 m high. The horizontal tunnel extending north maintains these dimensions for 80 m to a second entrance in a collapse sink 25 m in diameter. A prominent trail runs through the cave between these two entrances, and features carved steps in two segments of it. It may be that this trail is a recent short cut for foot traffic in the area, avoiding the more rugged and thickly vegetated terrain on the surface, but it is also likely to be quite old. The trail skirts a stone platform constructed in the shape of a rectangle measuring 3 by 11 m. It is flush with the cave floor and slightly depressed in the middle. Local residents did not know what its purpose was. A northern continuation of the cave extends past the sinkhole entrance, sloping down 70 m to a terminus.

2.2 Cueva Vidal Ramos

A dominant geographic feature of Xilitla is the Arroyo Seco, which drains from the town to the east. Though fed by a number of surface streams originating along a shale contact above Xilitla, these sink and the Arroyo Seco is generally dry as the name suggests. Much of this canyon is steep and cliff-walled, and it is in one of these cliff faces that Cueva Vidal Ramos is located. Local guides had no name for this cave, so it was decided to name it in honor of a local honey-collector who had died in a fall from scaffolding on the cliff side. However it may be the same as Cueva del Arroyo, explored by Ed Alexander on 31 May 1965. The dry resurgence entrance trends southeast for about 350 m to where an ascending rimstone series becomes too steep to climb. All accessible passage was mapped on the March 2004 trip, making the cave 447 m long with a height of 44 m above the entrance.

2.3 Cueva de la Chuparrosa

The valley of Cruztitla above Cueva Vidal Ramos drains into a complex sink containing multiple entrances to Cueva de la Chuparrosa. These all join up into a descending stream conduit which soon reaches a vertical drop, where exploration stopped in March 2004.

2.4 Sótano de Plan de la Florida

This pit swallows the drainage of the valley to the west of Cruztitla, which contains the village of La Florida. It is comprised of a series of drops of 30, 40, and 8 m to an extensive section of walking passage. The cave becomes vertical again with drops of 25, 8, 8 m to a wet sinuous canyon, followed by a final drop to a sump. This cave contains unusual chert balls that protrude from the walls in places. It is 938 m long and 180 m deep.

2.5 Sistema Huatecán

In June 2005 a group of Texans returned to the Cruztitla area with the goal of connecting Cueva de la Chuparrosa and Cueva Vidal Ramos, and this was readily accomplished. Several short drops were descended in Chuparrosa to a low airspace bathtub with a strong breeze going through it. This opened back up into large walking passage with side leads extending off that remain unchecked. The cavers finally reached the top of the big flowstone drop that connected to the rimstone series in Vidal Ramos, and the resulting Sistema Huatecán was 1001 m long and 152 m deep.

3. 2007 Explorations

With apparently plenty left to do in the area, a team of Texans, Mexicans, and Canadians spent a week caving in Xilitla in November 2007. Nine caves were mapped on this trip, and others located. One pit located in 2004 was explored called Sótano de Cilantro, located considerably higher than the town of Xilitla at 1500 m elevation. A 15 m entrance drop leads to a series of six more small drops with tight pitch leads, ending at a depth of 122 m. The bottom of the entrance pitch is strewn with trash thrown in from the village above, and there are also human remains in this area. The cave is rich in troglobitic fauna, including a pseudoscorpion which may represent a new species.

4. Groundwater Contamination

The Arroyo Seco, which drains the area around Xilitla but whose flow never reaches the local topographic low, was entered from the lower end to search for caves. A temporal resurgence cave was found and named Cueva de Boni after a local caving contact (Green, 2008). It is a horizontal cave containing bats that was mapped for 599 m and continues. It could be a key for assessing the base level groundwater of the area, which is almost a complete mystery thus far. While the perennial resurgence for the area is the prolific Nacimiento de Huichihuayán, few caves have reached base level groundwater, and no tracing work has been conducted or flow paths identified. This is a major concern, since Xilitla dumps its untreated sewage into the Arroyo Seco, and the nacimiento is used as a water supply. In addition, there has been an enormous increase in the use of caves as trash dumps in the area. Nearly every cave visited is being used for garbage disposal by adjacent households. One cave, Sótano de Apetzco, located by a road just above Xilitla, is a severe case. The bottom of the 118 m entrance drop has a large pile of truck tires, and nearby residents report that city garbage trucks were seen offloading into the entrance.

5. Conclusions

Despite intensive exploration in Xilitla over many decades, new and interesting caves are readily located. Although it is a well-known ecotourism destination, Xilitla persists with major subterranean contamination practices and an “out of sight, out of mind” attitude.

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WEBSTER CAVE COMPLEX SURVEY UPDATE

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The Webster Cave Complex Survey Group (WCCSG) is dedicated to the exploration and survey of the Webster Cave Complex, Breckinridge County, Kentucky, USA. Located in the downstream end of Sinking Creek Valley, Webster Cave has three known entrances and is the longest of a dozen or so caves in the area. The main trunk of this cave, thought to be one of the largest continuous trunk passages in the state, is 4.8 km long, and contains a series of lakes, some extending for over a kilometer with neck deep water from wall to wall. The WCCSG began in May 2005 and 46 people have since been involved in the survey of over 13.8 km in Webster Cave as well as about 1.0 km in four smaller caves. Webster Cave is prone to severe flooding. Thus, its survey is a story of frustration as trips are consistently rained out and seasonal sumps close off sections of the cave for years at a time. Over the past two years, the WCCSG project has seen more than 3.2 km of new survey, including 1.6 km of trunk passage on the far side of the seasonal Northbore/Mulu Sump. The cave still contains numerous leads that may yield more unexplored passages for the patient members of the WCCSG who wait in ready for the next dry spell.

1. Introduction

The caves of the Sinking Creek in Breckinridge County are well known by many Kentucky cavers, and they have seen years of exploration, especially by the Louisville Grotto. Most of that attention, however, has been focused on the largest and driest caves such as Thornhill and Big Bat. Currently, a new generation of cave survey and cartography has begun in the Webster Cave Complex – the downstream portion of the Sinking Creek system. While the Webster Cave Complex is made up of a dozen or so caves, Webster Cave is by far the longest, and it is here that those of us belonging to the Webster Cave Complex Survey Group have focused most of our attention. Enormous passages and tranquil subterranean lakes make Webster an amazing place to visit. The main trunk of this cave is 4.8 km long, with heights reaching over 10 meters and a width often exceeding 20 meters. In places, continuous lakes extend for over 500 meters with neck deep water from wall to wall. Furthermore, like many caves along Sinking Creek, Webster can violently flood: two to ten meter flood swells are common during heavy, widespread rains: flooding much of the known passage.

The Webster Complex has experienced sporadic exploration since discovery in the early 1970's. In late 1970, Angelo George was able to see the large karst head containing the Spring Entrance of Webster using aerial photographs of the area. A reconnaissance trip performed by D. Hale and Bob Walker on 28 November, 1970 turned up just what they had been looking for: a big cave. Local residents had known about the cave for many years, and many relate stories of having ventured down to the first lake inside the Main entrance, but there are no accounts of any deeper excursions.

Figure 1: A Lake in Webster Avenue. Photo by Chris Anderson.

In early December 1970, Pat Stephens, Bob Weller, and Angelo George visited the cave for the first time. It became apparent that boats would be needed to successfully explore the cave. Returning with a raft, over 1.5 km of main trunk was traversed. By 1971, the entrance area, about 1.5 km of the main trunk, and some of what would become known as Parks Avenue had been mapped (Fig. 1). In 1972, Bill Holmes and Ron Hubbard took over the project, and began the first comprehensive survey of the cave. Over the next five years, most of the main trunk and several side leads were mapped. By the time work had begun to slow in late 1974, about 11 km had been charted.

Due to the unavailability of the original survey, a second attempt was made by the Kentucky Cave Studies Group, beginning in 1985. By 1994, when the survey disbanded, only six of the Webster Cave System's estimated ten explored miles had been mapped by line plot. The main goal of this project was to locate any possible new entrances. None were found. By far, the most exciting discovery attributed to the KCSG was the North Bore and what lay beyond the North Bore Sump. This sump opens during drought conditions allowing access to the miles of passage beyond and as of yet unexplored wonders. Shortly after its initial discovery however, exploration and survey efforts ended. It would be a decade before any coordinated work began again.

2. Recent Exploration

In May 2005, a new attempt to survey the cave was begun. Chris Anderson, one of the cavers from the KCSG, had taken Ben Tobin and Ben Hutchins into Webster Cave on a photography trip to Mulu Passage and Pleasure Dome area. Chris explained to them that much of the passages on the far side of the Northbore/Mulu Sump had not been surveyed since the KCSG had disbanded. Under the auspices of the Webster Cave Complex Survey Group, a dedicated team of explorers has since been formed to take up the task of surveying the cave to current standards and push this and other previously unexplored areas of the cave. Initial trips focused on survey between the three known entrances of Webster Cave and the 5 km long main trunk, aptly named Webster Avenue. Survey of the Webster Avenue trunk ended at the karst window like feature named Dempster River. Perpendicularly intersecting Webster Avenue, the up and down stream sumps bound the known extent of Dempster River. This glimpse at the active stream passage in the cave has lead to much speculation into the roll of Webster Cave in the Sinking Creek Valley drainage system.

During a drier period in 2005, the main objective of the group switched to the area beyond the Northbore/ Mulu Sump to take advantage of low water levels. An inconspicuous hands and knees crawl behind a large piece of breakdown followed by this seasonal sump, leads to the beginning of Northbore, a 3 meter diameter passage beyond the sump (Fig. 2). This unassuming route provides access to what may ultimately be the majority of Webster Cave. During this initial summer of survey and exploration, Northbore and Eastbore were mapped, as well as the most significant discovery since Northbore itself. Eastbore continues past a major junction at the end of Northbore and fails to live up to its name since it quickly becomes a wet crawl terminating in the permanent Eastbore Sump. However, near its end, a small lead was pushed by Pat Mudd who squeezed through passage now called The Corkscrew into virgin, upper level walking passage creatively named Upper Eastbore. This discovery was significant for several reasons. First of all, Webster Cave is very horizontal, and this signified the first vertical relief in the cave (approximately 10 m). Secondly, this upper level passage led to a dry, paleo-trunk passage: the first found within Webster Cave. This passage, dubbed Holmes Hall, is the most significant upper level development currently known in the cave, and survey in this area is far from complete. The extent of upper-level development in this area is still unknown, but it also suggests that high leads elsewhere in the cave deserve close scrutiny. Unfortunately, the nature of Webster Cave was again made apparent: after the third survey trip Holmes Hall, rain caused the seasonal Northbore/Mulu Sump to close, leaving that area of the cave inaccessible for three years. Bypassing the sump via an in-cave connection or a new entrance became the priority for the WCCSG. Ridge walking yielded potential digs, and leads in the cave continued to be pushed.

Figure 2: The Northbore Passage. Photo by Chris Anderson.

Despite the inaccessibility of what will no doubt be several kilometers of cave beyond the Northbore/Mulu Sump,

Figure 3: A Scoterpes copei *Millipede in Parks Avenue. Photo by Andrea Croskrey.*

there is ongoing survey and exploration in a number of leads on the near side of the sump. Many of these leads have good air movement as well as flowing water. These passages range from narrow canyons to very tight, wet crawls. A number of these leads still hold good potential for either another breakout or a possible fourth entrance. To date, these leads have combined to yield over 3.5 km of cave with numerous promising leads remaining.

The fall of 2008 brought dryer weather to the region and renewed access to leads on the far side of the Northbore/Mulu Sump. The main goal of expeditions during this time was once again redirected from the side leads along Webster Avenue to the area named Mulu. This area was first explored during the 1990s and is the left lead off of the end of Northbore (Eastbore and The Corkscrew up to Holmes Hall being the right lead). Mulu is a large trunk (typically 3m wide and 5m tall) with isolated sections of spectacular speleothems. Four trips in 2 months to the passage surveyed a total of 2 km of trunk passage, with several side leads and the main passage continuing. Unfortunately, November brought large rain events throughout the drainage basin and closed the Northbore/Mulu Sump, leaving its enticing leads for a future date.

Over the last 4 years, 46 cavers have participated in 70 trips and surveyed over 14.8 km in Webster, Melody Hill, Parks Valley, Van Lars and Briar Hole Caves. All of this survey has since been drafted (Fig. 4). At the end of 2008, more than 50 leads remain unsurveyed in Webster Cave and the smaller, associated caves. Along with these leads, initial biological observations indicate that the cave may be home to a rich fauna that warrant future study (Fig. 3).

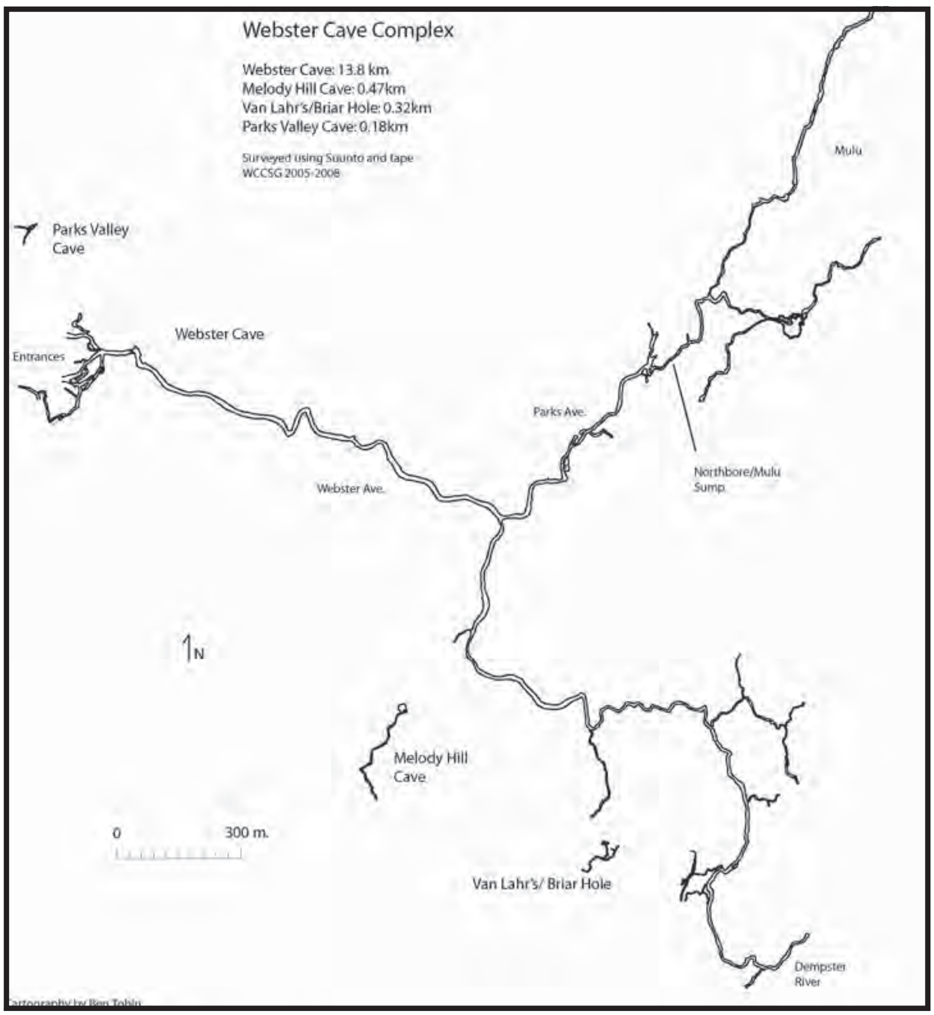

Figure 4: Current overview map of Webster Cave.

PROYECTO AKEMABIS 2008

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In 1990, the Groupe *Spéléo* Alpin Belge (GSAB) found and explored Sótano de Akemabis in the Sierra Negra in the south of Puebla State, Mexico. Even though the cave continued past the -1015 m point that they reached, they were nearing the end of their expedition and went no further. The years passed, and as they were in the habit of exploring different parts of the sierra, the exploration of Akemabis remained on the "to do" list. Following discussions with our Belgian friends, in 2007 we decided to mount an expedition to the area. We only reached -700 m due to lack of time following the distraction of finding a new cave, "El Santo Cavernario," -593 m deep and 1616 m long.

Then in April 2008, and after four weeks in the Sierra Negra, we thoroughly explored Akemabis with a group of 19 cavers, from 15 clubs and six countries. As with the previous year, the organization and the most numerous group was Mexican.

We rigged and re-mapped the entire cave. In the end we found three "bottoms": the first at -1051 m "El Sifón de los Espeleo-políticos Ciegos" (Blind Speleo-politician Sump). The second deepest point reached was: -1092 m, "Las Tripas de Pinto" (Pinto's Guts – clearly a less than pleasant place). The third and deepest point is beyond a narrow section and four pitches down to where the water disappears between boulders at the base of a large ascending shaft: "Salón del Final Feliz" (Happy Ending Chamber) at -1101m.

After adding about 150 m of extra depth we extended the cave to 1101 m deep and 3219 m long. We also found another new cave "El Santito" (Little Saint), which we surveyed to -523 m with no end in sight.

1. Proyecto Akemabis 2008

Olga, Franco and Pablo finally got back to the surface after spending three days underground at the bottom of Akemabis – a thousand metres down in the cave that we had tried to explore the year before, but for various reasons were not able to. Those of us in base camp were happy to see them, worn out, but happy, as they brought the very latest news from the bottom of the cave. "What happened?" "Does it continue?" "Did you find anything interesting?" "Does it go, or does it end?" We did not give them a moment to eat or drink, just continued to bombard them with news from their 'voyage of discovery'.

Once more 15 of the 18 cavers involved in our project were in the Sierra Negra, Puebla State, in the centre of Mexico. This time, for all of April 2008 under the leadership of Franco Attolini, Al Warild and Gustavo Vela, we would be continuing with the objectives left from the year before-like having a good time and bottoming Akemabis. This time we had arrived with more people, better equipment, and more determination.

And so it began, at the end of March, some stayed behind in the nearest city of Tehuacan to buy the food while others went on ahead to arrange the permissions, rent burros and begin to set up base camp in front of don Doreteo's house on the ridge at 1850 m asl.

The history of Olbastl Akemabis began in 1990 when a group of cavers from the GSAB (Groupe Spéléo Alpin Belge), found and explored the cave to -1015 m deep. With time, their explorations led them to other parts of the sierra and the end of Akemabis was left unfinished. The cave's name comes from Olbastl-pit in the local dialect of Nahuatl and the GSAB cavers asking the name of a cave nearby. They were told "Akemati" ("I don't know"). Their new cave was so close that it had to connect, so they added a 'bis' and called it Akemabis. It never did connect.

The GSAB cavers were happy for us to take a look and see how Akemabis ended, so in 2007 we went to see what we could find. After 20 years (that is before GPS!), the correct cave was hard to find, but we did manage to find a different and new cave. At least for our return in 2008 we knew exactly where Akemabis was and what the first part was like.

One of the great things about expedition caving is that it is a mix of team work and individual effort. While one team is resting in base camp, another is rigging in the cave and another is prospecting the hills for more caves to explore. But it does not stop there. Every member of the team needs to be physically and mentally prepared to contribute to the team effort. We tended to rig in pairs and in five days we were at -910 m. In those same five days we had run a survey down to -875 m to the same survey point that the GSAB team had left their topo in 1990. The point was obvious: a few spare spits, a scrap of blue rope and a "pepperami" wrapper (empty!). A little way below we hit the last point that we believe the GSAB group reached. Below this 28 m pitch at -949 m there were no footprints or marks of any kind.

Rigging and mapping was taking longer and longer. It was on one of these trips that Al, David and Vladimir passed the last known point and after an 8 m drop entered a much larger gallery that ran north-south. This up to 10 m by 20 m, 400 m long collector we called "calle Sierra Negra" (Sierra Negra Street) due to its unusually large dimensions in this otherwise narrow cave. They ran from one end to the other always expecting to find another pitch, but only encountered three domes and a small continuation. Having already been in the cave for quite some time they had to leave the exploration and start the long climb out. Vladimir said that he was so tired that he did not know what hurt more: his entire body, or the prospect of having to climb 1000 m of rope.

At the same time as Akemabis was being explored, teams were prospecting the higher areas above base camp on the slopes of Tzontzecuiculi. They found only a few small caves that went nowhere. Others began exploration of a new cave only 38 metres from Santo Cavernario, our unexpected new 593 m deep cave of the year before. At first we were so convinced that this new cave was little more than another entrance to Santo Cavernario that we even called it El Santito. The more rope we took in, the further Santito diverged from Santo. With no more time, we stopped at the top of a 50 m pitch and no Santo Cavernario in sight.

As the previous group down Akemabis did not have time to explore all the leads in calle Sierra Negra, Al and Gustavo went to take a look at the northern part. They dropped a short pitch to a muddy, narrow area with a rumbling water sound in the distance. Another uncomfortable drop led to a narrow slot with gushing white water, but no space for humans. Heading the other way back under a perched lake was even more mud-coated. Slithering on down they reached a shores of a lake that had dozens of white, presumably blind isopods swimming in it. We too took a swim, but found nothing and in honor of the isopds called it "el sifón de los espeleo-políticos ciegos" (Blind speleo-politician sump). We had been down there for hours, we had no bivvie gear. It was time to start climbing.

Trips to the bottom were taking too long and too much energy for the amount of exploration we were getting done. The trouble was we had not come prepared to bivouac, so we scrounged around camp-a spare sleeping bag here, an old foam mat there.

Three days later Pablo, Olga and Franco set up "Campamento Miseria" right at the calle Sierra Negra T-junction at -1004 m. They then set to work pushing the south end of the calle and after a lot of effort, Olga got past a tight spot to more pitches and another gallery. It made no difference following the re-found water or passing over blocks high above, both routes ended at the foot of a dome where the water disappeared between the rocks-"salón del final feliz" (happy ending room). There were still passages to map and leads to push so Fonso, Gustavo and Guillaume tried their luck, but found no way on. They pulled the gear back to the last lead and started on out. On the way up they thought it was a little wetter than they remembered. A bit concerned about being hit by rocks moving down the cave in the higher water, they continued on up. Nearing the top of the 310 m pitch the flush came, and a name for the pitch "el gran pozo de los ratoncitos casi ahogados" (Big pitch of the [almost] drowned little mice). A few anxious hours as we waited for Fonso to arrive without a snorkel, but he was just taking his time…

A few days to let the water levels drop and we had a last push, Marta, Kasia, Zape and Al moved on down to look at that last lead. It was tight, it was dirty, it was wet-"Las tripas de Pinto" (Pinto's guts – Pinto was Doreteo's dog. He would visit our camp each night stealing food and spreading rubbish everywhere. Thanks only to his owner's influence he was still free and wagging his tail). Las tripas de Pinto ended in a dome only a fraction shallower than the previous deep point. They also got the cave derigged to -800 m.

The last week of the expedition and Tzontzecuiculi began to bear fruit. A small 'walk-in' entrance at 2400 m led to a pitch, then another with airflow. Pablo, Olga and Fonso took another long walk to give it a try, but ran out of rope, still unable to see the bottom.

In another direction, trips down Santito got the topo to -527 m and exploration to -580 m, and Akemabis took another couple of hard days to get all the gear out.

Thanks to Auriga, our lightweight trip could still get the results before we went home: sifón de los espeleo-políticos ciegos: -1051 m, las tripas de Pinto: -1092 and salón del final feliz: -1101, and 3219 m long.

And so, after 18 years since it was first explored, a conclusion to Akemabis has finally been reached. The most probable resurgence is Coyolatl, some five kilometers away to the east. All the other new caves we have found lie between these two points, so we will keep exploring these unknowns. This expedition will also go into the books as the first -1000 m exploration done mainly by a Mexican team.

Expedition Leaders: Franco Attolini, Gustavo Vela, Al Warild.

Expedition members: Kasia Biernacka, Alfonso (Fonso) Calvo, Marta Candel, Luis (Wicho) Díaz, Mike (Papa Mike) Frazier, Olga García, Marc Kotte, Roberto (Legas) Legaspi, Pablo Martínez, Enrique (Zape) Ogando, Guillaume Pelletier, Vladimir (Vladimitzin) Ramírez, Homero Resendiz, David Tirado, Bev (Beverlitzin) Shade.

CAVES OF COSTA RICA (CENTRAL AMERICA) AND THEIR GEOLOGIC ORIGIN

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The territory of Costa Rica, as well as the rest of Southern Central America, originated as an Island Arc that resulted from intraoceanic subduction between the Caribbean and the Cocos- Farallón plates since the Cretaceous. In Costa Rica, there are more than 250 explored caves found in different geological conditions and origins (e.g., dissolution or karst, fluvial or marine erosion, tectonic, volcanic, or combinations).

In Costa Rica, approximately 2000 km^2 of karstic regions contain many caves that have been explored since the late 1960s by the *Grupo Espeleológico* and the last decade by *Grupo Espeleológico Anthros*. Other international groups like the National Speleological Society and Swiss Speleological Society have explored the country. The most common and known caves are due to solution (karst) in Cenozoic limestones: Barra Honda (Paleocene), Zona Sur and Damas (Middle Eocene), and Venado (Miocene). The well-developed karsification in Barra Honda was designed as a National Park in 1974 Maximum thickness of the karstified rocks does not exceed 250 m. This mature karst, which caps hilltops with karrenfields on top, represents remnants of a continuous carbonate platform. The caves develop vertically and the deepest cave is the 125-m deep Pozo Santa Ana. The Zona Sur in the southern part of Costa Rica exist is the biggest karstic region in the country. More than 145 reported caves in this region can be divided into sub-regions: Cajón, Rio Claro, Fila Zapote, Abrojo, and Neilly. Abrojo is characterized by vertical development in the caves and contains the deepest cave in the country, the 169-m deep Serpiente Dormida cave. The longest cave system is near Ciudad Neilly, La Bruja – Corredores, with approximately 6 km of horizontal development. The Zona Sur region is affected by faults that imbricated the rocks and repeated the sequence. The karst features sinkholes and dry valleys are well developed in fault zones. In Damas (Central Pacific), the karst is classified as mature, developed in Fila de Cal limestone, and exhibits an intricate system of galleries, halls and quite a few peripheral springs that permanently yield considerable volumes of water. The Venado is an important karstic development with sinkholes and blind valleys, and the Venado (or Gabinarraca) cave has 2741-m of longitude; in this cave paleoclimatologic studies has been realiced. The area is a mature karst with predominant horizontal development. Other karstic areas are developed in Cabo Blanco, Valle Central, Turrialba, Pacuare, Limón, and Baja Talamanca areas. Nevertheless, these areas need more exploration and studies.

Along the Pacific coast, many tectonics caves in basalts (Cretaceous to Paleocene) or sandstones (Cretaceous to Miocene) are modified by marine action. An example is the development of caves in Playa Ventanas (Central Pacific). Other important marine caves were built in the basaltic rocks of Cocos Island (Upper Pliocene) or in the debris avalanche deposits (Middle Pleistocene) of Guacalillo cliff. Volcanic caves formed in the Quaternary volcanoes, particularly in lava fields, but generally there are very small. A peculiar case is the cylindrical caves (tunnels) development by the rotting of rain forest trees of different dimensions that were engulfed by debris flows (lahar) deposits.

1. Geotectonic Context

The territory of Costa Rica, as well as the rest of southern Central America, consists of a Neogene-Quaternary volcanic belt that overlies Mesozoic oceanic basement of Caribbean Plate origin (Dengo, 1968; Mann & Burke, 1984; Escalante, 1990) this region referred as Chorotega block. Costa Rica is located along the convergent plate boundary between the Pacific, Cocos, and Nazca plates and the southwestern margin of the Caribbean Plate. The Cocos and Nazca oceanic belt are being destroyed along the Middle America Trench (Fig. 1-b). This geologic setting provides the different processes (chemical action, tectonics, erosion and

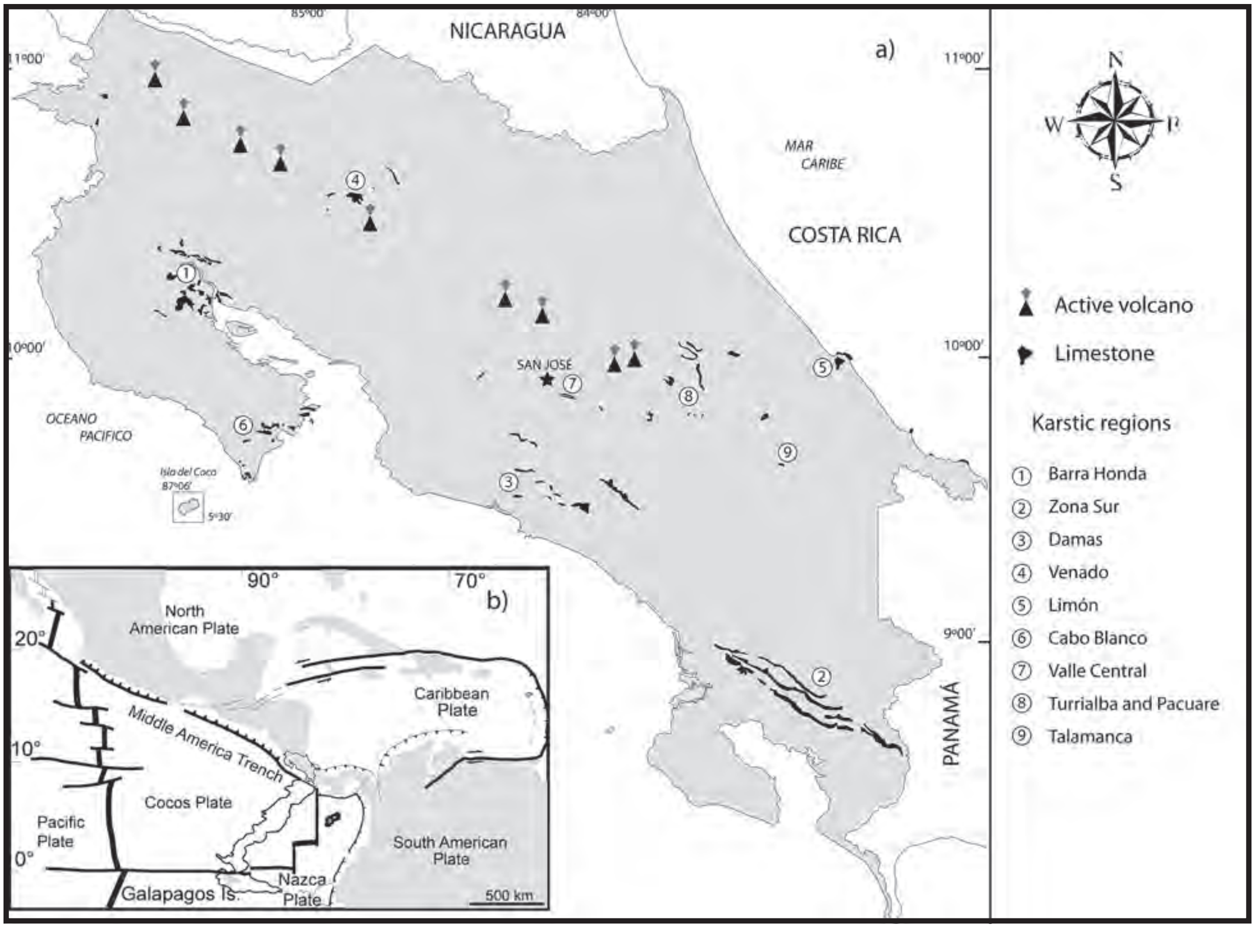

Figure 1: (a) Map of Costa Rica showing the limestone (in black) and active volcanoes, modified from Denyer & Alvarado, (2007). (b) Regional tectonic situation.

volcanism) that made caves possible in the national territory. Figure 1-a shows the principal karstic regions in Costa Rica and the location of active volcanoes.

2. Caves in Karstic Regions

The majority of the karstic regions and solution caves in Costa Rica are developed in Tertiary calcareous rocks, although a minor part formed in Cretaceous limestone (in the northwest part of the country). The caves in karstic regions are the best studied in the country. The speleology in Costa Rica started in the late 1960s with *Grupo espeleológico* (GE) and in the last decade with *Grupo Espeleológico Anthros* (GEA). Other international groups like the National Speleological Society (NSS), the Cave Research Foundation (CRF), and Swiss Speleological Society (SSS) have also explored the country's karst.

2.1 Barra Honda region.

This area is located in the vicinities of the Tempisque River, near its mouth into the Nicoya Gulf. The karstic region is developed in the Barra Honda Formation, a Paleocene micritic limestone (Jaccard *et al.*, 2001) and predominantly restricted to a platform origin (Mora, 1981; Calvo, 1987). The thickness of this formation does not exceed 250 m and the peripheral outcrops around these hills are not thicker than 90 m (Troester *et al.,* 1987).

This karst is considered mature (Mora, 1987) and its principal characteristics are: hilltop caps with karrenfields that represent remnants of a continuous carbonate platform (Mora, 1992); sinkholes; some blind creeks (Mora, 1987); and springs in the base of the hills (Goicoechea, 1989). The development of caves in this area is chiefly vertical, controlled by joints and faults. The karst does not carry superficial water circulation systems. This situation makes it impossible to find the water table level in the caves because there is not enough incoming water to clean the mud and fallen blocks in the passages and halls (Hempel & Werner, 1989).

Many caves have been discovered in this Park, but only thirty of them are significant. The deepest cave is the 125-m deep Sima Santa Ana where some beautiful cave pearls are found. Speleothems like stalactites, stalagmites, and columns are common in these caves. The only tourist cave in the region is Terciopelo Cave, this is an appealing cave, but some speleothems have been broken by tourists.

2.2 Southern Zone:

The "*Zona Sur*" is the largest karst region of the country, and the limestone from Fila de Cal Formation is located roughly from Cajón (Térraba River) to the Panamá border in the extreme southern part of Costa Rica. The Fila de Cal Formation is Middle – Upper Eocene (Malavassi, 1961) limestone and that is characterized by the presence of macroforaminifera. Mora (1979) defined two subunits for the formation: the reef and detritic subunits. Hempel *et al.* (1993) mentions two subunits for the formation: a) The Corredor Limestone (upper), is an approximately 440-m thick, buff-colored calc-rudite composed of large fragments of coralline algae and large foraminifera. It is associated to a reef front facies grading into a reef and lagoonal facies; b) the Fila de Cal Limestone is a grey biosparite with some volcaniclastic inclusions, and represent sediments that were deposited near the reef margins, the thickness is 10-m. Near the upper contact Fila de Cal Formation is characterized by volcaniclastic inclusions and its stratification suggests that the reef dies by volcanic activity in the Upper Eocene. Fila de Cal Formation is the base of Térraba basin and crops out along *Fila Costeña* that exposes three major thrust faults that imbricate the late Tertiary forearc basin sequence (Fisher *et al.,* 2004).

The principal karst features of the region are sinkholes, dry valleys, karrenfields, canyon-rivers, and caves. There are close to 145 reported caves in this region and the majority present a fault controlled systems, for example Cerro Corredores System, Carma, and Emus caves (Hempel *et al.*, 1993). Two main levels separated by an elevation difference of about 25 m, in larger caves, may reflect a rapid uplift during the Quaternary (Hempel *et al.,* 1993; Day, 2007). The principal insurgences are found principally in clastic/limestone contacts or faults (e.g., insurgences in: La Bruja, Quebrada Seca, and Carma caves).

The Zona Sur region can be divided into sub-regions (based on location): Cajón, Rio Claro, Fila Zapote, Abrojo, and Neily. Cajón has an incipient karst where small caves and sinkholes are found. The limestone in this sub-region, e.g., at La Danta Cave, is from distal reef facies, characterized by the presence of planctonic foraminiferal and cherts. The best studied cave in Rio Claro sub-region is Emus Cave. This cave presents a structural control; the entrance is the end of a dry paleostream passage that was abandoned by the cave stream during down- cutting. A gypsum cover has also been reported in a section of this cave (Hempel *et al.*, 1993). Fila Zapote is an important karstic sub-region characterized by vertical development caves (e.g., Pozo Barranquilla, -64 m; Sima Guayabi, -142 m) with potential for deeper caves (Hapka *et al*., 1992). Abrojo sub-region is characterized by vertical development in the caves and contains the deepest cave in the country, the 169-m deep Serpiente Dormida cave. The best studied karstic region is around Ciudad Neily, site of two important cave systems: La Bruja - Corredores and Quebrada Seca. The longest cave system, near Ciudad Neily, is La Bruja-Rectangulo-Corredores, with

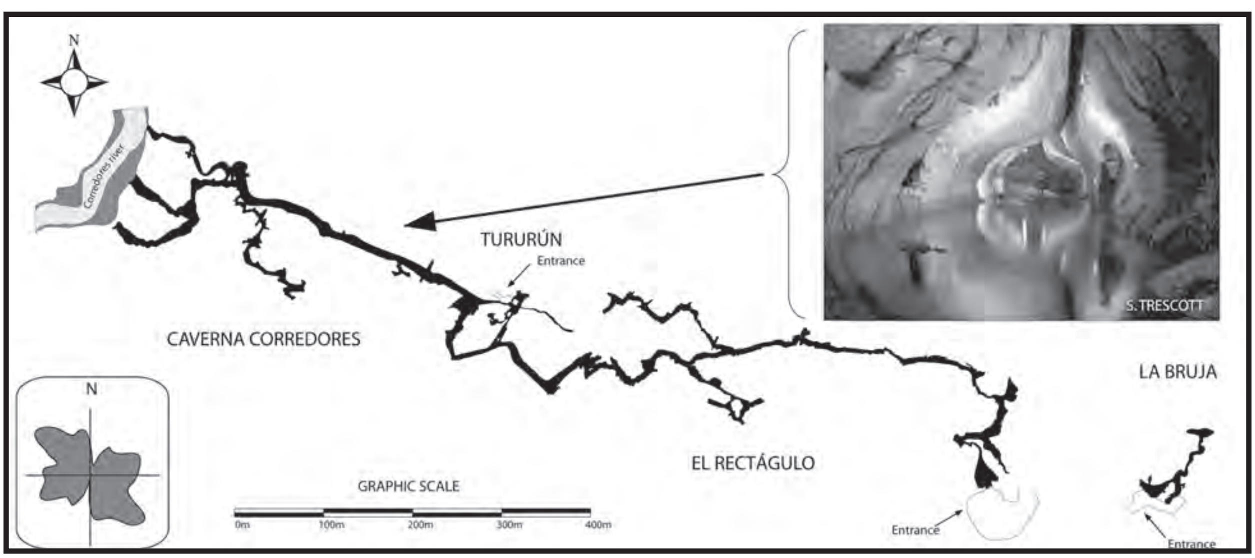

Figure 2: Structural control in Corredores – La Bruja cave system, the principal alignment is northwest - southwest associated whit reverse faults. Modified from Hempel et al., (1993).

approximately 6 km of horizontal development. Hempel *et al.* (1993) said that this is a prime example of fault controlled passage development and the water from the La Bruja Basin is captured by an extension of the Quebrada Seca fault zone and channeled via the cave to the current regional base level, Corredor River (Fig. 2). The longest cave in the country is Bananal in Quebrada Seca section, which has a 3000 m length and 72 m depth.

2.3 Damas:

This karstic region is located in Central Pacific and is developed in Fila de Cal Formation. The karst exhibits an intricate system of galleries, halls, and quite a few peripheral springs that permanently yield considerable volumes of water (Mora & Valdes, 1983). There are three caves reported, but only the Damas cave has been utilized for tourism (Ulloa *et al.*, 2008). This cave has a length of approximately 286 m and has several big chambers with beautiful stalactites and stalagmites (Saenz, 1960).

2.4 Venado:

This karstic region is in the north of Costa Rica, in San Carlos plain. There are bioclastic limestone, *packstone* (Dunham classification) and *biomicrite* and *bioesparite* (Folk classification) with some volcaniclastic minerals (Obando, 1986). The limestone age is Middle Miocene (Malavasi & Madrigal, 1970) and the sedimentary sequence represents a semi-enclosed estuary with an external bioclastic sand bar. The sequence is constituted by approximately 100 m of sediments associated with two depositional systems: lagoon or back barrier and carbonate sand bar (Calvo & Bolz, 1987).

This area is characterized by the presence of sinkholes (some aligned with fractures), insurgences, underground rivers, some karrenfields and caves (27 mapped). The principal development in this region is horizontal, but some small (15 m) pits are found. The deepest cave reaches a depth of 70 m (Goicoechea, 1997). The caves of this area present structural patterns, and the longest cave of the region is 2741 m long Venado Cave (or *Gabinarraca* Cave).

The Venado Cave hydrologically is located in a shallow local groundwater flow system, ensuring a fast transit time of rainfall to the stalagmite sites, because of this reason, the cave was select for Lachniet *et al.* (2004) for paleoclimatologic analysis of stalagmites. He obtained information about Holocene monsoons for a period from 8840 – 4920 yr B.P.

2.5 Limón

Limón presents Pliocene coralline limestone outcrops associated to uplifting of a shoreline (Denyer *et al.*, 1994). The karst in this region is classified as mature (Mora, 1987) and holds a special importance due to the presence of an important karst aquifer, which is vulnerable to contamination. The typical karst features of this area are sinkholes (some are insurgences) and caves (Ramos, 2005). This region is close to the base sea level. For this reason, the caves are not deep and their principal development is horizontal (Goicoechea, Pers. Com., 2008).

2.6 Other karstic regions:

There are more karstic regions with cave development in Costa Rica. In Punta Cuevas-Mal País (near Cabo Blanco), a small cave is developed in Fila de Cal Formation and associated with a fault. The abrasion platform at the beach presents an important karrenfield. In Valle Central, the Miocene Limestone of San Miguel Formation crops out locally with an incipient karst and small caves associated. Turrialba and Pacuare regions hold small caves developed in Paleogene Limestones. Mora (1987) reports the presence of micro karst in this area, but the area needs further exploration.

The Talamanca region is very difficult to access because of the presence of heavy tropical jungle and very rugged topography. Therefore, geologically, it is practically unexplored. In this region, Indian reports indicate the presence of caves and some adventurers report limestone in the region, apparently of Miocene age. This area needs a lot more exploration.

3. Caves in Volcanic Rocks

Few volcanic caves in Costa Rica have been studied and only a preliminary abstract and and isolated reports have been presented..

3.1 Lava tubes

Mora & Alvarado (personal communication, 2008) reports that lava tubes are mostly small caves or grottos and are located in: Cervantes (Irazú volcano), where some *punkas* are observed in lava fields; Los Ángeles (Barva volcano), where a cave of 20 m depth is reported (Goicoechea, 1970); Cariblanco (Poás volcano) and Turrialba (Turrialba volcano). Other lava tube was found during the construction of the hydroelectric project, El General. All these caves are on volcanoes that have been active in the last 20,000 years.

3.2 Mold caves in volcanic rocks

A tree mold cave was found during the building of the hydroelectric project, El General. This cave, 2 m in diameter and 15 m deep, was found in a *debris flow* (Fig. 3). According to Bella & Gaál (2007), this cave could be classified as epigenetic associated with a biogenic mechanism process.

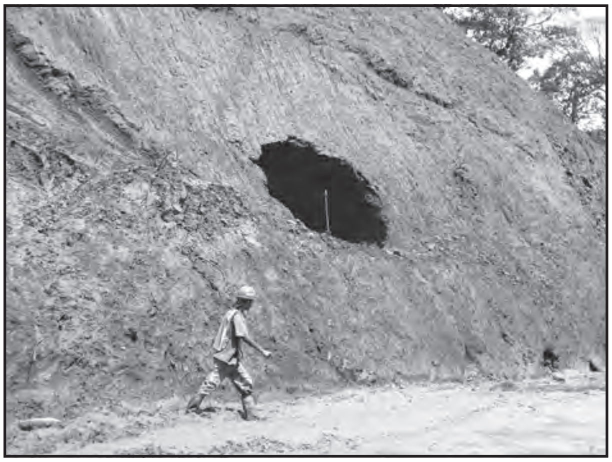

Figure 3: Tree mold cave in debris flow, hydroelectric project El General. Photo: Leonel Rojas.

3.3 Marine caves in volcanic rocks:

These caves are generally close to a cliff or an erosion-abrasion platform, developed in oceanic ophiolites, which are generally dated as Cretaceous-Eocene in the littoral Pacific (e.g., Punta Islita Beach). Isla del Coco is the only sub-aerial exposure of the volcanic Cocos Ridge and 46 caves have been reported there (Benumof & Lockwood, 2000). These caves are associated to fracture enlargement by wave action. There are basalts and trachy-andesitic rocks and some dikes are found, dated around 1.9 and 2.4 Ma (Alvarado *et al*., 1992). In playa Guacalillo cliffs (Pacific Ocean coastline), small caves are in volcaniclastic rocks (*debris flows/avalanche*). The caves developed by the erosive action of waves and, in some cases, are visited by tourists during low tide.

3.4 Other caves in volcanic rocks

Cerro Blanco, a 60 m thick outcrop of blocks and ash flow is located in the northern part of Costa Rica, in the San Carlos plain. At the base, a small cave associated with a fracture has been found in the wall of the ash flow front. Three cave entrances have been observed, but they are still unexplored.

Other caves in volcanic rocks are formed due to fluvial erosion. An example is *Cueva de la Muerte* (Death Cave), in the left margin of Toro river (Venecia, San Carlos). In this cave there are some volcanic gases (CO_2) that inhibits life (Alvarado, personal communication, 2008).

4. Caves in Siliciclastic Rocks

In siliciclastic rocks, only marine caves have been reported. Some marine caves are visited by tourists during low tide or on boats. The most popular marine caves are in Arcos and Ventanas beaches (Central Pacific), both developed in fine sandstone and mudstone intercalations of the Térraba Formation (Oligocene – Lower Miocene). These caves are associated with faults enlargement by marine action. Some caves are up to 20 m deep.

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USE OF SPELEOLOGICAL TECHNIQUES IN ANCIENT MINE EXPLORATION

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Abstract

Many ancient mines were discovered and mapped in Pagaeon Mount in Northern Greece with the use of speleological techniques during 2008. Both horizontal passages and vertical mine shafts were explored by Greek cavers. Many dangers are encountered because of the rock instability and the defective human constructions. Breakdown obstructs the continuation of the exploration in many cases. The mines are dated from their morphology and the archaeological findings. Big networks of passages with several branches, different levels and many entrances are the main characteristics of these human constructions. In many cases, air circulation is disturbed by the fallen blocks and the closed corridors. The use of caving exploration methods such as single rope technique facilitates the exploration and study of the ancient mines.

RECENT EXPLORATION AT JEWEL CAVE

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Abstract

Jewel Cave is located in Jewel Cave National Monument, South Dakota, USA. With the completion of the *Cave and Karst Management Plan* in November 2007, exploration trips are now being led by several trained trip leaders, and exploration is being done throughout the cave. Previously, the focus had been primarily at the periphery of the cave system.

Since August 2007, over 4.8 km of passages have been mapped. Over one-and-a-half kilometers were discovered on short, "close-in" trips, averaging 140 m per trip. Over 2,400 m were mapped on three overnight trips to the southeastern part of the cave. Although there were no breakthrough discoveries, efforts through the middle of 2008 still resulted in a few leads that show great promise.

Because of the climbing expertise among current explorers, more effort has been made to climb ceiling leads. Most of the PC Junction area has been completed, but there remain some leads to check, including one enticing ceiling lead.

Recent rumors not withstanding, Jewel Cave remains the second-longest cave in the world, with over 228.6 km surveyed as of June 1, 2008. The current surveyed length is always available at www.nps.gov/jeca.

LARGE CAVES IN CHINA

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Seventy-eight caves more than 5 km long, 60 caves deeper than 250 m, 22 cave chambers with more than 25,000 m^2 in floor area, and 83 sub-surface river systems with more than 20 km in total length have been discovered so far in China. Most of these caves and subterranean river systems are distributed in South China, in particular in southwest China. Carbonate rocks in southwest China are massive, thick, and continuous in distribution. The climate is the warm and humid.

Geologically, these caves occur in Cambrian to Middle Ordovician carbonate rocks in north China, and in Lower Cambrian to Lower Ordovician, middle Devonian to Lower Permian and Lower to Upper Triassic carbonate rocks in south China.

Geomorphologically, large caves are distributed in the transitional zone from Yunnan-Guizhou Plateau to Sichuan Basin and from Yunnan-Guizhou Plateau to Guangxi Basin in southwest China, and from Shanxi Plateau to Huabei Plain.

Hydrogeologically, most of larges caves have a close relation with subterranean rivers, and they are close to gorge karst rivers. An example is the Yangtze River Gorge, and its big tributaries, Qing River in western Hubei Province and Wu River in South Chongqing, where the longest cave of 117 km and seven of 22 shafts more than 400 m deep (including the deepest shaft of 1020 m) have been explored.

There are only two large caves explored in southeast China and in n northeastern China. Carbonate rocks there are small in extend and scatter in distribution. In the very western part of China, for example in west Sichuan –Yunnan and in east Tibet, there are few large caves, although carbonate rocks there are widespread. This is possibly because not many caving expeditions have worked there due to difficult conditions.

1. Introduction

Carbonate rocks are widespread in China. The exposed area is 910,000 km^2. The total areal extent of carbonate rocks, including those concealed by insoluble rocks, is more than 3,400,000 km^2 (Fig.1), and the total thickness is more than 10,000 m covering different geological times (Li, 1983). Thousands of caves are developed in carbonate rocks, but most of them are distributed to the south of Qinling Mountain-Huai River line, which is the important geographical boundary between semiarid-temperate zone and humid-subtropical zone, in particular in the provinces of Guizhou, Guangxi, Yunnan, Sichuan, Chongqing, west Hunan, west Hubei and north Guangdong in southwest China with a continuous area of 500,000 km^2 (Yuan et al.,1991). For example, there are 657 reported caves in Guizhou, 564 in Guangxi, 201 in Yunnan, 176 in Sichuan, 233 in Chongqing, 121 in Hubei, and 46 in Guangdong. There are some caves developed in northeast China and southeast China by advantageous climate, precipitation, and hydrogeology. For example, 65 caves in northeast China, 30 caves in Hebei and Beijing, nearly 300 caves altogether in Shandong, Jiangsu, Jiangxi, Zhejiang, and Anhui, 26 caves in Fujian are known. But, caves to the northwest of Qinling Mountain-Huai River line are fewer and small. There are 11 caves in Tibet, seven in Xingjiang, three in Gansu, 24 in Shanxi, and five caves in Inner Mongolia. Of them, only four caves are more than 500 m long.

Most large caves (more than 5 km long) have been explored by international cavers since 1985. The first international caving team from the British Cave Research Association (BCRA) was invited by the Institute of Karst Geology, Chinese Academy of Geological Sciences, in 1985, and coordinated by Andy Eavis to make cave expedition in Guilin, Guangxi Zhuang Autonomous Region, and in Guiyang, Guizhou Province. After that, cavers from UK, France, USA, Australia, Italy, Russia, Japan, Spain, and elsewhere made nearly 100 cave expeditions around China, and explored lots of caves. For example, the 117 km long Shuanghe cave is the longest cave have been explored by

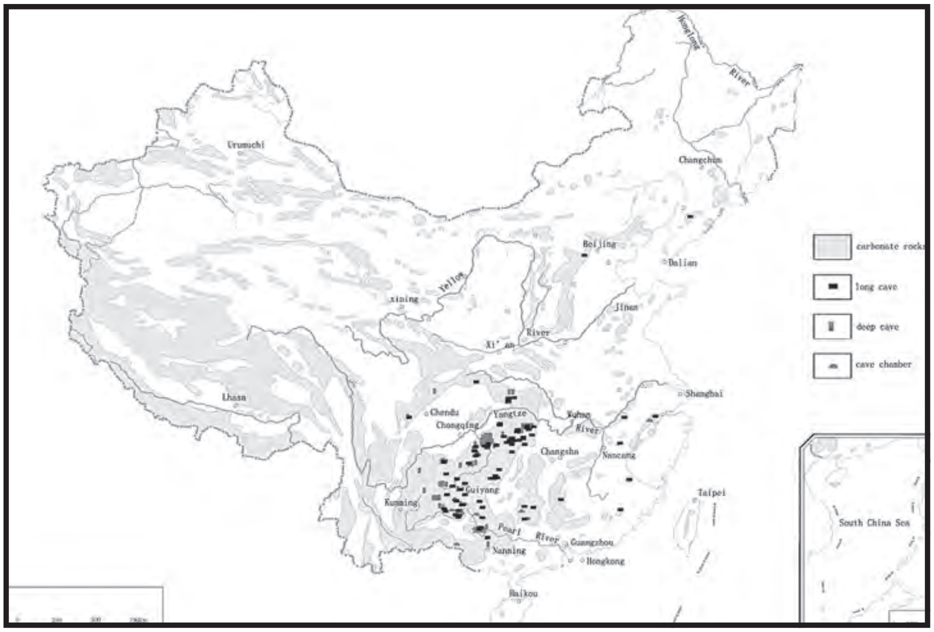

Figure1: Large caves distribution in China.

Plongée Spéléo Club Jeunes Années (Vénissieux, France) for the last 20 years; Tianxing cave with 1020 m of depth, the deepest cave by Hongmeigui Caving Club (Chongqing, China), an international caving team.

2. Large Caves and Cave Chambers

Up to June 2008, 78 caves more than 5 km long, 60 caves deeper than 250m, and 22 cave chambers more than 20,000 m^2 in floor area have been documented. Of them, 23 caves more than 10 km long (Table 1), nine caves more than 500 m deep (Table 2), as well as 14 cave chambers more than 25,000 m^2 in floor area (Table 3) have been surveyed in China. The longest is Shuanhe cave with 117,068 m of passage in Shuiyang County, Guizhou Province (Li, 2008). The deepest is Tianxing cave, 1020 m deep in Wulong County, Chongqing City (Lynch, 2008). The biggest cave chamber is Miao with 116,000 m^2 in floor area in Ziyun County, Guizhou Province (Jin, 1990).

The seventy-eight longest caves are mostly distributed in southwest China (Fig. 1), except for six caves in east China: 5 km-long Shui cave in Liaoning, 5 km-long Shihua cave in Beijing, 5.4 km-long Taiji cave in Anhui, 6.8 km-long Shennong cave in Jiangxi, 7 km-long Yuhua cave, and 7 km-long Longdong cave in Fujian. The sixty deepest caves all developed in southwest China. The twenty-two largest cave chambers are mostly distributed in southwest China, except one in east China, which is Biyun cave chamber in Zhejiang Province.

These large caves are lithologically developed in limestone, dolomitic limestone, and dolomite, except for Longmen cave which formed in conglomerate in Sichuan Province, and geomorphologically in cone karst area at elevations ranging between 100-2000 m. The deeper caves are distributed in altitude of more than 800 m. Interestingly, deep caves are mainly distributed in Wu Jiang (river) drainage area and Hongshui He (river) drainage area including Beipan Jiang and Nanpan Jiang, which are respectively the tributaries of Yangtze River and Pearl River. For example, Shuanghe cave and Tianxing cave are situated in the upstream and resurgence end of Furong River, the tributary of Wu Jiang respectively. Dashiwei cave and Jiangzhou cave are in tributaries of Hongshui He.

3. Large Subterranean Rivers

Subterranean rivers are mostly distributed in south China, which is to the south of Qinling Mountain, to the east of Kunming in Yunnan, and to the west of Guilin-Yichang, with 2836 rivers of 13,919 km in total length and 1482 m^3/s in total flow (Yang, 1985). Guangxi, Guizhou, and Yunnan contain 59.8% of the subterranean rivers as carbonate rocks in southwest China are massive, thick, and continuous in distribution, and the climate in southwest China is warm and humid.

Subterranean rivers are distributed in the transitional zone from Yunnan-Guizhou Plateau to Guangxi Basin, such as Disu, Bailang in Guangxi and Daxiaojin in Guizhou. They feature a long flow path, big drainage area and depth, complex texture, large passages, and very big discharge within widespread carbonate rocks distribution, gentle folds, and dissected landform. Subterranean rivers are also distributed in the watershed between Yangtze River and Pearl River. They feature a shorter flow path, smaller drainage area and hydraulic gradient, alternating subterranean and surface flow along short axis folds and low-relief landform. There are also underground rivers in the Wujiang drainage area, Qingjiang drainage area, and the tower karst area in Guangxi. They feature mostly short flow paths and single texture for zonal distribution of carbonate rocks and insoluble rocks, extending along geologic structural line.

No	Length (m)	Names	Administrative district		Gelogical time & lithology	Elevation m	Temperature & rainfall	
			County	Province			( )	(mm)
1	117 068	Shuanghe	Shuiyang	Guizhou	1 O1 dolomite	670-1200	15.0	1200
2	40 582	Tenglong	Lichuan	Hubei	T,dolomitic limestone	940-1060	12.7	1328
3	37 939	Jiangzhou	Fengshan	Guangxi	P1 C2 C3, limestone	400-600	19.2	1550
4	35 480	Tianxin	Wulong	Chongqing	2 O1, limestone & dolomite	280-1200	16.9	1105
5	34 767	Sanwang	Wulong	Chongqing	O1, limstone	800-1400	16.0	1080
6	28 055	Mawang	Zhen'an	Guizhou	P, limestone	600-1300	16.1	1076
7	26 021	Erwang	Wulong	Chongqing	O1, limestone	800-1400	16.0	1080
8	22 450	Baishui	Jiangkou	Guizhou	,limestone & dolomite	400-1000	16.2	1369
9	21 100	Duobin	Xiuwen	Guizhou	T3, limestone	800-1400	12.0	1694
10	20 000	Longzihe	Zhenyuan	Guizhou	, limy dolomite	400-1000	16.4	1093
11	19 000	Feihu	Longshan	Hunan	T, limestone, dolomitic limestone	500-1300	14.3	1356
12	17 600	Chuanyan	Anlong	Guizhou	T2, dolomitic limestone	410-1400	15.6	1256
13	16 130	Wanfu	Chenkong	Guizhou	1,dolomite-limestone	400-800	15.8	1200
14	15 876	Yunmen	Chenkong	Guizhou	P1,limestone	400-800	15.8	1200
15	13 795	Jiangjun	Chenkong	Guizhou	1, dolomite-limestone	400-800	15.8	1200
16	13 190	Longmen	Lushan	Sichuan	K E, Conglomerate	1000-1500	15.9	1295
17	11 896	Gebihe	Ziyun	Guizhou	T3, limestone	700-1500	15.3	1330
18	11 761	Gaolu	Liuzhi	Guizhou	T3,dolomite,limestone	800-1500	14.5	1470
19	11 026	Jinfo	Nanchuan	Chongqing	P1, limestone	1600-2100	17.8	1434
20	10 932	Dadong	Wufeng	Hubei	O1, limestone	650-1400	14.3	1320
21	10 582	Crwwn	Guilin	Guangxi	D2 D3, limestone	150-380	19.0	1976
22	10 557	Cizhu	Qianxi	Guizhou	T3, limestone	700-1200	13.6	1050
23	10 484	Sanyan	Fengjie	Chongqing	T1, limestone	600-2000	14.0	1200

Table 1: Caves more than 10 km long in China.

No	Depth (m)	Name	Administrative district		Main landform area	Elevation m
			County	Province		
1	1 020	Tianxin	Wulong	Chongqing	Cone & gorge karst between southern Sichuan Basin and Dalou Mt., resurgence of Furong River	1200
2	964	Xiaozhai	Fengjie	Chongqing	Cone & gorge karst between eastern Sichuan Basin and mountains in western Hubei, upstream of Jiupan River	1300
3	837	Dashiwei	Leye	Guangxi	Transition cone karst zone between Yunnan-Guizhou Plateau and Guangxi Basin, in the middle of Bailang ground river	1400
4	775	Dakeng	Wulong	Chongqing	Cone & gorge karst between southern Sichuan Basin and Dalou Mt., resurgence of Furong River	1200
5	560	Baiyu	Panxian	Guizhou	Gorge karst in the middle of Yunnan-Guizhou Plateau, and watershed of Nanpan River and Beipan River	1900
6	555	Shuanghe	Shuiyang	Guizhou	Middle-northern of Yunnan-Guizhou Plateau, upstream of Furong River	1200
7	552	Zhaidong	Hefeng	Hubei	Gorge karst, upstream of Lou River	1400
8	545	Mawang	Zhenan	Guizhou	Middle-northern of Yunnan-Guizhou Plateau, upstream of Furong River	1100
9	508	Yanzi	Dongnan	Guangxi	Transition cone karst zone between Yunnan-Guizhou Plateau and Guangxi Basin, in the middle of Bailang ground river	900

Table 2: Caves more than 400 m deep in China.

No	Area (m^2)	Height (m)	Cave - cave chamber	Administrative district	
				County	Province
1	116 000	70	Gebihe-Miao	Ziyun	Guizhou
2	400*200	40-60	Xiniu-xiniu	Anlong	Guizhou
3	50 700	200	Dacao-Hongmeigui	Leye	Guangxi
4	46 200	50	Zhijin-Weibu	Zijin	Guizhou
5	41 500	40	Chuanlong-Chuanlong	Fengshan	Guangxi
6	38 400	150	Mawang-Nantianmen	Fengshan	Guangxi
7	33 500	20	Wolong-Wolong	Jinxi	Guangxi
8	29 250	50	Yuanyang-Yuanyang	Fengshan	Guangxi
9	27 600	260	Maoqi-Sunlight	Leye	Guangxi
10	26 240	50	Badong-Bala	Tian'E	Guangxi
11	26 220	105	Lvhe-Lvxi	Fengshan	Guangxi
12	26 000	60	Daxiaojin-Heidong	Luodian	Guizhou
13	25 900	100	Gantuan-Dongkou	Fengshan	Guangxi
14	25 500	28	Fengfu-Lotus	Lipu	Guangxi

Table 3: Cave chambers more than 25,000 m2 in floor area in China.

No	Length (km)	Name	Administrative district		Geo-time	Drainage	Average	Elevation	Belonged river system
			County	Province		(km^2)	l/s	m	
1	241.1	Disu	Du'an	Guangxi	D3-P1	1004.0	7434.0	110-350	Hongshui
2	159.0	Bailna	Leye	Guangxi	D3-P1	835.5	3182.0	375-1050	Hongshui
3	142.0	Buqua	Longan	Guangxi	D3-P1	913.0	2346.0	170-550	You
4	110.0	Liulang	Qiubei	Yunnan	D2-T2	2064.0	10500.0	1400-2300	Nanpan
5	102.9	Zuoden	Debao	Guangxi	D2-T1	783.0	3679.7	120-780	You
6	88.0	Luofan	Ceheng	Guizhou	T2	1240.0	8400.0	450-1380	Beipang
7	85.0	Daxiao	Luodian	Guizhou	D3-T2	1560.0	11390.0	1100-1500	Hongshui
8	81.5	Gubu	Tianyang	Guangxi	D3-T2	873.1	5633.4	470-900	You
9	81.5	Poyue	Bama	Guangxi	C2-P2	1484.5	5797.0	350-650	Hongshui
10	79.6	Shuiyu	Linyun	Guangxi	D3-P1	291.2	1620.5	650-1200	You
11	78.7	Baibu	Debao	Guangxi	D2-P1	598.7	2875.7	750-1200	You
12	72.4	Banwen	Dongnan	Guangxi	C1-P1	352.0	1480.0	170-990	Hongshui
13	70.3	Banshe	Dahua	Guangxi	C1-P1	677.3	2930.0	170-375	Hongshui
14	69.0	Longbai	Qinlong	Guizhou	P1-P2	524.0	2820.0	890-1450	Beipang
15	68.5	Eli	TianE	Guangxi	C2-P2	183.1	1330.0	350-900	Hongshui
16	59.0	Shuiya	Qinlong	Guizhou	P2	290.0	1093.3	735-1400	Beipang
17	57.1	Shangbu	Jinxi	Guangxi	D2-T2	290.7	1063.0	770-1250	You
18	56.9	Mofan	Tiandong	Guangxi	D3-C1	210.2	1055.6	230-600	You
19	56.5	Huangh	Dushan	Guizhou	C P1	445.0	1549.0	460-950	Hongshui
20	56.0	Masha	Mashan	Guangxi	C3-C1	342.4	939.0	340-800	Hongshui
21	53.8	Qiaojia	Longan	Guangxi	D2-C2	790.0	1178.0	200-500	You
22	53.2	Toubu	Jinxi	Guangxi	D2-T2	1050.0	1462.0	700-1130	You
23	50.0	Nandon	Kaiyuan	Yunnan	T2	1684.2	4230.0	1070-2000	Nanpan

Table 4: Subterranean rivers more than 50 km long in China.

Twenty-three subterranean river systems with more than 50 km in total length have been discovered (Table 4), which are distributed in the transitional zone from southeast Yunnan-Guizhou Plateau to Guangxi Basin, and in cone karst area with elevations from 110 m to 2000 m, and the upstream reaches of Peal river system, which is in the drainage area of Hongshui River, You River, Nanpan Rive and Beipan River, in particular close to their gorge banks area.

The longest in flow path is the Disu subterranean river in Guangxi Province, which is 241.1 km in total length, a 1004 km^2 drainage area, and 544.9 m^3/s maximum flow, consisting of 12 tributaries (Chen,1988). The biggest drainage area is Liulang Dong subterranean river system in Yunnan Province, which is 2064 km^2 in drainage area and 23.2 m^2/s in average flow (Ji,1990).

4. Large Cave Development

4.1. Carbonate rocks

Carbonate rocks in southwest China are distributed in wide areas of hard, pure and thick bedrock that facilitate cave and speleothem development. Carbonate rocks in central China are widespread but impure limestones. Speleogenesis is inferior here compared to southwest China. Carbonate rocks in northeast China, central-east China, and southeast China are small in extend and scatter in distribution, and there are only six explored large caves. In the very western part of China, for example in west Sichuan –Yunnan and in east Tibet, there are few known large caves, although carbonate rocks there are widespread. This is because carbonate rocks are characterized mainly by crystallized limestone with interbedded clastic rocks, and possibly because not many caving expeditions have worked there due to difficult conditions.

These caves occur in Cambrian to Middle Ordovician carbonate rocks in north China, especially caves developed well in Middle Ordovician rocks. Caves also occur in Lower Cambrian to Lower Ordovician, Middle Devonian to Lower Permian and Lower to Upper Triassic carbonate rocks in south China. Upper Devonian to Lower Permian carbonate rocks are thick and continuous, which is advantageous for large caves development.

4.2. Geomorphology

Caves are mainly developed in transitional zone between Yunnan-Guizhou Plateau to Guangxi Basin, to Sichuan Basin and to Central Hunan Basin, Yangtze Gorges area in south China, and in transitional zone between the Loess Plateau to north China Plain, that is to the south-most of Taihang Mountain and to the north-most of Taihang Mountain in north China, and in the hilly regions in central-south Shandong, Jiangsu, Jiangxi, Zhejiang and Fujian Provinces in east China.

Large caves are distributed in the transitional zone from Yunnan-Guizhou Plateau to Sichuan Basin and from Yunnan-Guizhou Plateau to Guangxi Basin in southwest China, serving big recharge and large hydraulic gradient areas.

4.3. Hydrogeology

Most large caves have close relation with allogenic water recharge in cone karst areas, which is originated from non-karst area and are strongly erosive. Hydrogeologically, they have another close relation with subterranean rivers, and they are close to gorge karst rivers. An example is the Yangtze River Gorge, and its big tributaries, Qing Jiang in western Hubei Province and Wu Jang in South Chongqing, where the longest cave of 117 km and 17 shafts more than 400 m deep (including the deepest shaft of 1020 m) have been explored.

4.4. Neotectonic movement

Neogene tectonic uplifting is very important for large caves development in China, which is characterized by layered cave passages where fossil caves coexist with active water caves. For example, lots of caves developed 10-40 m above the active subterranean river level, and features big passages and rich formations in Guangxi (Yuan, 1991). Three- to five-layer, large cave passages developed 100-200 m above subterranean river level in Yunnan-Guizhou Plateau.

4.5. Climate

The temperature, rainfall and distribution, runoff, and corrosion are influenced by climate. The regions mainly feature monsoon climate, rainfall, and temperature changes in the same seasons (wet in summer and dry in winter), but differ between regions. For example, very small caves developed in northwest China where there is little rainfall and a dry climate. Large caves developed in southwest China due to the humid climate and big rainfall.

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CONTRIBUTED PAPERS ON THE HUMAN SIDE: ART, HISTORY, MEDICINE, PHILOSOPHY, AND THE SOCIAL SCIENCES

THE PRESENCE OF FLOYD COLLINS IN THE MAMMOTH CAVE (KY) AREA TODAY

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It has been over 80 years since the tragedy at Sand Cave Kentucky, now inside Mammoth Cave National Park, that eventually claimed the life of Floyd Collins. Recent happenings seem to have Floyd Collins embedded in the history and culture of the Mammoth Cave area. Probably the area's most "famous son", Collins' presence is still apparent today. Web sites about Collins on the internet, a recent reenactment video about his ordeal targeted for sale and for the cable TV market, a Floyd Collins museum, a possible Hollywood movie directed by Billy-Bob Thornton, and historical signs around Sand Cave erected by the National Park Service are all visible. The Floyd Collins story is often told to tourists throughout the Mammoth Cave region, and historical exhibits are displayed at the American Cave Conservation Museum in Horse Cave, Kentucky. Modern books about Floyd Collins by noted cavers such as Roger Brucker and Wm. Halliday have added many insights to the story. A play about Collins has made the national rounds. The town of nearby Cave City has even sponsored "Floyd Collins Good Ole Days" as a community wide event. Some remnants of the Collins saga are slowly disappearing and need to be documented for future use and study. Many historians say that Mammoth Cave would never have been designated a National Park if not for the publicity about Collins in 1925.

Floyd Collins was trapped and eventually died in Sand Cave Kentucky in February 1925. Inside what is now part of Mammoth Cave National Park, reports of the Collins ordeal of 17 days were spread far and wide. The national newspapers, radio broadcasts, even Congress, gave daily reports on the ongoing rescue attempts. No doubt the publicity helped finally establish Mammoth Cave as a National Park in 1941. Collins was looking for a possible show cave closer to the main route to Mammoth Cave, where tourists were already flocking. Floyd had discovered a beautiful cave on his family's farm in 1917 but it was too far off the beaten path and seldom visited by tourists due to the unimproved rural roads heading to that destination. A 27-pound rock doomed Floyd Collins to death.

Present day accounts have Floyd Collins firmly embedded in the history and culture of the Mammoth Cave region. Probably the area's most "famous son", Floyd Collins' presence is still apparent in the area today. Nearly everyone in the Mammoth Cave region knows who Floyd Collins was, and quite a few have their own Floyd stories or tales. Floyd lived during the "cave war" era; at one time or another, over 30 different caves in the Mammoth Cave region have operated as show caves, fighting for the tourist dollars. Most have been marginally successful, with Mammoth Cave being the initial and main draw. Even in death, Floyd has helped to draw tourists to the area, with the privately owned Floyd Collins Crystal Cave, advertising with a billboard, "TO SEE THE BODY OF FLOYD COLLINS", where Floyd's body rests inside a casket and was exhibited on show cave tours until the 1960's.

Sand Cave today sits on the eastern boundary of Mammoth Cave National Park. The National Park Service maintains a short trail to the site, although this has largely been taken over by nature. The small-gated entrance to Sand Cave is underneath the sandstone rim of a large sinkhole. Several historical signs tell the story of the Floyd Collins saga. Just southeast of the Sand Cave site sits the old Sand Cave ticket office on the old Bee Doyle farm. The old ticket office is on private property, but can be seen from the road. Around the bend is the Wayfarer Bed and Breakfast, with its Floyd Collins Museum run by Becky and Larry Bull, innkeepers. They provide an excellent re-creation of some of the events surrounding the tragedy, as well as old pictures, clippings, even a bust of Floyd. Displays of Floyd Collins can be seen at he American Cave Museum in downtown Horse Cave Kentucky and also in the dental office of Dr. Tim Donley in Bowling Green Kentucky.

There have been 3 books written about Floyd Collins in recent times, all by cavers. Roger Brucker's (and R. Murray's) *Trapped* gives an excellent historical account of the rescue attempt; William "Bill" Halliday penned *Floyd Collins of Sand Cave*, with several previously unpublished photographs, and *The Life and Death of Floyd Collins* was written by Jack Lehrberger as told by Homer Collins, one of Floyd's brothers. In 1999 a video about Floyd Collins was filmed, featuring reenactment scenes of the rescue attempt, as well as actual black and white film footage from 1925. An off-Broadway musical play about Collins has made the rounds in major US cities and Australia. A Hollywood movie about Collins is contemplated for the near future. Producer/actor Billy Bob-Thornton has acquired the rights and has said a film on Collins is in the works.

Floyd Collins 'Good Ole Days' are celebrated each summer in nearby Cave City, complete with crafts, vendors, a parade, a beauty contest, a tractor pull and other attractions. The only known picture of Floyd with a caving helmet (with electric light!) is depicted on a monument at the entrance to the Cave City Convention Center. An authentic Floyd Collins signature exists in Salt Cave, dated 1912, and another inside Crystal Cave, dated 1917, which is the year Floyd discovered the cave. Floyd's signature can also be found in Longs Cave. All are off today's tourist trail routes, and all are in script; Floyd could only write script, not block letters, relates Dr. Stan Sides, a cave historian. Collins only attended school a few years, as did most of the locals in that time period.

Flint Ridge, inside Mammoth Cave National Park, is where the Collins family homestead was located and also Floyd Collins' Crystal Cave. In 2005 the NPS started a preservation project to stabilize the Crystal Cave ticket office and Collins homestead buildings and protect these historic buildings (each over 50 years old). A usually gated gravel lane winds for over a mile to the old Collins farm and these structures. A drive and or hike out to this beautiful but desolate farm reveals how hard it would have been in 1925 to attract tourists to this location. Floyd's father, Lee Collins, is buried in the nearby Daniels Cemetery. Further on is an abandoned junkyard with remnants of caskets 'worn out' caskets while Floyd's body was on display inside Crystal cave. High humidity and condensation in the cave caused relatively frequent replacement of the caskets in which Floyd was displayed.

Fading into memory are items such as the Floyd Collins monument that was formerly in Horse Cave, just off Highway 31W, but after at least 3 vehicles wrecked into it, the monument was not rebuilt after 1965. Also the old capper booths, from which competing show caves would hawk their caves or steer one away from a rival cave are all but gone. Many souvenir items are sought by collectors, such as records, post cards, brochures, pennants, and other memorabilia involving Floyd Collins.

Floyd Collins body was stolen in 1929 from where it was displayed inside Crystal Cave. Never proven, it was believed that rival show cave operators had it stolen because the display of the body gave too much of an advantage to Crystal Cave in the drawing of tourists. The body was eventually recovered and returned to Crystal Cave, where it remained until 1989, when the National Park Service, at the request of the Collins heirs, had Floyd re-buried in the Mammoth Cave Baptist Church Cemetery on Flint Ridge in Mammoth Cave National Park.

Floyd Collins has been buried 5 times. First, inside Sand Cave in February 1925, and second in April 1925, when the Collins family paid to have the body safely removed and re-buried near the Crystal Cave ticket office. In 1927, Dr. Thomas purchased the cave and had Floyd re-interred inside Crystal Cave. Fourth, the body was stolen and re-buried back in Crystal Cave. The fifth and final time was in 1989, when Floyd came to rest where he is today, in the cemetery on Flint Ridge.

Look up the newspaper from any town in the United States (and many around the world) that published in 1925. If you check the dates from late January to around mid February in 1925, I assure you that the headlines and articles will reveal news (not all of it accurate) about Collins and the rescue attempt that lasted for over 2 weeks.

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STATISTICAL ANALYSIS OF AMERICAN CAVE ACCIDENT DATA

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This report is based primarily on the data from American Caving Accidents (ACA) reports which document caving accidents between 1967 and 2006. Of these accidents, there were 1708 cave accidents that had injuries and/or callout of rescue teams. These include 1583 accidents in the USA, 21 in Canada, and 105 in Mexico. Data from these accidents were studied to detect patterns in the dates, locations, and types of cave accidents.

The Mann-Whitney rank test (a nonparametric statistical test) was used to test whether two samples were drawn from similar populations. The Mann-Whitney test accepted the null hypothesis that the distribution of dates for Canadian accidents and the distribution of dates for USA accidents came from the same population. Null hypotheses that the distributions came from the same population were also accepted for: (1) the dates for Mexican accidents and the dates for USA accidents, (2) the days of the week for Canadian accidents and the days of the week for US accidents, and (3) the months for Canadian accidents and the months for US accidents. The null hypotheses were rejected for: (1) the days of the week for Mexican accidents and the days of the week for US accidents and (2) the months for Mexican accidents and the months for US accidents. Dates for Mexican cave accidents differ from similar data for US cave accidents because of collection bias, that is, most Mexican accidents reports are from US expeditions – not from typical trips by Mexican cavers.

The early years of ACA only reported accidents from the USA. The first report of accident outside of USA was from 1971 when 2 Boy Scouts from Texas drowned free-diving a pool in La Gruta del Carrizal in Nuevo Leon, Mexico. The first Canadian cave diving accident reported was in 1973 in Yorkshire Pot, British Columbia. With the exception of a cave diving fatality in Quebec in 1988, all reported Canadian cave accidents have been in Alberta or British Columbia. About 75% of the non-diving cave accidents in Mexico occur in (in descending order) Oaxaca, San Luis Potosi, Chiapas, Puebla, and Tamaulipas. Over 80% of the cave diving accidents in Mexico occurred in Quintana Roo and Yucatan. In the USA, over 70% of the cave diving accidents occur in Florida, followed by Hawaii, California, and Texas. Over 50% of non-diving US cave accidents occurred in West Virginia, Tennessee, Kentucky, Alabama, Indiana, and New Mexico.

For caving accident reports in the USA that mentioned the gender of the victim, 83% of the victims were male, but this rate is dropping. Cave accident victims are roughly 5 times more likely to be males than females. This paper suggests several possible reasons for this difference. The average age for male cave diving fatalities is 30.6 while for females it is 29.5. For non-diving fatalities, the average age is 26.2 for males and 25.5 for females. The first deaths of NSS members in cave accidents were on 16 July 1961 at Show Farm Cave in Indiana when two NSS members drowned when the cave flooded. There have been at least 24 NSS members who have died in cave diving accidents and 15 in non-diving caving accidents.

1. Cave Accident Locations

American Caving Accidents (ACA) reports for the years between 1967 and 2006 documented 1708 cave accidents that had injuries to humans and/or callout of rescue teams. These include 1583 accidents in the USA, 21 in Canada, and 105 in Mexico (Figs. 1-5). For the United States, West Virginia has 13% of non-diving cave accidents, followed by Tennessee, Kentucky, Alabama, and Indiana with 10%, 9%, 8%, and 7% each. No cave accidents were recorded for seven states: Connecticut, Delaware, Louisiana, Michigan, North Dakota, Rhode Island, and South Carolina. At least 72% of the cave diving accidents were in Florida. Eleven percent of the fatal non-diving cave accidents were in Tennessee, followed by Hawaii, West Virginia, Alabama, and Texas with 7% each.

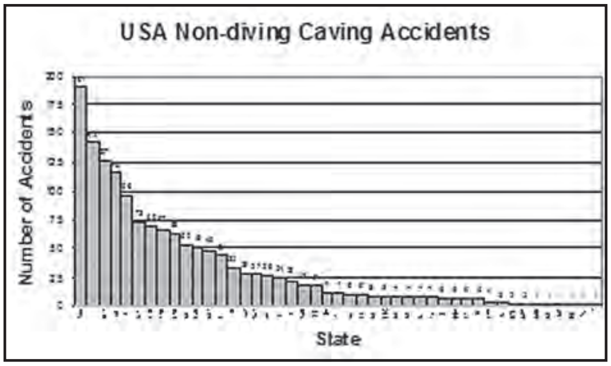

Figure 1

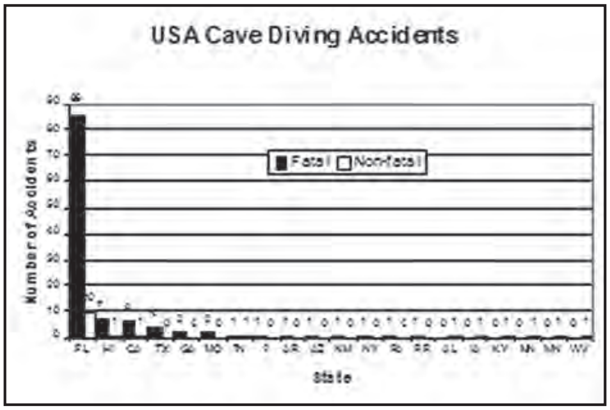

Figure 2

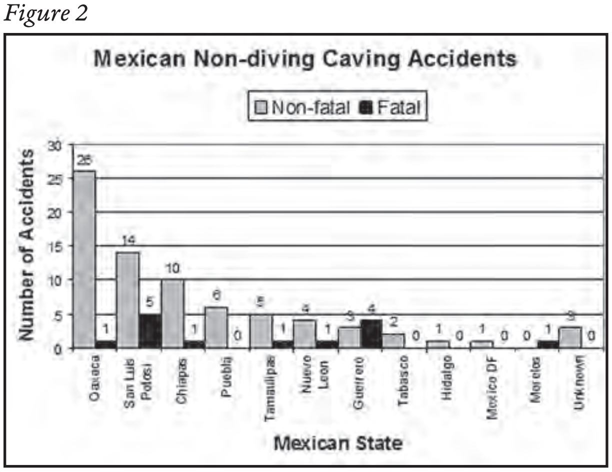

Figure 3

In Mexico, Oaxaca, San Luis Potosi, and Chiapas had 30%, 21%, and 12% of the non-diving cave accidents, while Quintana Roo and Yucatan had 55% and 25% of the cave diving accidents.

All but one of the reported cave accidents in Canada have been in western Canada. Since there are numerous caves in Ontario, New Brunswick, and Nova Scotia, the scarcity of reports from eastern Canada probably indicates a reporting bias, that is, the people who submit cave accident reports are active in western Canada. Two alternative explanations for this discrepancy are (1) the caves in western Canada are more hazardous than those in eastern Canada or (2)

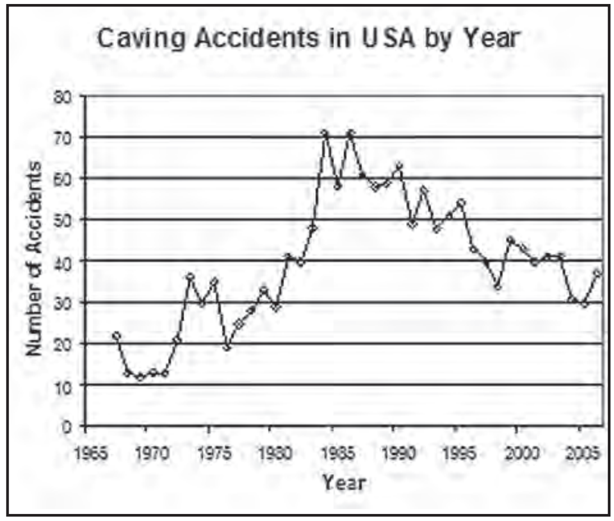

Figure 4

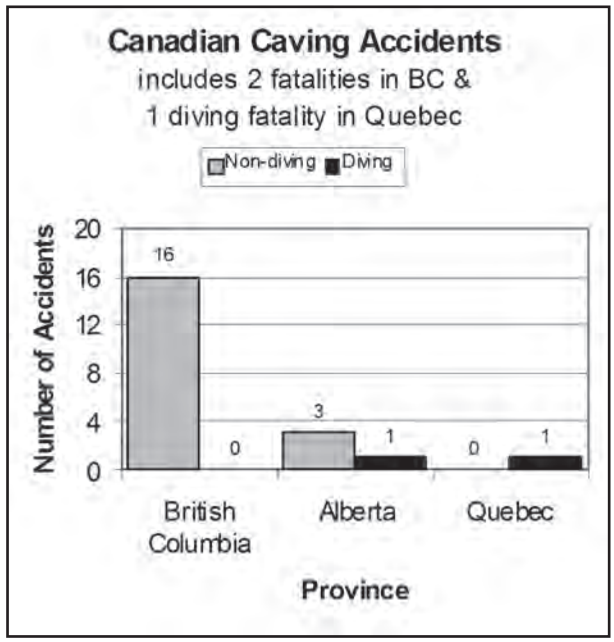

Figure 5

this is more caving in the west. The present analysis cannot determine which, if any, of these reasons is correct.

2. Mann-Whitney Test and Dates of Accidents

Figures 6 and 7 show the number of cave accidents by year for USA, Canada, and Mexico. Although the number of accidents for Canada and Mexico are far fewer than the cave accidents in the United States, one might ask whether the different samples are from the same population; that is, do the shapes of the graphs represent the same distribution? Since we do not know what the shape of the distribution should be, it is necessary to use a statistical test that makes no (or few) assumptions about the distribution. The Mann-Whitney test is such a nonparametric test (also called a distribution-free test). This test is described in many statistics books including W. J. Conover (1971). The Mann-Whitney (M-W hereafter) test uses two sets of independent data, sorts the combined data, and assigns a rank (1, 2, 3, ..., n) to each measurement from the sorted set. The test statistic is based on the sum of the ranks from one of the two samples. The result of the test is a determination whether the samples are from the same distribution (based on the significance level we have chosen). The two-tailed M-W test at a 0.10 level of significance rejects the null hypothesis that the years for Mexican cave accidents and years for US cave accidents have the same distribution. Similarly, null hypothesis that the years for Canadian cave accidents and years for US cave accidents have the same distribution is also rejected.

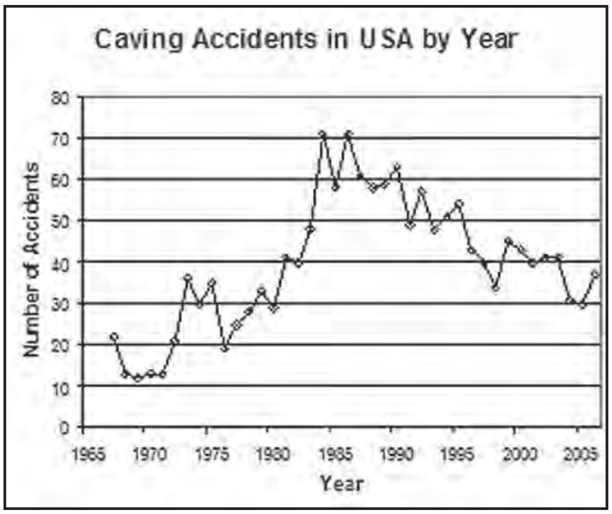

Figure 6

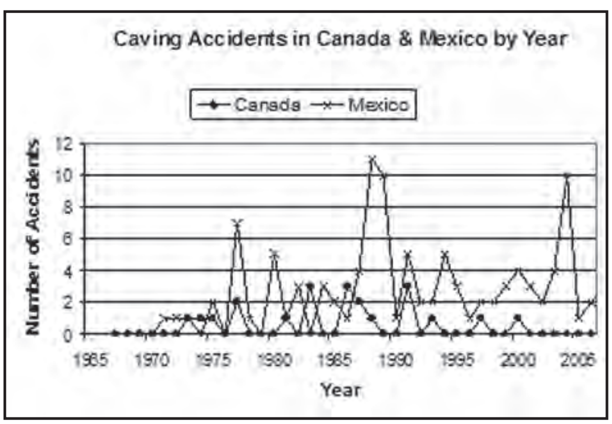

Figure 7

Figure 8 shows the number of cave accidents in the USA by Julian date, i.e., the number of days since the beginning of the year. One might expect that the number of accidents would be higher around holidays since more people might have time around holidays to travel and explore caves. In the USA, the holidays that have the same Julian date in nonleap years are New Years Day (Julian date = 1), Fourth of July (185), and Christmas (359); other holidays vary with the calendar. Neither these three dates nor 5-day running averages around these dates have unusually high number of cave accidents. The graphs for Julian dates of cave accidents in Canada and Mexico are not shown. The M-W test accepts the null hypothesis that the distribution of Julian dates for cave accidents in Canada is the same as the distribution of Julian dates for cave accidents in the USA, but rejects the similar hypothesis when comparing the Julian dates for accidents in Mexico versus the Julian dates for accidents in the USA.

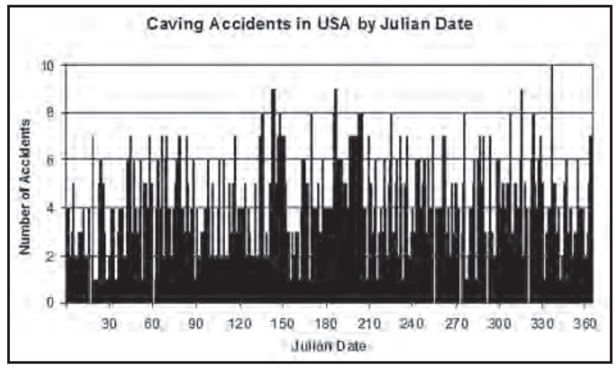

Figure 8

Figure 9 shows how the number of cave accidents varies by month. This is shown as the fraction equal to the number of accidents for each month divided by the total number of accidents during the year. For the USA, this fraction is rather consistent throughout the year but varies from 0.06 in January to 0.11 in July. For the Canada, this fraction varies from 0.0 in January and February to 0.19 in July, and for the Mexico, this fraction varies from 0.01 in June to 0.26 in July. The M-W test accepts the null hypothesis that the distribution of the number of cave accidents by month in Canada is the same as the distribution of the number of cave accidents by month in the USA, but rejects the similar hypothesis when comparing the number of cave accidents by month in Mexico versus the number of cave accidents by month in the USA. That is, the statistical tests by month yield the same conclusions as the statistical tests by Julian date. This is as expected.

Figure 10 shows the fraction of cave accidents by the day of the week. In the USA, 66% of the cave accidents occur on either Saturday or Sunday, while the percentages for Canada and Mexico are 50% and 44%. The M-W test accepts the null hypothesis that the distribution of the number of cave accidents by the day of the week in Canada is the same as the distribution of the number of cave accidents by the day of the week in the USA, but rejects the similar hypothesis

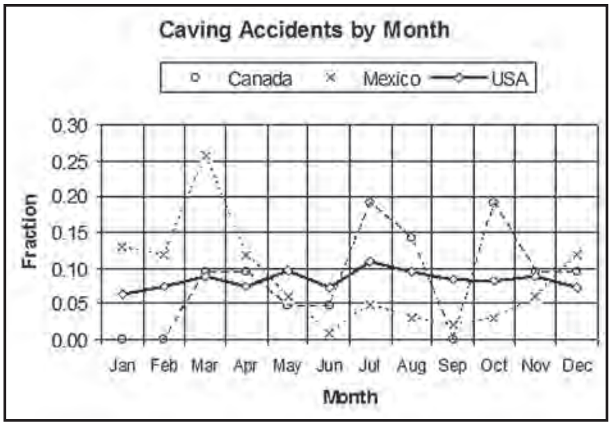

Figure 9

when comparing the number of cave accidents by the day of the week in Mexico versus the number of cave accidents by the day of the week in the USA.

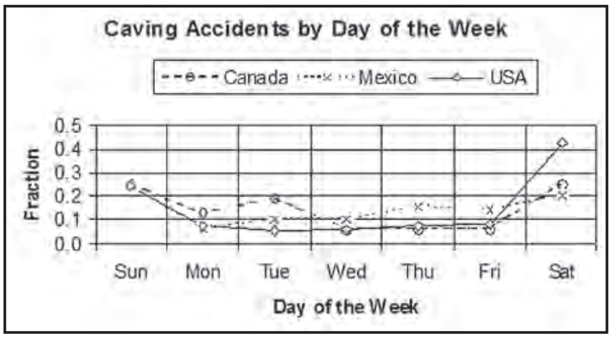

Figure 10

A significant number of cave rescues performed are not to help an injured caver but to search for a person overdue from a caving trip (Fig. 11). Inexperienced cavers often enter caves with inadequate caving equipment, especially lights. They are forced to wait for help once their lights fail. Both experienced and inexperienced cavers are sometimes trapped when a cave floods. Figure 11 shows the number of cave accidents involving lost cavers divided by the number of cave accidents and expressed as a percentage. The values varied from 0% in 1971 to 30% in 1975. The figure also has a linear regression line and the 90% confidence bounds for the data. According to the regression line, the number of lost groups

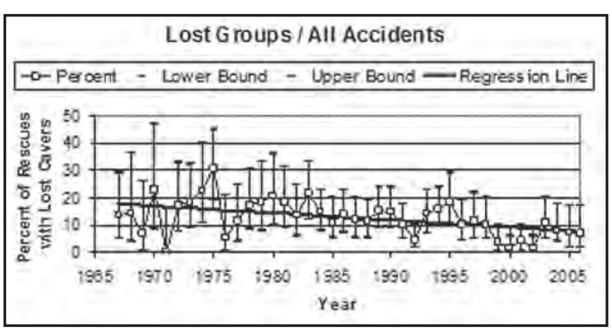

Figure 11

was about 18% of all accidents in 1967 but has fallen to 8% by 2006.

3. Gender of Cave Accident Victims

Most, but not all, accident reports list the number and gender of the victims. Other reports are ambiguous and state something like "members of a church youth group were found lost in the cave". Figure 12 plots the percentage of male victims when the gender of the victim was stated or could be surmised from the victim's name. The percentage of male victims varied from 69% in 1996 to 100% in 1968 and 1971. The figure shows a linear regression line for the data. According to the regression line, the percentage of males was about 92% in 1967 but fell to 76% by 2006. Another way of expressing this is that in 1967, a cave accident victim was 10.8 times more likely to be a male than a female, but by 2006 this number had dropped to 3.2. Possible reasons for the accident victims being overwhelming male include:

- males are more likely to go caving,
- males explore more hazardous caves, and
- males are more foolhardy than females.

The data in this report cannot identify the reason males are more likely victims of caving accidents.

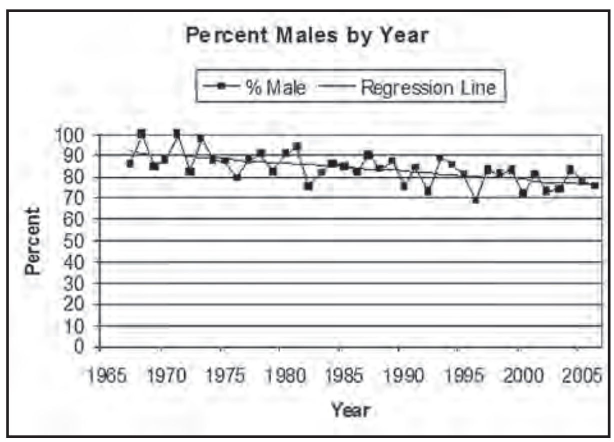

Figure 12.

4. Cave Accident Fatalities

Figures 13 and 14 show the age distributions of caving fatalities for both non-diving and cave diving victims.

Table 1 shows the statistics for the ages of fatal cave accident victims. Nine percent of the non-diving cave fatalities and 20% of the cave diving fatalities were NSS members. Figure 15 shows the NSS numbers of victims of fatal cave accidents plotted against the year of the accident. There were 13 NSS victims of fatal non-diving caving accidents and 24 NSS victims of cave diving accidents. All the victims were men

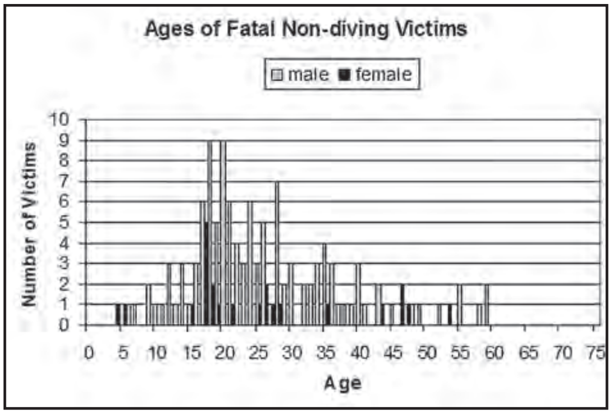

Figure 13

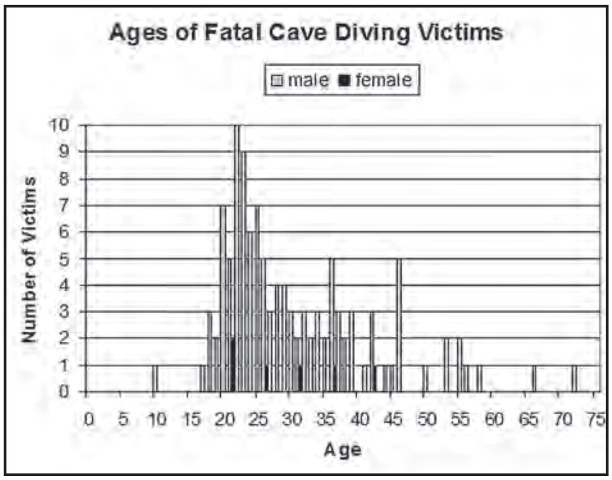

Figure 14

except for two NSS women who died in vertical accidents in 1997 and one NSS woman in a cave diving accident in 1988. There were no NSS member caving fatalities in the first 20 years of the NSS. The first two NSS fatalities occurred when Show Farm Cave in Indiana flooded on 16 July 1961.

5. Conclusions

ACA data published for cave accidents between 1967 and 2006 is most complete for the USA. The data from Mexico are skewed because reports are usually from international expeditions. The Mann-Whitney test confirms that cave accident data from Mexico is significantly different from US data. Although 83% of the cave accident victims in the USA have been male, the trend has been decreasing. The average

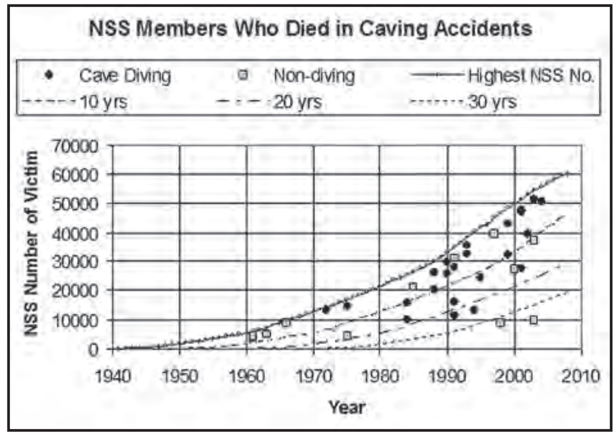

Figure 15

age for non-diving fatalities is 26 and 30 for cave diving fatalities. Nine percent of the non-diving cave fatalities and 20% of the cave diving fatalities were NSS members.

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Age Statistics of Fatal Caving Accident Victims				
	Number of fatalities	**Range of ages**	**Mean age**	**Median age**
Male fatalities (non-diving)	119	6 - 59	26.2	32.5
Female fatalities (non-diving)	23	4 - 53	25.5	28.5
Male fatalities (cave diving)	115	10 - 72	30.6	27.0
Female fatalities (cave diving)	6	21 - 42	29.5	28.5

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THE MYTH OF THE AMERICAN CAVE MAN

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Extended Abstract

The cave man has long been a staple of Western cultural history. In the Middle Ages, for example, there were stories of "wild men" who shunned society, living in rocky retreats (FRIEDMAN, 1981; CHAZAN, 1995). Beginning in the nineteenth century, however, the idea of a cave man took on a new meaning in Europe, referring to human ancestors who supposedly lived in caves in prehistoric times. In America, meanwhile, the legendary Mound Builders made shift as an illusory sort of cave man until the newer idea established itself.

In 1812, the French paleontologist Georges Cuvier famously declared *l'homme fossile n'existe pas* (fossil man does not exist) (CHARLESWORTH, 1957; LYON, 1970). By 1823, human fossils were being found in the caves of Europe, as by William Buckland at Paviland Cave in Wales (NORTH, 1942). It was eventually concluded that there were cave men among several species of hominids, including our own (*Homo sapiens sapiens*), and the American paleontologist OSBORN (1930) went so far as to refer to "the Cave Period of Europe." DUNBAR (1949) presented three species of what he called cave men in his widely-used textbook of historical geology. The underlying idea was that hominids became cave dwellers as a result of climatic deterioration during the last Ice Age (WHITNALL, 1926), a theory that was applied widely in biospeleology (e.g., VANDEL, 1965). Among other primates, the cave-dwelling trait apparently extended to *Australopithecus*, in South Africa (KEMPE, 1988).

Artists, working to the conception of French archeologist Marcellin Boule, provided a widely-influential caricature of what a cave man supposedly looked like (MOSER, 1992). WHITNALL (1926), however, elevated the status of the cave man almost to sainthood, making him responsible for the development of family life and other social virtues, creating a scientific version of the Noble Savage concept.

In recent times, a more skeptical attitude has entered. The naturalist Ivan SANDERSON (1965) argued that "Hominids never as a whole passed through a cave-dwelling stage. For one thing, there are not enough caves to go around, and those that are available are primarily in areas where the surface rocks are limestones. These are comparatively limited in extent, and the very nature of limestone itself constitutes a second-rate botanical environment for the support of animal life. The notion that men did 'pass through' such a stage is probably due to the fact that the best and often the only places where the remains of early man have been preserved are in caves."

Likewise, the geologist Derek AGER (1992) directly attacked what he called "the myth of the cave man," reiterating Sanderson's critique, adding that "I saw no caves in the Olduvai Gorge in Tanzania, where early men lived for so long, and there could be no caves along the shore of Lake Turkana in Kenya, with its famous hominoid fossils."

Nonetheless, the cave man concept still thrives in popular culture worldwide, appearing in cartoons, fiction, and movies (e.g., GAMBLE, 1992; BERMAN, 1999; McCABE, 1999).

In nineteenth century America, before the idea of a cave man in the European sense became widely known, there was a parallel American cave man myth, involving a supposed lost prehistoric race of Mound Builder Indians. According to archeologist R. Clark MALLAM (1976), "The Mound Builder myth occupies a prominent position in American cultural history. Its central thesis, that the earthen mounds of North America were constructed by a superior vanished race unrelated to the Indians touched off a major academic controversy that lasted throughout the nineteenth century." Ultimately, the Mound Builders turned out to be simply ancestors of the aboriginal peoples (SILVERBERG, 1968).

When human mummies were found in the Mammoth Cave region of Kentucky, USA, in the early nineteenth century, they were attributed to this vanished race, as documented by speleohistorian Angelo GEORGE (1994). The Mound Builders filled the vacuum until cave men in a modern, scientific, European sense, were written into the landscape (e.g., as in summary by MacCURDY, 1937).

The state of Minnesota, USA, where the present author resides, provides another example. The most widely publicized Minnesota cave hoax involved Chute's Cave, under what is now the city of Minneapolis, in the years 1866-67. While the cave actually exists, the elaborate hoax story involved elements borrowed directly from Squier and Davis's *Ancient Monuments of the Mississippi Valley*, a classic work on the supposed Mound Builders, published by the Smithsonian Institution in 1848. The authors of this anonymous hoax described the cave as having been both constructed and inhabited by this vanished race (BRICK and PETERSEN, 2004).

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SPELEOPHILATELY: SOME ODD CAVE STAMPS

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Speleophilately may appear as a futile pastime, the fact is if you do not limit the activity to a mere collector's hobby, which may be somewhat obsessive, speleophilately presents many aspects of our underworld neglected by most of our colleagues, cavers or speleologists. The investigations necessary for the study of these diabolical perforated images are the most interesting aspects of the discipline.

Rather than presenting a global panorama of the underground world shown on stamps, I have collected material that gives an idea of the richness of the subject of speleophilately. An example of this material is the *Lettre du Spéléo-club de Paris*, a short monthly newsletter I created in 1981. Each issue is "stamped" with a speleo stamp, and since the first issue, more than 270 postage stamps have been used, all different. A complete speleo stamp collection certainly includes over 1,000 stamps. Some collectors add cancellations, first day covers, maxi cards, souvenir sheets, or other philatelic products. Further areas of interest include postage stamps with oddities or mistakes, and some striking facts I have discovered during my investigations in speleophilately.

Résumé

La spéléophilatélie peut apparaître comme un passe-temps quelque peu futile. Elle offre en fait au spéléophilatéliste qui veut bien aller au-delà de l'activité de collectionneur, parfois obsessionnelle, bien des ouvertures sur le monde souterrain souvent négligées par ses collègues spéléologues. Les recherches que nécessite l'étude de ces diaboliques vignettes dentelées constituent l'intérêt principal de cette discipline.

Mon but n'est pas de présenter un panorama global de l'univers des cavernes sur timbre. Pour donner un aperçu de la richesse du domaine, je citerai l'exemple de *la Lettre du Spéléo-Club de Paris,* modeste bulletin de liaison créé en 1981, qu'un timbre à sujet spéléologique "affranchit" à chaque numéro et dans lequel plus de 270 timbres, tous différents, ont été présentés. Une collection visant l'exhaustivité devrait dépasser les 1000 timbres auxquels s'ajouteraient les flammes ou oblitérations, les enveloppes « premier jour » et autres produits philatéliques. Je me contenterai ici de parler des seuls timbres-poste en limitant mon propos à quelques bizarreries, erreurs, pièges ou faits marquants rencontrés au cours de mes recherches sur cette discipline, la spéléophilatélie, qui a notamment pour caractéristique de nous emmener en voyage dans le monde entier.

1. When Post Offices Make Errors

1.1.Sof Omar Cave, Ethiopia

In 1983, Ethiopia issued a set of five stamps showing Sof Omar Cave. This cave is located at an altitude of 1300 m and is the longest in the country. Visited in 1897 by Arthur Donaldson-Smith, then in 1913 and 1938 by Italians, this huge cave with 42 entrances was originally surveyed by British cavers in 1966 (8,000 meters), then in 1972 by the British Speleological Expedition (15,100 m).The cave got its name from a Moslem sheik, Sof Omar, who took refuge to escape from religious intolerance when Islam had just started. Later the cave became a place of pilgrimage. After the scientific study made by two Soviet speleologists, Vladimir Kisseljov and Alexander Klimchouk (now Ukranian), the cave has been opened to the public. Two Sof Omar stamps are notable. One of them represents the first cave map ever published on a stamp (Fig. 1). The other stamp shows a view of the Chamber of Columns. But there is a misprint: *Camber* instead of *Chamber*, a rather frequent mistake as we will see with the following stamp (Fig. 2).

1.2 The Venus de Brassempouy (Landes, France)

This famous ivory statuette is a tiny prehistoric work of art, 3.6 cm high, carved out of a mammoth's tusk. It was

Figure 1: Sof Omar Cave: The first cave map on a stamp (width 4.5 cm).

Figure 2: Misprint: Camber for Chamber (4.5 cm).

discovered in 1894 by two French archeologists, Edouard Piette and Joseph de la Porterie, at the entrance of a small cave, the Grotte du Pape, in the southern end of the Landes department, in the southwest corner of France. The excavations in the cave were conducted during the 1890's under complicated circumstances. For instance, the site was looted in 1892 by members of the French Association for the Advancement of Sciences! Despite the poor methods of excavation of the time, by modern standards, Piette, a dedicated and honest scientist, did save part of the stratigraphy. The statuette was made during the Gravettian period, a cultural phase (ca.28,000-22,000 B.P.) which succeeded the Aurignacian. It is considered as one of the earliest, if not the earliest, representations of the human face ever discovered.

The term "Venus de Brassempouy" is used for several anthropomorphic statuettes, including one headless statuette discovered in 1892 representing part of a human body. The statuette on the stamps is generally mentioned by specialists as the "Dame à la capuche" (The Hooded Lady). In 1976, the French post office issued a stamp presenting this prehistoric masterpiece (Fig. 3). In 1994 the post office of the Republic of Mali followed suit, but unfortunately the

Figure 3: The Hooded Lady (4.4 cm).

Figure 4: The "rotten" Hooded Lady (4.3 cm).

hooded lady was given the name of "Venus de *Brassempoury*", the additional *r* sounding particularly bad because in French *pourri* means "rotten" (Fig. 4)!

1.3 Bulgarian horseshoe bat

In 1989 Bulgaria issued a fine set of 4 bats, all living in caves, the Noctule bat (*Nyctalus noctula*), the Greater mouse-eared bat (*Myotis myotis*), and the Parti-coloured bat (*Vespertilio murinus*). The fourth one is presented as a *Rhinolophus ferrumequinum*, the Greater horseshoe bat (Fig. 5). The genus *Rhinolophus*, comprising some sixty-nine different species, is characterized by its nose-leaf used for directing their ultrasounds. When you take a close look at the animal on the stamp, you can see great differences, the most obvious being its remarkably long ears. Actually the bat on the stamp is a Long-eared bat of the genus *Plecotus*. We can also clearly see a tragus, the fleshy projection within the opening of the ear, which does not exist in all horseshoe bats. But is it a *P. auritus*, the brown long-eared bat, or a *P. austriacus*, the gray one? It is quite difficult to tell. Only a dissection of the penis could identify the animal!

Figure 5: The Bulgarian Horseshoe bat is a Long-eared bat (4.3 cm).

1.4 The Capri Blue Grotto

The celebrated marine cave, the Grotta Azzurra, was issued in large format (7 cm x 5 cm) on a 1972 Ajman stamp (Fig. 6). As with most stamps of the United Arab Emirates, its philatelic value is quite poor, and very few stamps from Ajman are considered postally valid, especially the stamps issued between 1967 and 1972. For this reason, it is very difficult to find a copy of the stamp. One year later, Argentina issued a stamp showing a painting by an Argentine artist, Emilio Pettoruti, *Homenaje a la Gruta Azul*. The cubist painting was not at all comprehensible to me, until the day I looked at the stamp upside down, and there the cave appeared with its ray of light coming through the ogival entrance (Fig. 7). In 2001, during a trip to South America for the International Congress held in Brasilia, I went to Buenos Aires to try to see the original painting. The lady who owned the painting, which is considered a national treasure, did not allow me to view it, but I was welcomed at the Pettoruti Foundation, also in Buenos Aires. The young ladies there did not know anything about the stamp, but they told me that there are two similar Blue Grotto paintings by Pettoruti, the first one was made in 1918 and the second one, the painting printed upside down on the stamp, in 1958.

Figure 6: The Capri Blue Grotto (7.3 cm).

Figure 7: The stamp is upside down, not the cave (4.3 cm).

suffered from Hitler's crimes during the German occupation in World War II. It is strange that the Yugoslavian Post Office has chosen this special Trechinae whose scientific name is *Anophtalmus hitleri*. The first specimen of *A. hitleri* was found by an amateur speleobiologist, Kodric, in nearby Steska Jama in June 1932. He sent it to Oscar Scheibel in Zagreb. An admirer of the Führer, Scheibel described it as a new species and gave the beetle this name in 1937. It is now impossible to change the name of the animal according to the rules of scientific nomenclature, unless the entire genus, i.e. *Anophtalmus*, is revised, and there is no scientific reason to change it. The genus includes many species that are not threatened, but *A. hitleri* is endangered by over-collecting, because it has been the object of energetic hunting among the fanatics of the German Führer longing for the return of the Nazis and collectors of Third Reich paraphernalia. The price of a specimen of the beetle can fetch over US$1000. In Munich a few specimens of the precious beetle were stolen from a local museum. The poor insect is on the brink of complete extinction. *Anophtalmus* means "eyeless", so could the name of the beetle be an allusion to Hitler's "blindness".

Figure 8: Pekel Cave and its Anophtalmus hitleri *(4.4 cm).*

2.2 Spiennes, Belgium

Some speleophilatelists were fooled by a 1968 Belgian stamp (Fig. 9). The engraved image looks like a natural maze cave with various passages inhabited by prehistoric men as shown by two tool artifacts, including a knapped flint. Actually the stamp shows the bottom of one of the numerous flint mines excavated by archeologists at Spiennes, near Mons, Belgium. These mines are the earliest and biggest known center of Neolithic flint mining in Europe. The site was inscribed on the UNESCO World Heritage List in 2000. The first flint mines were opened at Spiennes 6000 years ago. Several thousand pits were worked for 1800 years, thus giving an idea of the importance of flints in the Neolithic economy. These mines consist of pits, most of them six to ten meters deep and at the bottom, are radiating gallery tunnels following the flint seams. The deepest mine was 16-m deep, where flint slabs of nearly two meter long were extracted, each weighing several hundred kilos.

Figure 9: Not a cave, but a prehistoric flint mine (3.2 cm).

2.3 Pamukkale, Turkey

A 1958 Turkish stamp shows a view of Pamukkale (The Castle of Cotton) (Pamukkale, 2002) (Fig. 10). These formations look like beautiful cave rimstone pools, but this is an outstanding surface feature of quaternary travertines. They result from the deposit of carbonates by a highly mineralized water, rich in CO_2 of geothermal origin. Pamukkale is one of the rare world sites where thermal waters come out at a temperature close to the temperature of the human body. Pools and petrified waterfalls have formed and the place has been recognized for over 2000 years as a cure for many diseases, including cardiovascular illnesses, arteriosclerosis, rheumatisms, skin affections. The presence of these petrifying sources explains the foundation of Hierapolis, the "holy city," a rich archeological site, dating to the second century B.C., located on the plateau above Pamukkale. The city was abandoned in 1334 after an earthquake.

Recently the miraculous water has been less abundant, due to the place becoming a victim of mass tourism. Hotels were built near the plateau and diverted the precious liquid to fill up their own swimming pools. Since 1988, the area has been inscribed on the list of UNESCO World Heritage Sites and a National Park has been created. The hotels were destroyed, the last one in 2000, and access to the natural pools is forbidden. Today the public may go bathing in concrete pools, now covered by calcite.

Figure 10: Rimstone pools, not in cave (4.4 cm).

2.4 The Col des Roches Underground Mills, Switzerland

Unfortunately, this 1996 Swiss stamp does not show that this place is an extraordinary underground site (Fig. 11). In the 17th century, three millers living at Le Locle, a large Swiss village near the French border, close to La Chaux-de-Fond, found an ingenious solution to a serious problem: what source of energy could they use for their mills. The plateau is drained by a slow river, the Bied, and its waters disappeared into a vertical cave. So the three millers installed the wheels of their mills inside the cave. Soon after, an influential man of the region, Jonas Sandoz, put in a real underground power plant consisting in five hydraulic wheels turning millstones that crushed hemp, fruit, wheat, corn, or acorns for animals, and also operated saws and an

Figure 11: The Col des Roches Underground Mills (3.2 cm).

oil-mill. From the end of the 19th century to 1966, the underground mills were abandoned and the cave was used to dump rubbish, especially the scraps from a slaughter-house! Switzerland has not always been one of the world's cleanest countries! Since 1973, the cave has been cleared of all its rubble by an association of passionate volunteers, fond of history and speleology, the Confrérie des Meuniers (The Millers' Brotherhood). Today this extraordinary cave with all its machinery is open for the public and is really worth the visit.

2.5 Cueva del Gato and Cueva de la Pileta, Spain

Benaojan is a small town of the sierra. In 1938, during the Spanish civil war, it issued a few "local stamps", including these cave stamps (Figs. 12, 13). All are real philatelic rarities, unlisted in "official" stamp catalogues. The Cueva del Gato (the Cat Cave) is located 90 km west of Malaga, Spain, not far from the Cueva de la Pileta. This underground part of the Río Gaduares can be followed upstream for 3 km. The cave belongs to the Hundidero-Gato system (-250 m). The Cueva de la Pileta is open to the public and it has many speleothems, white stalactites, draperies, and helictites. This 1500-m cave has only a few Paleolithic paintings, some quite remarkable and famous. They are the most southerly located ones in Europe.

3. Field Checked Stamp

3.1 Cape Sounion caves, Greece

With their small images, stamps present enigmas sometimes. One of the frequent questions to be resolved by speleophilatelists is: Is there a cave on the stamp or not? In *Speleophilately International*, a review edited by Jan Paul Van der Pas since 1981 (former title: *Speleo Stamp Collector)*, David Brison started a column called "Stamps in Need of Field Checks". In his column, Brison (1994) mentioned a 1961 Greek stamp showing Cape Sounion, at the end of the Attic peninsula, some 60 km SSE of Athens. The ruins of the spectacular classic temple of Poseidon overlook the sea there. At the base of the headland, in the rock cliff, a black spot appears on the stamp like a huge gaping cave entrance (Fig. 14). But no report could confirm this point. After reading David's article, I sent him a paper by Mairetet (1981) from which it was inferred that the black spot was not an "illusory cave", but a large sea cave, Mairetet and Eric Gilli, a caver and geologist from Nice, had explored and mapped in 1980. On 27 August 2005, after the 14th International Congress of Speleology, held in Athens, I went to visit and check this Poseidon Cave. You have to pay for the entrance of the Cape Sounion tourist site, but you are free to visit the place, without a guide. So I went down the hill, then climbed

Figure 12: Two stamps of the Spanish Civil War. Cueva del Gato (3 cm).

Figure 13: Cueva de la Pileta (3 cm).

down the steep cliff. At the base of the cliff, I followed the coast on my left, passed in front of a darker high rock recess without any cave entrance, and reached the pile of rocks visible on the stamp. There I discovered a small sea cave, six-meter wide at the entrance and some 15-m long. However, the entrance of the cave is not visible on the stamp, as it is hidden behind round white boulders. This was not the Grotte de Poséidon described by Gilli and I did not find any other cave. The next part of the cliff was out of reach, and does not appear on the stamp. Poseidon Cave is further away and is not on the stamp either. The black spot is only the darker rock niche I saw in the cliff.

So the rule is: speleostamp "field checking" has to be done on the spot! Bibliographic references can be misleading.

Figure 14: Is the black spot a cave entrance? (4 cm).

4. Homage to Jacques and Brigitte Choppy

4.1 Chinoyi Cave, Zimbabwe

Chinoyi Cave, formerly Sinoia Cave, is presented here in homage to Jacques Choppy (1926-2004). It was the last cave he visited, just a few days before his death. Jacques Choppy was a close friend, and one of the great contemporary French speleologists, a caver who tried all his life to understand "why the caves are formed" — this was title of his last posthumous book, his speleological testament, *Pourquoi se creusent les grottes?* We have to include in this tribute his wife Brigitte (1933-2008), a caver too, who was known for her keen sense of observation in caves. She was with him in Chinoyi Cave.

The cave is located at 100 km NW of Harare, capital of Zimbabwe, formerly Rhodesia. The underground lake of this 887-meter long cave, the Sleeping Pool, was dived to 135 m by US Navy divers in 1992, and sounded to 172 m. Two stamps show Chinoyi Cave (Figs. 15, 16). One is from Zimbabwe, issued in 1991 and the other is a *cinderella*, a vignette with no philatelic face value, but quite expensive to buy! It was issued in 1976 by the Rhodesia Association for the Prevention of Tuberculosis (RAPT).

Figure 15: Chinoyi Cave, Zimbabwe. The last cave visited by Jacques Choppy (3.2 cm).

Figure 16: The former Sinoia Cave, Rhodesia (4.5 cm).

5. Conclusion

Speleophilately, as we have seen in this paper, takes us to places where cavers do not usually wander too often: history (the Spanish Civil War, the Third Reich), the world of mining, the fine arts (cubism), and so on. Moreover, a few caves, not presented here, have also been shown on stamps before any caver ever explored them. So, it is the remote aspects that speleophilately brings to our underground activity, the small windows it opens on other fields of human life which gives to this pastime a much wider scope beyond the dimensions of the images it promotes.

Acknowledgement

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AMERICAN UNDERGROUND: "EXPERIENCES OUT OF TIME" AND CHRONOBIOLOGY

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On the occasion of the 15th International Congress of Speleology in the USA in 2009, my paper highlights the American scientific experiments in Midnight Cave in Texas and Mammoth Cave in Kentucky, for their great experiences in "temporal isolation" or "experiences out of time," These studies made important contributions in the medical field: the neurobiology of sleep, chronobiology, human biospeleology, and occupational health. These scientific experiments were conducted by the eminent American physiologist Nathaniel Kleitman (co-discoverer of Rapid Eye Movement [REM] and his assistant Bruce Richardson) at Mammoth Cave in 1938, and by the second underground experiment of the famous French speleologist Michel Siffre at Midnight Cave in1972. Siffre's work was part of a NASA study on transmeridian flights and prolonged space flights, which was a step forward in understanding human biology and better assessing its psycho-physiological abilities from a new approach: the temporal-space paradigm.

The second part of the paper further highlights the place of these American "experiences out of time" as a source of reflection based on religious sources: The Holy Scriptures, concerning the *History of 'Ashab 'al-Kahf* ("People of the Cave") reported by the Holy Koran in the *Surat'al-Kahf* ("The Cave") No. 18, also known as *The History of Seven Sleepers of Ephesus* in the Christian tradition. My paper gives a new scientific reading regarding the nature of sleep of *People of the Cave* (verse No. 18/18) in the light of paradoxical sleep (experimental results of Nathaniel Kleitman) and the duration of their sleep (verse N°25/18) in the light of the experimental results of Michel Siffre.

The conclusion showcases the compatibility between religious sources and scientific data drawn from the American "experiences out of time" underground experiments, and on the lengthening of the biological circadian rhythm of sleep with "jet lag" in underground experiences.

It is hoped the significance of the Mammoth Cave and Midnight Cave studies will become better recognized not only in the fields of archaeology, history, and tourism, but especially in medicine, chronobiology, occupational health, and even religious studies of "life out of time."

LE MONDE SOUTERRAIN AMERICAIN, " EXPERIENCES HORS DU TEMPS "ET CHRONOBIOLOGIE

A l'occasion du 15ème Congrès International de Spéléologie aux USA,ma communication met en relief les expériences scientifiques menées au niveau de la Grotte de Midnight au Texas et la Caverne de Mammouth à Kentucky, pour leurs prodigieuses expériences en «isolation temporale» ou «expérience hors du temps».Ces études ont conduit à une importante contribution dans le domaine médical en neurobiologie du sommeil,en chronobiologie,en biospéléologie humaine et en médecine du travail. Ces expériences scientifiques ont été menées par l'éminent physiologiste américain Nathaniel Kleitman (co-découvreur du Rapid Eye Movment (REM)) et son assistant Bruce Richardson (Caverne de Mammouth, 1938) et la seconde expérience par le célèbre spéléologue français Michel Siffre (Cave de Midnight, 1972). Le travail de Siffre a été considéré dans les travaux de la NASA sur les vols transméridiens et le domaine aérospatial, qui ont conduit à mieux comprendre l'homme biologique et à mieux évaluer ses aptitudes psycho-physiologiques à travers une nouvelle approche: paradigme temporo-spatial.

La seconde partie ma communication met en relief la place des « expériences hors du temps » américaines, comme source de réflexion basée sur des sources religieuses: les Ecritures Saintes, concernant *l'Histoire de 'Ashab al- Kahf* » («Les Gens de la Caverne») rapportée par le Saint-Coran dans la *Sourate 'Al-Kahf* («La Caverne») No. 18, connue aussi sous le nom de *L'Histoire des Sept Dormants d'Ephèse* dans la tradition Chrétienne. Ma communication donne une nouvelle lecture scientifique de la nature du sommeil des « *Gens de la Caverne* » (verset No. 18/18) à la lumière du sommeil paradoxal (résultats des expériences de Nathaniel Kleitman) et la durée de leur sommeil (verset No. 25/18) à la lumière des résultats de l'expérience de Michel Siffre.

La conclusion, présente une compatibilité entre les sources religieuses et les données scientifiques puisées des «expériences hors du temps» Américaines du monde souterrain ,et sur l'allongement du rythme biologique circadien du sommeil avec «un décalage horaire» dans les expériences souterraines.

En espérant à une valorisation des études de la Caverne de Mammouth et la Grotte de Midnight seront beaucoup plus reconnues dans les domaines de l'archéologie, histoire et tourisme, mais particulièrement en médecinel ,en chronobiologie, en médecine du travail, y compris les études religieuses de la «vie hors du temps».

1.0 Introduction:

Today biospeleology, a young discipline in speleology, studies the life of the fauna and flora in the underworld land or water, but also the psycho-physiological variations of humans during their stay in the dark and hostile world, where the humidity is supposed to be increased, outside of time references.

These expeditions in underground caves and chasms were known as the "out life" operations in the underground world, which led the short stay and difficulties, until the expedition of the French speleologist Michel Siffre into the cave of Scarasson (France in 1962) obtained results in variations in biological circadian rhythm of sleep.

Outside time references and in particular the ambient natural factors such as the light and other environmental cues such as noise, has led to the of study the psycho-physiological parameters especially the studies of sleep – biological rhythms (chronobiology).

In "free running", the human in the underground world, does not incorporate the movement of the earth into their biorhythms. Instead they begin to live a longer frequency day, about 25 hours. The chronobiologists consider the relation between the innate biological rhythms and an internal "biological clock" is mainly cerebral (pineal gland) with secretion of melatonin. These experiences in the underground environment have been called "experience out of time" or the "method of temporal-isolation."

The interest of these experiments in the underground world saw other experiments such as "bunkers" (dark and constant area), in which volunteers have spent time while studying biological circadian rhythms of sleep. These experiments were conducted by the German Professor Jurgen Aschoff in the 1960s at the Max-Planck Institute in Munich.

Researchers at NASA have also studied human's psycho-physiological abilities in astronauts and pilots in such environmental conditions as "life out of time," and the media impact was seen to be considerable.

Chronobiology, a revolution in medical understanding of human biology, has a place in occupational medicine in the study of psycho-physiological changes s in night work or shift work. Thus performance in the workplace has been studied by Anudsen (1950), Carpentier and Cazamian (1976), and by Wisner(1976) for his great contribution in ergonomics and these results have found their place in speleology.

With the results, by the human biospeleology during experiments outside of time, chronobiology has continued to attract new researchers in molecular biology in the study of the molecular mechanisms of circadian clock. After the success of "experience out of time", the studies of two Americans, Konopka and Benzer, on fly Drosophila concerning their biological clocks, led to the discovery of the first clock gene called period (per), for which various mutations have been identified. A few years later, the gene (timeless) (tim) was identified as another gene (Clock), where a better understanding of the molecular basis of the clock could raise problems related to shift work or jobs requiring changes in schedules.

The "experience out of time" noted the scientific interest on the sleep of the child in the womb and after birth through the studies of French neurophysiologists, Marie-Joseph Challamel and Thirion (INSERM, Lyon) showing the lengthening of circadian rhythm sleep of the child in "free" 0-4 months after birth (25 hours) with Jet-lag about one hour.

Thus the general principle in human physiology to "explain the living" reported by the famous French physiologist Claude Bernard, the "homeostasis," or the ability of the body to maintain a state of equilibrium between the internal and external environment (1830). This principle has led to the concept of "biological constants" in medicine and received more criticism in the light of chronobiology.

Although chronobiology has demonstrated the fragility of this principle concerning the human body, it seems that the principle of Claude Bernard is still in use in medical area. The Italian Antonio Damasio proposes to use the term "homéodynamique," to clarify that there is not a "homeostasis" but "homeostasis"(in plural), which differ depending on the time, month, or year. The famous French chronobiologist, Professor Alain Reinberg, emphasized that the biological circadian rhythm is one of the fundamental properties of living matter.

Through this new temporal-space approach, another field needs to be emphasized. The underworld and marine professionals who work in these environments such as compressed air habitats without regular contact to the surface needs further research. In light of this scientific approach, that reveals the place of human biospeleology, this method of temporal isolation in medicine and its contribution to chronobiology in this new paradigm "Man-Environment-Time" where the factor "time," the fourth dimension, that has received a prominent place in quantum physics and relativity, will have its rightful place in the definition of "biological man" and even in the study of aging and human longevity.

Finally, my paper highlights the place of "experience out of time" in religion as a tool for thought through a comparative study between the scientific data drawn from the "experience out of time" based on the results of the first scientific studies conducted by the American physiologist Nathaniel Kleitman and the French speleologist Michel Siffre in American underground, and religious sources of Holy Qur'an in Surat Al-Kahf No. 18 also known as the *"History of the Seven Sleepers of Ephesus"* in the Christian tradition.

2. The experiences of Nathaniel Kleitman in Mammoth Cave (USA, 1938):

Nathaniel Kleitman (1895-1999), famous American physiologist and a pioneer in sleep research nicknamed "the father of research on sleep" (University of Chicago, USA). He is the co-discoverer of a new state of sleep, Rapid Eye Movement (REM) with his assistant Eugene Aserinsky in 1953.The REM state was later called "paradoxical sleep" through the work of famous French physiologist Michel Jouvet in 1962. This medical discovery led a new scientific classification of sleep stages in 1968, but also the relationship that may exist between REM sleep and dream.

No doubt, this important discovery by Kleitman on the REM in 1953 must emphasized and not neglected other medical studies, particularly the experiments in Mammoth Cave in Kentucky in 1938. The interest of Kleitman on sleep-wake cycles began very early, by studying various parameters of men and the changes as alertness, body temperature and also the effects of sleep deprivation. The experiment was with his assistant Bruce Richardson during a stay of 32 days in the underground world outside time references indicating cycles of 28 hours rather than 24 hours. This experiment marks a step forward in the "experience out of time" that the annals of human biospeleology and chronobiology have stressed and among American physiologists is a precursor of chronobiology.

3. The Experiments Michel Siffre in the Cave of Midnight (USA, 1972):

Michel Siffre is a famous French speleologist that led scientific expeditions in the underground environment including the cave of Scarasson (France, 1962). By studying physiological and psychological variations, including biological rhythms including the circadian cycle of sleep during his long underground stay (after 2 months "experience out of time", carried out in France and later, with a sponsorship of NASA, at the Midnight Cave in Texas in 1972, the results of his long stay in solitary outside time (205 days)) a considerable scientific interest on the studies of biological rhythms and especially the biological circadian rhythm of sleep which was found to be 25 hours, rather than 24 hours. The presence of a time difference of one hour outside time was seem as a results of environmental factors including the light, known "zeitgebers" in German or "time giving" in English. This natural biological rhythm reflects the presence of a "biological clock" which regulates the human biological body of human being. This "autonomy" of the biological rhythm marked a giant impact in the field of genetics for a better exploration of the mechanisms of the circadian clock (molecular biology.)

4. The "experience out of time" in "History of the People of the Cave":

From the "experience out of time", my paper highlights its pace in the a new scientific reading of text of the Holy Qur'an to discuss some mysteries of the *"History of 'Ashab al-Kahf"* (People of the Cave) reported by the Holy –Qur'an, in *Surat "Al-Kahf* (The Cave) No. 18 concerning *The History of 'Ashab al-Kahf"* is described in full. These are young people, believers in one God and who have been persecuted by pagan people. They took refuge in a cave, accompanied by their dog. Their deep sleep, in 309 years seems to have lasted one day at most after their awakening.

The majority of ancient Muslim scholars, and contemporary European authors used some data of the Eastern Christian tradition drawn from the legend of the *"Seven Sleepers of Ephesus"* for the dating of the time and determination of the historical place of the cave, but unfortunately the results have been inconclusive so far, even the archaeological researches cannot solve the problem.

An attempted explanation was advanced by some authors including ancient Muslims and contemporary scholars, based on historical data but not reported by the Holy Qur'an. According to them, "People of the Cave" have lived at the time of Emperor Decius (249-251) which the Roman solar calendar was used, while during the time of revelation of the Qur'an, the lunar calendar was used.

On the basis of these historical and astronomical data, according to these authors "People of the Cave" have lived for 309 years into a deep sleep, reflects duration of their sleep of 300 solar years equal to 309 lunar years, expressed in an Arabic expression in verse No. 25/18.

"But they stayed in their Cave three hundred years, and added nine"

My paper further highlights a new reading of the text of the Holy-Qur'an, based on a critical support of Arabic language and the data of the human biospeleology and more "experiences out-of time" allowed me to place the text of the Qur'an in its full text, including the place of its details neglected by the authors in the study of the "People of the Cave." .The notion "Outside time reference" is expressed in verse No. 16/18, with no environmental factors, leads to a dark cave and gives a constant temporal isolation area (noise, temperature and light):

"We have struck their ears deafness in the Cave for a number of years" (verse No. 11/18)

"You will see the sun when it rose move to the right of the entrance to the cave, and when he slept away on the left, and they were in a spacious place of the Cave" (verse No. 16 / 18)

and taking into account the importance of the goal in the history of "People of the Cave" expressed in different expressions in these verses:

"Can we awake them to see the two opposing parties argue the duration of their stay, and know which would assess the best" (verseNo.12/18), "We are awake them then, so they asked each other. One of them asked: How long are we still here? One day, replied the other, or only part of the day. God knows better than anyone took the other, while we have remained" (VerseNo.18/18)

"God is still the best informed of the duration nor heaven nor earth have no mystery for him. He knows so well see everything, hear everything, ls have no control outside person does it and its judgments" (verse No. 26/18)

According to the temporal-space approach, in the light of the "experience out of time" it seems clear to explain the duration of sleep of "People of the Cave" expressed in such expression in Arabic verse 25/18, where the 300 years are separated from the number nine (9) by the word "wa 'izdadu" (in Arabic) means (and added). The nine (9) solar years are an increase in 300 solar years, corresponding to a time difference of 0, 72 hours/day, i.e. the lengthening of a circadian biological rhythm of sleep of "People of the Cave"

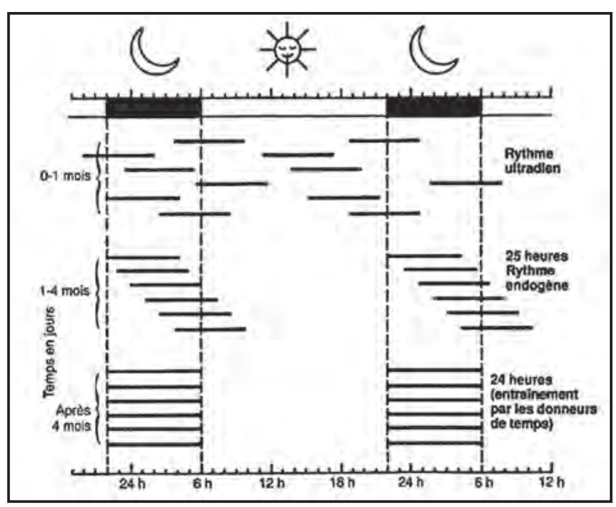

Figure 1: Length of cycle awake-sleep/day is about 25 hours.

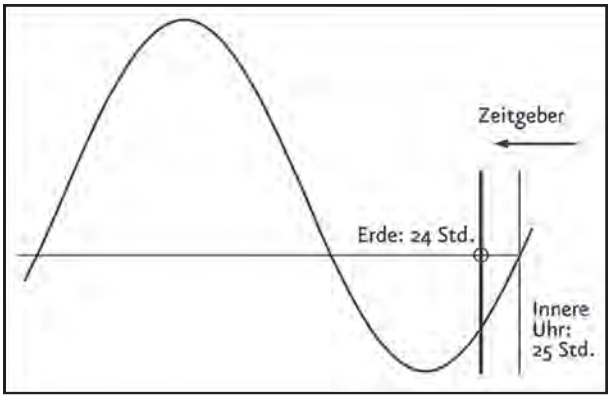

Figure 2: Jet-Lag of natural rhythm is about one hour.

is 24, 72 hours, (more accurate than the scientific advances) with a coefficient of resynchronization 3% increase of time (309/300 = 1.03 and 1.03 x 24 hours = 24.72hours).

About the nature of sleep of "People of the Cave" reported in Surat Al-Kahf "in **verse No. 17:**

"You would have thought they saw and yet they slept deeply."

Many Muslim commentators and former contemporary authors have attempted to interpret this verse with sometimes imagination took place in the reading of this story. In this verse No. 17/18 How an observer can make mistakes in front of a these actions of "People of the Cave"?

The word "Ruqud" (in Arabic) means "deep sleep" but what can believe in "being awake" or the blink of an eye, quite possible that the most acceptable explanation is in the comparison of a REM sleep or "Rapid Eye Movement". The word (inarabic) "Tahsibuhum" expresses the meaning of optical illusion.

Thus, in the light of the results obtained on sleep by Nathaniel Kleitman, a tool for thought of this verse of the *Surat 'Al-Kahf*, I consider the only scientific explanation of this verse concerning "The People of the Cave" have been in the cave in a "life outside of time" in a peaceful, restorative sleep and a constant natural rate, probably comparable to life of the baby in his mother womb?

Whereas research of the cave of *"The people of the Cave"* and *The Seven Sleepers,* through a historical approach or the geographical way is speculative and free approach.

The conclusion showcases the compatibility between religious sources and the American "experiences out-of time".

5. Conclusion:

It is hoped the significance of the Mammoth Cave and Midnight Cave studies will become better recognized not only in field of archaeology, history, and tourism, but especially in human biospeleology, medicine, chronobiology, occupational health, and even religious studies of "life out-of time." We must mention the studies in molecular biology and chronobiology of the American researchers Konopka and Benzer, without forgetting of course the role of this unknown American doctor who was among the first to evaluate the psychological performances of Michel Siffre in France, 1962 when he finished his "experience out-of time" in the Abyss Scarasson in 1962.

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38 YEARS OF PUBLICATION OF THE SPELEOLOGICAL ABSTRACTS

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The evolution of the Speleological Abstracts (BBS/SA) is presented as a function of the number of completed abstracts and the modifications to the classification system. Currently the BBS/SA contains 4,500 abstracts per year.

Current possibilities for consulting the BBS/SA on the Internet will be presented as an adjunct to the printed version. The 18-year compact disc, and its equivalent on the Internet, makes it possible to consult 18 years of publication, or ~80,000 abstracts.

38 ANNÉES DE PUBLICATION DU BULLETIN BIBLIOGRAPHIQUE SPÉLÉOLOGIQUE

Résumé

L'historique du Bulletin bibliographique spéléologique (BBS) est présenté à travers l'évolution du nombre de publications spéléologiques et de la technologie.

1. What Are the Speleological Abstracts?

The Speleological Abstracts (SA, in English; Bulletin Bibliographique Spéléologique, BBS, in French) is an annual review of the world's speleological literature, published by the Commission of Bibliography of the International Union of Speleology (IUS). It covers approximately 5000 titles each year, and is usually accompanied by a short abstract in French, English or in some other non-Cyrillic language of the IUS. The selected titles are those which appeared or were available between January and the end of December of the abstracted year; the publication of the SA is scheduled for the summer of the following year.

2. History and evolution of the Speleological Abstracts

2.1 Bibliographie Spéléologique Suisse

In 1969, Pierre-Jean Baron published a Swiss speleological bibliography that covered all the documents published in Switzerland between 1782 and 1968.

Since 1958, the Swiss national library in Bern has published annually in its "Bibliographia scientiae naturalis helvetica" in its chapter "Höhlenkunde / Spéléologie" (speleology) the speleological literature relating to Switzerland and created in collaboration with Raymond Gigon (1929-1981), then Reno Bernasconi. This annual national bibliography started being reproduced in the magazine Stalactite in 1972.

The "Bibliographia scientiae naturalis helvetica" stopped being published in 2005 and therefore its collaboration with the SA ended. Through the initiative of Raymond Gigon and Reno Bernasconi, two issues of the national speleological bibliography, named "Bulletin Bibliographique Spéléologique" and abbreviated BBS, appeared in 1968 and 1969. Unlike the other bibliographies, the BBS included a short summary of each described reference.

2.2 Internationale Bibliographie für Speläologie

As early as 1950, Hubert Trimmel published a large speleological bibliography work in the series "Wissenschaftliche Beihefte zur Zeitschrift 'Die Höhle'". Unfortunately this annual publication got behind schedule and then stopped in 1964.

2.3 Current Titles in Speleology (CTS)

In 1969, Ray Mansfield published an international speleological bibliography work published annually. Current Titles in Speleology appeared from 1969 to 1990. CTS was soon appreciated in the English-speaking countries, because it appeared regularly and included references.

2.4 Bulletin Bibliographique International / Speleological Abstracts (BBS/SA)

During the 5th International Congress of Speleology in Stuttgart in 1969, the General Assembly of the International

Year covered	Issues	Number of Abstracts
1969	N° 1 March N° 2 September	
1970	N° 1 April N° 2 October	
1971	N° 1 May N° 2 November	
1972	N° 1 April Supplement N° 1 N° 2 November	
1973	N° 1 May N° 2 December	
1974	N° 1 June N° 2 December General Index	
1975	N° 1 June N° 2 December	3957 (1969-1975)
1976	N° 1 June N° 2 Dec. 1976	
1977	N° 1 June Supplement N° 2 N° 2 December	
1978	N° 17	
1979	N° 18	
1980	N° 19	16929 (1969-1980)
1981	N° 20 Supplement N° 3	2601
1982	N° 21	2376
1983	N° 22	2920
1984	N° 23	2791
1985	N° 24	3332
1986	N° 25	3825
1987	N° 26	3890
1988	N° 27	3599
1989	N° 28	3815
1990	N° 29	4322
1991	N° 30	4366
1992	N° 31	3782
1993	N° 32	4307
1994	N° 33	4932

Table 1. Publication dates of the Speleological Abstracts.

Union of Speleology (IUS) resolved to create a commission for speleological bibliography and elected Reno Bernasconi to the presidency of the commission. The tentative beginnings of the SA in Switzerland and the creation of this commission took over Hubert Trimmel's bibliography.

A first report on the activities of the commission was presented at the time of the 6th International Congress of Speleology in Olomouc in 1973 (Proceedings, vol. I: 55-56).

At the instigation of Raymond Gigon, all publications received at the library of the Swiss Speleological Society were consistently and systematically abstracted by Reno Bernasconi and Raymond Gigon. This lent an international dimension to the SA as early as 1970. The Bulletin Bibliographique Spéléologique /Speleological Abstracts appeared twice a year. A general index of the years 1970-1974 (issues 1 to 10) initiated by Raymond Gigon appeared in 1975 and covered 3,957 abstracts.

From 1975 on, volunteer contributors collaborated with the SA, which increased the number of abstracts considerably. The publications received at the library of the SSS were sent by mail to the collaborators to be abstracted.

In 1978, the SA began being published annually and each issue contained several indexes. The SA was soon appreciated in continental Europe because it appeared regularly and because the topics were current.

Meanwhile, the Société Helvétique des Sciences Naturelles (the Swiss Society of Natural Sciences) – currently called the Académie Suisse des Sciences Naturelles, or ScNat for short – provided financial support to the SA, which helped with its printing.

In 1980, the Fédération Française de Spéléologie (French Federation of Speleology), thanks to Claude Chabert, joined the editorial ranks to integrate the French speleological bibliography into the SA and to ensure its distribution in France. In 1988, it was the turn of the Società Speleologica Italiana (Italian Speleological Society) to do the same, through the efforts of Paolo Forti.

Around 1990, the British Cave Research Association (BCRA) stopped publishing "Current titles in speleology" and joined the SA. Thereafter, starting with the issue n° 32 (1993), four societies took part in the drafting and publishing of the SA: the Société Suisse de Spéléologie, the Fédération Française de Spéléologie, the Società Speleologica Italiana and the British Cave Research Association. For a few years, the SA was named: BBS/SA/CTS. Currently the French name is "Bulletin

Year covered	Issues	Number of Abstracts	Annual CD-ROM	Global CD-ROMs and Number of Abstracts
1995	N° 34	5452	CD 1 (28-34)	
1996	N° 35	5057	CD 2 (28-31)	
1997	N° 36	6674		Special CD 3 (28-36)
1998	N° 37	4635	CD 4 (32-37)	
1999	N° 38	4740	CD 5 (38)	CD 12 years (27-38)
2000	N° 39	5263	CD 6 (39)	
2001	N° 40	5236	CD 7 (40)	
2002	N° 41	4493	CD 8 (41)	
2003–2004	N° 42-43	6474	CD 9 (42-43)	CD 17 years (28-43)
2005	N° 44	5230	CD 10 (44)	CD 18 years (28-44)
2006	N° 45 (to be published)			
2007	N° 46 (to be published)			
2008	N° 47 (to be published)			

Table 2. Publication dates of the Speleological Abstracts and of the CD-ROMs.

Bibliographique Spéléologique" (BBS) and the English name is "Speleological Abstracts" (SA).

2.5 From index cards to the computer

Around 1980, the SA abstracts were machine typed on A6-format index cards, and sorted manually by chapters and sub-chapters. Each card was assigned a serial number, using a numbering machine. Raymond Gigon then typed the ready-for-publication final draft on an electric typewriter. After Raymond died in 1980, a professional typist carried out the final typing on A3-format pages, which were then photographed for offset printing.

In 1986, Reno Bernasconi bought his first computer. After some testing, he settled for a Macintosh SE, in spite of the small, built-in screen. With the help of this computer, he compiled the indexes (geographical, by author, list of the abstracted publications) and created the cross-indexes at the end of the sub-chapters.

The purchase of a laser printer made it possible to print the pages of the SA in typographical quality. The first attempts appeared in issue n° 27.

The technique of computer-assisted desktop publishing made great progress and starting with issue n° 30 (1991) Reno was able to directly print the SA on his laser printer. At his request, some macros were developed by a data-processing specialist in Filemaker 2, which subsequently facilitated the indexing work.

In 1995, CD-ROM 1 of the SA appeared. It included in the form of databases the complete contents of issues 28 to 34. This database created with an autoexecutable version of Filemaker Pro 2 was the first attempt to electronically distribute the data of the SA, with, of course, the capability of searching by author, classification, title, etc.

With the following issue, the CD-ROM became an indispensable addition to the paper version. The CD-ROM 12 Years contains a compilation of the first eight CD-ROMs into which issues 28 to 31 were integrated, and which were recovered from the page-layout software or scanned from the paper version.

2.6 From the computer to the Internet

The Commission of Bibliography of the IUS publishes an annual SA, whenever possible during the spring of the following year. There is always a printed version, in spite of the printing costs and a progressively smaller number of printed issues. The International Union of Speleology financially supports the printing of the SA, and several national caving federations joined the editorial group, forming an important base of purchasers and contributors to the SA.

Practically since the beginning of the international SA, the Swiss Academy of Natural Sciences (ScNat) provided major financial support toward the implementation of the

SA. Since 2008, this support benefited only the electronic version and it allowed the setting up of the infrastructure needed to look up data by Internet (a server, computer connection, subsequent developments).

The Internet version that will be available in the spring of 2009 will pick up all of the abstracts of the 18-year CD plus subsequent annual updates.

The annual CD-ROM can be bought separately or together with the printed SA. Each annual CD can be imported into the global CD (currently the 18-year CD) and constitutes an annually updated worldwide speleological bibliography.

Thanks to the increased computerization of all the steps needed for processing the abstracts, the Editor is trying to make up for lost time and delayed releases by immediately publishing the abstracts submitted by more than 30 collaborators.

2.7 Editors

At the beginning, it was Reno Bernasconi and Raymond Gigon, sporadically Grégoire Testaz (until 1973), Jean-Claude Lalou (1977-1978), and Bruno Klingenfluss (1978). After that, Reno Bernasconi, assisted by Christine Bernasconi, took on the editing and the coordination of the SA until 1998. After 27 years of editorial work and collaboration in the SA, Reno and Christine Bernasconi retired from it. The presidency of the Commission of Bibliography was entrusted to Patrick Deriaz during the International Congress in Brazilia. Patrick Deriaz, together with Daniela Spring, a librarian and professional proofreader, now continue producing the SA, assisted by more than 30 international collaborators.

3. The Current Implementation of the BBS/SA

Each collaborator directly enters his/her abstracts into a database, which is sent to the national coordinator where the abstracts are corrected and combined.

The data are then passed on to the President of the Commission of Bibliography who collects the data from the entire world, combines the regional databases and applies global corrections.

The database version has an export feature for the layout software that produces the paper version.

The CD-ROM or Internet version is created in another database named "consultation" by importing the entered data.

4. Internet Version

A complete version of the SA collection is available as of the beginning of 2009 on the Internet (www.ssslib.ch/bbs) and will be the subject of a presentation during the 2009 International Congress of Speleology.

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AFRICAN AMERICANS AND THE USE OF CAVES AS HIDDEN SPACES IN THE ANTEBELLUM AND CIVIL WAR SOUTH

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The author undertook an examination of historical sources to ascertain how African Americans in the American South conceived of, and utilized, caves during the Antebellum (1815-1860) and Civil War (1861-1865) periods, including literature on the Mammoth Cave, saltpeter mining, and scattered 19th century cave references. Another important source for this study, now on-line and searchable using keywords, is the Library of Congress's Born into Slavery: Slave Narratives of the Federal Writers Project, 1936-1938. Combined, these sources give a broad view of the ways African Americans interacted with the underground environment, elucidating an important part of the history of American caves.

The results of this study reveal that African Americans used caves in ways similar to Euro-Americans at the time, but that their emphasis was different; caves were adjuncts to domestic economies, providing shelter, water, and cold storage of foodstuffs; caves were industrial spaces where African Americans worked as enslaved miners extracting saltpeter, and African Americans played an important role in cave tourism, a non-extractive industrial use of the environment. American blacks also occasionally used caves as social spaces, and some saw caves as cultural curiosities worthy of exploration and admiration, though these latter two uses appear to be less common in the black population than in society as a whole. On the other hand, the most important (and common) use of caves for enslaved persons was as hidden spaces, which was not true of American culture overall.

Because of slavery, and their degraded legal and social status, African Americans frequently turned to caves, both natural and man-made, as hidden spaces both before and during the Civil War. Runaway slaves used caves as they tried to hide from slave patrols, both as they were trying to escape to the North and also in the more frequent cases where they remained in the South, near family and friends. Enslaved persons also hid their own property in caves, as did all Southerners, with the breakdown of civil authority during the Civil War. Blacks were also hidden by whites in caves (as a form of property), especially when the Union Army approached. African Americans sometimes spent many years in caves, some staying hidden until after emancipation in 1865. The use of caves as hidden shelter was the most significant environmental interaction by the black population in the South, spawning folktales, such as the repeated story of African American children, born and raised in a cave and hidden from daylight, who later became blind after they left the cave's darkness.

1. Introduction

African Americans culture was distinctive in some important aspects, both because elements of African heritage persisted, and because of the degraded legal and social status of enslaved American blacks, Yet African Americans were also part of a vibrant, larger American culture which strongly affected their lives in innumerable ways. Widespread religious, economic, and political developments in the United States deeply touched them, as did an emerging national popular culture. The question for environmental historians then, is to what extent did African Americans' interactions with the environment differ from or parallel those of the larger society within which they lived? This paper examines how African Americans in the American South conceived of, and utilized, one element of the natural environment, caves, during the Antebellum (1815–1860) and Civil War (1861–1865) periods.

These were critical periods for all Americans, but especially American blacks, as the time span saw the rise of cotton as the dominant plantation crop in the American South, the growth and geographic spread of chattel slavery, the rise of an abolition movement in the North, and finally a bloody Civil War which ultimately ended the institution of slavery. It was in this period that a distinctive African American culture developed out of its Eighteenth Century roots and spread throughout the South. These were also critical times in the history of American caves, as Americans increasingly explored the underground, and began to utilize it in a variety of ways, some in tension with others (Douglas, 2001). Caves still provided basic necessities in karst regions, such as water, shelter, and cold storage of foodstuffs. But caves were now more than ever also commodities, supporting both extractive (saltpeter mining) and non-extractive (tourism) industries. In both popular culture and in practice, caves were hidden spaces, where hermits, criminals, and criminal activity could sometimes be found. Caves were also increasingly seen as social spaces, places to hold a dance or a meeting, or to take a tourist trip with friends. Finally, the romantic view of caves as sublime wonders and natural curiosities fully blossomed in American culture at the time, as seen vividly in the many published cave narratives which appeared.

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2. Research

The author undertook an examination of historical sources including both primary and secondary literature on the Mammoth Cave, saltpeter mining, and the general and specific histories of 19th century caves. While useful, many of these sources were written by Euro-Americans and must be used with caution. To help understand how African Americans thought of and utilized caves, from their own perspectives, an especially important source is the Library of Congress's *Born into Slavery: Slave Narratives of the Federal Writers Project, 1936-1938*, now on-line and searchable using keywords. Some sixty interviews with former slaves, conducted by the Works Progress Administration, mentioned caves and were examined. Combined, these sources give a broad view of the ways African Americans interacted with the underground environment, elucidating an important part of the history of American caves.

3. Caves as Necessities: Water and Cold Storage of Foods

The historic usage of caves for practical necessities such as shelter, water sources, and the storage of foodstuffs was widespread in the South, with many practices extending back to American Indian usage, some to prehistory. For Euro-American and African American "settlers" the sheltering function was usually short–lived and was quickly replaced with built housing, but caves remained important as adjuncts to domestic economies as springs, springhouses, and root cellars throughout the Nineteenth Century and beyond (Douglas, 2005). Although these activities are generally poorly documented, African Americans utilized these domestic resources in ways no different from their neighbors or masters; blacks obtained water from caves and stored various foods underground just as Euro-Americans did.

It is clear that caves were a vital source of water for all in the many karst regions in the South. Hammett Dell (b. 1847) was enslaved in Rutherford County, Tennessee and everyone on the farm, including the four bondsmen, was dependent on underground water. In a 1937 interview he stated that "[w]e got our water out of a cave. It was good cold limestone water. We had a long pole and a rope with a bucket on the end. We swing the pole round let it down then pull it back and tie it. They go to the other end and git[*sic*] the bucket of water. I toted [a]bout all the water to both places what they used." (*Born in Slavery*: H. Dell) Such environmental interactions were common. Indeed entire communities containing both blacks and whites were centered upon, and dependent upon, cave springs: Horse Cave, Kentucky, Berlin Springs, Tennessee, and Huntsville, Alabama among many others.

Numerous caves were historically utilized to store food by people of all complexions in the South, with many examples across the region. These were either "cellars or spring-houses," noted ornithologist Alexander Wilson as he travelled across the countryside in 1810, with dry caves serving as the root cellars and damper ones being used for storing butter, eggs, milk, and other humidity tolerant items (Wilson, 1810). African Americans embraced this folk usage without reservation. When interviewed in the 1930s, Ruben Woods, who as a child had been enslaved in Alabama, stated that he and other blacks on the plantation hid in a cave when the Union Army arrived and fighting commenced, but that they had food stored in the cave so they could eat. (*Born in Slavery*: R. Woods) As is well known, at the Mammoth Cave of Kentucky, America's premier show cave since early in the Nineteenth Century, the guides were enslaved African Americans working in the burgeoning cave tourism industry. One of them, Stephen Bishop, acquired a national reputation and became one of the best known blacks in the United States. Yet even at this bustling commercial operation, the folk practice of storing food underground existed for decades. Englishwoman Harriet Martineau visited the Mammoth Cave in 1835 and wrote that "[t]he entrance of the cave serves as an ice-house for the family of the guide. They keep their meat there, and go to refresh themselves when relaxed by the heat." (Martineau, 1837) This observation was confirmed by Elizabeth Fries Ellet in her 1853 trip to the cave. She wrote that "meat is preserved for weeks by being placed near the [cave] entrance." (Ellet, 1853).

4. Caves as Commodities: Tour Guides and Miners

The importance of African American guides at the Mammoth Cave is well documented in many sources. (Schmitzer, 1993; Meloy, 1977) While the earliest generations of guides were white, by the late 1830s enslaved African Americans became the standard guides, including men such as Stephen Bishop, Mat Bransford, Nick Bransford, and many of their progeny. While few African Americans visited the cave as tourists, they worked in the cave and nearby hotel. The guides were able to use their position as skilled slaves to carve out more freedom than typical. Theirs was an unusual existence; legally subservient but in a position of authority while underground, frequently armed with a pistol (to demonstrate the sonic properties of the cave , especially the rivers), and while officially unpaid they were sometimes tipped for their services. They understood the dynamics of cave tourism, and selling the cave experience as a commodity, very well. Sometimes the commodification extended beyond the experience. Nick Bransford collected and sold blindfish from the cave to tourists, earning enough money to purchase his freedom. He continued working at the cave as a free man for more than three decades.

While deeply involved in the commercial exploitation of America's greatest cave, operating such a venture was beyond their reach at the time, even if freed from slavery. But if they could not own and operate a show cave themselves, they could certainly extensively explore the cave at which they worked. Enslaved guides at the Mammoth Cave are rightly credited with finding many new sections, extensions, and wonderful features. Thus at least for these African Americans, the cave was a great curiosity worthy of intensive exploration. It could also serve as something of a social space; the guides lived nearby, and their families were in the cave on a regular basis. In the 1930s, Lulu Wilson told interviewers that when she was a little girl she "used to play in that big cave they calls[*sic*] Mammoth and I [wa]s so used to that cave that it didn't seem like nothin[g] to me. ((*Born in Slavery*: L. Wilson) While not as prominent as in larger American culture, blacks occasionally saw caves as social and quasi-religious spaces. But for many more African Americans, caves were a grueling workplace, a place where they toiled as miners in a grimy extractive industry focused on saltpeter.

African Americans, both enslaved and free, worked as miners in the American cave saltpeter industry. Starting in Virginia in the mid-1700s, the industry grew in scope, scale, and geographic extent until it was a major feature of the history of southern environment, affecting hundreds of cave sites. Large scale saltpeter mining clustered in periods of war, when need and supply diverged and the commodity obtained a high price: the Revolutionary War (1775–1781), the War of 1812 (mid 1790s–1815), and the Civil War (mid 1850s–1865) eras. Some small-scale cottage industry production persisted throughout the whole antebellum period. Virtually all of these saltpeter caves were in the South, for geologic and economic reasons. As with most antebellum and Civil War industries in the South, enslaved African Americans were an important part of the labor force, being hired out by their owners to independent saltpeter contractors or (in the Civil War) the Confederate States of America government.

In Kentucky, one of the first saltpeter manufacturers was purportedly an enslaved black man at Boonesborough, Monk Estill, who made gunpowder from saltpeter mined from Payton (now Adams) Cave in 1780. (George, 1987) Later, there is strong evidence that saltpeter mining in Kentucky in the early Nineteenth Century was largely conducted by black miners. At Great Saltpetre Cave in Rockcastle County, one of the nation's largest saltpeter production sites, enslaved miners were being utilized as early as 1804. They remained the work force until mining ceased and the cave was offered for sale in 1815. (George, 2001) At the Mammoth Cave the situation was the same; black miners were the rule. When Ebenezer Meriam visited the cave in 1813 he noted about 70 African Americans toiling in the cave. Others put the number somewhat smaller, but the racial composition of the workforce was not in doubt. (De Paepe, 1985) The enslaved miners lived in small cabins near where the Hotel was later erected. The labor intensive process industry continued until the price of saltpeter collapsed at the war's end. (Faust, 1967; George, 2001) Some remnant small scale cave saltpeter mining and processing persisted until the 1820s, including production by a former slave named "Free Frank", who mined caves and refined saltpeter in Pulaski County. But large scale production in the state never recovered. Vulnerable due to geography, Kentucky caves were not mined during the Civil War, unlike the Confederate States to the east or south.

While there are hints in the historical record of blacks, both enslaved and free, working as miners in saltpeter caves in Tennessee and Virginia, some of the best evidence for the importance of African Americans in the industry comes from Alabama caves during the Civil War, the subject of a recent study by historian Marion O. Smith (2007). Of the fourteen caves directly mined by the Confederate States Government, African American miners were working at six of them, with hints of slave labor at one other. Compared to some smaller saltpeter cave operations, at the larger mines there was a greater reliance on black labor. The largest saltpeter source of all, Sauta Cave, employed about 90-111 whites per month compared to about 163-191 slaves or free blacks. Blue Mountain Cave and the short term Prater Cave efforts also turned to black labor as much as white, while the other caves had anywhere from zero to ten African American miners, with anywhere from a handful to a few dozen Euro-American miners, many Confederate Army draftees. Some saltpeter cave operations utilized female slaves, presumably as camp cooks. At Blountsville Cave five or so whites worked alongside six enslaved persons. The black workers were ages 10, 15, 16, 16, and 30. As for the caves mined by private contractors, there were some forty in Alabama's Nitre Bureau District Nine and little is known of their labor force, though it is safe to assume it included both white and black saltpeter miners. As in so much of early America, African Americans provided much of the raw labor that helped develop the United States, working in the mines, fields and foundries alike. Ironically, in the Civil War, the labor of blacks was used by the CSA to prolong the existence of a system that denied them basic liberties, even humanity. But the tradition of mining in caves continued, as a few black laborers at least became small scale guano miners after the war.

5. Caves as Hidden Spaces: Hiding Property, Hiding Self

Historically, both Euro-Americans and African Americans used caves as both sheltered and hidden spaces. The sheltering function of caves was long known, but they were also by definition hidden from the surface. The usage was known from actual practice and from popular literature. People hid property in caves, and they hid themselves in caves. This often represented an extraordinary step and signaled social conflict or disruption. In the social dislocation of war, many found reason to hide property of all sorts (including caves) in caves to prevent capture from marauding armies or partisans. They might also provide a degree of personal safety. Additionally, criminals, social pariahs, or people in self-imposed social exile like hermits, lived in caves. This included, at least in the minds of many white Southerners, runaway slaves. Though their only crime was to seek their own freedom, they were seen as stealing property from their owners, themselves. And enslaved people in the South did flee to the mountains, swamps, and caves, both as they were trying to escape to the North and also in the more frequent cases where they remained in the South. Frequently some especially harsh action, like a viscous beating, triggered the flight, and apparently many African Americans lived for long periods in caves, some staying until emancipation. This made a deep impression in African American culture and spawned folklore among the last generation of bondsmen.

African Americans were well aware that Euro-Americans sheltered and hid property in caves, sometimes including their chattel slaves. Some slave traders stole black people, both free and enslaved, and hid them in caves as they moved them out of the area for resale. Mary Wright (b. 1865) reported in her interview with the Federal Writer's Project that slave traders tricked blacks, including runaway slaves, kept them at Campbell's Cave in western Kentucky, and then delivered them to a slave market. ((*Born in Slavery*: M. Wright) The practice continued into the war; Mag Johnson told her interviewer that her mother and a group of slaves were hidden in a Tennessee cave by slave traders for two weeks, with not much to eat, to avoid Union Army troops. Her mother was sold soon afterward, but they then gained their freedom. (*Born in Slavery*: M. Johnson).

With the approach of Union troops in the Civil War, many white southerners decided to hide their valuables underground, whether it was precious metals or food or livestock. African Americans knew this. Rachel Austin, in her W.P.A. interview, indicated exactly where the plantation master had dug an artificial cave and hidden his meat and silver, in the hog-pen. (*Born in Slavery*: R. A. Austin) When Union troops approached the Reeves plantation in central Arkansas, the landowner's son hid most of the family as well as the livestock in a large shelter cave in a bluff, though the slaves were left at the homestead, according to Elcie Brown in her W.P.A. interview. (*Born in Slavery*: E. Brown) In other incidents, white southerners hid mules, food, and money in caves. In Overton County, Tennessee the Copeland family had their slaves hide the meat in a cave for them; they were worried about a visit from feared Union partisan Tinker Dave Beatty. In western North Carolina, slaveholders sent their bondsmen, livestock, money, and food to the nearby mountains and caves to hide until the soldiers were gone. In one extra-ordinary case a white confederate deserter lived in a man-made cave near his former home. (*Born in Slavery*: R. Jones, H. Travis, J. G. Hawkins; Anonymous, 1977) African Americans made the most of this knowledge; in one episode, according to historian Stephen Ash (1988), a young enslaved woman from Wilson County, Tennessee walked six miles to inform Union troops her master had secreted horses, mules, and guns in a cave, as well as barrels of salt behind a garden fence.

Based on the W.P.A. interviews, African American seldom hid property in caves, with the one exception in which a bondsman stole whiskey from his master and hid it in a cave, only to be discovered and beaten. (*Born in Slavery*: B. Buntin) But blacks did hide their person underground, themselves. African Americans in the South knew that a hidden shelter like a cave could be very useful in an actual battle. In addition to the testimony of Ruben Wood previously cited, Lucinda Davis reported in her W.P.A. interview that she and other bondsmen witnessed a battle at Honey Springs, Oklahoma, in Creek Indian country. The enslaved people got into a large cave in the bluff and spent all day and night there, listening to the sound of the battle. Similar stories were told by other W.P.A. interviewees, though many fled the approach of troops even if there was no fighting. (*Born in Slavery*: V. Sims, E. King)

African Americans used caves as hidden spaces both on a temporary and a more permanent basis, depending on the particular goals of the person. While many slaves ran a way from abusive masters and overseers, a few used caves as temporary stops towards freedom. In his interview with the W.P.A. Rev. John Moore of Nashville noted that many slaves would run away and hide in caves and some would go on to Canada via the Underground Railroad, a clandestine organization of abolitionists who aided persons escaping from the South and slavery. (*Born in Slavery*: J. Moore) A few specific caves in the South are linked to the Underground Railroad but documentation for the activity is scarce and some of the sites are suspect. Brook Cave and Blankenship Cave in Tennessee, Phelps Cave in Kentucky, and Meremec Caverns in Missouri have folklore tying each site to the Underground Railroad, but the folklore remains unconfirmed at all, and it seems very unlikely at one, Phelps Cave, since it was owned at the time by a Confederate general. In general, Midwestern caves have a stronger claim in this regard. (Douglas, 2001)

As Tom Hawkins indicated to his interviewer in the 1930s, most enslaved persons did not run away to the North but instead ran off only to stay in the South. They were not welcome in much of the North, and at any rate they wanted to stay close to family and friends. A local cave was often considered a good place to hide while remaining in the general neighborhood. Relatives and friends on the plantation might secretly bring them food, or they could live off stolen food and berries, like interviewee Alice Baugh's uncle did. For some this was a temporary break and they eventually went back to the farm or plantation. Jordan Smith told of a black man who was brutally beaten by his master who then ran away and stayed in a cave for six months. He returned to the plantation, but after another beating he absconded again. Others sometimes stayed underground for years. Tom Hawkins told of a man who stayed fifteen years in a cave, while Isaiah Green told of a runaway who stayed in a man-made cave for seven years, until emancipation. (*Born in Slavery*: T. Hawkins, A. Baugh, J. Smith, I. Green) Whites knew "fugitive" slaves might be hiding nearby and were known to check local caves while looking for them. In 1846, in Maury County Tennessee, two local elites searched a surprisingly extensive and confusing cave late one night hoping to find slaves. And while that effort failed, sometimes whites caught runaway slaves in caves. Leithean Smith told her W.P.A. interviewer that several enslaved persons on her plantation ran away and took refuge in nearby caves, but all were eventually captured save one. Still, many blacks escaping slavery were able to remain in their underground homes for a considerable time. (Anonymous, 1846; Henderson, 1929; *Born in Slavery*: L. Smith)

7. Conclusions

The use of caves as hidden spaces by African Americans in the antebellum and Civil War periods found its way into southern folklore, especially among the generation that came of age after the war. There are two main motifs in the W.P.A. interviews, though they have numerous variants. One is an adaptation of older hermit folklore suggesting that when escaped slaves ended a lengthy stay underground they had become wild and hairy, almost like beasts. (*Born in Slavery*: L. Garrett, J. R. Cox, D. Franks) The other motif told of children born and raised in a cave by their runaway parents who, upon finally leaving the cave after emancipation, went blind, and according to one account soon died. (*Born in Slavery*: P. Smith, G. Womble) Neither folktale portrays caves in a particularly favorable light.

This short overview has not broached every aspect of the history of African Americans and caves, ignoring topics such as the disposal of African American murder victims in caves or stories of black criminals hiding underground. But it is clear that like all southerners in karst area, African Americans knew about, visited, and used caves in a variety of ways. These were similar to the larger American culture but with a different emphasis. The over-riding fact of life for many southern blacks was enslavement, and the key goal was to escape it. In that context the use of caves by African Americans can be seen as logical and adaptive. They knew that caves provided shelter and domestic necessities, that money could be made mining or showing them, and that they could be social spaces and cultural curiosities. But most importantly they were secret spaces where a person could hide from trouble. And the main trouble was slavery.

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THE NAICA CAVES AND HUMAN PHYSIOLOGY

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Naica Crystal Cave is an extremely hostile environment for human beings. However, it is also the most beautiful place on the planet for cavers. Any speleologist would like to visit it at least once in his lifetime. The caver's body is accustomed to physical efforts and the hostile conditions of the environment he explores, but this is not sufficient for survival in the Naica caves. In this place the temperature exceeds 45° C and humidity is well over 90 %. No human being can survive in these conditions for more than 15-20 minutes. A group of speleologists has planned and realized a simple and intelligent strategy that has allowed the exploration of this cave.

In this project, the medical aspects have assumed an important role, involving:

- a program of progressive adaptation for the speleologist to high humidity and temperature;
- a program of prevention and treatment of possible accidents, and;
- survey and analysis of the cardio-vascular, neurological and metabolic physiological activities.

The experience resulting from in this project has produced many data that will be analyzed statistically. Moreover, such data will support future analyses regarding human behaviour and physiology in caves and in extreme environmental conditions.

1. Analysis of the Induced Physiologic and Pathologic Phenomena on the Human Organism

Exposed at the Naica Cave

During the period of exploration activity carried out between 2006 and 2008, we gathered a series of clinicians and instrumentals data. The main purpose of the physicians was to oversee the involved people to ensure their safety. Subsequently, the recorded parameters were collected in a data base for a careful analysis. Various people were investigated: professional speleologists, photographers, video operators, electricians, and others. According to their assignments, the approach modalities of everyone in the cave differed as a precise and scientific medical analysis would have taken too much time. It was not possible because it would have hindered the documentation and exploration plans, which were the main objectives of the expedition. However, everybody was subordinated to a clinical and instrumental examination. We made some tests and evaluations at rest, before the activity of body weight and body mass index (BMI), body's temperature, heart pulse and respiratory rate, blood oxygen saturation levels, blood pressure, glycemia and urine analysis (proteins, specific gravity, and ketones), and electrocardiogram (EKG). Moreover, everybody was submitted to a neuropsycological test of the attention's evaluation (Wassler's test: test of numerical memory). The same assessments, tests and evaluations were repeated with every exit from the cave, considering: time of permanence, type of equipment used and amount of beverages drunk. Moreover, records were made of the appearance of symptoms like: dyspnea, palpitations, chest pain, dizziness, muscular pains, nausea, cefalea, weakness, and heavy legs' sensation. A visual-analog rating scale, was used to define the subjective suffering degree. The data were analyzed with SPSS, statistic program, and the analytical results will be published elsewhere. However, from these data we can understand that the use of a system of body's cooling, like the *Tolomea suit,* associated by a system of inspired air cooling , *Sinusit,* improve the endurance during the exploration and recovery upon exiting. Thank to this equipment, it is possible to survive for over an hour in the Naica caves. Survival for over 15 minutes is not possible without it. No important changes of hemodinamyc parameters, occurred. Sometimes, the body's temperature at exit was elevated but it never reached dangerous levels and all parameters (blood pressure, temperature, heart rate) in few minutes were readily restored. Nobody required important care beyond quick cooling with vaporized water, rest, and application of ice packs at the neck, axillae, and groins. No significant variations of body weight were detected because, in the environmental conditions of the Naica cave, the human body can not evaporate by sweating. However, the people were invited to drink constantly throughout the working day. There were many people that made many short stays in the cave without equipment. At each exit, they sweated so much because the temperature and humidity in principal tunnel (37°C and 70%, respectively) facilitated it. Unfortunately, these people were not monitored but only observed.

2. Emergency Planning

Base camp included a tent with conditioned air and contained a camp bed and equipment for medical emergency. Available inside was an oxygen tank, intubation and resuscitation kit, surgical kit, drugs, kit for intravenous infusion, electrocardiograph, and immobilization systems for limbs and vertebral column. Moreover, a basket stretcher and a truck were available for immediate transportation outside the mine.

A rescue team composed by a doctor and three people, all expert cave rescuers, was always ready . The team was equipped with light suits, special boots, helmets, protective gloves, a small cool-breather, a bandoleer of flat tape, and four non-locking carabiners. They also had to bring:

- A little backpack containing a tank with 110 liters of oxygen, emergency scissor, four flat tapes 4 cm x 4 m, one cervical collar;
- A small cool-breather for the injured;
- 2 portable radios for communication, one of these for the doctor; and,
- The stretcher.

If an accident should take place

- In the place of the accident;
    - alert rescue team immediately;
    - if the injured has fainted, lay him on a side, his head lower than his feet;
    - check if the breather is working correctly and set it for maximum air flow rate;
    - wait for the rescue team; and,
    - always consider the BLS procedure (Basic Life Support).

- At the base camp
    - stop any work activity;
    - in case of fainting, immediately alert an ambulance and start the chronometer;
    - get the rescue team ready;
    - follow the doctor's instructions; he is the head of the rescue;
    - the doctor's assistant stays in the medical station;
    - the members of the "human chain" transport team, get ready to enter at the doctor's call; (This a team of eight people with light suit, helmet, boots, and protective gloves ready to execute a rapid transport hand-to-hand of the stretcher, from the last area of the cave out to the base camp.) and,
    - remove all obstacles to transport the injured from the medical station to the ambulance parking site.

3. Response of the Organism to the Heat, Acclimatization, and Recovery

The human body is a homoeothermic system able to guarantee an internal constant temperature between 36.5°C and 37.5°C. This is possible thank to a correct thermal balance between the heat acquired and lost. The heat acquired derives from the metabolism and the environmental heat; the heat lost depends from the body's capacity to eliminate the heat, through systems of conduction, convection, radiation, and evaporation. The metabolic heat result by the sum of basal metabolic rate (BMR), muscular exercise, and possible diseases. Excluding diseases, the BMR, at rest, increase the body temperature of about 1.1°C each hour, whereas the muscular activity can increase the metabolism of 15 times, at least, coming to 1000 Kcal/hour. As regard to heat loss, it depends on the utilized system. Conduction is the transfer of heat via direct physical contact with a cooler object; it accounts for 2% of the body's heat loss. Convection is the dissipation of heath from the body to the air and water vapor surrounding the body; it accounts for 10% of the body's heat loss (when air temperature exceeds body temperature, the body gains heath energy). Radiation is the transfer of heat to the environmental via electromagnetic waves; it accounts for most heat dissipation. As long as there is a temperature gradient between the body and the air, 65% of the body's heat is lost by radiation. Evaporation is the transfer of heat by transformation of perspiration and saliva into a vapor; it accounts for 30% of the body's heat loss. Now, the principal forms of body's heat loss in a hot environment are: radiation and evaporation. However, when air temperature exceeds 35°C, radiation of heat from the body ceases and the evaporation becomes the only mean of the heat loss. But evaporation is maximally efficient in a dry environment and if humidity reaches 100%, evaporation of the sweat is no longer possible and the body loses its ability to dissipate heat.

In the Naica caves, the temperature is 47°C and relative humidity nearly to 100%! When the heat gain exceeds heat loss, the body temperature rises and, if it exceeds 41.1°C, the situation becomes very dangerous. To promote blood cooling, the cardiovascular system increases its activity by shifting the blood from inside to the skin, which is the more important system for heat dissipating. In the skin, the sweat glands are stimulated to produce more sweat. In this way the vital organs are protected from overheating. This effect is associated to increase of cardiac activity, but the increase of the internal temperature produces also other effects. The central vasoconstriction can cause intestinal ischemia with release of toxins, but at the same time inflammatory proteins with protective action called *heat shock proteins* are released. These effects are person-related and a regular acclimatization procedure can significantly change the result. In fact, acclimatization training improves adaptation and endurance of the organism in hot and humid environments, reducing the risk of heat damage. This is a process that requires several days (7-8 days) to achieve the following effects:

- earlier onset and increased production of sweat that will contain less mineral salts;
- enhanced vascular output and cardiovascular performances;
- the endocrine apparatus ensures a salt conservation and the expansion of plasma volume;
- the renal apparatus increases the filtration rate of the blood; and,
- heat shock proteins are produced to increase the resistance at the toxics products.

The clinical manifestation that can be observed after prolonged exposure to the heat, heat exhaustion and heatstroke, are described in Table 1.

To improve the physical performances of the explorers and reduce the risk of hot damage, the following protocol was proposed:

- 90 minutes of daily of exercise in hot conditions for at least one week and gradually increasing exercises for intensity and duration
- Take a bath or hot shower before the exposure
- Drink before the exposure, 400–500 cc of cold fluids (200mOsm/L, enriched of mineral salts)
- Monitor body weight before and after exposition:
  - For reduction of 2–3% rehydrate / proceed to work
  - For reduction of 5–6% rehydrate to normal weight / proceed with light work
  - For reduction over 7% rehydrate to normal weight /stop the work and rest
- Immediately stop activity at the appearance of one of the following symptoms
  - Nausea, vomiting
  - Headache, dizziness
  - Shiver, piloerection
  - Fainting feeling, Tachycardia, 90-100/bpm at rest
- Constant control of the physical activity: slow movements and reduced workload

The program of recovery after exposure to the cave and in presence of symptoms was as follows:

- Slowly oral rehydration with prepared solutions (enriched of mineral salts, 200 mOsm/l)
- Remove clothes
- Physical rest
- To spray on the body tepid water and expose it to a powerful fan
- Apply ice packs to the neck, axillae, and groins
- Cover the body with a wet sheet

SYMPTOMS OF HEAT DAMAGE

Tc ≤ 41°C **HEAT EXHAUSTION**	Tc ≥ 41°C **HEATSTROKE**
Fatigue, weakness, fainting	Central Nervous System disfunctions
Nausea and vomiting	-impaired judgment
Headache, myalgias, muscle cramps	-bizarre behavior
Dizziness	-hallucinations, confusion, disorientation
Irritability	Cerebral edema, coma
Tachycardia, blood pressure change	Decreased cardiac output, shock, hypercoagulation
	Respiratory distress, pulmonary edema, renal failure

- o Insulation in air-conditioned environment at 30° to 32°C
- o It is necessary to avoid the immersion in cold water because it could lead a reverse of the blood torrent from the periphery at the core of the body. This action will cause a shiver reaction that could cause further increase of the temperature and the complete loss of the control system

Despite all the attention, the call for caution, and the respect of rules, two accidents occurred. Both were due to human error. The first happened to an excellent speleologist during an exploration of a remote and not already known area of the cave where he was found alone. The cool-breather apparatus has broken and was found quickly to breathe the warm air of the cave at 48° C. He quickly suffered the symptoms of heatstroke: weakness, dyspnea, near fainting, and he was unable to call for help because he did not have a transceiver radio. He moved very slowly in the direction of the exit and only when it was possible to view him with a camera positioned in the last area of the cave, did he receive the aid. With a correct cooling and rehydration, he was recovered without consequence. The second accident occurred to a technician at the end of a day of intense work. He had to exit the cave to retrieve filming equipment. He went alone, without adequate boots and without his helmet secured. In these conditions and without experience, he fell down for five meters and suffering an head injury that resulted in confusion, disorientation, and temporary memory loss. He was accompanied to the hospital and discharged, fortunately, two days later without consequence.

4. Communications

An efficient system of communication is fundamental for ensure rescue support. We used a transceiver system constituted by a station allocated in the base camp. An omnidirectional antenna, vertical rod, was positioned in a high place in the cave. Each person must use a handheld transceiver battery powered and equipped with laringophonic microphone. The handheld transceivers were allocated a little space inside the cool-breathers to ensure their cooling. Indeed, the overheating of the radios occurred when used without protection from the heat, causing numerous failures.

5. New technologies

The Department of Bioengineering in the University of Milan (Italy) designed a telemetric system for monitoring of the vital sign. This system uses technology called "smart shirt" and makes it possible to monitor several parameters. Conductive fibers are incorporated into the design of a specialized T-shirt that can detect: heart rate, EKG, respiration, temperature, and more. The detected signals are transmitted via radio to a personal computer where they can be analyzed, noting if there are problems. The system that we used was experimental and capable to measure: heart rate, EKG, respiration, temperature and more. For the first time, it was utilized in caving activity. In this particular environment, it had demonstrated limitations especially on the transmission of data and requires placement of many radio repeaters and antennas. However, it was shown to be an interesting technology for surveillance of people employed in activities at risk in extreme environments.

6. Conclusions

Once again the caving meets science and experimentation by providing a valuable aid in the development of technologies and analysis of physical and human environment. On this occasion, the team used the beauty of the Naicas caves to get involved by tackling the risks. This could be the beginning of a new era where caving is not only adventure and geographical records, but a new way to experience a fascinating sport, even if not for all.

Acknowledgments

For this experience and studies, thanks are due to Naica Project, Speleoresearch & Films and Exploring Team La Venta

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EVOLUTION OF SPELEOLOGY IN COSTA RICA

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Abstract

Caving in Costa Rica started with the English adventurer John Cockburn in the 16th Century, when he tried to get back to England. He hired several Indians, who took him by sea to a particular point. The trip was in a canoe, and he was convinced to cross a rock tunnel, under an island, with a length of "one legua."

In 1902, in his Geographical Dictionary of Costa Rica, Félix Noriega mentioned, for the first time, the pit-caves of Barra Honda of Nicoya. In 1912 a school teacher visited some small caves in the center of the country, and in 1920 another teacher hiked up the Barra Honda hills and is shown 5 openings. In 1960 the French caver Robert Vergnes, in the company of a journalist, went to the Cave of Venado, where they explored approximately 330 meters. In 1967 Julián González M., of the Badalona Caving Group (Spain), arrived in the country and excited several members of the Costa Rica Mountaineering Club. In September of 1967 he descend the Pozo 110 (110 Pit) in Barra Honda. Months later the Grupo Espeleológico (GE) was formed; the first Costa Rican caving organization. In 1972 the Cave Research Foundation (CRF) explorated Barra Honda and this work, along with the explorations of the GE, lead to the declaration of these hills as a National Park (1974). In 1985 several ex-members of the GE got back together and formed the Asociación Espeleológica Costarricense (AEC). In 1987 AEC contacted the NSS and a 5 year caving program began, which yielded excellent results. During that same year the caves of Southern Costa Rica were explored by members of the Gruppo Grotte Carlo Debeljak, of Italy. In 1991 several cavers of the Societé Suisse d'Espeléologie (SSS) explored the caves of the Southern region and other sites.

During 1995 a group of young cavers created the Grupo Espeleológico Anthros (GEA). This group began studying and investigating the karstic phenomena in Costa Rica and other parts of Central America. In 2000 the GEA, with the support of INBIO (National Institute of Biodiversity), a started training program with formal courses of speleology and cave rescue. This group also edited its first book: *Introduction to Speleology in Costa Rica* (2001). At the first international seminar on karst management, held in Coban, Guatemala in 2003, GEA presented the idea of the ICEKE (Central American Institute of Karst and Cave studies). This project provided for a developing cave network of cavers in the Central American region. In 2006 the GEA, joined with the Honduras Speleological Union (UEH) and organized the first Central American Speleological Congress held at the Caves of Talgua, Honduras. This meeting set the basis of a common development of a regional speleology and consolidated the project (ICEKE) and its regional karst and cave registry. The speleology in Costa Rica has since developed links within the academic community and other mountaineering organizations, co-funding the official mountain sport federation FECODEM.

OVER 130 YEARS OF STUDY AND RESEARCH OF SCHELLENBERGER ICE CAVE AND THE ICE CAVES AT UNTERSBERG (BERCHTESGADENER LIMESTONE ALPS, GERMANY)

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Abstract

The German Speleological Federation has recently proposed setting up an archive for cave climate data that has been collected over the past 130 years in several German caves by local speleologists or caving clubs. The archive will insure that the data will not be lost and may be used for future studies on cave climate. These older measurements include a study carried out by Professor Eberhard Fugger in the 1870s-1880s in the ice caves of the Untersberg. They also include time series of ice-level measurements from the Schellenberger Eishöhle by Gustave Abel from the 1920s and by the former cave guide and speleologist Fritz Eigert (†) during his work from 1957–1986. The Schellenberger Eishöhle is in the German Alps near Marktschellenberg at 1570 m above sea level. The Eigert data was collected not only during the summer months, when the cave is accessible and open to the public as a show cave, but also during winter time when it is closed due to avalanche danger. Recently a new cave climate mearsuring program has been initiated at the Schellenberger Eishöhle.. These two reasons: data backup and new research in the Schellenberger Eishöhle, have led to analysis and presentation of the combined data.

Older archival data presents opportunities and problems which will be discussed on the example of the data from Schellenberger Eishöhle and the other ice caves at Untersberg. The difficulties lie mainly in the documentation of how and where exactly the data was collected and the time lag concerning the circumstances (morphology, anthropogenic influence, ice ablation) in the specific ice caves etc. The analysis of the ice-level measurements and the temperature data will be presented. The focus here lies on the magnitude of change in ice-level on an inter-, as well as an intra-annual, basis and on the relation between ice-level change and outside air temperature and precipitation. Theories concerning the processes, dynamics and controls on the ice-levels in the caves will be presented. The authors have attempted to reconstruct the history of the ice caves at Untersberg in the last 130 years.

JOSEF ANTON NAGEL AND HIS 1748 MANUSCRIPT ABOUT HIS CAVE EXPEDITION TO CARNIOLA (SLOVENIA) AND MORAVIA (CZECH REPUBLIC)

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Joseph Anton Nagel, a native German born February 3rd, 1717, in Rietberg/Rittberg, Westphalia, was educated as a mathematician at the "Hohe Schule von Paderborn." Possibly on recommendation by his country lord, Wenzel Anton Graf Kaunitz, Nagel was able to continue his studies at the University of Vienna. He found employment at the imperial-royal court where he worked in the administration, a position that did not challenge his profound mathematical talent.

Franz I, the Emperor of the Holy Roman Empire of German Nation (reigned 1745–65), ordered Nagel to study natural curiosities. This task took Nagel traveling throughout the Empire, first within Austria in 1747 and then for several week in the summer of 1748 to Slovenia and Moravia. Nagel reported about his findings in a 1748 manuscript kept at the National Library in Vienna entitled: "*Beschreibung deren auf allerhöchsten Befehl Ihro Röm: Kayl: und Königl: Maytt: FRANCISCI I untersuchten, in dem Herzogthum Crain befindlichen Seltenheiten der Natur.*" It has 98 double pages and was written in Current, the German office handwriting, now out of use. In 17 chapters, Nagel describes such important caves as the Adelsberger Grotte (Postojnska jama), the caves near Planina, the Cave of Corniale (Vilenica), the cave at Lueg (Predjama) in Slovenia, and the cave at Sloup and the Machocha abyss in Moravia. It also contained 25 sketches on 22 plates. So far it has been transcribed only once (in 1914) and has never been published in total (see Shaw, 1992). We are now working on a complete transcription of this manuscript, a High-German interpretation and an English translation. Slovene and Czech translations are to follow. A book is planned with the Slovenian Academy of Sciences. This manuscript was written in the spirit of the Period of Enlightenment and is entirely devoted to reasoning. As the last course of things Nature instead of God is assumed. In spite of a long preface devoting the manuscript to Franz I, Nagel also dares to advise about the style of government by stating "*God may preserve Your Majesty throughout many years in the most highest delighted well-being: so that those who love art and science can venerate a most gracious father in Your holy person for a long time and that the community may continuously experience the truth of the platonic sentence under your Majesty's glorious government: Since he (Plato) is calling such a republic the most fortunate that has a world-wise for king.*" It is the first manuscript devoted to a systematic cave oriented expedition and is singular in speleological history. It is also an example of the rise of scientific thinking. In addition to the manuscript Nagel left inscriptions in Latin in the investigated caves.

At around 1760 Nagel became mathematician of the Habsburgian court and teacher of Erzherzog Karl Joseph and traveled abroad to France, England, the Netherlands, Hungary and Tyrol. On initiation by Maria Theresia he began to work on a map of the city of Vienna (1770 and 1779) and its suburbs (published 1780/81). He served as the director of the physical cabinet from 1770 until after 1790. In 1775 he was appointed director of the Philosophical Faculty of the University of Vienna, a position he held until his retirement at around 1790. Nagel died in Vienna either in 1800 or in 1804.

1. Introduction

The science of speleology has many historical roots (Shaw, 1992). Caves were curiosities early on, but also object of mystery and places of evil. Bones, discovered in caves, proved the existence of "dragons" on the one hand but made a good source of income on the other hand by being mined for medical purposes (KEMPE et al., 1999). Sold as "*unicornu fossile.*" tons of bones of cave bears and other extinct animals ended as powder in drugstores or were used to cure sores of animals. Two caves in the Harz Mountains, Northern Germany, illustrate this double dichotomy specifically well: The Baumann's Cave that was the first to become a regular show cave protected by decree (April 10th, 1668, by the Dukes of Braunschweig-Lüneburg who also appointed the first official cave guide known: Jürgen Becker; for review see KEMPE et al., 2004) while the Einhornhöhle (Unicorn Cave) was exploited for its bone deposit (REINBOTH, 1978). Many early natural scientists, some of them without ever having seen a cave inside (e.g,. Kant: see KEMPE, 2008 not in references), were also concerned with cave formation, advancing the most curious hypotheses about it. Original reports were often copied and enriched with all sorts of stories. This was also the technique of Georg BEHRENS, who in 1703, published the "*Hercynia curiosa,*" one of the first books almost solely devoted to caves but full of prejudices and misconceptions. This approach to caves gradually disappeared in the Period of Enlightenment when natural scientists, among them many well educated but intellectually under-employed Protestant ministers, started to question the wisdom of traditional biblical views.

One of these early natural scientists was the mathematician Joseph Anton Nagel (1717-1800). He visited the caves of Carniola (Crain) in 1748 and left a hand-written manuscript about his visits, one of the few papers devoted almost entirely to cave and karst questions from the middle of the 18th century.

2. Biography

Joseph Anton Nagel was born in Rietberg (Rittberg), Westphalia on February 3, 1717, and received his training as a mathematician at the "Hohe Schule von Paderborn" (WURZBACH, 1869; SCHÖNBURG-HARTENSTEIN, 1987; KILLY & VIERHAUS, without year). Possibly on recommendation by his country lord, Wenzel Anton Graf Kaunitz (since 1764 Reichsfürst of Kaunitz-Rietberg), who held various offices at the court in Vienna since 1737, Nagel was able to continue his studies at the University of Vienna. After a short stay at Brünn (Brno) and an administrative position at the Upper-Hungarian salt mine of Soowar, he found employment at the imperial-royal court where he worked in the administration, a position that did not challenge his profound mathematical talent.

Franz I (reigned 1745–1765), the Emperor of the Holy Roman Empire of German Nation (not to be confused with Franz II, the last Emperor of the Holy Roman Empire reigning 1792–1806, who became Franz I, the Emperor of Habsburgian Austria, in which function he reigned 1804–1835) ordered Nagel to study natural curiosities, finally a task up to his talents. This took Nagel on travels throughout the Empire, first within Austria in 1747 and then in Crain (Slovenia) and Moravia in summer 1748. The three travel reports of his travels in the Ötscher Mountain in 1747, about his travel to Crain and Moravia in 1748, and about his journey to Holic/Hungary were not published at the time (see SHAW, 1992). Nagel's account of the earthquake of 1768 was, however, published.

During the several-weeks-long journey to Slovenia in summer of 1748 Nagel visited many caves and left his signature in at least four of them. Back in Vienna Nagel dutifully wrote an extensive report addressed to the Emperor (NAGEL, 1748). The manuscript is kept at the National Library in Vienna entitled: "*Beschreibung deren auf allerhöchsten Befehl Ihro Röm: Kayl: und Königl: Maytt: FRANCISCI I untersuchten, in dem Herzogthum Crain befindlichen Seltenheiten der Natur.*" ("Description of the curiosities of nature of the dukedom Crain studied by highest order of his Roman Emperial and Royal Majesty, Franz I.").

At around 1760 Nagel became mathematician of the Habsburgian court and teacher of Erzherzog Karl Joseph and traveled abroad to France, England, the Netherlands, Hungary and Tyrol. On initiation by Maria Theresia (the wife of Franz I) he began to work on a map of the city of Vienna (1770 and 1779) and its suburbs which was published as a copper etching in 1780/81("*Ground plan of the Imperial-Royal Residence City Vienna, its suburbs and neighbouring towns*"). He also produced a map of the inner city of Vienna in 1774. Furthermore, he served as the director of the physical cabinet from 1770 until after 1790. In 1775 he was appointed director of the Philosophical Faculty of the University of Vienna, a position he held until his retirement at around 1790. Nagel died in Vienna either in 1800 (SHAW, 1992) or in 1804 (KILLY & VIERHAUS, without year).

3. Nagel's 1748 Report

The 1748 Nagel manuscript (MS N. 7854) has 98 double pages and was written in Current, the German office handwriting, now out of use. In 17 chapters, Nagel described such important caves as St. Canzian (Rak valley, Zelške jame), the "Gotscheer" caves (Kočevje), the three weather holes at Ober-Gurck (Krka), the curious spring at Ober-Laibach (Vrhnika), the cave at Planina / Kleinhäusler Grotte as the source of river Untz (Unica) (Planinska jama), the Adelsberger Höhlen (Postojnska jama), the Magdalenen-Grotte (Črna jama), the Lueger Höhle (Jama pri Predjami), the cave at St. Servolo (Sveta jama or Socerbska jama), the cave at Cornial (Vilenica), plus the cave at Sloup in Moravia and the huge Macocha sinkhole. The manuscript also contained 25 sketches on 22 plates. So far it has been transcribed only once (in 1914) and has never been published in total (see SHAW, 1992). We are now working on a new transcription of this manuscript, a High-German interpretation, and an English translation. Slovene and Czech translations are to follow. A book is planned with the Slovenian Academy of Sciences. This manuscript is a profound example of the spirit of the Period of Enlightenment because it is entirely devoted to reasoning. As the last course of things, Nature -instead of God- is assumed. In spite of a long preface devoting the manuscript to Franz I, Nagel also dares to advise about the style of government by stating "*God may preserve Your Majesty throughout many years in the most highest delighted well-being: so that those who love art and science can venerate a most gracious father in Your holy person for a long time and that the community may continuously experience the truth of the platonic sentence under your Majesty's glorious government: Since he* (Plato) *is calling such a republic the most fortunate that has a world-wise for king.*" It is the first manuscript devoted to a systematic cave oriented expedition and is singular in speleological history. It is also an example of the rise of scientific thinking.

The manuscript has the following chapters (German in the original spelling; numbers refer to the manuscript pages, 1=front, 2=verso):

02.2Vorrede (Introduction)

08.1Von dem Circknitzer See (of Lake Cerknica)

23.2Von der Hölen bey St. Canzian (of the caves of St. Canzian, i.e. the Rak Valley)

28.2Von der Gotscheer Hölen (of the Cave of Kočevje)

33.1 Von dreyer Wetter-Hölen bey Ober-Gurck (of three weather cave near Ober-Gurk)

36.2 Von einer wunderlichen Quelle bey Ober-Laibach (of the wondrous spring near Ober-Laibach)

40.1 Von der Hölen bey Planina (of the cave near Planina)

42.1 Von der Adelsperger Hölen (of the cave near Adelsberg)

47.1 Von der Magdalenen-Höle ohnweit Adelsperg (of the Magdalena-Cave near Adelsberg)

50.1 Von der Lueger Höle in Inner-Crain (of the Lueg cave in Inner Carniola)

53.2 Von der Höle bey St. Servolo (of the cave of St. Servolo)

61.1 Von der verwunderlichen bishero unbekanten Höle bey Cornial (Of the wondrous and up to now unknown cave neat Cornial)

69.2 Von einem besonders gearteten Nuß-Baum (of a special nut tree)

72.1 Von den Muschlen, so man Dattili del Mare nennet (of the bivalve, called dates of the sea)

77.2 Von der bey dem Dorff Schloup in Mähren gelegenen Höle (of the cave near the village of Sloup in Moravia)

92.2 Von einem in Mähren befindlichen Abgrunde die Machoza genanet (of an abyss in Moravia called Macocha)

Figure 1: The entrance of the Planinska jama as seen by Nagel in 1748 (Nat. Libr. Vienna).

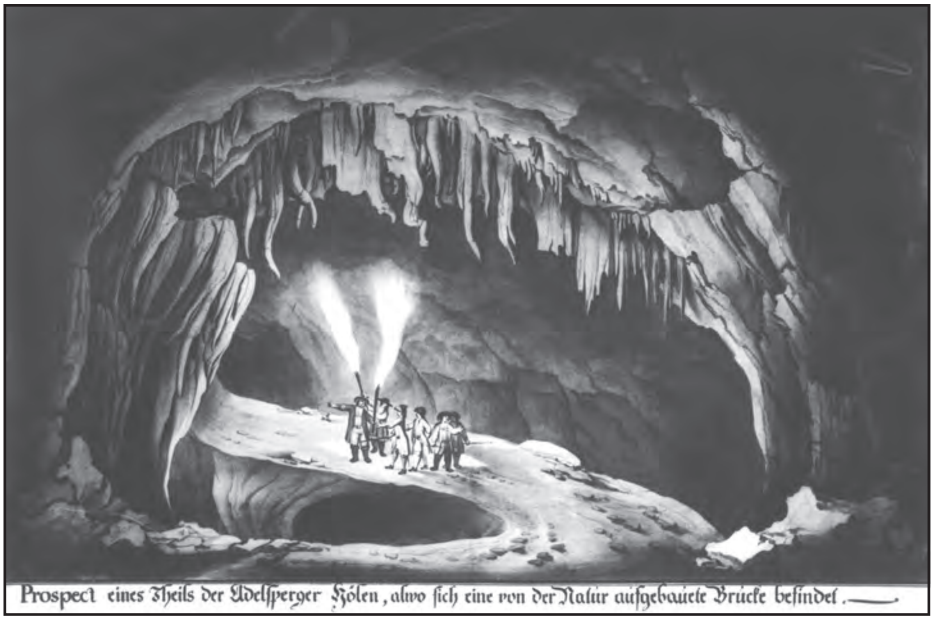

Figure 2: The natural bridge in old part of the Postojnska jama as seen by Nagel in 1748 (Nat. Libr. Vienna).

Figure 3: View into the Vilenica Jama as seen by Nagel in 1748 (Nat. Libr. Vienna).

In the beginning of his report, Nagel clarified some of the tales in VALVASOR'S epic chronicle (1689) that, as he explains, rest on wishful thinking, unproven hearsay and superstition but not on reality. In many cases he corrected doubtful passages by own observations or by factual logic. He lists the following examples of distorted facts:

- catching crabs by whistling;
- hunting „Pilliche“ (i.e., Bilche, Siebenschläfer, engl. dormouse, *Glis glis*) with boots and coats spread out on the ground;
- attracting leeches in Lake Cerknica (Cerkniško jezero) by singing;
- making „Heimchen“ (i.e., the house cricket, *Acheta domestica*) appear by magic spells;
- cemeteries on the top of Beuscheza Mountain and on the Steiner Alpe;
- the occurrence of eye- and featherless ducks after floods in Cerkniško jezero that can see and fly after two weeks again (which probably is a distorted early account of the endemic *Proteus anguinus*);
- that the condensed fog drifting from caves represents devilish smoke.

He reacted to such absurdities with the appeal that the authors should refrain from pleasing eulogies and distorting flourishes in "*history books.*" Rather they should describe the reality and stick to truth.

Nagel dealt with famous Cerkniško jezero in great detail. Among other facts he described:

- Changing water levels – up to complete dryness – and their dependence on precipitation;
- the existence of numerous connections between the lake bottom and the conduits in the karst mountains;
- artesian bursts of water after torrential rains;
- water-level-limiting "swallow holes";

97.2 Catalogus (catalogue of collected items) and he discussed the connectivity of the water courses above and below ground. The observed interdependencies and the conclusions drawn from them are finally packed together into a logical hydraulic model including abstracted inputs and outputs and water-level-depending discharges. Furthermore he postulated underground connections between caves and Cerkniško jezero in the order: Cerkniško jezero – Cave of St. Canzian (Rak valley, Zelške jame) - Piuka - Adelsberger Grotte - Kleinhäusler Grotte - Untz.

Nagel dealt with the phenomenon of noisily flowing water masses in karst cavities as well as with the thunder of so called "weather holes" (Hexenlöcher, Coprniška jama). He continued to describe his observations in the Karst, specifically about its caves, sketching their accessibility, spatial dimensions, length, divisions into compartments and remarkable flowstone formations.

These descriptions were flanked by reports about other natural curiosities, such as a special nut tree (i.e. a tree with an extremely short vegetation period), the *Dattili del Mare* (marine bivalves that can drill into limestone) and a waterfall at Freistritz in Upper-Crain.

4. Nagel's Cave Inscriptions

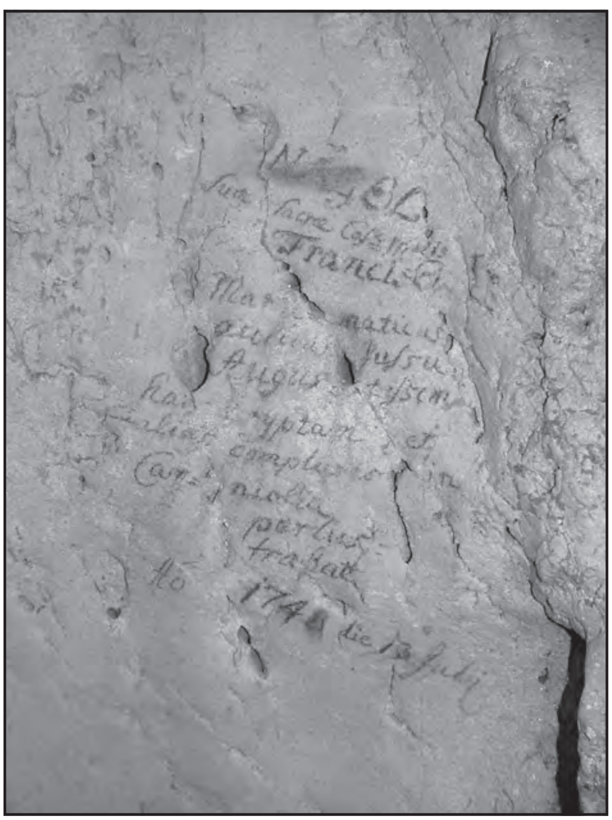

Figure 4: Photograph of Nagel's inscription in Jama pri Predjama.

In addition, Nagel has left his name in at least four different caves. Three of these still exist but the fourth, the only one he admits to have written (in Velinica), is either lost or has not been located as yet. The longest inscription is known from Jama pri Predjama (Fig. 4; KEMPE et al., 2006). It is in Latin and reads: "*NAGEL suae sacrae Caesareae Majestatis* (abbreviated) *Franci. I Mathematicus aulicus Jussu Augustissimi hanc cryptem et alias complures in Carniolia perlustrabat A//o 1748 die 13 Julii* " ("Nagel, His Holy Emperor and Majesty Franz I Mathematicus on order of his highest (lord) (has) this crypt and others many in Carniola (Crain) investigated Anno 1748 day 13 July). HABE (1981) reported that the inscription had first been identified by the Coleopterologist Egon Pretner. Comparison of Habe's 1981 picture with ours shows that the inscription was damaged in the meantime: The letters NAG suffered substantial smear. Obviously someone touched the inscription accidentally while pointing at it. The inscription in Postojnska jama is rather short (HABE, 1986; KEMPE et al., 2006), giving only name and date of visit: *"NAGEL 1748 19 Julii"*. The one in Sloup Cavern reads (Fig. 5): "*NAGEL Mathematicus 1748 Iussu Imperatoris Francisci I hanc cryptam perlustrabat*" ("Nagel, Mathematicus, on order of Emperor Franz I has investigated this cave").

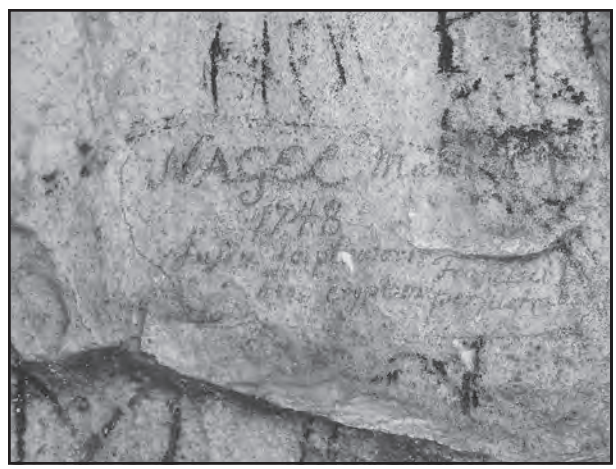

Figure 5: Photograph of Nagel's inscription in Sloup Cavern.

5. Conclusions

A citation from the manuscript may illustrate the spirit in which Nagel approached his science: "*Among those water bodies, that have caused admiration in the world due to their unusual course or other incidentally occurring circumstances, one may count the lake near the market town of Cerknica in Middle Carniola. In nearly all debates and books that relate to the dukedom of Carniola this water must flow from mouth and quill. Therefore I will put it – as the most widely known natural wonder of this country – at the beginning of my description.*

But because many people have (….) strange thoughts about it I am determined not only to relate its curiosities in the present paper but also if possible to discuss and to point out that about which people tend to wonder so much, as it is necessitated by the actual properties. (I will reach this) *not by far-fetched fantasies about an unproved subterraneous structure such as others did. Rather I will show how one can deduct from a few experiences* (observations) *everything else irrefutably and that one conclusion must follow necessarily on the other*." Thus he uses his mathematical principals on geological and ecological problems. There is no room for superstition, reference to biblical accounts (like they appear in many writings of his contemporaries) or reproduction of hear-say. In all what Nagel writes he appears very modern. He is also one of the first to calculate flowstone growth by observing flowstone thickness on old inscriptions. Nagel's manuscript is therefore not only important for the early history of cave and karst science but for the science history as such.

Acknowledgement

We are indebted to the National Library, Vienna, for providing copies of the Nagel manuscript and the permission to edit it. There are many colleagues who contribute to this project, first of all Andrej Kranjc and Maja Kranjc (both Postojna) and Hans-Peter Hubrich and Horst-Volker Henschel (both Darmstadt). We are also grateful to Trevor Shaw for his persistent encouragement in these historical studies.

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EARLY CAVE VISITS BY WOMEN AND THE TRAVEL ACCOUNTS OF LADY ELISABETH CRAVEN TO THE GROTTO OF ANTIPAROS (1786) AND JOHANNA SCHOPENHAUER TO PEAKS CAVERN (1803)

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Even though men wrote the earliest caving reports, women were also among early cave visitors. Two sisters-in-law, both a Mrs. Meyer, were the first female cave visitors known by name to the authors; they visited the Baumann's Cave, Harz, on July 28, 1692. A few cave inscriptions of the 18th century also document early female visitors. Education in classical history and mythology -where caves and grottos played a prominent role- was the rule in the 18th century. Wilhelmine of Bayreuth (1709–1758), inspired by the novel "*the Adventures of Telemach*" by Fénelon, created the first baroque landscape garden in Sanspareil/Frankonia (completed in 1749) that included numerous grottoes named after places in the novel. Wilhelmine also had her portrait painted sitting in a grotto. The lack of academic education for women in the 18th century is the reason why there are no early scientifically oriented cave reports written by women. Nevertheless, the first woman who ever obtained a PhD degree from a university, Dorothea von Schlözer (August 25, 1787, University of Göttingen), studied natural sciences and visited even the deepest mines in the Harz. The first reports of cave visits by woman appeared in travel literature in the late 18th and early 19th century. The oldest of these accounts are those of Elizabeth Craven (1750-1828), who visited the Grotto of Antiparos, Greece, in May 1786, and of Johanna Schopenhauer (1766–1838), who visited Peaks Cavern, Yorkshire, in the summer of 1803. Both women belonged to the intellectual elite of their time and have very interesting biographies.

1. Introduction

The earliest reports of cave visits are of three categories: (i) Site descriptions in geological catalogs (e.g., mentioning of the Baumann's Cave in Toll, 1636), (ii) objects in textbooks on natural sciences or geography (e.g. the Unicorn Cave in LEIBNIZ, 1749, the Zoolithen Cave in ESPER, 1774, the Baumann's Cave in MERIAN, 1650 and 1654; compare also KEMPE et al., 2004) and (iii) in travel literature, written either by travelling scientists (e.g., the physicians KUNDMANN, 1737, and ZÜCKERT, 1763, see KEMPE, 2004, und KEMPE et al., 1999) or by people on an educational trip (e.g., UFFENBACH, 1753/54). All of these accounts were written by men: This does not, however, exclude the fact that women were also among early cave visitors. BEHRENS (1703, p. 8) even makes fun of female visitors to the Baumann's Cave: „*They look like miners or wagoners as they follow the guide with the borrowed outfit uphill where the cave is. All the while they laugh at each other and that all the more if some of the company look especially cute, just as I saw a courageous and curious damsel going to the cave about whose poses even the most grumpy and melancholic person could have laughed himself to death…*". KUNDMANN (1738) reports that one of the difficult climbs in the Baumanns's Cave was made easier because "*it was cumbersome for the damsels in their long skirts, so that boards were placed on the left side which made the passage somewhat narrower but also more comfortable*". According to others cave visits were much too dangerous for women and JAKOB REISELSBERG (1820) versed:

Für Frauenzimmer taugt sie nich, -
Genug wenn ich´s erzähl,
Wär es nicht schad, wenn Hälschen bricht
Ein´ Schöne wegen Höhl.

"*They are no good for damsels, enough if I tell about them; it would be a pity if a beauty broke her neck because of a cave.*"

The first female cave visitors known by name to the authors were two sisters-in-law, both named Mrs. Meyer, who visited the Baumann's Cave, Harz, on July 28th, 1692. One was the wife of Nikolaus Meyer, vice director from Halberstadt, and the other the wife of Dr. Albert Meyer from Bremen (HOFFMANN, 1692). The other ladies in the party remained unnamed. A few cave inscriptions of the 18th century also document early female visitors.

2. Wilhelmine von Bayreuth

Knowledge of Greek and Roman history and classical mythology was prominent in education of the 18th century. Caves and grottoes play an important role in this context, not only for the rising class of educated citizens but also for the reigning nobility. Wilhelmine of Bayreuth (1709–1758), the elder sister of the Prussian King Frederick the II (the Great) married Margrave Friedrich of Bayreuth November 20, 1731. She set out to make Bayreuth a center of culture. Even today her rococo theater is one of the tourist attractions. Less known is that she planned the first baroque landscape park as well. For this she chose an 800 m long, cavernous, rocky dolomite ridge near the old castle of Zwernitz, between Hollfeld and Kulmbach. There her architect Joseph Saint-Pier created her "*Sanspareil*" ("*without comparison*"; completed in 1749), by using the sites described in the novel "*the Adventures of Telemach, Son of Ulysses*" (written by F. FÉNELON, e.g., 1782) as a motto. Thus many of the grottos were named after places of Greek mythology. Grottos were a fashion and one of the best known portraits of Wilhelmine, painted by Antoine Pesne, shows her sitting in a grotto (Fig. 1).

Figure 1: Portrait of Wilhelmine of Bayreuth in the habit of a pilgrim and sitting in a grotto, 1750 by Antoine Pesne.

3. Dorothea von Schlözer

The lack of academically educated women in the 18th century is the reason why there are no early scientifically oriented cave reports written by women. Nevertheless, the first woman who ever obtained a PhD degree from a university, Dorothea von Schlözer (1770–1825; dissertation Aug. 25, 1787, University of Göttingen), studied mineralogy (SCHLÖZER, 1923). She was examined in geology, technology of mining and mathematics. Reportedly she had visited the deepest mines in the Harz, even the Samson mine at Andreasberg, 220 Lachter (ca. 440 m) deep. If she also visited the caves in the Harz, however, is not, known.

4. Lady Elisabeth Craven and the Grotto of Antiparos

Consequently we find the first reports of cave visits by women not in the scientific but in the travel literature. This proliferated in the 2nd half of the 18th century when the "grand tour" became part of the education of the well-to-do. The oldest cave visit report we have been able to trace is that of Lady Elizabeth Craven, who visited the Grotto of Antiparos, in May 1786. Antiparos is a small island in the Aegean Sea (now Greece) and its cave is about 100 m long and 30 m wide, leading steeply down. It became known by visits of the French Ambassador to Constantinople, Marquis des Nointel, at the end of December 1673, and of Monsieur TOURNEFOURT (1717). Two accounts of Nointel's visit exist, the first by Cornelio Magni, which was published by KIRCHER in the 3rd ed. of his "*Mundus subterraneus.*" 1678. Nointel's own report was published as late as 1892 by OMONT. The next one to visit the cave was Marie-Gabriel-Florent-Auguste Comte de CHOISEUL-GOUFFIER (27.9.1752 - 17.8.1817) who published two opulently illustrated folio volumes entitled "*Voyage pittoresque de la Grece*" (1782,1809, and 1822), which included three magnificent copperplates (probably the best cave pictures published up to then) showing entrance, interior and map plus section of the cave (Fig. 2). They were later copied by ROSENMÜLLER & TILESIUS (1805) and BERTUCH (1807) without citing their source.

Lady Elizabeth herself was an unusual and beautiful woman (Fig. 3), born December 17, 1750, daughter of the Earl of Berkeley and the Lady of the Bedchamber of the Princess of Wales in England. Raised by governesses, she married Earl William Craven at the age of 16. The

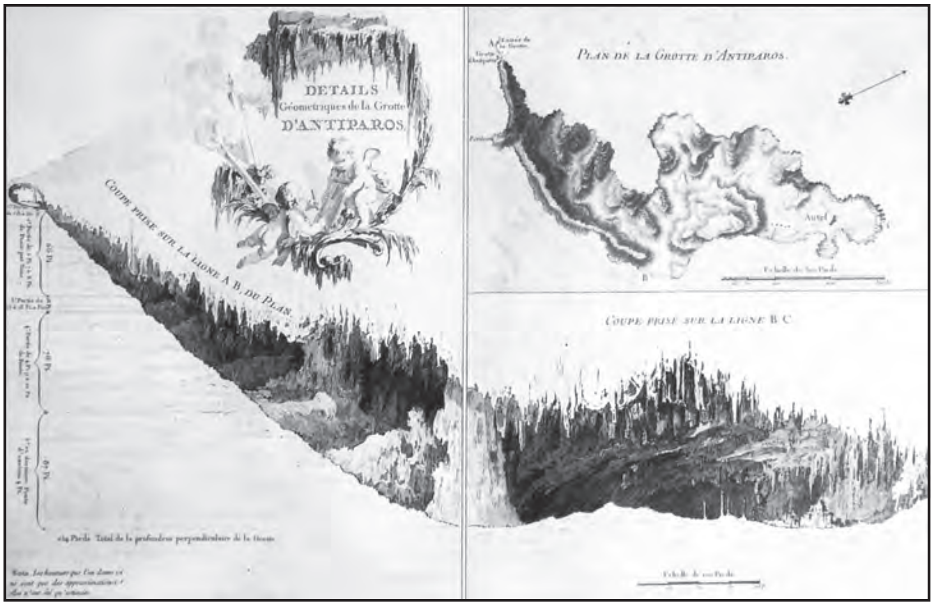

Figure 2: Map and section of the Grotto of Antiparos, copperplate, Choiseul-Gouffier (1782). The map has scale, (in Parisian feet) and north arrow. The etching does not name surveyor, drafter, or sculptor (original: Hochschul- und Landesbibliothek Darmstadt).

wife of the Margrave had died, married the Margrave in 1791. For a few months, she even became the owner of Wilhemine's Sanspareil. The Margrave, however, abdicated that same year, partly on the advice of Lady Craven. The couple moved to England, where they lived for the remainder of their lives and where Elizabeth wrote her autobiography (CRAVEN, 1826). Alexander died in 1806 and Elizabeth in 1828. The full text of her description of the Grotto of Antiparos is reprinted in KEMPE et al. (2005).

couple had seven children within 13 years before, after various affairs, they split without a divorce. Elizabeth was a talented author; her play, "*The Sleep Walker*," was first shown in 1780. We find her in Paris in 1785, where she met the Margrave of Brandenbourg-Anspach, Christian Friedrich Karl Alexander. From Paris she departed on a grand tour through Europe, relying on the hospitality of noble families and on the services of her servants travelling with her. This journey led from France, where she also visited the Vaucluse, to St. Petersburg, through Crimea to Constantinople. There, as a woman, she was allowed to obtain insight into Turkish harems. In Constantinople she met Count Choiseul-Gouffier, who invited her to join him on his private frigate and to descend into the Grotto of Antiparos as its first woman visitor. Lady Elizabeth reported on her travels and the visit to Antiparos in letters addressed to the Margrave, letters she signed as "*your most affectionate sister.*" These letters were published in several languages in 1789 under the title: "*A Journey through the Crimea to Constantinople. In a series of letters from the Right Honourable Elizabeth Lady Craven, to his Serene Highness the Margrave of Brandebourg, Anspach, and Bareith.*" accompanied by copper etchings (Fig. 4). The report (Letters 53 and 54) contains personal impressions of the visit and a few remarks about the speleothems and their genesis. The volume had at least two English editions (1789a,b) and German (1789c), French (1789d) and Dutch translations. After her travels Lady Craven moved to Anspach and operated the theatre there, writing further screen plays, and finally, after both her husband and the

Figure 3: Portrait of Lady Elizabeth Craven (1778) by George Romney (1734–1802); painting, Tate Gallery (old postcard: collection S. Kempe).

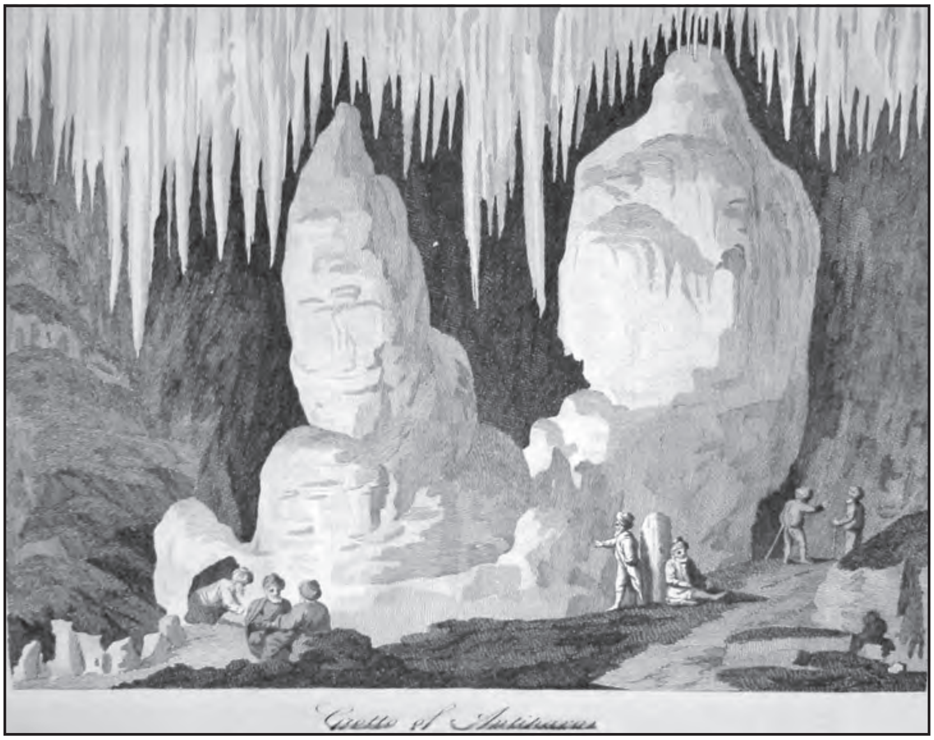

Figure 4: Copper etching of the big stalagmite of the Grotto of Antiparos from the Dublin edition of Craven (1789b) (original: collection S. Kempe).

5. Johanna Schopenhauer and Peaks Cavern

The second oldest description of a cave visit by a woman is that of Johanna Schopenhauer to Peaks Cavern. Johanna, born 1766, was the daughter of a well-to-do German merchant family from Gdansk and obtained a thorough education as a child. She spoke English, Polish, and French and was instructed in natural sciences (SCHOPENHAUER, ca. 1985). In 1787 she and her anglophile husband, the merchant Heinrich Floris Schopenhauer, 20 years her senior, travelled to England for the first time. Their plan was to give birth to their child there so that it would automatically obtain English citizenship. However, the parents had second thoughts and travelled back to Gdansk in the winter, where Johanna gave birth to Arthur, who became a famous philosopher. Johanna's second child, Adele, also obtained a certain amount of fame as an artist of shadow portraits. On her second journey to England in 1803/04, Johanna visited Peaks Cavern alone with a tourist group. Like the Grotto of Antiparos, the cave was already a well known tourist attraction. Peaks Cavern near Castelton in Yorkshire was first mentioned in the literature in 1211 (SHAW, 1992). It has an impressive entrance with a river flowing out of it. It is the only cave to which ROSENMÜLLER & TILESIUS (1799 and 1805) devoted two chapters. Today the cave is 24 km long, but the part shown to tourists measures only 800 m. Johanna's report of the visit (see also KEMPE et al., 2005) was published in 1814 in her book „*Erinnerungen von einer Reise in den Jahren 1803, 1804 und 1805*" (SCHOPENHAUER, 1973). The report is mainly an account of Johanna's personal impressions. Apart from the length of a few cave passages, not much scientific information can be obtained from it. On the other hand the living conditions of the inhabitants in the vast entrance hall were critically commented on. After the death of her husband and a quarrel with Arthur about the inheritance, Johanna moved with Adele to Weimar, the "*Athens of the North*" in 1806, where she established herself as a writer (Fig. 5). Goethe paid her a visit on October 20th, accompanied by his newly-wed wife, Christiane, formerly

Figure 5: Portrait of Johanna and Adele Schopenhauer (after the original at Stiftung Weimarer Klassik).

his "*bed treasure*" for 18 years. Johanna was the first to meet her unconditionally and became famous in the literature by stating: "*I think, that I can give her a cup of tea if Goethe gives her his name.*" Apart from her travel book Johanna wrote short stories and novels ("*Gabriele*") and was a praised novelist of her time (SCHOPENHAUER, 1830/31). She died in 1838 in Weimar.

6. Conclusions

Even though women apparently were regular visitors to the Baumann's Cave at least since the middle of the 17th century, we do not find any reports by women about their cave experiences. Only after women discovered travelling and the possibility of expressing themselves by writing travel books, were the first accounts of cave visits found. Elizabeth Craven, a rich noblewoman, was one of the earliest woman writers to publish an account of her travels in 1786. In her text, she takes great pride in being the first woman to descend into the Grotto of Antiparos. Thus she must have had a sense of adventure. Nevertheless, she reports on the speleothems in a rather factual manner. Her account is quite in line with similar reports by male travelers at the time. Johanna Schopenhauer's report on Peaks Cavern is much shorter and dates to a time when regular tourism was already well established in England. For her, the visit was not so much an adventure as a personal experience. Compared to the amount of travel literature available, these two reports appear to be rather unique, and even today books and other texts on caves written by women remain rare.

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VISITOR INSCRIPTIONS IN THE OLD PASSAGE OF POSTOJNSKA JAMA (ADELSBERGER GROTTE) / SLOVENIA

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Postojnska jama, Slovenia, was known for centuries as "Adelsberger Grotte". Until 1818, when the access to the present day tourist cave was discovered, only a small part was known, including Imenski rov, the "Name Cave". There we documented ca. 400 inscriptions and another ca. 250 in the historic part of Predjama (Lueger Höhle); twenty of them are correlated with independently historically known persons. Johann Melchior Ott(o) left his name in 1642, the oldest signature of a historic person as yet documented in a cave. He was a painter in the service of Johann Anton zu Eggenberg (1610-1649) the owner of the Castle of Adelsberg. The second oldest is that of Josef Anton Nagel 1748, a German mathematician in service of Emperor Franz I. who also left also an elaborate signature in Latin in Predjama and in Sloup Cavern, Moravia. All other inscriptions of historic persons date after 1800. Among them are those of three personalities that shaped the history of the first decades of Postojnska jama as a show cave: Franz Graf von Hohenwart, Joseph Petsch Ritter von Löwengreif and Alois Schaffenrath (who also singed in Predjama). They signed several times in Imenski rov and elsewhere in the cave. The historically known and "noteworthy persons" represent people of the nobility and/or were state employed. Overall, the signatures shed light on the section of society that was able to travel and interested in natural sciences.

1. Introduction

Slovenia - with >7000 caves - is one of Europe's outstanding karst regions. Two cave systems have attracted historically large numbers of visitors: Postojnska jama (historically known as "Adelsberger Grotte") and Predjama ("Lueger Höhle"), playing also a prominent role in the early history of speleology (e.g., Shaw, 1992). In these caves, several thousand visitors documented their presence over the last five centuries. In addition to names, dates or initials, short prayers, Christian symbols and, more rarely, coat of arms, small sketches or short texts were left on the cave walls. Because of the varying shape and quality of these walls and their flowstone cover inscriptions occur in groups (termed panels; see example Figure 1). Most of the inscription are, however, younger than 1818, when Luka Čeč discovered in Postojnska jama the entrance to new sections of the cave forming today the bulk of the of 20.57 km world-famous show cave (Kranjc & Kempe, 2007). Specific sets of these inscriptions were discussed in Kempe et al. (2004) and Kempe (2005) und Kempe et al. (2006a). Older inscriptions can only be found in Imenski rov "Name Passage" (Kempe, 2003) and in Črna jama ("Black Cave"). Those in Črna jama are, however, almost illegible due to the pronounced weathering caused by seasonal exchange of air, while those in Imenski rov are mostly preserved beautifully. Due to its easy accessibility, this passage was visited early on. Volpi (1821) and Hohenwart (1830, 1832 a,b) published copperplates with inscriptions copied by Alois Schaffenrath from Imenski rov. There, the oldest date given is 1213, often quoted as the oldest cave inscription world-wide. However, in our photographic documentation of the 400 inscriptions on 17 panels in Imenski rov, conducted in February 2007, we were not able to locate this inscription and nobody else apparently knows where to find it. Because Schaffenrath copied Arabic numerals, it is highly doubtful that it is an original 13th century inscription because at that time dates were written with Roman numerals. Most probably Schaffenrath simply misread the date, with 1575 as a possible alternative. The oldest clearly readable date that we found was 1412. But even it is of questionable authenticity because of the type of numerals used: In 1412 the Arabic "4" should have been written as the upper half of an "8". In February 2007 we also documented ca. 100 inscriptions in 22 panels in the historic part of Predjama situated just below the castle of Lueg, today Predjamski grad. Here we report about some of the Christian inscriptions and about those signatures that can be related to visitors that are also known from other historic sources, all in all 20 persons. This is the concept of "noteworthy persons" (Wurzbach, 1856-1891), designating people of historic importance.

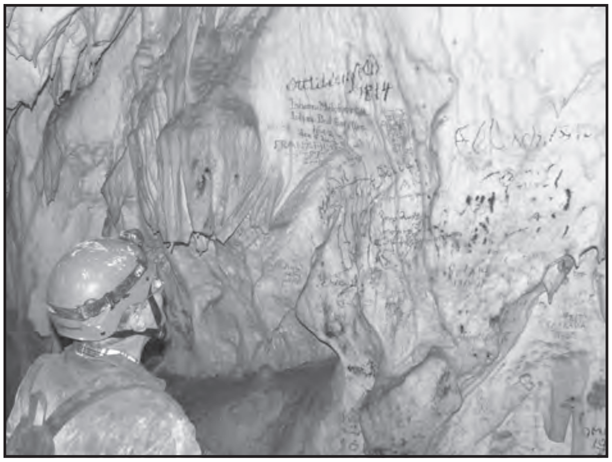

Figure 1: Flowstone-framed detail of Panel 12 of the Imenski rov, Postojnska jama, with inscriptions of "Ottilenfeld 1814, "Corrada," "Franz Himer. Drechslergesell aus Baiern 1634," "Johann Melchior Ott Johan Paul Sarcher 1642 den 6. Iuni" with the coat of arms of the Eggenbergs, their employers, among others (for scale: Hans Peter Hubrich).

2. Nature of Inscriptions

The nature of the inscriptions varies widely, the following elements may be present: Initials, family name, Christian name or name and title of a profession, military grade or unit designation, town of residence or place of birth, year, precise date, Christ monogram or combination of initials with the latter, crosses or other religious signs or short prayers, coat of arms, union sign of craft, and additions of all sorts. Inscriptions may be in German, Slavic languages, French, English, Italian, Latin and possibly Greek.

The majority of the inscriptions are written with Latin letters, variant "Roman-Italics (Antiqua-Kursive)", few with Latin block letters, others in German Current, a form of handwriting with letters much different from those of the familiar Latin letters. Current (or the late 19th and early 20th century "Sütterlin") was in use throughout German-speaking areas for official documents and private correspondence until forbidden by Hitler in 1941. We only found dates (day, month, year) in Arabic numerals in the manner called "Dürer " or younger. The version "Dürer" came into use beginning with the 16th century in Germany and most probably also in Austria. No Latin numeral date was noticed.

Also writing material varied widely: Charcoal, red crayon (Rötel), metal pencil (lead, tin or silver), graphite pencil, copy pencil or the soot of an open flame were used. Inscriptions by scratching are rare (Imenski rov, panels 5, 13, 17).

Deciphering these texts can be difficult due to bad handwriting or the use of inadequate writing material. Some inscriptions also suffer from later obliteration by overwriting, smearing or by the diffusion of color, from fading or the encrustation of later flowstone deposits. Sometimes the same name occurs both in Latin and in Current lettering and in a few cases calligraphic approaches are apparent. Frames around inscriptions and flourishes are another feature sometimes noted. Specifically descending wavy lines or extensions of the last letter were fashionable.

3. Christian Inscriptions

Many of the early inscriptions are classified as "Christian". A short prayer "gnad Dir Gott" (God my grace you) is found several times (Fig. 2) as well as the Jesus monogram "IHS". It is a well kown "Nomina sacra" abbreviation (e.g. Traube, 1907) derived from the Greek spelling of Jesus: Iota Eta Sigma Omicron Upsilon Sigma. The two first letters retain their Greek form, while the S is written with a Latin S and not with the Greek Sigma (Σ). Likewise Christus, spelled Xi Rho Iota Sigma Tau Omicron Sigma, was abbreviated to XP, XPI or XRS and combined to the so called Labarum, ☧ used by the Christian Roman emperors as field standards.

IHS and Labarum are often combined, with the Labarum resting on the horizontal dash of the H as if standing on an altar (Fig. 3). Later the IHS was used by holy Íñigo López de Loyola (1491–1556) and became the sign by the Jesuits. Apart from the original meaning many others have been attributed IHS. Most common is "in hoc signum" vinces (in this sign you will win), referring to the dream of Constantine the Great before the battle at the Milvian Bridge in 312 AD. The "v" is sometime added below the monogram in the form of the three crucifix nails. The Jesuits also saw "Iesus Hominum Salvator" ("Jesus, Savior of Mankind") or "Iesum Habemus Socium" (we have Jesus as Companion), while the layman interpreted it as "Jesus, Heiland, Seligmacher" (Jesus, Saviour, Beatifier). It therefore was a very common sign, present in almost all Roman Catholic churches, including the one in Postojna.

The most enigmatic finding in Postojna is, however, the reversed IHS form, i.e., SHI (Fig. 4). At first it was thought to be an error, but we found this reversed form also on a decorative architectural spolia from the cathedral in Mexico City, on display in the Museum of the Great Pyramid. An explanation for this usage of the nomina sacra has not been found yet.

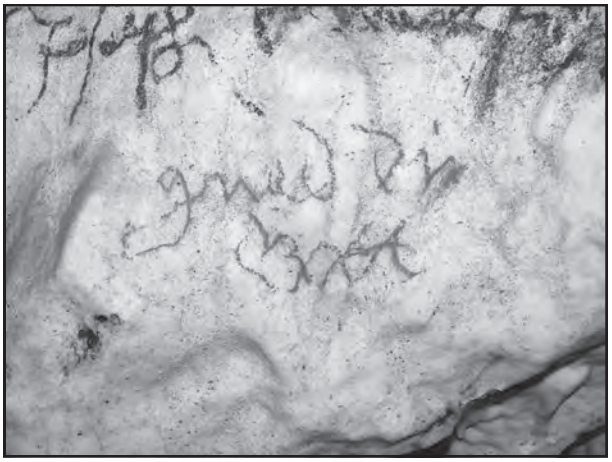

Figure 2: The short prayer "gnad dir Gott," a detail of Panel 11 of the Imenski rov, red crayon, in another examples associated with dates from the end of the 16th century.

Figure 3: The typical Jesus monogram "IHS" with the labarum rising from the center of the H, 1796, a detail of Panel 2 of the Imenski rov, red crayon.

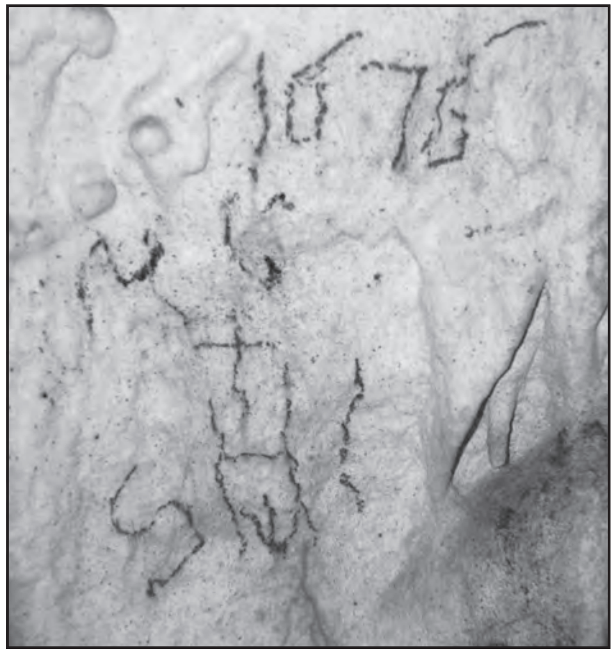

Figure 4: The reversed form of Jesus monogram "SHI" with a cross and three nails, 1676, a detail of Panel 10 of the Imenski rov, red crayon.

4. Signatures of Noteworthy Persons

So far, we were able to correlate 20 of the names with independently historically known persons with those of Bellegarde, Kotze, Mihanović and Karl von Zur remaining only tentative.

The oldest signature of an historically known person is that of Johann Melchior Ott(o), who left his name three times in 1642 (Fig. 1). Ott (†1670) was a painter in the service of Prince zu Eggenberg (pers. com. Dr. Barbara Kaiser). Ott's name is accompanied by that of Johann Paul Sarcher not yet identified and a drawing of a coat of arms all in red crayon. In the table depicting 53 inscriptions from the cave copied by Schaffenrath (published by Hohenwart 1832b, Plate 19), it is already recorded. The other two signatures of Ott are much shorter and read "Io Mel. Ott" and "Io.. Melchior Ott /1642"; both written in charcoal. The coat of arms is that of their "employer", the reigning Prince (Fürst) Johann Anton zu Eggenberg (1610-1649), the owner of castle and town of Adelsberg at the time. The Eggenberg's carried the coat of arms in the depicted form from 1628 to 1647, fitting the date of 1642. The five segments represent the Eggenberg estates at the time: Center: Three crowned ravens facing each other (Eggenberg, near Graz, Austria); top left: Five roses (Krumau = Česky Krumlov, Bohemia); top right: Eagle (Adelsberg, since 1608, Slovenia); left bottom: Anchor (Pettau = Ptuj, since 1626, Slovenia); right bottom: Wheel (Radkersburg, Austria since 1618/1623).

The second oldest is that of Josef Anton Nagel 1748 who also left an elaborate signature in Latin in Predjama and in Sloup Cavern, Moravia. Nagel (1717–1794), a German mathematician at the Habsburgian court in Vienna visited the cave on order of Emperor Franz I on a travel to study caves and other natural phenomena in Crain and Moravia. He left an elaborate manuscript now being edited by us (Kempe et al., 2006; see paper this volume).

All other inscriptions of historic persons date after 1800. Among them are those of three personalities that shaped the history of the first decades of Postojnska jama as a show cave: Franz Graf von Hohenwart (1771–1844; 3 inscriptions), Joseph Petsch (or Poetsch) Ritter von Löwengreif (1775–1844; 14 inscriptions known, more than anybody else) and Alois Schaffenrath (1794–1836;

five signatures, also in Predjama). All these signed several times in Imenski rov and elsewhere in the cave (Kempe et al., 2004). Johann Fercher (biographical data still unknown), mine supervisor, and his miners from the Idrija mercury mine left notes during their survey of the cave in 1833 (Kempe 2005; Kempe et al., 2006a). Ivan Andrej Perko (or Johann Andreas; 1876-1941) signed five times at various places, albeit before he became responsible for the cave as its director in 1909. In 1890 he signed (14 years of age) together with "M. Petrič", one of the Petrič brothers (possible Leo), co-founders of the speleoclub Hades from Triest. A visiting caver was also Josef Franz Eggenhöfner (Fig. 5) from Trieste, the developer of Grotta di Padriciano who signed in 1801 (or 1809) and 1820. For the many cave guides that signed we list Alois Čeč leaving his name 1913. Notable is also the discovery of signatures of natural scientists: Karl Beyrich (a botanist, born 1796, who signed probably in 1819 and who did research in Brazil and who died during an expedition in Arkansas, 1834), Johann Ritter von Hauer (1778-1863, from Vienna, Imperial Counselor of War and interested in Paleontology, who signed in 1836 in Pisani rov shortly after its opening), Johann Natterer (1787-1843, a biologist, who signed in 1815 and went to Brazil for 19 years, known as the founder of the zoological collections of the Natural History Museum in Vienna), and Giuseppe de Volpi (from Trieste who signed in 1820 and published first evidence of cave bear presence in Postojnska jama; Volpi, 1821). Volpi reported that he obtained a cave bear skull (he called it "Palaeotherium," i.e. fossil animal) (Kempe et al., 2005) from "Herrn Distriktförster Mühleisen". Obviously Mühleisen had access to the cave and had the authority to remove bones from the cave. He therefore most probably was the one who left his name "Mühleysen" in Imenski rov in 1817, one or two years before he found the bones in the newly discovered passages. The signature of Karl von Zur was found seven times in various combinations. Since in three cases there is a close association with Löwengreif's signature, it must be concluded that they visited the cave together several times. As to his identity we could only trace a Franz Zur, who was employed at a martial court as auditor having obtained peerage in 1792. Possibly he was stationed with the military in Adelsberg and had a son Karl who liked to accompany Löwengreif to the cave. Other persons like Bellegarde (either Friedrich Heinrich Graf (Count) von Bellegarde, 1769 – 1845 or one of his sons, if one reads a second line as "Fähnrich," i.e., an ensign - Graf August (* 1795) or Graf Heinrich (* 1798); they could have been on leave from the army as young officers after the end of the Napoleonic wars), Adrienne Brandis Desenffans (1810-1834) and her brother Karl Graf Desenffans (1811-1855) signing in 1833 (Fig. 6), Carl von Kotze who signed in 1818(?) (possibly Hans-Karl v. Kotze 1795-1851), and Mihanović who signed in 1822 (possibly Petropoljski Antun Mihanović, 1796-1861, author and diplomat, famous for having written the Croatian national anthem) came for day-visits only. Last, but not least the famous classicistic Prussian architect Karl Friedrich Schinkel (1781-1841) signed three times, albeit not in Imenski rov, but in the historic part of Predjama (Shaw 2008). All the last mentioned represent people of the nobility and/or were state employed. Overall, the signatures shed light on the section of society that was able to travel and interested in natural sciences. For further discussion of the topic see Kempe & Hubrich (submitted).

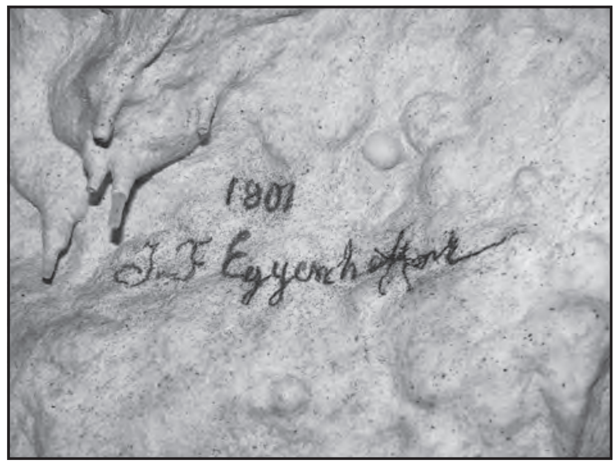

Figure 5: Two-line-inscriptions of Panel 10, Imenski rov, reading " J.F. Eggenhöfner / 1801", a visiting caves from Triest.

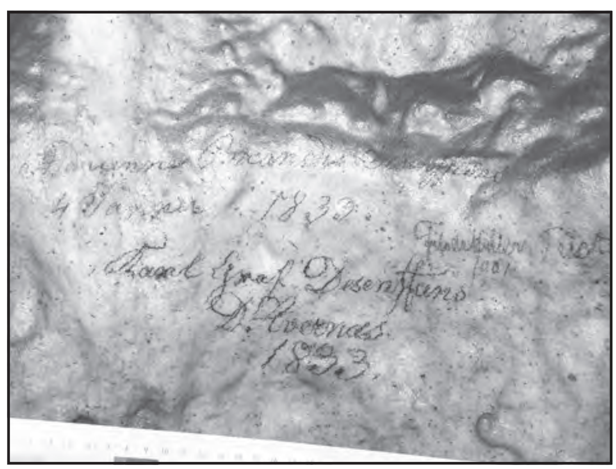

Figure 6: Five-line-inscription in Panel 17D, Imenski rov, reading "Adrienne BrandisDesenffans / 4. Jänner 1833 / Karl Graf Desenffans / D. Avernas/1833", similar in handwriting, but different in boldness, graphite pencil.

5. Conclusions

The investigation of the historic Imenski rov and Predjama signatures (all in all ca. 650) show that most are still entirely

Period	Prior to 1800	1801 – 1810	1811 – 1820	1821 – 1830	1831 – 1840	after 1840
Frequency	2	2	12	6	4	7

Table 1: Frequency of dated signatures of identified persons in various periods.

or partly legible. Of these we could (plus the signature of Hauer from Pisani rov) correlate 20 with historically otherwise known persons. This is less than 5% of available inscription body. For most of these names we can identify the writers with certainty. The correlation of Bellegarde, Kotze, Mihanović and Karl von Zur with historic persons is only tentative and even with Hauer we cannot be entirely sure. Interestingly only one of the persons (i.e. Schinkel) discussed here match those Shaw (2000, 2008) covers in his book about foreign travellers that wrote about cave visits in Slovenia. Apparently these people were not particularly inclined to leave their names in the cave (though corresponding signatures may still be found along the main passage). It is also remarkable, that we did not find any signatures of "official" visitors, i.e., persons of reigning nobilities or governmental members (Shaw & Čuk, 2002). Table 1 shows the frequency the dates of the visits of these remarkable persons (excluding the 14 signatures of Löwengreif who visited the cave on official business).

Thus only two signatures of historically known persons are older than 1800 (i.e., Ott, Nagel), while the majority of the inscriptions falls into the time shortly before or after the discovery of the main passage. Apparently the old cave was still visited during the first years after this discovery. Possibly it was shown as an alternative when the bridge across the river was not useable (see discussion of the early state of the bridge in Shaw, 2000).

Interesting are also multiple signatures, like those of Nagel and Schaffenrath that signed both in Predjama and in Postojnska jama, and Schaffenrath, Löwengreif, Hohenwart, Fercher and Perko who signed not only in Imenski rov, but also in other parts of Postojnska jama. All those mentioned are also the most "remarkable persons" concerning the speleohistory of these caves. To the group of speleologists that signed in the cave also belong Eggenhöfner, A. Čeč and possibly M. Petrič. The status of Karl von Zur is doubtful. All others are probably one-time visitors. Among those we find the natural scientists Beyrich, Hauer, Natterer and Volpi while the others visitors were just interested tourists.

Acknowledgements

We thank Dr. Tadej Slabe and the administration of Postojnska jama for permission to visit the cave beyond the tourist trails. We also thank Mrs. Maya Kranjc, librarian of the Karst Research Institute, Postojna, and Leon Drame who accompanied us and helped in reading names. We are also indebted to Dr. Lupold von Lehsten (Institut für Personengeschichte in Bensheim/Germany) for help in searching biographical data and the possibility to use his library and to Dr. Barbara Kaiser (Landesmuseum Joanneum in Graz) for providing data on J.M. Ott and the Eggenberg coat of arms.

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A CAVE SURVEY PROJECT FOR THE DUKE OF EDINBURGH'S SILVER AWARD

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The Duke of Edinburgh's Silver Award is the second level of a flexible program that invites young people between the ages of 14 and 25 to participate in a number of voluntary activities, covering physical recreation, skill, and adventure. At the commencement of his Silver Award project, to complete a survey drawing of Cerberus Cave in the Jenolan Caves Reserve, New South Wales, Australia, Stephen Kennedy was aged 15. The Cerberus Cave is an exceptionally well-decorated horizontal cave 100 m long, and has been developed for tourism. The initial phase of the project was a literature search for details of a previous survey of Cerberus Cave by Oliver Trickett, published in 1925. During this review, the history of the discovery of the cave and its original name were unearthed. At the time of discovery, the most significant and rare find in the cave was an aboriginal skeleton, hence the original name, Skeleton Cave. After the rights of indigenous people were recognized in Australia, the cave was re-named Cerberus Cave. The location of the skeleton has been designated a sacred site and is no longer featured on tourist visits to Cerberus Cave. Phase 2 was drawing the layout of the cave, and for this the survey information Stephen utilized was a line plot of a total station traverse carried out in 1987 which largely followed the tourist path, and included survey station numbers. These stations needed relocating and then had to be marked, if not already. Four digital photographs were then taken at each station so that the stations could be easily located in the future. This was followed by the detailed sketching required for the preparation of a cave plan. To accomplish this Stephen had to learn and use the standard symbols for speleothems and other cave features. To prepare a reliable sketch, several of the traverse legs were too long so Stephen assisted in the surveying of intermediate points using a wide variety of surveying instruments. At all survey points, he collected left, right, up and down data and drew a cross section. Stephen then contributed to the drafting of the plan and cross sections using Adobe Illustrator. The Compass-surveying program was subsequently used to prepare a 3D representation from the data collected in the cave. In addition, Stephen took the data necessary for a projected long section as this was considered the best representation of the cave for tourists information. The final phase in this project was to name the speleothems and other features in the cave. This was not a simple task as some names had changed, a number of times, in the 106 years since its discovery. Identifying and naming features in Cerberus Cave involved Stephen working with a member of the Jenolan Caves Historical and Preservation Society. A project such as this has great educational value, as it could not be carried out by Stephen alone, requiring assistance and supervision from experienced speleologists; for example, geologists, chemists, hydrologists, anthropologists, and historians. Interactions such as these have enormous value in educating young cavers in many aspects of speleological research as well as conferring knowledge of the conservation of this valuable resource. Stephen's Cerberus Cave survey was a success and he received the Duke of Edinburgh's Silver Award. The techniques he acquired in this project are to be tested further, in the different environment of the wild Michelmas Cave. In this cave, Stephen will act as a leader for the survey and start from the beginning by first surveying the cave and finishing with a publication of the complete survey. This will be for his Duke of Edinburgh's Gold Award.

1. Introduction

Two decades ago, the Jenolan Caves Survey Project Group undertook to prepare a "State of the Art" survey of the Jenolan Cave System, New South Wales, Australia (Fig. 1) (James et al. 1988). After a hiatus, and the advent of advanced computerisation, the Project Group took the decision in 2005 to "go modern" and finalise the extensive survey of the Jenolan Caves using computer drafting techniques. When Stephen heard of this, he asked if he could participate in order to complete one of the components of his Duke of Edinburgh Silver Award. It was decided that Stephen could help with the "mapping" of the Pool of Cerberus (Fig. 2).

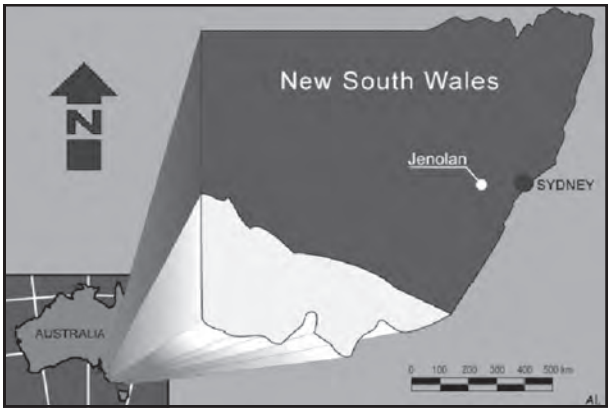

Figure 1: Location of the Jenolan Cave System within New South Wales, Australia.

2. The Duke of Edinburgh Award Program (DoE 2009)

The Duke of Edinburgh Award program began in 1956 in the United Kingdom. The program was designed with care by a small team, led by HRH Duke of Edinburgh, with the aim of motivating boys aged between 15 and 18 to become involved in voluntary self-development activities to take them through the period between adolescence and adulthood. Over the following two decades, the program was altered to include girls and to cover ages between 14 and 25 years. The flexibility of The Award made it ideally suited to adaptation and integration into different cultures and societies, and it was soon adopted by schools and youth organisations throughout the World; it now reaches young people in over 120 countries. The Award began in New South Wales, Australia in 1962 and today is a program of New South Wales Department of Arts, Sport and Recreation. There are over 480 organisations currently registered to operate The Award in New South Wales, such as schools, youth organisations and community groups, including those involved with Youth at Risk and Indigenous Youth. There are 3 levels to The Award, all taking different lengths of time and with varying minimum ages and component activity completion requirements.

3. Stephen's 2007–2008 Project

At the commencement of his project, Stephen Kennedy was aged 15 and his first task was a literature review of the history of the Pool of Cerberus. He established that The Pool of Cerberus, as shown in Figure 2, was discovered by Wiburd, Edwards and Bailey as part of two major extensions of the Lucas Cave in 1903 and, originally, the new passage was named the Skeleton Cave. Trickett, in his 1903 annual report for the New South Wales Department of Mines, had declared this discovery "*the most important event at Jenolan of recent years*" and described the new passages and chambers in glowing terms: "*....highly decorated chambers, with some terraced stalagmites of singular beauty... many grand caverns, one whose walls are covered with draperies, fluted columns, etc, for a height of 100 feet... a superb mammoth, pear-shaped, amber tinted stalagmite rests on a gracefully curved base, which terminates in a charming canopy... superb shawls 20 to 25 feet in length... a succession of fairy-like grottoes, commencing with rich fringes, partly concealing groups of 'mysterious', and ending with a truly marvellous collection of these curious twisted formations*." A map of the Lucas Cave, which Trickett had included with

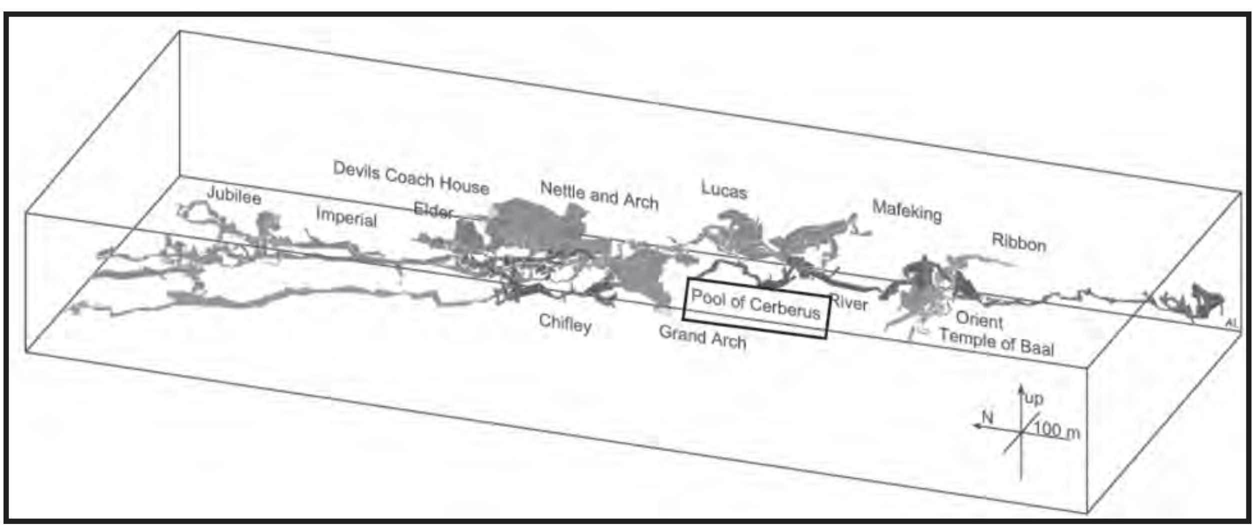

Figure 2: Location of the Pool of Cerberus within Jenolan Caves.

the report, showed the new Skeleton and River Caves.

Trickett and Etheridge (1903) had produced a separate report for a human skeleton found in one extension (Skeleton Cave) which gave a detailed account of the remains, their location, and how the person, presumed to be Aboriginal from the evident age of the material, could have reached this place. Etheridge, who was the Curator of the Australian Museum at the time, no doubt contributed the technical description of the bones, together with comparisons to Aboriginal remains found in other caves; Trickett provided the detailed information regarding their location, the difficulties the explorers had in reaching it and the relative position of other chambers. The report was reprinted the following year in the *Records of the Geological Survey of New South Wales*; a coloured map accompanying the reprint varied from that of the original report in that the Orient Cave, a further extension of the new River Cave discovered in the meantime, had been added.

Stephen's research found that the name change from Skeleton Cave to Pool of Cerberus occurred in 1987 and that it was a response to what had become a culturally sensitive issue. The New South Wales Aboriginal Land Council had considered the literature and publicity that freely advertised the remains (the Aboriginal skeleton) as being grossly insensitive to the feelings of the local Gundungurra people. At their request, the skeleton is now neither displayed nor interpreted. The Pool of Cerberus was chosen as the new name because it is the largest pool of water in the cave and is the final sighting of the River Styx before it disappears to re-emerge at Jenolan's Blue Lake.

The next stage was the detailed sketching necessary to produce a plan of the Pool of Cerberus. To accomplish this, the next task for Stephen was to obtain a line plot of a total station traverse carried out in 1987/90 (James et al. 1988) that largely followed the tourist path, and included survey station numbers. In the cave, using the line plot, Stephen located and marked, if not already, the old survey points. Once this was done to the satisfaction of his speleological mentors, Stephen then needed to take four digital photographs of each station (one from the direction of each neighbouring station, a close up of the station's locality and a macro-shot of the station marker) so that the stations could be easily relocated in the future.

To undertake the sketching itself, Stephen needed to gather a team of at least one other person to operate a laser measurer so that the dimensions of the passage and locations of significant features were as accurate as possible. Several of the traverse legs were found to be too long for reliable sketching, so Stephen assisted in the surveying of intermediate points using a wide variety of surveying instruments. In order to sketch Stephen had to become familiar with the standard symbols for speleothems and other features (a modified set of the International Union of Speleology survey symbols). At all survey points, Stephen and his team collected left, right, up and down data and Stephen drew the section. Stephen then contributed to the computer drafting of the plan and cross sections using Adobe Illustrator (Fig. 3). The plans make use of layers for recording different aspects of the plan such as the tourist paths.

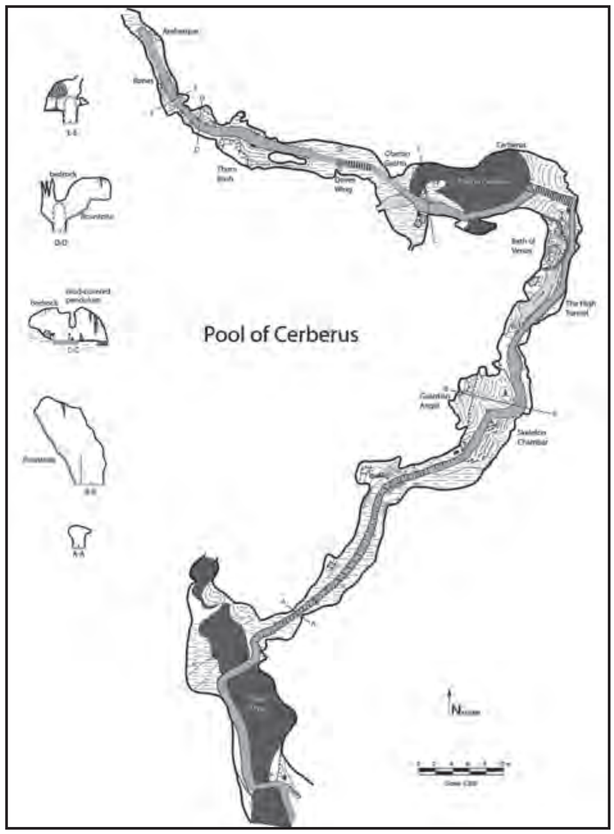

Figure 3: Plan and sections of the Pool of Cerberus as produced by Stephen.

To create a more useful and informative product, it was decided that the names of significant features needed to be placed on the cave maps. This required the undertaking of further research and Stephen collaborating with members of the Jenolan Caves Historical and Preservation Society to compile the named features and locate them in the cave. The most prominent names are incorporated into Figure 3. This task was complicated by the fact that, over 106 years, the names of some features had changed with time or, in some cases, a name existed for a feature that had vanished all

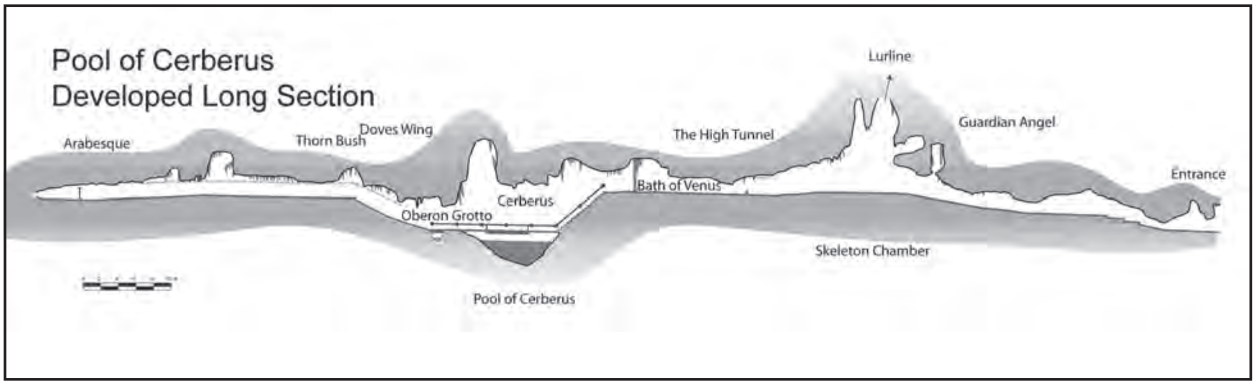

Figure 4: Developed long section of the Pool of Cerberus.

together. The latter was the result of either speleothems that were "souvenired", a common practice in the early periods of cave tourism at Jenolan, or were damaged (broken off) or even removed during installation of early infrastructure.

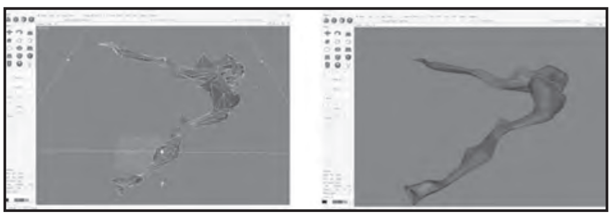

Figure 5: 3D models of the Pool of Cerberus. The first screen shot shows the 12 pt skeleton and the second shows the smoothed 3D model.

Finally, two further mapping variations were performed by Stephen: the first was to prepare a developed long section incorporating the significant named features (Fig. 4). This is the form of presentation preferred by the Jenolan Caves guides as it clearly shows tourists what they will encounter when visiting a cave. This is something that the cave plan fails to depict adequately to those that are not familiar with the graphic representation of a cave as a plan. To prepare the developed long section, Stephen utilised up and down data and plotted all the all survey legs on the same bearing.

The second mapping variation required the collection of 12 point cross section data similar to the collection of left, right, up and down data but also at ± 30º and ± 60º. The 12 pt data stations were taken in short survey legs and most importantly where the cave passage changed shape. This data was then used to produce a 3D image of the Pool of Cerberus (Fig. 5) by the method described in James et al. (2009). Stephen again worked with his speleological mentors to obtain and plot the data and then produce the 3D models.

onclusions

Whether as a project for an end product like the Duke of Edinburgh Award or simply to introduce a youth to the wonders of history and nature, there is great educational

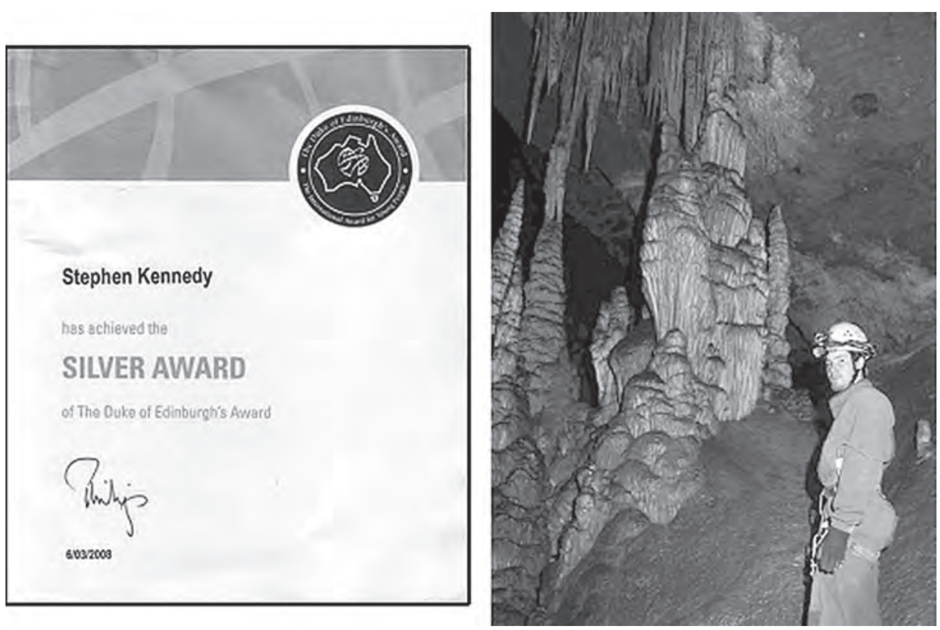

Figure 6: Stephen Kennedy in Croesus Cave in Tasmania during a wild cave trip in January 2009 after completion of his Duke of Edinburgh Silver Award and his award certificate.

value in an exercise that requires working hand-in-hand with cavers of all persuasions, from speleologists to historians to managers and hobbyists. Stephen learnt a number of skills useable for more than just caving, as well as being exposed to and learning to cooperate with others of different skills, education and philosophy. This is valuable, not only to Stephen in his developing maturation, but also to the transfer and spread of knowledge of an area of the environment that many do not know about. In the end Stephen's project was a success and he received the Duke of Edinburgh Silver Award (Fig. 6). Not to rest on his laurels, Stephen intends to complete the Gold Award and to use his newly acquired knowledge and skills to survey and map a "wild' cave, Michelmas Cave. In this future endeavour, Stephen will act as a leader for the survey team, employing and directing the expertise of others to publish a complete survey of the cave with its accompanying documentation.

Acknowledgements

Jenolan Caves Reserve Trust for their support. The Jenolan Caves Historical and Preservation Society members who have contributed to this project. Numerous cavers who assisted with this project.

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THE OLDEST PRINTED CAVE MAPS IN THE WORLD

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Abstract

For ages men were impressed by cavern environment that is frequently represented in or is the background of various art crafts made during Centuries, such as petrogliphs within caves, a bronze plate of an Assyrian King throne, Roman mosaic floorings, Maia manuscripts, a Tibetan ivory sculpture, etc. Only a few centuries ago, men became interested in the true form of the underground cavities. Therefore the first cave maps were printed only in the XVI-XVII centuries. Until now, it was generally accepted that the first map of an artificial cave was printed in 1546 by Georg Agricola in his "*De natura eorum quae effluent e terra. De ortu e causis subterraneorum*", while the first map of a natural cave was edited more than hundred years later by Robert Southwell in his "*A description and draught of Pen Park Hole in Gloucestershire*" (1683). Two years ago, while cataloguing the engravings owned by to the "Franco Anelli" Spelological Documentation Centre in Bologna, Italy, two small cave maps were found. They were clearly cut off from a book, but they completely lacked captions. As a consequence, it was impossible to define both name and location of the caves as well as the year in which the maps were made. Later, by comparing these maps with several other engravings of the same collection, it was possible to attribute one of the two maps to the cave of St Rosalia on Mt Pellegrino (Palermo, Sicily). In the XVII century, this small natural cave was transformed into a church dedicated to the worship of the young lady, Rosalia Sinibaldi (St Rosalia), who spent most of her life therein. In order to identify the second cave, the book from which the two engravings had been removed, and to date the maps, a further and challenging bibliographical search was carried out. This search was very complex and difficult because all the bibliographic material regarding the caves was contained in holy books, which were printed in few copies scattered in small libraries often lacking any kind of catalogue. The search was successful and enabled us to establish that the two maps had been removed from a book printed in 1627 by the biographer of St Rosalia Giordano Cascini, while the engravings were made by the Belgian artist Odon Van Maelcote. It was also possible to ascertain that the second engraving represents the map of the first cave in which Rosalia Sinibaldi started her "troglodytic" life: the St Rosalia cave at Quisquinia, Sicily. These findings represent the proof that the most ancient print maps of natural cavities were made in Italy, and date 56 years earlier than known insofar.

CAVE CONSERVATION THROUGH THE ARTS: CARLSBAD CAVERNS NATIONAL PARK'S ART GALLERY

LOIS MANNO
Director of the Cavern Arts Project

Caves inspire awe, curiosity, and fear. Perhaps because they were used as havens and sacred sites during the evolution of mankind, caves continue to fascinate us with their dark promise of adventure. As psychological archetypes, they touch humanity's deepest, most primal emotional core. Since the discovery of Carlsbad Cavern in New Mexico in the late 1800s, adventurers, photographers, writers, and artists have explored its depths, seeking to capture the elusive beauty that fills its enormous chambers and intimate grottos.

The arts have proven to be a potent vehicle for many types of message, including that of conservation. For example, promotion of the national park system through a poster series generated during the WPA era ignited a cultural craving among Americans looking for new spots to vacation. In addition, increased public awareness of the natural wonders in our parks stimulated new interest in protecting wilderness in its many forms. Ansel Adams, the greatest landscape photographer in American history, further raised the profile of the country's wild places as something to be cherished and protected. Caves, too, can only benefit from being interpreted through the creativity of artists, writers, and musicians.

Visions Underground: Carlsbad Caverns through the Artist's Eye is the title of a new exhibit featuring works of fine art and photography inspired by the Caverns, and is part of the park's newly renovated visitor center. It is also the title of a book about the history of artists at the national park, which will be released in 2009. Lois Manno, author of *Visions Underground*, worked for over two years with National Park Service managers as primary coordinator for the exhibit. The National Speleological Society is a sponsor of both the exhibit and the book. Approximately half a million visitors will view the permanent exhibit annually, which features original prints by the world-renowned photographer Ansel Adams.

1. Introduction

"Our time is short, and the future terrifyingly long. Believing as we must that things of the heart and mind are most enduring, this is the opportunity to apply art as a potent instrument of revelation, expression, and perpetuation of wilderness actualities and moods. Through art of brush, pen, and lens, each one no less than another, we possess a swift and sure means of touching the conscience and clearing the vision. —Ansel Adams, 1902-1984

The photographer Ansel Adams wrote these words with America's most beautiful wild places in mind. He wasn't thinking about caves, but the concept that art can be used as a powerful tool for conservation is just as applicable to caves as it is to national parks, wilderness areas, and wildlife.

For the purposes of this paper, "cave art" refers to art depicting caves or cave life, not prehistoric human drawings that appear in caves. "Artists" are defined as people working primarily in visual media such as painters, photographers, and sculptors. However, these concepts can easily be expanded to include writers, musicians, and other forms of artistic expression.

2. Artistic Vision: The Foundation of the National Park System

Artists have been instrumental in the protection of America's wild places since the very beginning of the national park System. In 1871 Thomas Moran traveled to Yellowstone with the earliest surveyors, and his vivid paintings helped inspire Congress to designate Yellowstone as the country's first national park. Many other artists served similar purposes for other parks. As photography became more useful in the field, it became the most popular means of capturing the beauty of wilderness. Ansel Adams propelled landscape photography into the highest realms of art, and his legacy lives on in the hearts of art lovers and nature lovers worldwide.

3. The Carlsbad Caverns Art Collection

Since its discovery in the late 1800s, Carlsbad Cavern has been visited by many artists. One of the earliest was Santa

Fe painter Will Shuster, who dropped into the cave in a guano bucket and painted by lantern light in 1924. He created more than a dozen paintings; five of these are part of the permanent art collection at the park. Ansel Adams photographed the caverns in 1936 and again in 1941 for the Department of the Interior's Mural Project. He did not enjoy his stint as a cave photographer, and wrote about his experience as being one of the most difficult challenges of his photographic career. Twenty-five original, signed Adams prints were "discovered" at the park in 1978 by NPS Cave Specialist Ron Kerbo, who was cleaning out a large cabinet at the time. The prints were displayed briefly in Albuquerque, and were then sent to a storage facility in Tucson.

4. The Cavern Arts Project

The art collection of Carlsbad Caverns National Park is full of beautiful treasures documenting the history of the cave's discovery, exploration, and development. Unfortunately, in 2006 the collection was in disarray, stored in several different places, and in need of conservation and framing before it could be placed on display. The Cavern Arts Project was formed for the purposes of bringing the collection together and preparing it for exhibit in the visitor center at the park once the remodeling of the center was complete in 2008 (Fig. 1).

Figure 1: A five hundred square foot permanent gallery space was set aside in the newly remodeled visitor center at Carlsbad Caverns National Park to showcase the park's art and photography collection. Other exhibits featuring cave-inspired art will be rotated periodically through the space. The gallery is currently divided into two sections; this photograph shows the general space where a variety of artists' work is displayed.

he project scope also included fundraising, as the park had only limited funds available for the collection. Several organizations contributed money to the project, including the National Speleological Society. This made it possible to hire a professional museum conservator to stabilize and repair the Ansel Adams prints, and to have them framed with special archival housing to prevent further deterioration of the prints during exhibit (Fig. 2).

Figure 2: A smaller area of the gallery space has been set aside as the Ansel Adams section. Here four original prints are displayed, along with reproductions of his other Carlsbad Caverns photographs and interpretive signage about Adams' life. Two large window banners also show Adams images with historical information about his work at Carlsbad.

In addition, though the park had a wealth of historic photographs and other works of art, there was a lack of representation for contemporary artists. Lois approached many of the best cave artists and photographers who have worked at the caverns over the past 30 years, and most of them donated at least one piece of art to the park, greatly expanding the permanent collection. Much of this work is now on exhibit at the caverns, both in the formal 500-square-foot gallery that is now part of the visitor center, and throughout other areas of the building.

After spending two years researching the art collection of Carlsbad Caverns National Park, Lois Manno began work on a book, *Visions Underground: Carlsbad Caverns through the Artist's Eye*, about the artists and photographers who have been inspired by the cave since 1900. The book contains most of the photographs shot by Ansel Adams in 1936, scanned from the original signed prints. This is the first time these images have been published. She was fortunate to interview Ansel's son Michael Adams, who worked with his father for several years as photographic assistant.

The book is a combination of park history and art history; it tells the exciting story of early exploration through the eyes of photographers, painters, and poets. *Visions Underground* brings the story of Carlsbad Caverns National Park forward to the present-day, showcasing photographs and other artwork by the best speleological artists alive today. The National Speleological Society is a sponsor of the book, which will be released by Rio Grande Books in the summer of 2009.

5. Art as a Tool for Cave Conservation

Though most caves are not blessed with the art collections of Carlsbad Caverns or Mammoth Cave National Parks, the arts can play an important role in cave conservation anywhere. When trying to raise public awareness of the value of cave conservation, it's valuable to take a multi-pronged approach, because people resonate to different messages. Some people are drawn to the scientific appeal of caves, others to the mystery and adventure of exploration. Still other people will respond to a conservation message that describes the animals that inhabit caves. But a more universal aspect of caves, one that has a proven track record of appealing to huge segments of the population, is their beauty. Promoting the beauty of a wild place is a time-tested, proven way to build a constituency of supportive people who appreciate that place and want to see it protected.

Art has the added benefit of mobility: it can be transported and presented to the general public without generating additional impact on the cave environment. Art can be used to reach out to people who would never willingly enter a wild cave (and that's still the vast majority of people, though we cavers tend to forget this). The stunning photographs of bats in materials published by Bat Conservation International have done much to dispel the public image of bats as frightening, diseased nuisances, transforming them instead into beautiful, beneficial creatures worthy of protection.

Education through the arts is also a proven way of generating interest in and empathy for nature, and can easily be focused on cave conservation. Children can view photographs and videos about caves, and then draw their own ideas about what caves and cave animals are like. They can learn about what caves and karst features might exist in their own neighborhoods, and capture these features using photography. Many beautifully illustrated books exist for children that educate them about caves and their delicate ecosystems.

Similarly, adults can be reached through art and photography exhibits about caves; workshops can bring artists into developed caves, and with the help of experienced cavers, some artists can be introduced into the spelean world in a safe and low-impact manner. Peter Jones leads non-caver photographers into Carlsbad Cavern for multi-day photography workshops. It is doubtless that these photographers come away with a new appreciation for—and support of—caves in general. In this way, art conducted within commercial caves can promote the conservation of all caves.

In addition, a cave conservation organization that utilizes the fine arts to deliver its message opens up a new avenue for fundraising that might not be available to an organization that focuses strictly on scientific or environmental issues in its conservation message. A cultural event that focuses on cave photography and other visual media will reach people in the community who might otherwise not be interested in caves. Some of those people will have money to give to a group that they see as protecting nature and supporting the arts. Many foundations and other organizations will give money for projects that combine science and fine art in new and interesting ways. Cave art surely fits that description.

6. Conclusion

The value of visual art as a means to promote cave conservation cannot be overstated. Beauty is one of the universal ways that people can be inspired, and beauty can be found in any cave, whether it is the Caverns of Sonora or a colorful lava tube. A beautiful piece of art or a stunning photograph can bring a cave to many viewers at once, without any additional impact on the cave itself. Ansel Adams knew that the way to influence public opinion is to showcase the fragile beauty of wild places and show it to as many people as possible. The greatest challenge to cave conservation is a combination of ignorance and apathy. The arts can help the general public love caves…and what we love, we protect.

Biographical Information

Cavern Arts Project Director Lois Manno has been a caver for over 30 years. She has spent the last 15 as a volunteer at Carlsbad Caverns National Park. She is a Fellow of the National Speleological Society and the Cave Research Foundation, and has a degree in Fine Art and English. *Visions Underground: Carlsbad Caverns through the Artist's Eye* is not Lois' first book, but it is her first book about caves and artists.

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ETHICS OF SPELEOLOGICAL EXPEDITIONS TO FOREIGN COUNTRIES

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Cave and karst exploration is sometimes done in foreign countries that share the same culture and degree of development, or the same view of the world as the explorers' one. In other cases, local populations and speleologists have a very different view of our activities due to their different history, values, geopolitical views, and due to their thoughts on past activities. These differences are important; they strengthen our international speleological community.

Positive values from different countries should be added, in order to make our speleological community stronger. Sometimes, values should be balanced. In any case, local values should be respected. Although potential conflicts may be more difficult to solve when the difference of culture or habits is larger, it is not always the case. On the other hand, difference of culture may be much larger than we think. For instance, similar reactions do not mean similar thoughts. Similar words may express very different things.

- We should be aware of everyone's sensibility and sensitivity and be conscious of the weight of culture. We should bear in mind that apparently "westernized" habits do not necessarily reflect the real, genuine, way of life and way of thinking. We have to be open-minded and ready to foresee and accept differences. We have to understand and practice the "social time" of explored areas.
- The knowledge of "the others" cannot be learned in the books. It is a matter of open-mindedness and of positive practice. Exploring abroad requires cultural preparation, and establishing all necessary contacts.
- Exploring caves abroad is a unique chance to learn more and share ways of life. It is a real chance to exchange on techniques, cave protection, a true necessity in a number of countries, and others.

Adapting to the habits and culture of the visited country is a must. Learning and speaking local languages helps in creating good relations with local people. Contacting officials regularly shows respect and creates friendship. A good practice is to involve local people as much as possible; you are entering their land, caves, and heritage.

Last, but not least, good relations with cavers of the explored country is of paramount importance, before, during and after the explorations. Everyone finding mutual benefit and foreign speleologists showing full respect of the work performed by local cavers or other groups is the best situation.

We can summarize the relations with a few words: open-mindedness, respect, friendship, mutual teaching and learning, and co-operation. All values of UIS and the UIS Code of Ethics have to be respected.

1. Introduction

At the time we wrote our first paper on ethics (Mouret & Chabert, 1984), cave explorations abroad were still not as common as they are nowadays. At the time, we lived in a non-globalized world, which was split between two main superpowers. One of them had associated countries almost closed to speleology by foreigners, though not completely. Today, the face of the world is completely different. Nevertheless, the world is still changing continuously and our relations with people from other countries need to be continuously adapted. This has a large impact on cave explorations and expeditions to foreign countries and it requires even more respect of people and better manners than in the past.

2. A Changing World

In the polarized world that existed before the end of most of the communist regimes in the early nineties, few western speleologists had the opportunity to go to closed "Eastern" countries. International congresses were a good opportunity, e.g. the UIS Congress in Olomuc near Brno, Czechoslovakia in 1973. During the rare tourist trips possible during the congress, a glance at some tourist caves was available. It was sometimes possible to be "invited," especially as a researcher. Coming to western countries was very difficult to most "Easterners," though it was possible for a number of scientists. Many "Easterners" were going to foreign countries that had the same ideology, for instance to Vietnam or Cuba.

There were also some more or less "neutral" countries, acquainted to both political "blocks" to a variable degree, which fluctuated through time. In this way, our Czechoslovakian and Hungarian colleagues could go for example to Libya and study caves there. These countries were also accessible to westerners and it was an opportunity to meet ... sometimes.

During this time, groups of people knew speleologists from the same "block" reasonably well, but, sometimes they held incorrect views concerning speleologists from the other block. Luckily, the International Congresses of the UIS were a privileged time to meet, to share views and friendship and to sympathize.

The International UIS Congress at Budapest (Hungary) in 1989 proved us that something was changing "in the East." That year, and even in 1988, we started to see "Eastern" speleologists in congresses and meetings in western Europe. Soon after 1989, the political regimes changed drastically fast within a few years. The USA became the only superpower in the world. Then new countries started to emerge as major powers and arrive at the forefront of the world, as China has during the first decade of the 21st Century, though the UIS International Congress in Beijing in 1993 had clearly shown us a lot of evolution in the country.

In UIS International Congresses at La Chaux-de-Fonds (Switzerland, 1997), Brasilia (2001), Kalamos (Greece) (2005) and now Kerrville in the USA, we all had (have) excellent opportunities to widely meet with people from all countries, create new links and make new friends. Many countries are now affirming their identity and some regions within existing countries desire "nationhood" based on cultural differences from other portions of their countries.

Today's world is global. Vegetables often come from other continents; planes, bicycles, and cars include parts manufactured in different countries; the market is the world. Transportation is by no means a limitation, thanks to an abundant and still cheap energy. The Internet has connected many of the world citizens. This is probably going to continue, despite some technical threats. People are traveling more and more.

Unfortunately, this is starting to change, because environmental degradation accelerates, because access to raw materials, ores and energy is gradually becoming more difficult, in addition to other difficulties (overpopulation, financial crisis, wars...). Traveling is likely to remain possible for a number of years, as long as energy remains sufficiently available and not too costly, but there are risks. Nobody can reasonably predict for how long this may last. The future is probably going to be very different from what we can imagine, though a large part of its components are likely to be around us already, but what are they and in what proportion will they be combined? What new solution or technologies will emerge?

For now, cavers are closer to each other than ever. Even if rising violence in a number of countries limits some explorations (nevertheless, a German team successfully explored caves in northern Iraq a year ago) and if current crises slow down actions and processes (making expeditions somewhat more costly), it is still possible to go caving widely abroad. It is very easy, as well, to receive speleologists from other countries.

Worldwide, minds have changed a lot over the last two decades. However, many differences remain in our views, in our approach, and in our opinions, because we still come from different cultures. Apparently common behavior is a (sometimes thick) varnish on us, but our differences are real. Nearly 20 years spent abroad, to a lot of countries, has taught me that the more we know each other, the more we observe differences that we did not even suspect at the beginning. Believing that people think like in our country everywhere would be a very false idea.

Our heritage and Speleology will become even greater if explorations abroad are a way to increase friendship among the different people, understand others' views, and be fully open-minded. This attitude and full respect can widely open doors and gain co-operation.

3. Open-Mindedness and Understanding the Others

Open-mindedness is required to be a good observer of people's manners, habits, beliefs and cultural background. It is a necessary quality to really understand others. It requires being aware of everyone's sensibility and sensitivity and being conscious of the weight of culture. We should bear in mind that apparently "westernized" habits do not necessarily reflect the real, genuine, way of life and way of thinking. We must be ready to foresee and want to accept differences. The same words may apply to different ideas.

Knowledge of "others" cannot be learned in the books. It needs positive practice. So, exploring abroad requires cultural preparation and establishing all necessary contacts. Speaking several languages is a very good preparation to the understanding of speleologists from other countries. Different people express the same facts in a different way. In English a big tree is a "big" tree. In French for instance, the same tree is a "tall" tree. In Indonesia, you should not say "no" and the Indonesian word for this is almost never used; there, negative things can be said only in a positive manner, otherwise you are considered as a very rude person. In the same country, even in English, saying "no" should be avoided, though it may be tolerated from foreigners under some circumstances. A commonly used word is "not yet" (*belum*). This is because respect is fully required, especially with elders.

Explorations abroad are unique chances to learn more and share ways of life. It is a real chance to exchange on techniques, cave protection –a true necessity in a number of countries- and other topics.

4. Explorations Abroad

First of all, the word "expedition" is used in this paper as a technical word only. In speleology, it concerns an exploration campaign, by people from one or several countries, run in another country, with or without national cavers. It has, in principle, no negative meaning. However, "Expedition" has the same roots as "to do something very quickly, in a somewhat rough manner". It can be easily observed that the word may have negative connotations in some people minds and can be a source of friction and lack of understanding. Some fifteen years ago, a western consulate refused visas to western cavers asking to run a speleological "expedition" in the country : these cavers were told that the targeted country is developed, so no "expedition" can be organized (Note: in our view, the use of the word "expedition" has nothing to see with the degree of development of a country). So, we have to be cautious with this word. It is used in the title of this paper, only because it is technically well adapted to the topic and used by many cavers. There is no easy word to replace it, in this case.

This example shows that there can be different perceptions of a word, which is viewed as benign by some people and with suspicion by some others. Accordingly, everything has to be carefully thought out in advance when we want to go abroad for explorations (with the scientific meaning of the word, as it is, for example, in the oil industry), because the word might also mean that the targeted country is under-explored, with all feelings that might be related to that. A comment made to the author is that, for some people," "exploration" may lead to exploitation of resources, which has happened a few times in the past." Yes, this is also something to be taken into account by speleologists.

Explorations abroad must be respectful of the country and of the speleologists who live there. If there are no local speleologists, which is rare, the habits of the country still have to be respected. The culture of expedition cavers, "westernized" or not, may not be the reference for others. Even if it seems to be the case at first sight, it does not mean much. What matters is the way our behavior will be perceived within the real cultural background of the country where we want to go. The interpretation of a fact, of a behavior, or of use of similar words, can be immensely different.

5. About Behavior, in General

Explorations abroad are a wonderful way to learn more and to make discoveries, whether our goal is pure speleological exploration or scientific/ cultural research. They are also an excellent opportunity to meet people of different cultures and make new friends, provided we try our best to understand them. Our manners have to be polite and "polished". In this way, explorations will be beneficial to all parties and will create genuinely good relations.

Harmful words should be avoided such as "speleological raid" (It can be found in literature!). The behavior of a team going abroad should be modest and humble. A team should never claim that they are going to do better than the nationals. This has happened too many times, and it is rather insulting to local cavers, who have a lot of merits.

Everyone should show an attitude neither of "superiority" nor arrogance. "Superiority" remains to be demonstrated and showing it is rather rude. Instead, a courteous attitude, together with respect, goodwill and open-mindedness will be fruitful and motivating. Expeditions can be a place for exchange and mutual teaching. One team may teach for instance techniques, while local participants can teach their own techniques, knowledge of the place (karst, geology, fauna, etc.), cultural aspects or so many other possible things.

So, cavers going abroad should inform in advance their local counterparts, share the expedition with them and local non-cavers, as much as possible. After the expedition, they should follow up contacts and share results. They should behave as guests in another country.

Visiting speleologists have to understand and respect local values, discuss with the people, respect their way of life and adapt to what we call here the “Social time.” Things go on a different pace and on a different direction than that which we may be used to. Taboos and potential dangers must be fully accounted for ; caves used by man (as a house, a shed or whatever) are like private properties and need on-purpose authorization. Local customs have to be respected (forbidden caves or trails). No shocking behavior or dress should be implemented. Care should be taken to be sure that nobody will “loose his face.” Also, in a number of countries, all caves are private and have to be considered as such.

It is very important that visiting cavers must not get involved in local conflicts. They are not our business and local conflicts cannot be understood with foreign views and values. This is often a difficult matter for many travelers to understand. In addition, visitor’s behavior has to fit what local people expect ; otherwise he will have to explain and try to be understood, if possible. There is in some cases a specific attitude expected from the visitor : not the same is expected from local people. Speleologists must always inform locals of what they are doing and why. This will avoid a lot of trouble. Of course, our attitude of respect for local values (we have to fit within the local frame) does not prevent us explaining our own values and habits in our country.

6. Behavior in Conflict Areas

Speleologists like to make new cave discoveries and a number of them are ready, even poised, to go to areas where an open conflict is going on. Of course, they should think “Safety first.” However, the call for discovery is sometimes so strong, that some speleologists go to dangerous areas that are in conflict including violent conflicts. Some areas are really discouraging, but some others can be “tried” with a lower risk (e.g. some parts of the Philippines, northern Iraq, some parts of Indonesia, etc.). Conflicts can be international wars, civil wars, tribe disagreements, tribes not wishing “intruders” on their land or whatever. Sometimes, there may exist places “that should not be seen.” Exploring such places is debatable and depends on experience, past-expeditions, contacts and so on. It must be kept in mind that any mistake in such areas can lead to disastrous situations, if not for the cavers, at least for local people. No discovery is worth a human problem, especially for local people, who often did not ask foreigners to come. It is better to abandon an exploration than to create even the smallest trouble to locals, who will stay in the place once foreign cavers are gone and face all resulting difficulties.

7. Respect to be Clearly Displayed

First of all, speleologists have to respect the society of the land that they wish to explore. All officials should be informed, as much as needed, whether they are administrative officers of the country, representatives of local tribes, chief of the village, landowners, etc. Preliminary information can be sent in advance and upon arrival, information meetings or courtesy calls can be held. In some places, foreigners will not be accepted if he has not paid his respects to the local chief. In other areas, he may be requested to leave.

Initial contacts with local cavers are a matter of politeness, but they will greatly help in dealing with people inhabiting the areas to be explored. Very often, local habits such as taboos or beliefs can hardly be forecast. Local cavers may help and provide a good avenue to share local culture.

Local speleologists need to be involved as early as possible. It is always a good thing, if not a must, to inquire about the caves under exploration by local speleologists or by other groups. Ignoring this could lead to duplicating others’ work or stealing others’ results. Often this creates conflicts that are difficult to solve. Several such conflicts have occurred over the last years and not all of them have been publicised.

Local speleologists are privileged contacts and must be considered future friends. This obviously indicates that they will be treated at the best level. They will be involved as much as possible in the explorations and other work.

After the exploration campaign, contacts should be followed up and results shared as agreed. Local officers, administrations, chiefs of villages and other persons or entities involved (libraries) should be sent a copy of the reports, publications, photos, etc. produced by the exploration team, because it is their land, their caves, and their heritage.

8. Relations with Speleologists from Third Countries

Sometimes, two expeditions go to the same area. This continues to occur many times. Co-operation would be the best option, but when it is not possible, for a variety of reasons, either one of the teams leaves, or the two make their work in their own way. Such situations may occur because not all necessary information has been requested or for other reasons. The best would be that the two expeditions do not go to the same cave or area. The team who started the work normally has the priority.

This is a call for greater sharing of information, but sometimes "force majeure" may hamper detailed publication for some time.

9. Conclusion

Respect of the others, open-mindedness, goodwill, and the will to discover other people culture and other speleologists' land are necessary to achieve good speleological explorations and good results of all kinds. The principles and comments presented here are the result of a 40-year experience with nearly one half spent in some 70 countries. Nevertheless, different people may have different experience and views and debate is always profitable.

Of course, the author fully supports and promotes UIS rules of ethics. UIS has always been the cement of speleologists all over the world and a promoter of good ethics.

Much more could be said, be detailed, but the main recommendation is that expedition speleologists consider the qualities of other people and do not pay too much attention to their less good sides. Have good explorations with good friends! And good results of course!

Reference

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HUMAN USE OF CAVES IN MARTINIQUE AND GUADELOUPE ISLANDS, WEST INDIES

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Martinique is made up mainly of volcanic and andesitic rocks, including lavas and tephras, significant quantities of volcano-sediments and some sedimentary rocks including limestone. Caves are neither very numerous nor extensive. A number of them have been used by man, for a variety of purposes.

Caves here are: (1) mainly marine, either fossil or still active (in a variety of rock formations, including those in limestone with extensive maze caves), (2) gravity-related cracks, (3) empty fossil tree trunks, vertical in the surrounding volcano-sedimentary deposits, (4) nearly horizontal channels resulting from water flow in empty fossil tree branches, (5) erosional caves along narrow valleys with sub-vertical walls, (6) submarine caves in volcanic and volcano-sedimentary deposits and in barrier reefs, (7) caves in limestone and (8) small caves dug by fauna.

There are many uses of these caves: (1) Guano was mined to be used as fertilizer despite the presence of histoplasmosis. (2) Some small caves and rock shelters were used for housing (Carrib people, lonely artist, and present-day fishermen). (3) Larger caves were used for military purposes, as in the early part of 19th Century, (4) Places for praying, often to Saint-Mary the Virgin (both in natural and man-built caves). (5) Caves were rarely a cause of alarm, but there was a case of guano burning in a cave that generated a panic with heavy smoke filling the sky. (6) Caves are a place for tourist visits (bat caves) and speleology. (7) Submarine caves are explored by sea-divers. (8) Cave protection and conservation, are overall, well implemented.

Guadeloupe consists of two, geologically very different, adjacent, islands: one is a plateau of mostly porous limestone, with characteristic karst landscapes. The second is mountainous and largely volcanic and andesitic. On the limestone island, the waste of a sugar factory is discharged into a cave. The temperature in this cave is around 50° C. In the active andesitic dome of Soufrière volcano, a cave was regularly visited during the 18th Century. A large chamber was discovered in the dome of this cave in 1984. Shafts on the top of the volcano have been explored.

On arid Marie-Galante, covered mainly with porous limestone, water was collected in a natural shaft. Another cave, Grand Trou à Diable, might owe its name to histoplasmosis or simply as being an entrance to the, supposedly evil, underground realm.

1. Introduction

Islands in the West Indies (insular Central America; Fig. 1) are of two types: younger ones (to the West) are dominantly made up of active, volcanic, andesitic arc formations; older ones (to the East) are made up of volcanic arc formations that have been covered with limestone to a vary degree. Martinique is mainly volcanic and shows some limestone areas, because the two, younger and older, arcs are geographically adjacent. In Guadeloupe, arcs are separate: Basse-Terre is mainly volcanic, while Grande Terre is mainly limestone, as are Marie-Galante and La Désirade satellite islands. Many of the volcanic, volcano-sedimentary and sedimentary formations contain caves of variable types

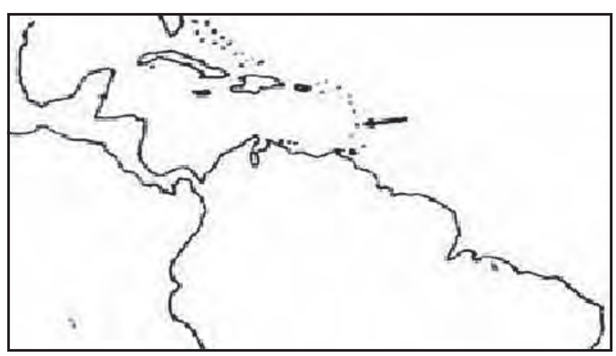

Figure 1: Locations of Martinique and Guadalupe.

and size. A number of them have been used by humans, regardless of their origin.

2. Overview of Caves in Martinique

Main caves in Martinique (Fig. 2) have the following origins:

- probable karst for Trou aux Chauves-Souris, though this is still to be demonstrated (mainly limestone).
- gravity-related : Grande Fente de l'anse Noire (North of Anses d'Arlets) in volcanic breccia, cave at Tombeau des Caraïbes (North of Saint-Pierre) in welded tuffs.
- marine : Grande Fente de l'anse Noire, grotte aux Chauves-Souris de l'anse Noire (breccia), grotte de l'îlet de la Grotte (off the eastern coast), probably the limestone cave on Ilet Hardy, etc.
- Volcanic-related : tree trunk forming a shaft (seen from below under a cliff overhang near the sea-shore at the foot of Macouba cliffs ; small channels corresponding to probable tree branches buried into pumice and ashes before rotting, leaving molds that guide vadose water to their small springs (Mouret, 1979) (Fig. 3).
- Erosional caves in narrow river valleys, mainly along meander concavities.
- Bio-related caves dug out by crabs, for instance, that can reach a 30 cm diameter and a one to two meters deep.

Figure 2: Map of Martinique.

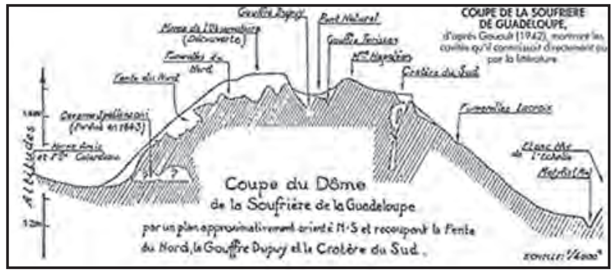

Figure 3: Cross-section of the Soufriere Volcano.

3. Human Use of the Caves of Martinique

3.1. Accommodation

House of fishermen: Ilet Ragot (also called Ilet de la Grotte) is a small islet due east of the city of Le Robert. It is less than 38 m a.s.l. and elongated nearly north to south, somewhat parallel to the fringe reef around the local lagoon. As all along the eastern coast of Martinique, much stronger waves come from the Atlantic Ocean than on the other side along the Caribbean Sea. Such waves have carved out the many small caves that are facing the ocean on that side of the island. On Ilet Ragot, a cave just above the sea level was formed at the top of the pebble to cobble beach facing the ocean. There, on the upper part of the beach, which is finer-grained, a fisherman has built a wooden house. The house is built right on front of the sea cave, which is therefore used as an additional, more comfortable room.

House-like shelter: A certain Médard Aribot, a self-taught artist and somewhat solitary man, used to live in a cave at Anse Cafard, which is a rocky, cliff-bounded, seashore area, nearly in front of Rocher du Diamant. The author located a series of caves there, covered with indurate rock (probable pedogenetic diagenesis). Their sloppy floor is about 3 m high above the sea level; they are 2 to 3 m high, and a few meters deep horizontally, at most. These caves are rather uncomfortable, despite their extension parallel to the shore, which can extend over up to 10 and even 20 m long. Aribot probably placed some kind of a rough wall facing the sea, but no information could be gathered on this in 2008. Médard Aribot was born in 1901 at Trois-Rivières, a nearby village, and was arrested in 1925. Aribot was sentenced to forced labor in Guyane. When he came back to Martinique in 1940, he did not stay anymore in his favorite cave or perhaps only on a very spotty way (Josse *et al*, 2007).

Shelter for Carrib natives: At the base of the northern cliff of the Macouba River canyon, at around 50 m from the seashore, a very large erosional rock shelter was probably carved out by the stream. The place was described by the R.P. Labat, a priest of the Dominican Order, who lived in the village of Macouba from 1696 to 1698 AD (Holo *et al*, 2006). He mentioned that the natural vault shows rounded holes in the curved part (the top, probably). He also wrote that Carrib natives may have used the cave as a hide-out.

3.2. Military use

HMS Diamond Rock: The Diamond Rock is a magnificent volcanic rock culminating at 176 m a.s.l., one of the most beautiful sites in Martinique. In 1804, the British army had in mind conquering Martinique so they could grow sugar cane and organize sugar trade. In order to help in the blockade of Martinique and to prepare some attacks, the British army settled on the Diamond Rock. A cruiser governed by Samuel Hood brought 200 soldiers onto the rock (Favre et al, 2007). Considerable work was made on the steep slopes and under rock shelters (consisting of curved hollows along the cliffs), in order to transform the place into a military base. Close to the sea level and besides two rock shelters (to the northwest and to the southeast), two gun batteries were installed. Another one was placed mid-height of the rock and another one at the very top. Rock was blasted off and several reservoirs were dug for permanent water storage, together with a cistern built nearby. Powder also allowed them to prepare place for barracks, houses and a hospital. Some eight months later, after a three-day fierce fight, the 107 soldiers present left the rock (Antoinette, 2005). It is said that British warships cruising in the area still pay respect to “HMS Diamond Rock.”

For our purpose here, it is important to note how some rock shelters of very limited horizontal extent, probably rocky and sloppy could be used and extended for military purpose.

Holes from gun bowls at anse Turin: These holes have been mentioned by Favre et al, 2007). They are most likely natural, as they are selectively located in pumice and not in intervening ash formations. A few are oblique to the cliff.

3.3. Religion

Natural caves used for worship: In the same cave in Macouba that was mentioned above as being a hide-out for Carrib natives, or close to it, Saint-Mary the Virgin has shown up, as it is believed (Holo et al, 2006). Josse *et al* (2007) give a slightly different version with a statue of the Virgin appearing in the cave, likely this one. The parish’s priest brought the statue into the church at the top of the cliff. Some time after, the statue disappeared from the church and was found at the same place in the cave. Because of this, a man-made cave has been built nearby and the statue, placed inside, has never moved away since 1953.

Man-made caves used for worship of Saint-Mary the Virgin: In Macouba, not far from the cave along the Macouba River, a man-made cave features the Holy Cave in Lourdes, Southern France. It faces the sea, close to the bottom end of the impressive, narrow, steep road that leads cars down the cliff to the sea shore. A pilgrimage occurs there every year on the Holy Friday. Similar man-built caves dedicated to Saint-Mary the Virgin exist in Fonds-Saint-Denis (two locations on either sides of the promontory holding the church, in Diamant (in the city proper), close to Morne Rouge, close to the north of Saint-Joseph.

3.4. Natural resources

Exploitation of guano: The Trou aux Chauves-Souris in Josseaud is a shaft leading down to a gently sloping passage. The total depth is 30 m. A chimney from the upper part of the passage used to lead to the top of the small hill where the cave is located (M. Madkaud, personal communication, 2008). According to other information, the chimney may have been dug or enlarged by man. A few years ago, a house was built on top of it. The cave is home to thousands of bats. During the first half of the twentieth century and probably before, locals used to go down to the bottom of the shaft and dig the main passage and other side areas to collect guano. The sloppy part bears stairs. The guano was sold or directly used for fertilizing gardens and fields. This lucrative job was either the main one on the island, or the only one. Guano miners were sick from their jobs from time to time and considered subject to “fevers.”

Bats exist in other places. One is a marine cave between anse Noire and Anse-à-l’Ane. One, not seen by the author, may be located close to Pointe Blanche, not far from L’anse-à-l’Ane. These locations are not known to have been exploited for guano, but this remains to be investigated more thoroughly.

Frightening caves: Caves are sometimes frightening. So are the “souffleurs”: waves enter holes or marine caves along the rocky coasts, compress air inside and a strong pulse of mixed air and water is ejected above if some narrow opening exists through the top rocky cover. Usually, nobody dares entering such a cave. Sometimes, they are not even approached, even by boat. A souffleur is located to the West of the village of Grand Rivière.

Underground slow guano burning occurred in a cave in 1976, probably at Pointe Blanche. It was witnessed by Denis Westercamp, a geologist at the French Geological Survey. Heavy, dark grey smoke exited from the hole over three weeks. Locals were frightened because they believed the smoke was related to the then erupting Soufrière volcano in Guadeloupe (200 km north!).

3.5. Tourism, leisure, and speleology

Caves as touristic places: The opening of Trou aux Chauves-souris in Josseaud was often visited in the past, as it is located on tourism maps. It is now severely restricted by the current owner, Mr. Madkaud, to protect bats. In 1976 and 1977, we did not observe bats at the entrance, but during our authorized visit in July 2008, we could see tightly packed bats hanging along the cave walls, as high as the cave opening, where they are sometimes caught and eaten by cats. The Grotte aux Chauves-souris located along the seashore to the north of Anse Noire is commonly approached by tourist boats (scores a day), but normally nobody enters it. Some locals reported to have entered the cave a few times, to satisfy their curiosity.

Speleology: Speleology is not a current activity in Martinique, as caves are short and not numerous. Nevertheless, Trou aux Chauves-souris de Josseaud was already regularly entered by local guano miners when first speleologists, J. Huon de Navrancourt, Father Pinchon and their team, explored the cave on the 3rd June 1951. Due to histoplasmosis, the author did not enter it.

Grotte de l'îlet Hardy was mapped by R. de Jaham and J.P. Marry (R.P. Pinchon, 1967) and Grande Fente de l'anse Noire was mapped by the author and André Gilbert in March 1977. Many observations were made by the author in 1973, then during two years (1976–1977) and 2 weeks in 2008. Between 1951and 1967, explorers left a limited information. Many caves have been described and explained by Mouret (1978, 1979 a & b, 1981, 1997). More data were acquired by the author in July and August 2008. Nevertheless, information is still missing due to the partial reporting of early explorations, difficult access (large bat colonies), and/or diseases.

Diving in submarine caves: Less well documented and not directly observed by the author, submarine caves are mentioned in "grey" literature, including guidebooks for tourists, leaflets, newspapers, etc. Despite common visits, no accurate description is available and available information is conflicting. In volcanic rocks, the most famous caves are in the submarine part of Rocher du Diamant. A cave was also mentioned, but not confirmed, in the Bay of Saint-Pierre. Submerged canyons are present close to Anse Dufour. Divers penetrate the first few meters of Grande Fente de l'anse Noire. Caves and open cracks are present in reefs, as for instance to the south of "Banc du Diamant", the barrier reef in front of the small city of Le Diamant.

3.6. Other uses

Treasure hiding: Along the way between the small mountain called Morne de la Caillerie (582 m asl, located to the southwest of the major Morne Jacob culminating at 883 m a.s.l.) and the small village of Sainte-Cécile (around 3.5 km to the southeast of the large village of Morne Rouge), a natural cavity has been described near the crest trail between the two locations (S. Favre et al, 2007: 165). It is named "le trou d'Argent" and it is described as a several-meter deep natural cavity. According to a legend, local Carribs are said to have buried a treasure inside. Its nature is not mentioned.

3.7. Negative aspects related to caves

Histoplasmosis: Following the 1951 exploration of Trou aux Chauves-souris in Josseaud, one caver died from histoplasmosis (a then unknown lung disease). Several others continued to have lung problems for life due to calcification (R.P. Pinchon, 1977, pers. comm. & J. Huon de Navrancourt, 1978, pers. comm.). Local guano miners probably developed resistance to the disease, suffering only from "fevers". They likely suffered from it, but probably mistaken the scientifically unknown disease for malaria. Some developed immunity (J. Huon de Navrancourt, 1978, pers. comm.). The disease is also present in narrow cracks and minor passages in limestone at Morne Castagne on the Caravelle peninsula (R.P. Pinchon, 1976, pers. comm.). We do not know if it is present elsewhere in the island, but a cautious behavior is highly recommended.

Garbage deposits: Such deposits are rare because Martinique is overall a clean island, and also because of the limited number of caves. However, in a very few cases, a moderate quantity of garbage and construction debris can be encountered, as at the inner end of Grande Fente de l'anse Noire. Such practices should be controlled and firmly discouraged. Of a very different nature is the rubbish floated on the sea and landed along the coast lines and associated marine caves. This is a problem now present all over the world.

4. Conservation of Caves in Martinique

Caves in Martinique present a variety of conservation concerns. None is protected for itself, but they are by the use which is made of them or by the characteristics of their area. Grotte de l'îlet Hardy is protected because of its location on an islet protected for birds. The Trou aux Chauves-Souris in Josseaud is now jealously protected, as well as the bats in it, as no access to it is normally allowed by the owner.

5. Caves of Guadeloupe

Although we have less information on Guadeloupe, it is worth giving available data as information is uncommon and the concern caves also not so common (Fig. 4).

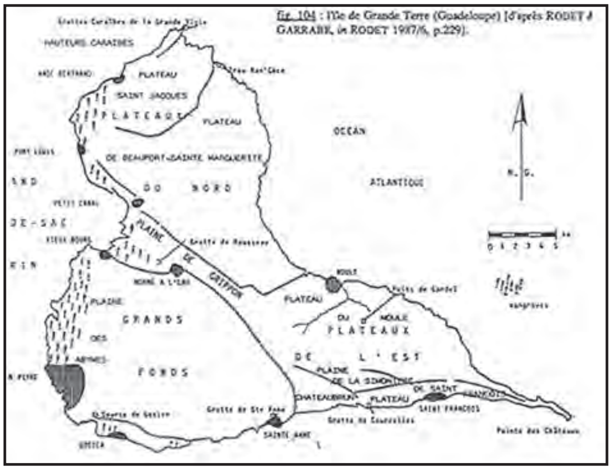

Figure 4: Map of Guadalupe.

5.1. Industrial waste disposal

Basse-Terre Island has a limited amount of pollution, but Grande-Terre is largely a succession of plateaus and its karstification is locally rather significant. Sugar cane is widely cultivated and the processing factory at Gardel produces waste liquids, very hot, which are sent into the underlying, nearly 800 m long (Barrabé, 1935) Grotte de Gardel. In early 1984 (Mouret and Rodet, 1984), we observed that the man-dug well (4 to 5 m wide, around 35 m deep, and the only access to the cave) was steaming with the temperature at ground surface no less than 45°C. Probably, most or the whole, cave had been invaded by the effluents.

5.2. Tourism

In 1730, J.A. Peyssonnel discovered a long cavern (total length between 150 and 300m), called Caverne Spallanzani, inside the andesitic dome of the Soufrière volcano in Basse-Terre. The cavern had three chambers (Mouret & Rodet, 1984) separated by narrower passages. There were cool places and others rather warm. For 40 years during the eighteenth Century, a local citizen called Bernard guided visitors inside the cave. After 1811, a temperature rise prevented any further visit and in 1836, no access was possible. In 1984, a large underground chamber was discovered after some digging by Mouret and Rodet (1984). It was called Salle Jules Verne, as there is no proof that it is part of the former Caverne Spallanzani. This newly known chamber (65 x 35 x 11m, with a 28° slope and the bottom at -35m) has seen some visits but not by common tourists.

5.3. Speleology

After Peyssonnel in 1730, and Bernard, new explorations on the volcano were reported by J. Gouault (1942) after French marines reached -126 m in the steaming shaft called "cratère du Sud." The discovery of Salle Jules Verne was made in 1984 by Mouret and Rodet (1984), who also explored several other caves and shafts. In the early 1990s, Gouffre Tarissan was explored down more than 100 m (Ferrier, 1992). In the limestone of Grande Terre, explorations were made in the early 1930s by Barrabé (1935), by Rodet's team in the 1980s and, by local groups since.

6. Other Islands Related to Guadeloupe

In karstified Marie-Galante, the "Petit Trou à Diable" is a nearly 25 m deep shaft that can be descended along a boulder collapse. The pool at the bottom was used in the past as a source for water on the arid part of the island where it is located. The "Grand Trou à Diable," a more than 500 m long cave may owe its name to histoplasmosis or as being an opening toward the supposedly evil underground realm. In La Désirade, Saint-Martin and Saint-Barthélémy, which are partly limestone islands, cave use is still to be documented, as it is in the volcanic islands called Les Saintes.

7. Conclusions

Despite their small size and the limited number of caves, volcanic islands in the West Indies have been widely used by humans for a variety of purposes. Some of these caves are highly original, as is the Caverne Spallanzani visited by tourists in the middle of the Eighteenth Century. Many more remains to be discovered in these islands and in neighboring ones.

The limestone areas also deserve wider investigations, despite the many already done.

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THE MAP OF ANCIENT UNDERGROUND AQUEDUCTS: A NATIONWIDE PROJECT BY THE ITALIAN SPELEOLOGICAL SOCIETY

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The project "The Map of Ancient Underground Aqueducts of Italy", started in 2003 by the Italian Speleological Society (SSI), and entirely dedicated to the study and exploration of ancient underground aqueducts, has allowed so far to collect a database of 125 ancient underground aqueducts, distributed in all the Italian regions. Historically, ancient aqueducts have been explored and studied by cavers. Their importance derives from a number of historical, engineering, and environmental reasons. These aqueducts represent a valuable documentation of the skill and engineering techniques of the ancient communities, and due to the mostly underground development, they have often been preserved intact for millennia. Main objectives of the project are: (i) implementation of a detailed inventory of the ancient aqueducts of the Italian territory; (ii) updating of the state of the art on the matter; (iii) encouraging new studies and explorations, in particular by cavers, regarding the ancient aqueducts; (iv) safeguarding and exploitation of these unique works of historical and engineering hydraulic importance.

1. Introduction

Since the establishment of the first settlements, man had to face the issue of water availability. Water was obtained through tapping, transporting and distributing the hydric resources by means of highly specialized works, many of which were actually extremely complex when considering their time of realization. Qanats (from a Semitic word meaning "to dig") are the oldest form of subterranean aqueducts engineered to collect groundwater and direct it through a gently sloping underground conduit to surface canals which provide water to agricultural fields or oases. They represent one of the most ecologically balanced water recovery methods available for arid and semi-arid regions, since do not upset the natural water balance, relying entirely on passive tapping of the water table by gravity. The best evidence (archaeological and written accounts) suggests that qanat irrigation was first invented in the Armenian-Persian region about 600-700 B.C. (LIGHTFOOT, 1996); however, other scholars indicate the first realizations of qanats as dating back to three thousand of years ago (WULFF, 1968). The art of tunnelling, and the expertise in realizing deep shafts and underground canals to transport water, were probably even older, as suggested by the drainage works realized at Kopais, in Boeotia, at the beginning of the 2nd millennium B.C. (KNAUSS, 1991), or by the attempts of the Mycenaean civilization to cross a mountain ridge with an artificial emissary discharging the water toward the sea around the 12th century B.C. (CASTELLANI and DRAGONI, 1997).

Management in drinking water supply has always been of fundamental importance. The need to having available the necessary amount of hydric resources for the populations pushed ancient populations to tremendous efforts in planning, realizing, and maintaining long and complex aqueducts, that developed underground for most, if not all, of their length. To provide just an example, when the engineer Sextus Julius Frontinus was appointed, in AD 79, as imperial water commissioner *(Curator Aquarum)* of the City of Rome, he became responsible for a supply of 800 megalitres daily into the city from nine underground aqueducts, with a total length of 420 km (BONO and BONI, 1996; PIKE, 1999).

Ancient populations (and particularly ancient Romans) understood the relevance of placing the aqueducts underground as a method of protecting their fresh water from external threats, represented by the many enemies. Three main advantages for building the aqueducts underground must be reminded (ASSANTE, 2007; TASSIOS, 2007): (i) to conceal and to protect them from enemies; (ii) to protect them from erosion and deterioration; (iii) to be less disruptive to life above ground. On the other hand, the main disadvantage was represented by the greater difficulties in maintaining and inspecting the systems (CASTELLANI, 1999, 2001). In many cases the final structure was a mostly underground aqueduct, with intervening sections above ground (Figs. 1, 2). Studying ancient underground aqueducts represents an exciting challenge, that may open new lights toward the capability of man to collect water in the past and, more generally, to work toward a sustainable use of the natural resources (LAUREANO, 1995; BURRI, 2008). On the other hand, the periodic hydrologic crises we experience, often related to over-exploitation and degradation of the water resources, demonstrate that several lessons may be learned from the analysis of ancient hydraulic works (CASTELLANI and DRAGONI, 1991; BURRI, 2003).

Figure 1:Above ground arcade section of an aqueduct near Rome (photo: C. Galeazzi).

2. The Project "The Map of Ancient Underground Aqueducts of Italy"

In 2003, the Italian Speleological Society (SSI) started a project, entirely dedicated to the study and exploration of ancient underground aqueducts, called "The Map of Ancient Underground Aqueducts of Italy." As a matter of fact, ancient aqueducts, as well as other subterranean hydraulic works (lake outlets, cisterns, tanks, etc.), have been since a long time explored and studied by cavers (Fig. 3). Their importance derives from a number of historical, engineering, and environmental reasons:

- they represent a valuable documentation of the skill and engineering techniques of the ancient communities;
- due to the mostly underground development, they have often been preserved intact for millennia;
- they are among the main works that testify the efforts by man to manage the territory, and to develop urban civilizations;
- even though lacking a continuous maintenance, several ancient aqueducts are still working today;
- some aqueducts might be put again at work through low-cost interventions, and constitute an additional water supply in case of droughts or during hydrologic crisis.

Main objectives of the project are, therefore: (1) implementation of a detailed inventory of the ancient aqueducts in the Italian territory, and evaluation of their present state; (2) updating of the state of the art on the matter. Many publications on ancient aqueducts are available in the historical and archaeological literature, but they have never been properly collected and organized so far; (3) encouraging new studies and explorations, in particular by cavers, regarding the ancient aqueducts; (4) safeguarding and exploitation of these unique works of historical and engineering hydraulic importance. Since the Italian territory presents a huge amount of ancient hydraulic works, the database of the project includes all the aqueducts responding to these two time and space requirements

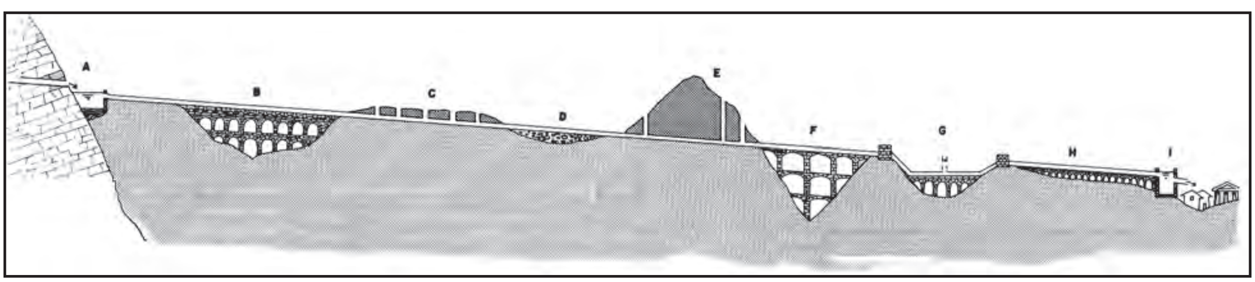

Figure 2: Sketch of a Roman aqueduct (after CASTELLANI and DRAGONI, 1989). Explanation: (A) spring tapping by draining conduits and silting basin; (B) viaduct channel with multiple arcades; (C) underground tunnel at low depth, with several wells; (D) channel on earthfill; (E) underground tunnel at great depth, with few wells, generally at its ends; (F) viaduct with continuous vertical pillars; (G) inverted siphon, realized according to Vitruvio's description; (H) final viaduct; (I) collection and distribution tank.

Figure 3: The main tunnel in the Triglio aqueduct (Taranto province, Apulia), one of the longest inventoried aqueducts in southern Italy, with a length of approximately 18 km.

(PARISE, 2007(a): (1) the upper time limit of the aqueduct construction is considered to be the XVIII century; (2) the aqueduct must be at least 400 meters long. As regards the latter requirement, some exceptions have been made, in case of smaller, but historically or hydrogeologically important aqueducts. The aqueducts have been temporally subdivided into three periods: (i) greek-roman time (until VI century B.C.); (ii) byzantine-medioeval time (VII–XIV century B.C.); and (iii) renaissance-modern time (XV–XVIII century B.C.).

In the first phase of the project, a specific form was implemented, in order to facilitate the collection of the main information about each aqueduct. The form, that soon became available in digital format at the dedicated website (address: http://www.antichiacquedotti.it/), consists of three parts: (a) general data; (b) technical data; (c) personal data.

The general data include all the relevant information about name and location of the aqueduct (region, province, municipality), length (with indication of the percentage of subterranean course), and availability of plan and sections. In addition, the present state of the structure, and the possible necessary works for its re-utilization, are also indicated. Eventually, the general data includes all the bibliographic references dealing with that specific aqueduct. The technical data of the form encompasses information about the geological and hydrological setting of the area where the aqueduct develops, with particular reference to geology of the spring area, and any geological (stratigraphic or tectonic) change along the course of the aqueduct. They also include the known notice about age of utilization of the aqueduct. The personal data, eventually, refer to name, address and correspondence of the form's compiler, in order to have the possibility to contact him/her for further requests.

A very important part of the project consisted in putting together, in a unique bibliography, all the references about ancient underground aqueducts, that are often dispersed in many local or sectorial publications, journals or conference proceedings. A thorough work of bibliographical research, and a subsequent phase of cross-checking among the main literary sources, allowed to develop a list of over 1,000 publications (January 2009 update). These were subdivided on a regional basis, and within each region they were in turn associated to each hydraulic work. While the first version has been recently released (PARISE, 2007b), the bibliography is continuously being updated.

3. First Outcomes

Up to date (January 2009) an overall number of 131 forms have been compiled, with a regional distribution of the aqueducts as shown in Figure 4. This number, certainly not a definitive one, expresses the great potentiality of the Italian territory as regards the presence of ancient hydraulic engineering works. The 131 forms correspond to 125 ancient aqueducts distributed over 19 regions of Italy (the only exception being Calabria, where so far no ancient underground aqueduct has been documented). As expected, Latium hosts the great majority of aqueducts, counting 40 hydraulic works (Fig. 4); it is followed by Marche and Campania (13), Apulia (11), Abruzzo (9), and Piedmont (7). A direct consequence of such a regional distribution is the presence of aqueducts in the different Italian provinces: Rome counts 28 aqueducts, and is followed at great distance by Naples (8), Ancona (7), Viterbo and L'Aquila (6), and by many other provinces.

The majority of ancient aqueducts is comprised between 1 and 5 km, but there is a high percentage of aqueducts with a longer course, that is more than 10 km (twelve aqueducts are longer than 30 km). Over four/fifth of the

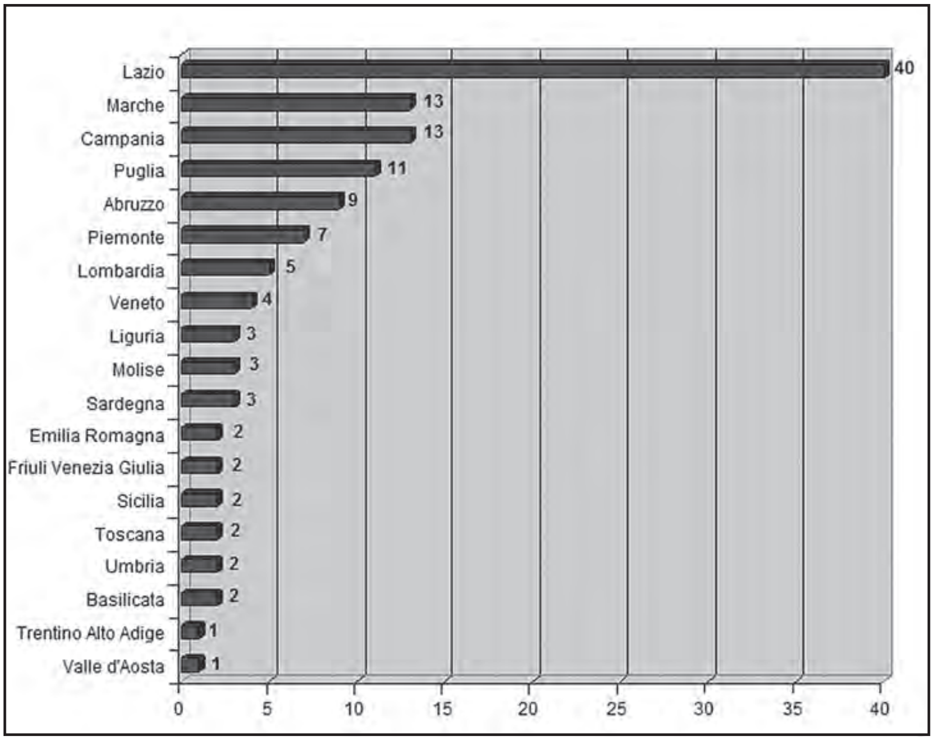

Figure 4: Regional distribution of the ancient underground aqueducts in the database (updated to January 2009).

inventoried aqueducts (precisely, 82%) is of greek-roman age. Only one aqueduct has been catalogued as byzantine-medioeval, but it likely follows an older (roman?) course, not yet documented, however. The remaining (13%) is of renaissance-modern time.

Some considerations have to be done about dating of the aqueducts: the date often comes from historical sources (for example, an ancient author indicates explicitly in the text the date of beginning, or end, of the work, together with the emperor's name); sometimes it is derived from the functionality of the aqueduct (for example, it provided the water supply to a roman colony, thus it is a roman aqueduct); in some case, it is just an hypothesis (for example, it is called roman aqueduct, but actually no documentation which can prove the date is available). Utilization of the aqueducts was rather diversified: they mostly took drinkable water and transported it to *domus*, *villae*, towns, thermal baths, and military camps (GERMANI et al., 2007). In a few cases, the waters were used to irrigate, while in others the hydraulic works drained waters from lakes. There is also one case where the aqueduct supplied water to mills and factories, by providing the purpose-built wheels with the energy for the production process (BIXIO *et al.,* 2007). In most of the cases, the aqueducts are subterranean, completely or in large part.

There is no uniformity in the geological setting of the source areas of ancient aqueducts. In most of the cases, rocks of sedimentary origin (35%) crop out in the areas where the springs are located. These are followed by carbonate (31%) and volcanic rocks (30%), while a much lower percentage interests debris deposits (4%). Analyzing the geology of the area where the hydraulic works are located, and even the difficulties related to the presence of different types of rocks to dig the underground tunnel is a very interesting topic, worth to be thoroughly studied (DEL PRETE and PARISE, 2007). More in general, it has to be noted that the deep knowledge the ancient populations had about hydrogeology, hydraulics and topography, in order to design, and correctly realize, underground aqueducts, is really astonishing.

4. Future Perspectives

The Project "The Map of Ancient Underground Aqueducts of Italy" is still in progress; the amount of sites to study, and where to collect further data, is actually enormous in a country as Italy. The efforts by the Italian Speleological Society have necessarily to be strictly linked to research centres and universities, in order to have the possibility to give continuity to the project and keep working on this subject. As regards the future, already planned, steps of the Project, in the next months the material available so far will be published on the web. This will open the possibility to new collaborations, and, hopefully, some sorts of funds, necessary to start additional explorations and researches, both at the local and the national level.

Recently, aimed at further co-operations with foreign scholars and cavers, a systematic research about bibliographic references to ancient underground aqueducts outside of Italy has also started. The interest on the topic is in fact great even outside the Italian boundaries, and especially in the other countries of the Mediterranean Basin, where many other important ancient hydraulic engineering works have been built and used during the different epochs. This part of the project, that was started a few months ago, have so far resulted in a list of some hundreds of bibliographical references about underground aqueducts distributed all over the world.

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VENEZUELA'S CHAIMA INDIGENOUS COMMUNITY AND ITS RELATION TO NATIONAL SPELEOLOGICAL PRACTICE

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Abstract

Guácharo Cave holds a special place in the history of Venezuela's speleology. It is, however, only one of many caverns that have been explored, surveyed, and scientifically studied in the greater region (most of them within the present boundaries of El Guácharo National Park). This paper provides a historical review of cavers' relation to members of the Chaima indigenous community that inhabit the area. This review is based on interviews, a review of both published and unpublished materials that resulted from expeditions in the region, and fieldwork in El Guácharo National Park, including the ethnographic account of two recent expeditions to the area that again involved collaboration with locals of Chaima descent. Informed by anthropological work concerned with the impact of scientific practice on local knowledge practices, I argue that cavers are uniquely positioned to highlight the existence and value of different knowledge systems associated with the places they explore and study. In fact, I suggest they have the responsibility to do so, although precisely how that responsibility might be assumed is anything but straightforward. In the case of the Chaima community in the mountainous regions of northern Monagas state, Venezuela, it has been cavers who provide ethnographically unique and valuable information about ongoing cultural practices. Their contributions take on an even greater meaning when these indigenous communities are threatened with extinction and/or are dismissed as "dead." This case is reviewed in light of changing indigenous politics not just in Venezuela but in many countries in Latin America. The implications of these politics on ongoing speleological research in the region and beyond are considered.

A RESCUE PRE-PLAN FOR LECHUGUILLA CAVE, CARLSBAD CAVERNS NATIONAL PARK, NEW MEXICO

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Lechuguilla Cave is over 205 km long and 489 m deep. It is the fifth longest cave in the world and the deepest limestone cave in the United States of America. It is an extremely complex vertical maze cave divided into three main branches. Each of these branches has 200-350 m of vertical development and requires ascending, descending and traversing many ropes to reach the farthest points in the cave. Over six km of rope are permanently rigged in Lechuguilla Cave. One way travel to the farthest reaches of the cave is approximately 5 kilometers from the entrance. In addition Lechuguilla Cave is a very delicate cave in respect to cave formations and microbiology. Cavers are actively exploring, surveying, inventorying, photographing and studying Lechuguilla Cave. As with any vertical cave, there is always the risk of a caver being injured and needing to be rescued. In 1991 a large scale rescue of a caver with a broken leg emphasized the challenges of performing a rescue in the delicate environment of Lechuguilla Cave.

In 2004 John Punches and Anmar Mirza began working with Stan Allison on a cave rescue Pre-plan for Lechuguilla Cave. The goal of the Rescue Pre-plan was to create a pre-plan that would serve as a tool to increase the safety and efficiency of a future cave rescue while minimizing impact on the cave. In order to achieve these goals, the Pre-plan utilizes simple rescue rigging that emphasizes minimal resources both in terms of equipment and personnel. Most of the haul systems in the Pre-plan involve counterbalance techniques that require minimal resources and could be used in many situations to conduct a self rescue. The Pre-plan covers the three main travel routes into the three major branches of Lechuguilla Cave and contains maps, photos and diagrams that demonstrate how to rig each obstacle encountered within the cave. In addition there are sections on anchors, rigging rationales, communications, operations, patient litter packaging and underground teams.

1. Introduction

Developing cave rescue pre-plans for large, complex caves that involve numerous trips along the same travel corridors have many advantages. These plans can significantly increase the likelihood of a successful rescue while reducing the amount of time needed to perform a rescue, thus increasing the probability of a positive outcome to a cave rescue. These plans assist cave managers and cavers in performing an effective, efficient cave rescue and help them to be better prepared when a cave rescue occurs. In addition, for more delicate cave environments, these plans can reduce the impacts caused by a cave rescue.

Lechuguilla Cave is an excellent example of a large, complex cave with numerous ongoing projects. Currently Lechuguilla Cave is the fifth longest cave in the world with over 205 km of survey. It is the deepest limestone cave in the United States of America at 489 m deep. After traveling through the entrance region, the cave splits into three major branches identified as the East, West and South branches of the cave. Each of these branches has 200-350 m of vertical development.

Lechuguilla is among the most complex maze caves in the world. While Lechuguilla is not one of the world's most difficult caves, it does involve single rope techniques (SRT) on numerous pitches of up to 100 m. Many of these pitches involve obstacles such as rebelays, redirects, traverses and sub-vertical pitches. Over 6 km of ropes are permanently rigged in Lechuguilla Cave. One way travel to the far reaches of the South and West Branches is approximately 5 km. One way travel to the end of the East Branch is about 4 km, but this is the most technically challenging route and has the longest travel times of all branches.

Most projects that take place in Lechuguilla are undertaken with the aid of cave camping due to the distances traveled and the amount of equipment required. The Deep Seas Camp in the West Branch requires about 4 hours of travel from the entrance. Accessing the most remote areas in the

West Branch requires an additional 3 hours from camp. The Big Sky Camp in the South Branch requires about 6 hours travel from the entrance and accessing the most remote areas in the South Branch requires an additional 3 hours of travel from camp. The Grand Guadalupe Junction camp in the East Branch requires about 8 hours travel from the entrance and the most remote areas of the East Branch require an additional 2 or 3 hours of travel.

The relatively warm 20° C temperature of Lechuguilla is comfortable when sleeping, resting, surveying or performing science. These high temperatures cause profuse sweating and overheating when moving through the cave. The high temperatures and humidity combined with rigorous exercise when moving through the cave can result in dehydration and other forms of heat stress.

Lechuguilla Cave is an extremely delicate environment in terms of cave formations. It is recognized as one of the world's most aesthetically beautiful and mineralogically diverse caves in the world (HILL AND FORTI, 1997). All but the first 150 m of cave remained sealed off from human access until May 1986. The cave surfaces are liberally covered with delicate formations that make it challenging to move through the cave without damaging them. Many areas of the cave have narrow trails passing through fragile formations. Rescue operations in such a delicate environment could cause a large amount of impact in a short period of time.

Lechuguilla Cave is also an extremely delicate environment in terms of microbiology. It is an extremely low nutrient cave environment that has resulted in a fascinating diversity of microbes. These microbes can be negatively affected by human activities inside the cave which can greatly elevate organic levels. In addition foreign bacteria and fungi brought in by human activities can eliminate native microbes and reduce biodiversity. (Northup et. al., 2000)

Lechuguilla Cave is located within Carlsbad Caverns National Park which is a World Heritage Site. The known cave underlies a surface area that is designated wilderness. Due to the delicate and technical nature of the cave, access is limited to experienced cavers performing research or survey, exploration and inventory. Recreational caving trips are not permitted in Lechuguilla Cave. During a typical year as many as 100 cavers will have the opportunity to work in Lechuguilla Cave.

In 1991 a caver suffered a broken leg near the start of the Western Branch of Lechuguilla Cave. The injury occurred about 2.4 km from the entrance and about 300 m below the entrance. The rescue involved a total of 173 people in the cave and on the surface. About 100 persons entered the cave during the rescue, but the most in the cave at any one time was probably about 60. From the time of injury it took 91 hours to extricate the injured caver. Despite the best efforts of everyone involved, there were impacts to the cave due to the rescue. Delicate floor areas with only one narrow path were impacted due to the necessity of hauling a litter. Four constrictions were enlarged so that the litter could pass. Additional expansion bolt anchors were placed. Plastic from the litter was scraped onto the cave. Red colored rope used in haul system left red fibers on white slopes. In addition there was the impact of having so many rescuers in the cave. One of the recommendations after the rescue was that a rescue pre-plan for Lechuguilla Cave be developed.

2. Methods

Main travel corridors in Lechuguilla Cave were identified and prioritized for rescue pre-planning. At over 200 km of surveyed cave, it was neither realistic nor desirable to pre-plan every cave passage. Routes to be pre-planned were chosen based on the amount of traffic they received and

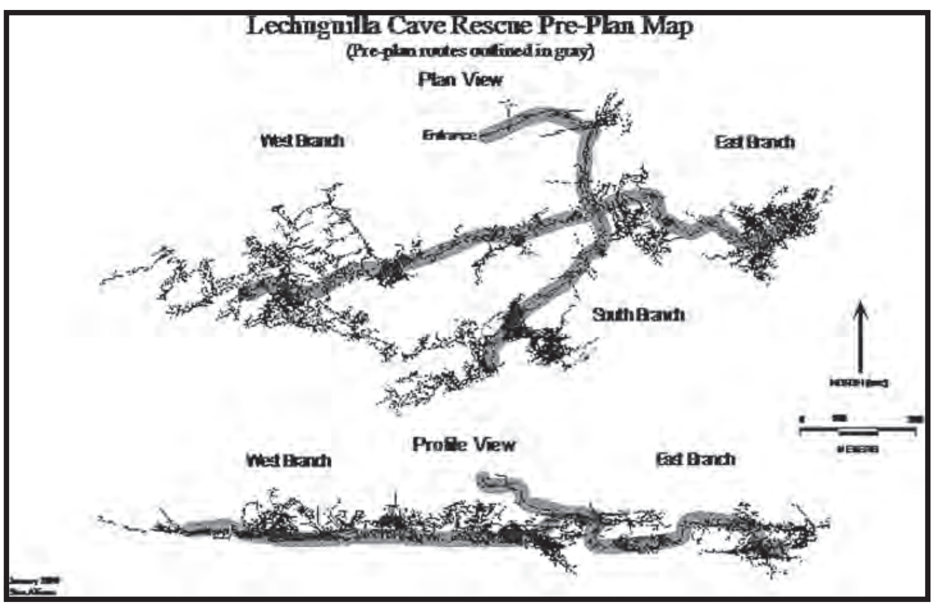

Figure 1. Map of Lechuguilla Cave showing pre-planned areas outlined in gray.

were generally the main travel routes to camps and some of the main routes beyond camps (Fig. 1).

Once the routes to be pre-planned for rescue were determined the actual field work could take place. Pre-planning was initiated at the entrance and moved deeper into the cave. Pre-planning in the cave involved a small group of cavers, typically three. It was determined that having larger groups involved in pre-planning generally resulted in too many opinions, and less work was accomplished. Each obstacle, whether horizontal or vertical, was identified, and then a plan was created for that obstacle. Measurements were taken for rigging needs, anchors were identified, and in some cases additional artificial anchors such as stainless steel bolts were recommended for rescue rigging. Numerous photographs were taken of the obstacle and anchors. In some cases, a thin piece of cord and small pulleys were used to quickly rig the rescue system proposed for the obstacle to determine any potential problems such as rope drag and edges requiring deviations or padding.

John Punches and Anmar Mirza approached the pre-planning with open minds and didn't confine themselves to the rescue rigging systems that had been used in Lechuguilla in the past. The previously used haul systems were equipment intensive to rig and required many people to operate. Instead, it was determined that much of the rigging for rescue in Lechuguilla could be done using resource efficient counterbalance systems. In general counterbalance systems have the following positive attributes. They use a minimum of gear and personnel and are simple to rig and operate. They require less space at the top of the pitch and don't tend to impact the resource as much as regular haul systems. They may also be used for small party self rescue. A disadvantage of counterbalance haul systems is that they place higher loads on anchors so riggers must be aware of forces and force multipliers involved. Anchors used for the counterbalance hauls were selected with these higher loads in mind.

After the field work was finished, John and Anmar would sit at their computers downloading pictures, going through notes, maps and creating the actual pre-plan. The pre-plan includes maps, photographs and diagrams of each of the obstacles (Figs. 2-7). Often times there would be questions about a specific obstacle that would be further evaluated on a later pre-plan trip to that area. Two of the obstacles requiring rigging in the pre-plan were actually rigged and tested with human loads but without litters. One of these obstacles was Boulder Falls, a 150-foot largely free-fall drop with the upper 40 feet against the wall. The counterbalance system worked very well enabling two 80 kg cavers to

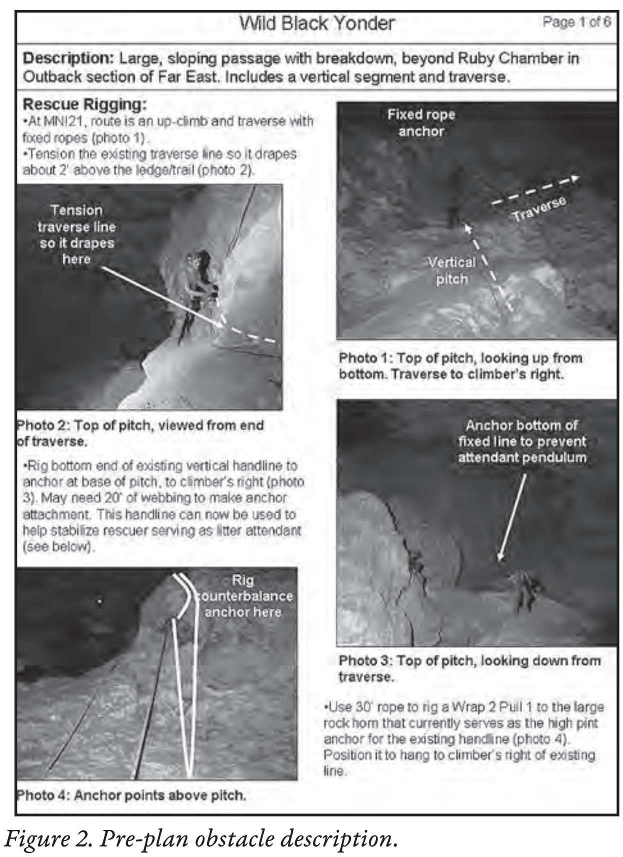

Figure 2. Pre-plan obstacle description.

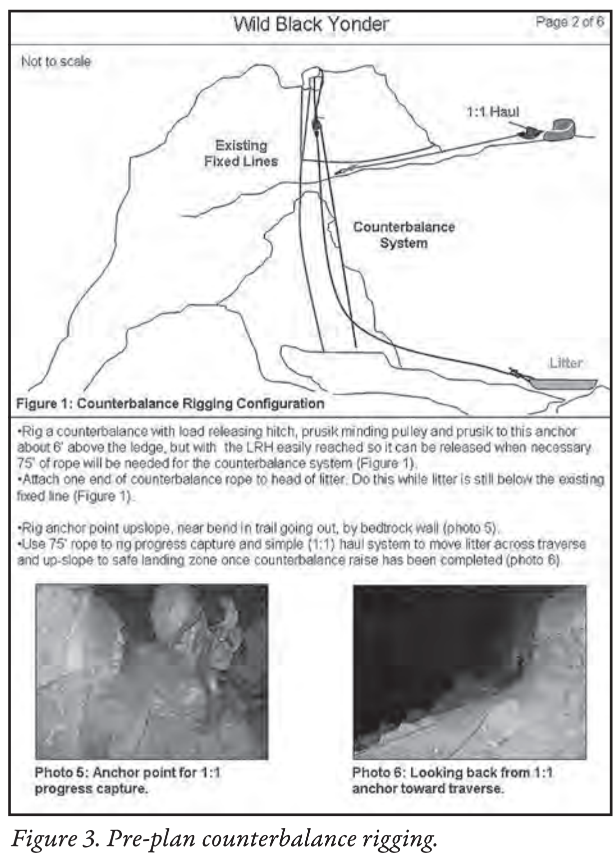

Figure 3. Pre-plan counterbalance rigging.

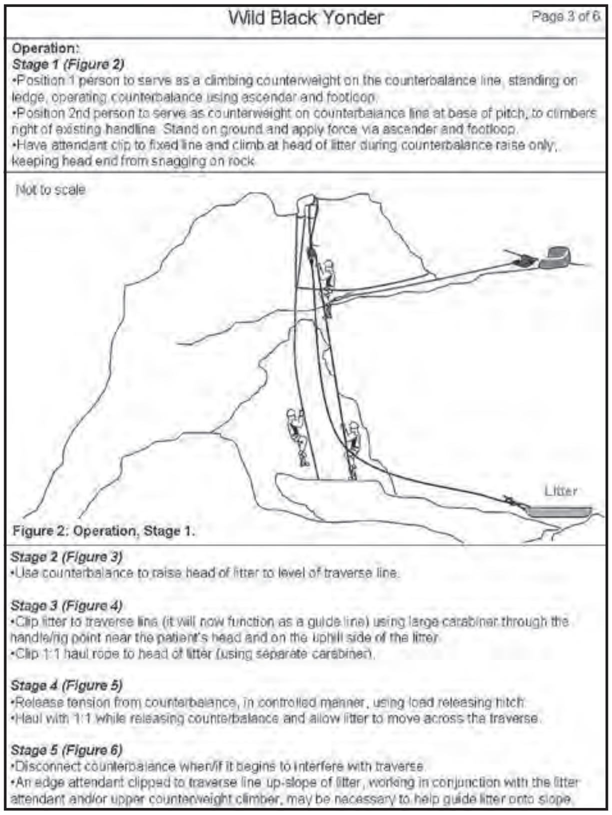

Figure 4. Pre-plan operation stage 1.

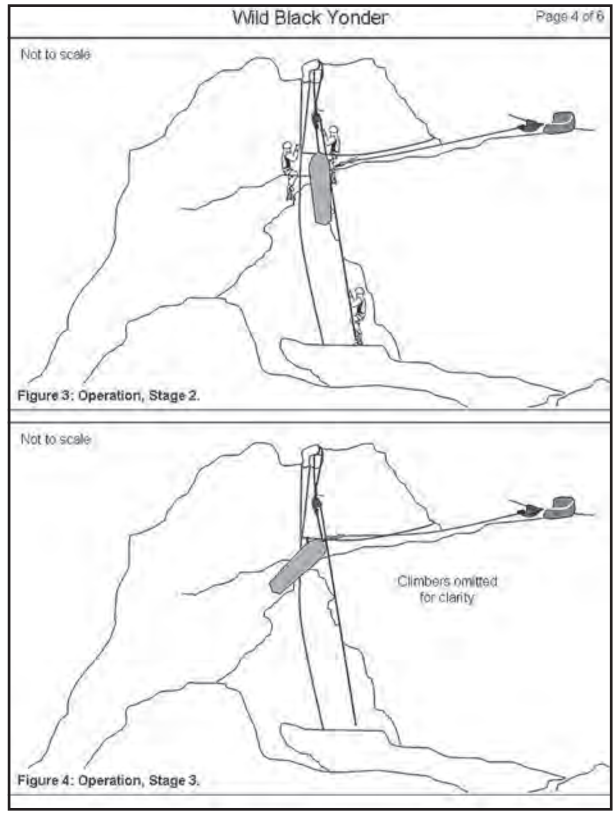

Figure 5. Pre-plan operation stage 2 and 3.

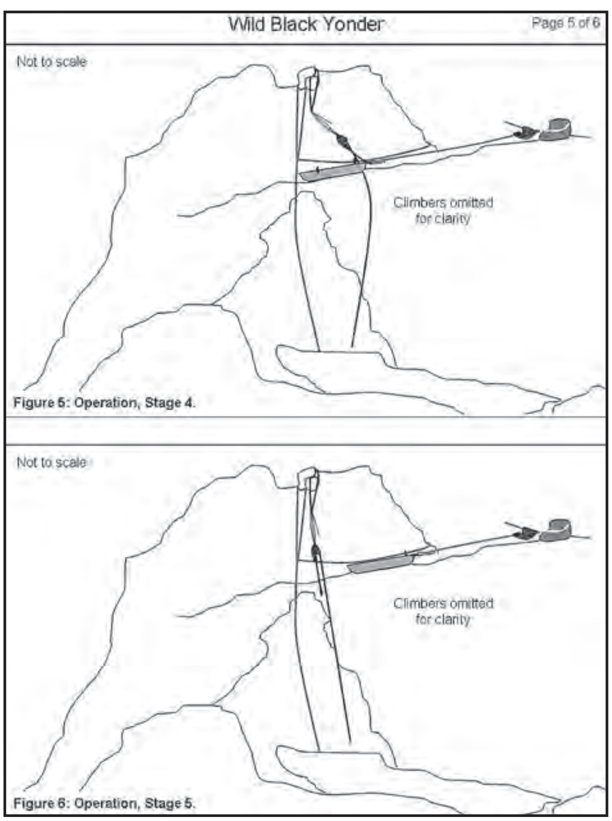

Figure 6. Pre-plan operation stage 4 and 5.

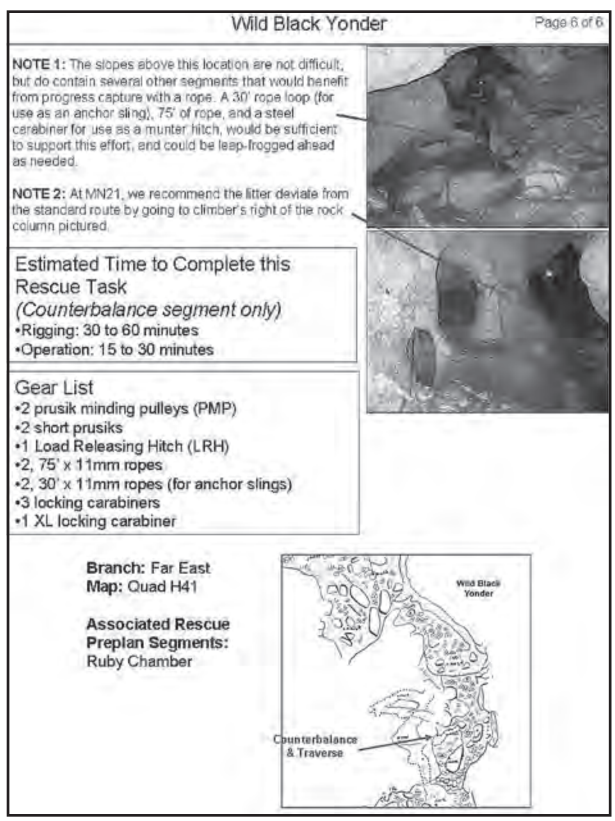

Figure 7. Pre-plan gear list and time estimate.

perform as counterweights for a 110kg caver. The second obstacle that was rigged in the cave was the lowest pitch of the Great White Way which is

a 60 meter pitch at a 70° angle. A major projection near the top of the pitch that introduced large amounts of friction into the system necessitated splitting the system into an upper and lower counterbalance system. The system was rigged and functioned extremely well giving us confidence in its application during an actual rescue. A total of 6 day trips and one 5 day camp were required to perform all of the field work for the pre-plan in addition to the testing of the two counterbalance systems.

In addition to the pre-planning of the various obstacles in the pre-plan there are also sections on anchors, rigging rationales, communications, operations, patient litter packaging and underground teams. Recommendations were made to the Park concerning creating call-out lists for the pre-plan and training cavers in the techniques involved in the pre-plan.

3. Conclusions

Fortunately, since work on the pre-plan began, there haven't been any large scale rescues in Lechuguilla Cave, so we haven't had a chance to test the pre-plan. However, there have been several self-rescues including that of a caver with a compound fracture to the forearm, a caver with a dislocated shoulder and a caver with an injured arm. The cavers involved in these self-rescues successfully used many of the techniques described in the pre-plan such as counterbalance haul systems to assist the injured cavers out of the cave demonstrating that these techniques work well for self-rescue.

The pre-plan is still a work in progress. Call-out lists need constant updating. Several areas in the cave need additional rescue pre-rigging such as additional expansion bolt anchors so that in the event of a rescue, precious time can be saved by pre-rigging some obstacles. More of the cavers involved in work in Lechuguilla Cave need to be trained in the rescue techniques employed in the pre-plan and be aware of the pre-plan.

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ARCH SPRING AND CAVE

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Arch Spring has been a landmark in Blair County, Pennsylvania since before Europeans first discovered the area around 1750. The spring is located between a sharp cutback of Brush (Bald Eagle) Mountain, in one of William Penn's Manors known as Sinking Valley. Although the spring was not shown on William Scull's 1770 map of Pennsylvania, it was featured in a 1788 article in "Columbia Magazine."

The cave is next to Fort Roberdreau, which was built during the Revolutionary War to provide protection for the mining of lead. Early settler Jacob Isett, built a stone house and a mill next to the Arch prior to 1805. The Pennsylvania Railroad described the site as an attraction shortly after it built its line to Pittsburgh in 1847.

The site has been reported in numerous historical and geological articles throughout the 1800's. Two attempts were made to commercialize the cave in 1947 and 1972. Each time, floods destroyed the efforts. The Western Pennsylvania Conservancy finally purchased this popular attraction in 1985. In 1988, Roberta Swicegood, an experienced cave diver, died in an attempt to connect the spring with the cave. Today the cave is open to the public under the supervision of the Huntingdon County Cave Hunters of the National Speleological Society.

1. Introduction

Arch Spring and Cave is small in size but has a large historical background. This predominate feature in central Pennsylvania became a landmark for the first settlers shortly after 1750. The spectacular arch or resurgence is easily seen from the valley road and the unique cave entrance lies in a sinkhole about a mile away. It became a site for early travelers to visit. Several attempts were made to commercialize the cave but nature reclaimed the efforts. Perhaps it's greatest story is the challenge to physically make the connection.

2. History

The area now known as Sinking Valley, in Blair County, Pennsylvania was first part of the land that the Penn family held for their own use. These parcels were known as Manors and were usually choice pieces of property. The limestone soil made this a desirable location for farming. Shortly after the Revolution, the state obtained the rights from the Penn heirs and sold the property. Although the French may have visited here as early as 1750 in search of minerals, it wasn't until 1763 that squatters came to prospect. In 1787, when Huntingdon County was formed, there were 164 freeholders in the original township of Tyrone.

During the Revolutionary War, lead was in short supply and desperately needed by the military. In April 1778, General Daniel Roberdeau of the First Continental Army was directed to command an expedition from Carlisle, PA to search for the mineral. It became necessary to build a small fort to protect the miners from savage Indian attacks. The ore was smelted and poured into 50-pound ingots to be transported by mule back east. The operation was abandoned in 1779. Some blame it on the hostilities and others on the poor quality of oar. However, from 1864 until 1870 the Keystone Zinc Company had a large-scale mining operation in the area and built a smelter near Birmingham. The operation mined several thousand tons of ore before closing.

In the fall of 1781, Indians raided the settlers of the valley. They shot and scalped Mathias Bebault and then continued to the home of Jacob Roller, Jr. Roller, a long time enemy of the Indians, was also killed while working in his cornfield. When these men failed to return that evening to the safety of the fort, a search party was assembled. Legend states that the Bedford Rangers traced the Indians to the mouth of Arch Spring Cave and then lost all trace of them. This gave rise to the belief that there is a secret entrance to the cave. Some have claimed that individuals have traveled through to the arch.

After the Indians were subdued the settlers again returned to the valley. Robert Marrow from Baltimore settled on a farm adjoining the cave sometime prior to 1780. Jacob Isett is also recorded as entering the valley prior to 1800. His large limestone house located near the Arch is still being occupied. Engraved in a large stone near the peak on the north side of this home is Jacob's name along with his wife's, Eleanor, and the date, 1805. Remains of other buildings including a store, post office and a mill on the stream are also still visible near his home. The first known written record of the arch and cave appeared in an article describing the Bald Eagle Valley published in *The Columbian Magazine* in 1788.

Figure 1: Nineteenth Century woodcut of the arch at Arch Spring.

Sinking valley lies between a sharp cutback of Brush Mountain (southern end of Bald Eagle Mountain), known as the Kettle, and Canoe Mountain (Brush Mountain on later maps) (Fig. 3). This extends about twelve miles from Tyrone in the north to Altoona in the southwest. The floor of the valley is composed of the Hatter Formation, a lower unit of the Ordovician Black River Group. The cave and arch are developed in the Trenton formation, more specifically a thin band of Carlin limestone that lies next to a band of Lowville limestone. The Church Caves downstream of the arch are also in this limestone band. Sinking Run, which has two tributaries, drains the valley into the Little

Figure 2: Nineteenth Century woodcut of the entrance to Tytoona Cave.

Juniata River, a tributary of the Susquehanna River. This stream disappears several places within its bed, flows underground, and then emerges as a large spring to continue further down the valley. Arch Spring is the largest, most picturesque and best known of these resurgences. There are also numerous sinkholes in the valley floor which collect run off from the mountain. In the past, most of these have served as dumps for the fieldstone and other trash.

In 1846 the Pennsylvania Railroad crossed the lower end of the valley as it headed west from Philadelphia to Pittsburgh. Eli Bowen reported in 1852 that the celebrated Sinking Spring was only a short distance from the Tyrone station.

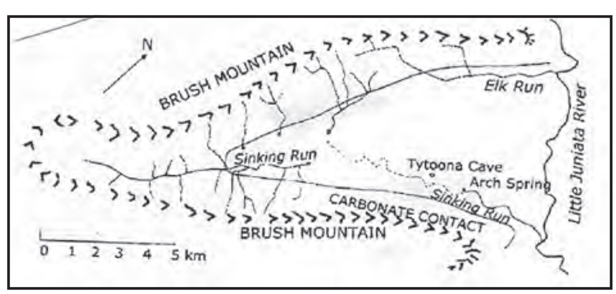

Figure 3: Sketch map of Sinking Valley. From Herman et al. (2008).

In 1875 William Sipes described the Arch Spring as a remarkably beautiful natural curiosity ranking among the most interesting places in the United States and included a sketch of the arch. To help encourage travel to scenic spots, the Pennsylvania Railroad hung a picture of Arch Spring at Grand Central Station in New York City along with other scenic spots along the line.

Several views of the cave entrance, looking from the inside out, and one of the Arch were produced by W.T. Purviance, a Philadelphia photographer, sometime in the early 1870's. James Quinlan of Mammoth Cave, reported that Purviance produced several formats of these views, one of which was included in a set of "Scenes of the Pennsylvania Railroad." These three different views are the only stereoviews known to exist of a Pennsylvania cave.

Albertyse Company of Brooklyn, NY produced a black and white postcard showing the exterior of the cave with a man standing in front sometime prior to 1908. The card was titled "Sinking Valley Cave, Pa." G.V. Miller & Co. of Scranton, Pa. also used a colored print of the Arch for producing a postcard for the Union News Company sometime prior to 1909. This card titled "The Cave in Sinking Valley near Tyrone, Penna."

In the early days the arch was well known and used as a recreational area. Many traveled by horse and buggy to have picnics and reunions beside the clear stream. Here photographers and artists have been challenged to capture the beauty of the scenery. Early articles were illustrated with sketches, some of which were not very realistic. The closest railroad station was at Birmingham. The landmark was clearly noted on the early 19th century maps of Huntingdon County.

The cave was noted in the First Pennsylvania Geological Report written by Rogers in 1858. Pennsylvania State Geologist Ralph W. Stone included Arch Spring in his first survey of Pennsylvania Caves written in 1930. There was no change on the report in his expanded 1932 edition. His 1953 NSS publication only updated the previous report. Stone made the following description: The arch is 12 to 15 feet in diameter and the ledge 20 feet thick. Behind it is a steep-sided sinkhole about 100 feet long, 50 feet wide and 30 feet deep containing a pool that nearly fills a cave opening in the ledge on the far side. The ceiling of this cave descends well below pool level about 30 feet back from the interior ledge. This is the lower end of Arch Spring Cave, completing a single underground stream channel about ¾ mile long, only the up-stream quarter of which is known to be traversible.

3. Commercialization

In July of 1947, Myrtle L. Kiser first opened the cave commercially with electric lights and mud trails. It was called Tytoona Cave, a name derived from the neighboring towns of Tyrone and Altoona. It was previously referred to as Arch Spring Cave or Sinking Valley Cave. Since the cave lacks scenic interest besides its spectacular entrance at the bottom of a sinkhole, this venture lasted but a short time. Spring floods washed the installation and put a fresh coat of mud on the trails.

On July 4, 1972 the cave was once again scheduled for a grand opening to the public. Art Kiser, son of Myrtle L. Kiser, had done considerable work installing lights, repairing the trail, and grading a path to the bottom of the sink. Just one week before the opening date, more than ten inches of rainfall in three days flooded the stream as a result of Hurricane Agnes and washed out most of the preparations. This condition was the worst flood in the state during this century. Although Mr. Kiser still had a desire to continue his work, a lack of funds prevented his dream from coming true. He had selected the name of "Indian River Caverns" and had it inscribed on his truck and barn. This all was removed shortly afterwards and in 1979 he sold the property to William A. and Naomi J. Wertz. The Wertz family is the owner and operator of nearby Indian Caverns along Spruce Creek.

The cave is accessed at the base of a steep wooded ravine or collapsed sinkhole. The spectacular 40 feet wide by 12 feet high triangular entrance is in the face of a 60 foot high nearly vertical exposed bedding of Trenton Limestone. The main passage is strike-oriented, dipping 15 degrees southeast. The stream emerges at the base of the sink, flows for about 75 feet before entering the right side of the cave. During the wet season, a surface stream also flows into the sink and will extend the usually ten foot wide stream to 30 feet. Much of the water that flows here rises in the bottom of the sink about 30 feet from the entrance. Nevin W. Davis pushed into this spring during low water and succeeded in going only about 30 feet into breakdown. The north or left side of the cave is several feet above the stream and about 10 feet wide. A trail here can be traversed over rocks about 175 feet before the stream is encountered. Several stepping stones in the stream can usually be found to continue back up onto the slippery mud trail. This path leads another 700 feet when the ceiling becomes low and drops into the water. A quick duck under yields another 200 feet of passage before the stream siphons in a log-choked sump (Fig. 4).

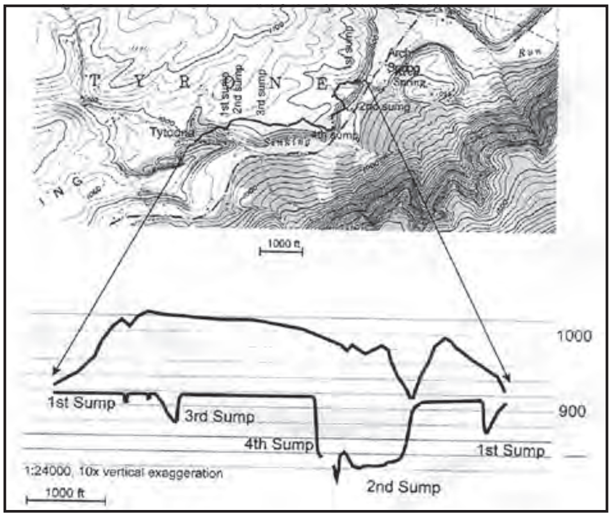

Figure 4: Plan and profile of Tytoona Cave. From Herman et al. (2008).

4. Exploration

Until 1965 a logjam in the first siphon of the cave prevented further penetration. In May of that year a team of divers including Rick Rigg, Bill Miller and Jim Faix, from Greensburg, PA tackled the difficult task of removing this obstacle and diving for 40 feet at 8 foot depth into an another room. This room is 260 feet long, 20 feet wide and 20 feet high contains some delicate soda straws which extend to within a foot of the water level. This room apparently forms an air pocket during the annual floods and protects the formations from damage. A large group of these straws are encountered ranging from 14 to 17 feet in length. At the time, they were believed to be the longest in the world. The report of this dive in the *NSS News* gave an inaccurate location of the cave due to a misunderstanding by the reporter. The divers needed to use care in this area to prevent the air and water currents from swaying the fragile speleothems and cause them to break. At the end of this room, a second siphon, 20 feet long and 5 feet deep, leads to a second room. This room has only water surface and is 120 feet long and 40 feet wide. No unusual formations exist here. A third siphon leads ENE and was penetrated only 75 feet. It wasn't until about 1985 that John Schweyen and Jim Brown pushed through into another chamber (doubling the length of the cave) to a fourth siphon measuring 100 feet long and 50 to 60 feet wide dipping down to a depth of 80 feet and ending in a large breakdown blockage.

The first recorded dive at Arch Spring Rising was by Oliver Wells in 1960. He found two openings at the bottom of the cliff. One was perhaps large enough to push but had only 18" of visibility with light. Submerged tree trunks on the pool floor also provided a nuisance. It would take many more attempts to push the entrance sump, about 150 feet long, and emerge into an 850-foot chamber. John Schweyen and Jim Brown pushed the second sump about 700 feet, which ends in large breakdown at a depth of about 80 feet. A lead from this sump extended another 200 feet to a depth of 105 feet.

The stream enters Tytoona cave at an elevation of 912 feet and exits the arch at 906 feet. It is believed that the connection between the two underwater passages is less than 50 feet.

Downstream from the Arch, behind the Church, are 6 additional small caves. The first is a small 5 foot deep pit in a limestone ledge about 12 feet above the stream bed. The second is a 100 foot long tunnel entering the cliff wall and pinches out in breakdown. The third entrance is about 50 feet down from cave No. 2 and is a 10 foot pit in the stream bead.

The fourth cave is the most obvious with a walk-in entrance and about 200 feet of passage. It is bereft of formations, but structurally interesting, the passages being primarily bedding controlled, but intersected by fissures along joints at different levels. The final room is a marrow deeply sloping bedding plane intersected by a fissure from which issues a fair sized stream which flows down the plane to form a pool below. Cave No. 5 is a drop type sink in breakdown around the corner of the cliff and contains a zigzagging 30 foot descent to water. Cave No. 6 is farther around the corner and seems to be a collapsed cave room. There is a deep water pool and a dome room about 25 feet high.

In 1985 the Western Pennsylvania Conservancy of Pittsburgh purchased 6.8 acres of property which contained Tytoona Cave (not including the arch) from Rev. Barry Vance. This was their first cave purchase. Their main interest was to protect the delicate soda straw formations within the sealed chambers. The Juniata Valley Audubon Society assisted them.

5. Tragedy

On June 18, 1988 two NSS certified divers, John Scheweyen and Roberta Swicegood, planned to conduct a series of survey dives at Arch Spring. John Scheweyen and Jim Brown had been working the system for the past 4 years attempting to connect the spring with the cave. Due to constricted passageways, heavy silt and poor visibility, solo dives were conducted. When Swicegood failed to exit on schedule, Scheweyen re-entered and made a search. When she could not be found, he initiated an NCR rescue call down.

Five well-known cave divers (Rob Parker, Tom Morris, Bill Stone, John Zumrick and Jim Brown) were called to assist Schweyen in the rescue. After three days of remarkable work the divers retrieved Roberta's body from sump II, more than 1800 feet from the arch at a depth of about 72 feet. They reported that the cave was scary and like swimming in chocolate milk.

Roberta H. Swicegood, age 36, was well trained with over 300 logged cave dives. She specialized in sump dives and was familiar with this cave. She was known to be levelheaded, very professional in her approach to cave diving, and as tough as nails. Several scenarios have been discussed by the best of divers as to what actually happened, but the exact cause of the accident will never be known. The best assumption was that the accident was the result of a line entanglement. An examination of Swicegood's equipment showed no mechanical problems. Both of her high capacity air tanks were empty and she died of asphyxiation. No recognized or standard procedures were violated and there haven't been any fundamental changes in the way people dive due to the situation. Due to the tragedy of Robarta Swicegood, diving in either the cave or the arch is prohibited by the owners.

6. Current Status

During the early 1990's the Huntingdon County Cave Hunters (HCCH) worked hard to clean up the property. Due to the popularity of the cave, it was becoming trashed and vandalized. It became the site of many parties and even served as a hideout for stolen property. The constant efforts of the HCCH managed to have five individuals arrested for trespassing and underage drinking and discourage others from using the area for other than it's intended purposes.

Sinking Valley is such a unique area that it has been the source many scientific studies. Dr. William B. White, Professor Emeritus of Geochemistry from the Pennsylvania State University is one of the main investigators. Several MS thesis (Evan T. Schuster and Rachel Bosch) and a Ph.D. thesis (Ellen Herman) along with numerous papers have been prepared reflecting the hydrology of this system.

In 2006 a disease commonly called White Nose Syndrome was discovered on bats in the northeast. In 2007 it is believed that it caused the death of thousands of bats in New York and Vermont. Not knowing the cause, the NSS closed all of its preserves including Tytoona Cave in 2008. Although only a few bats have been observed in its passages, it was felt that biologists could study the problem better if the bats were undisturbed.

7. Conclusion

It will be interesting to see what the future will add to this speleological feature in Sinking valley. Certainly, the system will be studied further. Although diving at the arch is prohibited at present, the challenge still awaits for better techniques and proper timing. The cave continues to be a great educational tool for those of the area. Many will still visit the site for its impressive scenic beauty.

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NATIONAL AND INTERNATIONAL PARTNERSHIP BUILDING FOR SPELEOLOGY: THE U.S. NATIONAL CAVE AND KARST RESEARCH INSTITUTE

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The National Cave and Karst Research Institute (NCKRI) of the United States (U.S.) was created by the U.S. Congress in 1998. Initially, NCKRI was a branch of the U.S. National Park Service, but changed in 2006 into an independent non-profit institute for greater flexibility to accomplish its mission. Major NCKRI partners and supporters include the U.S. National Park Service, the State of New Mexico through the New Mexico Institute of Mining and Technology, and the City of Carlsbad. NCKRI's purpose is to advance speleological science, encourage and provide public education, promote environmentally effective cave and karst management, archive speleological information, and develop cooperative relationships with people and organizations interested in caves and karst.

While NCKRI is a young institute, it has already developed national and international partnerships, knowing its goals can best be met through additional strong and diverse cooperative relationships. The best programs do not develop in isolation, but instead grow through synergy and diversity. Until construction of NCKRI Headquarters is completed in 2010, little funding is directly available to support partners and projects. However, NCKRI is in an excellent position to join or lead team efforts and better leverage funding from other sources. NCKRI is also available to advise and assist partners with information and staff time when possible. NCKRI can often connect partners with under-utilized or unknown resources. The Karst Information Portal is a team project that preserves karst information and makes it easily accessible to facilitate research, education, and stewardship. A proposed network for the sharing of equipment and facilities is another example. Each partnership with NCKRI is voluntary, and its form depends on the conditions that best suit each partner. With internationally limited funds, equipment, and personnel for speleology, and diverse multidisciplinary needs, NCKRI hopes to build partnerships throughout the U.S. and world for the greatest efficiency and effectiveness.

1. Introduction

The National Cave and Karst Research Institute (NCKRI) of the United States (U.S.) was created by the U.S. Congress in 1998 as a federal entity within the U.S. National Park Service (NPS). It was located in the City of Carlsbad, New Mexico, and given the following mandates:

- further the science of speleology;
- centralize and standardize speleological information;
- foster interdisciplinary cooperation in cave and karst research programs;
- promote public education;
- promote national and international cooperation in protecting the environment for the benefit of cave and karst landforms; and
- promote and develop environmentally sound and sustainable resource management practices.

In 2006, NCKRI changed to a non-profit corporation, operated through the New Mexico Institute of Mining and Technology (NMT), to maximize its flexibility in creating partnerships with other entities, raising funds, and responding quickly to new opportunities. More precisely, NCKRI is a hybrid non-profit, through its status as an independent corporation, while maintaining its Congressional mandates, obligations, and funding. The NPS now transfers annual federal appropriations to NMT on behalf of NCKRI. Additionally, NCKRI has maintained its key initial partnerships: the federal government through the NPS, the State of New Mexico through NMT, and the City of Carlsbad. Each partner has a permanent position on the NCKRI board and actively participates in NCKRI activities as a formula for success.

Productivity has been high, though NCKRI is a young institute with a currently small staff. During the previous fiscal year, NCKRI conducted 14 notable staff projects and supported eight student research projects, which generated 26 research publications and conference reports.

NCKRI staffed displays at 12 national and international conferences, planting seeds for future partnerships and projects. Educational efforts included multiple lectures, community outreach, and our first children's book. Critical, if less interesting, tasks to strengthen NCKRI's administrative foundation demanded much time. Several documents and procedures were written or revised to reflect NCKRI's change into a non-profit corporation. We have been working with the U.S. Congress to revise our enabling legislation and increase NCKRI's ability to work with federal agencies. We refined and completed architectural plans for the construction of NCKRI Headquarters; construction began in November 2008.

NCKRI's fifth mandate calls for national and international cooperation to protect karst environments. That effort demands cooperation with politicians, and especially individual and organized cave and karst explorers, scientists, managers, and educators. This is true of all of NCKRI's goals. The purpose of this paper is to introduce NCKRI to the international speleological community, explain some of NCKRI's goals and hopes for the near and distant future, and establish partnerships to make those dreams real.

2. Current and Developing NCKRI Partnerships

NCKRI partnerships begin with its Board of Directors. Each Director represents an organization which supports NCKRI through formal or informal agreements. In addition to the three primary partners mentioned above, other supportive organizations through the board include:

- federal agencies (U.S. Bureau of Land Management, U.S. Forest Service, and U.S. Geological Survey);
- state agencies (Edwards Aquifer Authority);
- universities (Claremont Colleges, University of New Mexico, University of New York at Plattsburgh, University of South Florida); and
- scientific associations (Geological Society of America, National Speleological Society [NSS]of the U.S., and Southwest Research Institute).

Each group provides various levels of expertise, data, resources, and leverage for NCKRI activities and projects, some of which are mentioned below. Together they and other partners and supporters form the core of NCKRI's cave and karst information network.

The Karst Information Portal (KIP), the result of a four-way partnership, is the most tangible form of the information network. As the Managing Organization, NCKRI promotes and organizes KIP activities. The University of South Florida is the Operating Organization, in charge of the hardware and software which make KIP possible. The University of New Mexico develops and evaluates research and resource concepts for the KIP. The International Union of Speleology conducts outreach to the worldwide speleological community. KIP is an online source of digital research tools, databases, and collaborative workspaces (www.karstportal.org). It was designed to solve the problems of data access, management, and evaluation that challenge the progress of cave and karst science, stewardship, and education. Currently, KIP resources include databases, datasets, bibliographies, general images, a scanning electron micrograph repository, gray literature, mainstream cave and karst literature, and links to key electronic karst resources. KIP continues to grow as users and developers bring more information into the network. Recent additions through partnerships include efforts with the NSS to digitize back issues of the NSS News, SpeleoDigest, and National Cave and Karst Management Symposium proceedings to add them to the KIP catalog. As another example, KIP is the only electronic, online source for Association for Mexican Cave Studies publications from three of their series dating from 1965 to 1977. KIP staff have also conducted and posted six oral histories with some of the leading names in karst science and cave exploration from North America and Europe.

NCKRI's efforts to fulfill its cave and karst education mandate are currently focused on the *Cave and Karst Studies Program*, housed primarily within the Earth and Environmental Sciences Department at NMT, and with Western Kentucky University (WKU). The NMT program is largely funded by NCKRI and directed by Dr. Penelope Boston. It has supported undergraduate to doctoral students studying cave and karst geology, hydrology, mineralogy, and microbiology in six U.S. states, three countries, and for two planets. At WKU, NCKRI funded a program for graduate-level training of several federal cave and karst resource managers and scientists. Nascent partnerships exist with a number of universities where NCKRI staff serve as advisors to graduate students and as collaborators with resident professors and research scientists. Examples of such joint research projects include:

- geomicrobiological projects with scientists at NMT, Northern Kentucky University, University of New Mexico, Western Illinois University, and WKU;

- cave micrometeorology investigations with NMT, NPS, and the University of Nevada in Reno; and
- global mapping of karst through the development of an on-line geographic information system, that will be open internationally to contributions via the KIP, and supported by graduate thesis work at the University of Arkansas and by The Nature Conservancy and U.S. Geological Survey.

NCKRI's hydrogeologist, Dr. Lewis Land, also works for New Mexico Bureau of Geology and Mineral Resources (NMBGMR). He serves as the liaison that facilitates the exchange of information, expertise, and technical services between NCKRI and NMBGMR. Joint NCKRI-NMBGMR activities, conducted mostly in south-central and southeastern New Mexico, include:

- geologic mapping of karst regions;
- hydrogeologic characterization of the karstic Roswell Artesian Aquifer and southern Sacramento Mountains;
- evaluation of large (100-m diameter), catastrophic sinkhole collapses in halite; and
- hydrological and paleoclimatic study of Snowy River, the world's longest cave deposit, in Fort Stanton Cave.

Despite NCKRI's tremendous interest in conducting research, educational, and cooperative programs, much of its funding, time, and efforts are currently expended on the construction of its headquarters in Carlsbad, New Mexico. The two-story, 1,609 m^2 building is designed as an outstanding model of sustainable construction that allows NCKRI to conduct research and business in ample laboratory, library, and office space, while educating the public about the importance of caves and karst though its museum, classrooms, and bookstore. With technical expertise from Bat Conservation International, NCKRI Headquarters will be the world's first building to include a bat roost as part of its design. The roost will be monitored with cameras, microphones, and probes. Frank Binney and Associates is designing the museum plans, which will include several unique, state-of-the-art exhibits, some of which will tie into the bat roost, rainwater harvesting system, and ground-source heat pump, to combine sensible environmentally friendly design with NCKRI's research and educational programs. Construction is expected to finish near the beginning of 2010, but the building won't open to the public until the middle or end of the year pending the installation of its exhibits and equipment. When NCKRI Headquarters is completed, additional staff will be hired and more funding will be available to pursue partnerships and projects.

3. Proposed NCKRI Partnerships and Projects

NCKRI is a major sponsor of the 15th International Congress of Speleology, not just to support an excellent and significant conference, to but better introduce itself to potential partners from around the world. Following are some projects being considered.

- Establish a local to national karst education program with curricula for K-12 and universities, with outreach programs for agencies and organizations.
- Establish an international cave sample archive facility for preservation of materials to facilitate research and to reduce unnecessary sampling from caves.
- Initiate a consortium of international partnerships with the goal of working together in a more effective manner to be more competitive in receiving funding, and to solve basic and applied problems.
- Develop an international karst research coalition, to include a network of cross-disciplinary laboratories and field research sites where data, equipment, and facilities can be shared.
- Establish a series of publications, including *Current Best Practices in Cave and Karst Science* to fill a critical need for providing up-to-date state-of-the-art information in a quickly published and widely disseminated format.
- Work with partners to create a series of traveling cave and karst exhibitions for display at museums, institutes, schools, and special events around the world.
- Reestablish the NCKRI Visiting Scholar Program and begin a student research and internship program tied to NCKRI projects and partners.

4. Conclusions

NCKRI is a young institute that is establishing itself as an important source of support and knowledge in speleology. Despite current limits on staff and funds, NCKRI is well poised to join or lead team efforts, better leverage funding from other sources, and advise and assist partners with under-utilized or new information and resources. Its goal is to establish itself as a center for excellence in cave and karst research, education, and applied science in all speleological fields. As with NCKRI's great progress to date, this goal can be best achieved by establishing an international consortium of partners whose individual efforts are supported to promote cooperation, synergy, flexibility, and creativity, and cost efficient multidisciplinary use of limited funding, equipment, and general resources for cave and karst studies.

SPELEAN HISTORY REVEALED WHEN NAMING FEATURES FOR A CAVE SURVEY

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The poster/paper will illustrate the aspects of spelean history encountered when adding names to features in the 2008 Jenolan Caves Tourist Cave System Survey. This is a joint project of the Jenolan Caves Historical and Preservation Society and the Jenolan Caves Survey Project team. The Jenolan Cave System is in New South Wales, Australia is some 20+ km in length and some 8 km of it have been developed for tourism. Since the discovery of the caves in 1838 and subsequent development of sections of the cave system for inspection by tourists in the 1840s there has been numerous documents and books written, engravings drafted and photographs taken. This literature has been searched and tables created as to how the feature names have changed with time. The names are referenced back to the publication and or/photograph in the Jenolan Caves archives or other sources where Australian spelean historians have made their archives available. The location of the features was carried out in the caves as fair copies of the 2008 survey plan were produced. The authors took copies and the available illustrations to first identify the features and placing the name on the survey plan. Some proved very difficult to locate, due to the development of the tourist cave paths over time. Jenolan tourist cave guides both past and present have contributed information and assisted in locating the named features in the caves. The names were then added to the Adobe Illustrator survey plan files as separate text layers: modern names and historical names. To date (November 2008) there have been 567 named features identified. A bonus of this detailed examination of the cave features has enabled us to create "Then and Now" files in which older engravings and photographs can be compared with the present state of the features. The modern feature is photographed using a digital camera for future comparisons and the archive photographs are scanned, in order, to be stored with the survey data. The poster/paper will illustrate examples of these "Then and Now" studies. During this detailed naming of features study it has been possible to identify, that only modest damage has been done to the Jenolan Caves in over century and half of visitation.

1. Introduction

The Jenolan Caves Survey Project Group undertook to prepare a "State of the Art" survey of the Jenolan Cave System, New South Wales, Australia (Fig. 1) (James et al. 1988). The Jenolan Cave System (Fig. 2) is composed of several 'caves' that are sections of a cave system. The names of these caves are of historical origin and are associated with the necessity to limit the length of, and increase the number of tours available to the public. These will be used when discussing the spelean history revealed when naming features for the survey.

Figure 1: Location of the Jenolan Cave System within New South Wales, Australia.

The caves were known to the local Aboriginal population (Gundungurra people) for thousands of years as Binoomea, "Dark places." Local settlers involvement in the area began in 1838 with the first recorded discovery by a pastoralist James Whalan. According to legend however, Whalan was not the first settler to lay eyes on the caves, with that honour going to James McKeown, an ex-convict and possibly an outlaw, reputed to have been using the caves as a hideout.

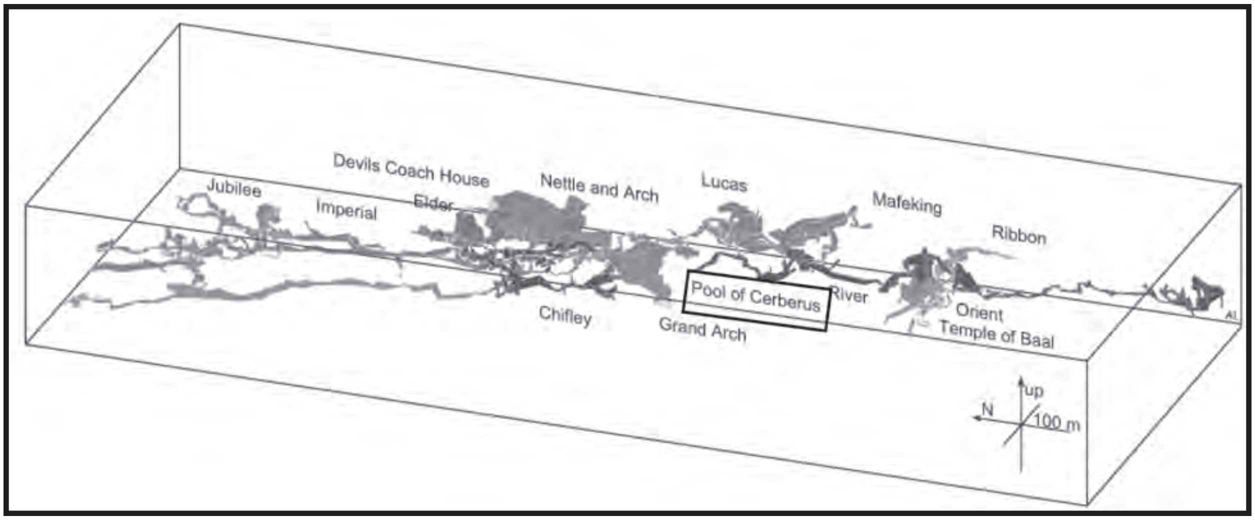

Figure 2: The Jenolan Tourist Caves.

Original Cave Name Date of Discovery	Present Cave Name	Reason for Name Change
Devils Coach House Discovered 1838 then named Easter Cave* in 1878	Devils Coach House	James Whalan came suddenly upon the mouth of the cave and it so impressed him with its rugged grandeur and weirdness than when he returned home he reported that he had been to the end of the world, and had got into the Devils Coach House (Cook 1889). Renamed Easter Cave in April 1878 by P.F. Adams after the day on which it was first surveyed (Foster 1890).
New Cave Discovered 1860	Lucas	Known as New Cave till 1878, then renamed after the Hon John Lucas MLA, who was responsible for preservation of the caves by bringing them under Government control (Dunlop 1969).
Left Imperial Discovered 1880	Chifley	Thought to be originally named after Prince Imperial of France. Changed to Chifley in 1952 after Hon J B Chifley MP, who represented the electorate in Federal Parliament, and who later became the 16th Prime Minister of Australia (Dunlop 1969).
Slattery Discovered 1893	Jubilee	Opened to public in 1897 and renamed then in commemoration of the Diamond (60th) Jubilee year of the reign of Queen Victoria of England (Dunlop 1969).
Skeleton Discovered 1903	Pool of Cerberus	Originally named due to human skeleton preserved therein. Changed due to cultural sensitivity in 1987, after concern raised by NSW Aboriginal Land Council.
Eastern Branch of the Orient Cave Discovered 1904	Ribbon	Ribbon opened in 1931, change of name to distinguish as a separate tour from Orient Cave (Dunlop 1969).

Table 1: Cave name changes at Jenolan.

When the caves were discovered in 1838, they were first called the "Fish River Caves" (Cook 1889) and then later Binda/Bindo/Bendo Caves. The Government Gazette, in announcing Wilson's appointment (the first keeper of the caves) used the name 'Binda Caves' which was thus their first official title. They had, however, become generally known as the Fish River Caves, and this name appears in official references. (Dunlop 1969). On 19/8/1884 it was officially announced in the Government Gazette as "*an alteration in the name of the Natural Limestone Caves, situated in* *the Parish of Jenolan*" and the caves were officially named Jenolan Caves (Dunlop 1969). In addition, for a variety of reasons some of the caves in the system have changed their names (Table 1).

2. Finding Named Features

The first step was to examine the material contained in libraries and archives for engravings, paintings and photographs of named features and collate them into tables. A similar and more detailed exercise was done for Postojnska Jama (Shaw 2006). A cave that was written about long before Australia let alone Jenolan Caves were known to Europeans. Shaw found the following "*Very many of the place names in caves derive from natural, architectural and other familiar objects such as animals, birds, plants, rain, parts of churches, curtains and human anatomy. Others are purely descriptive. Some result from the likeness to specific people (saints, emperors, heroes and explorers).*" At Jenolan the same miscellany of names was encountered, although they were largely in one language albeit Australian English. Most features at Jenolan have retained their original names although not all are used on present day tours. The more obscure names are pointed out on the historical tours. The next step was to scan the source material which was then placed in the data base. The printed material was taken into the cave with the survey plan. This exercise was often carried out by a small party with a photographer. However, it benefited greatly if the group contained other members of Jenolan Caves Historical and Preservation Society especially those that have been associated with the caves for a long time or have been on the staff of the Jenolan Caves Reserve Trust. Even with the right people in the party the named features were difficult to locate, for example, Figure 3A shows one of the largest and Figure 3B one of the smallest of the features identified.

Some are readily recognizable for example the Broken Column (Fig. 4). Some bear little resemblance to their name as they have been named for a particular event. For example, General Cronje appears amongst other features relating to the relief of Mafeking. Mafeking (Fig. 5) was discovered in May 1900, the month in which the city in South Africa was relieved by the British from being under siege by the Boers. Examples in the other caves include The Statue of Liberty which became Don Bradman when that sportsman became the most famous of Australian cricketers. The Shark's Fin has become Harry Potter's Hat and The Unicorn has become ET's Finger to fit in with the current popular literature and visual media. Tourists still exhibit interest in the feature names and at times they are invited to offer their own suggestions.

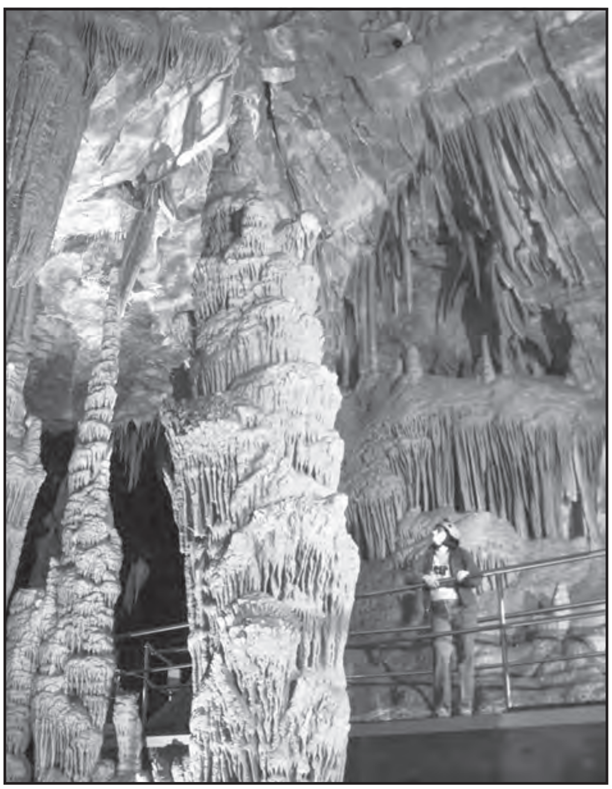

Figure 3A: The Pillar of Hercules, Orient Cave (photo G. Whitby).

Figure 3B: The Diminutive Horse's Head, Chifley Cave (photo R.Whyte).

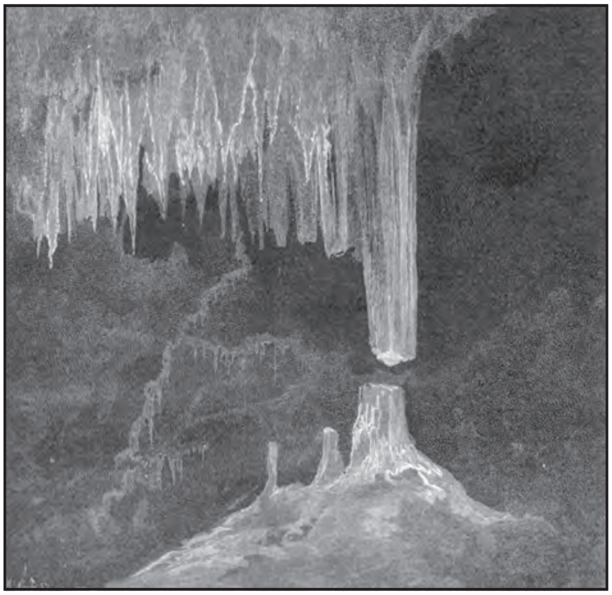

Figure 4A: An engraving of The Broken Column from (Garran 1888).

Figure 4B: A photograph of The Broken Column 2009 (photo R.Whyte).

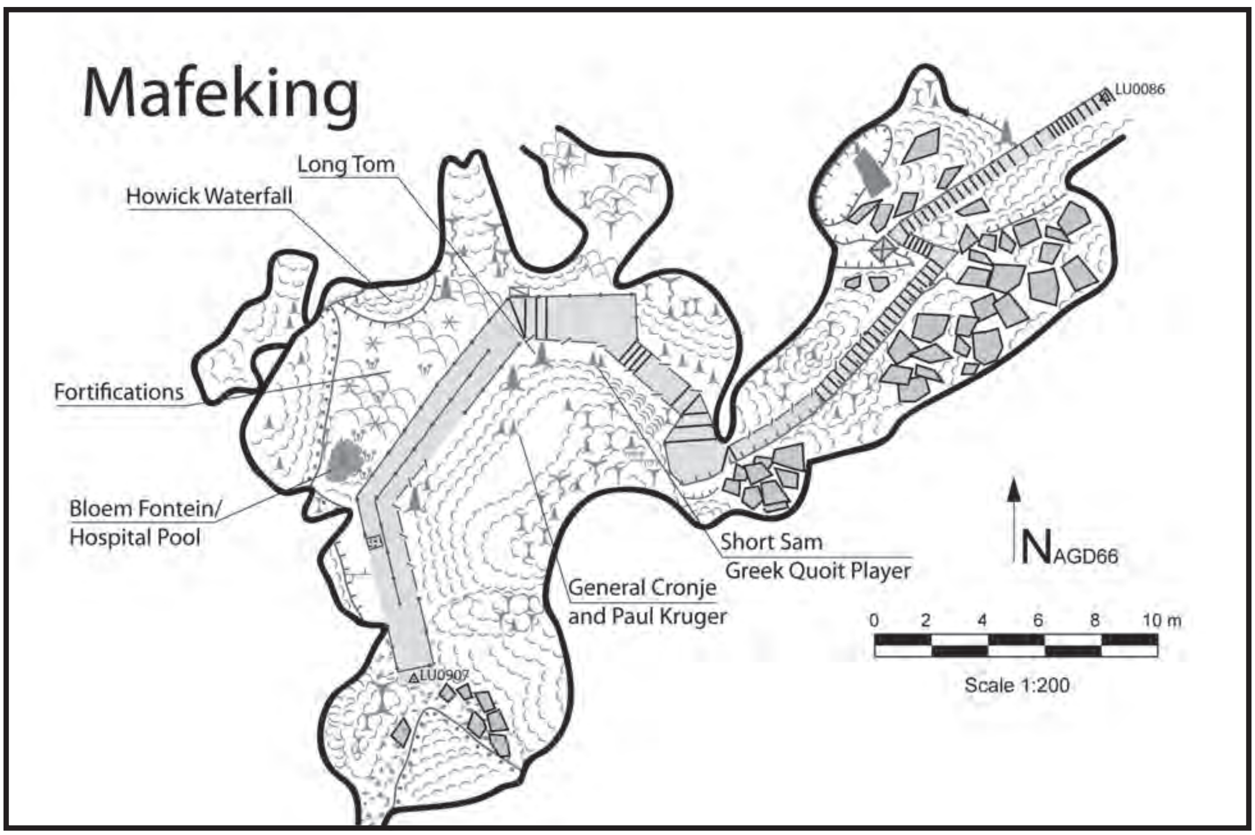

Figure 5: The plan of Mafeking, showing named features.

3. "Then and Now" Comparisons'

The detailed examination of the cave features has enabled the creation of 'Then and Now' files in which the older engravings and photographs are compared with the present state of the features. The modern feature was photographed using a digital camera for future comparisons and the archive photographs were scanned to be stored with the survey data. As only modest damage has been done to the Jenolan Caves in over century and half of visitation many of the comparisons are favorable and show no significant damage to the caves. However, occasionally a different message is portrayed. Careful examination of Figure 6 shows

Figure 6A: The Lyre Bird's Nest. The illustration was taken from Phillips (circa 1912).

Figure 6B: The photograph was taken in 2008 (photo K. Bellamy).

Figure 7A: Diana's Grotto The illustration was taken from Phillips (circa 1912).

Figure 7B: The photograph was taken in 2009 (photo R.Whyte).

there is a stalactite missing either it has been accidently broken and removed or taken as a souvenir. Figure 7 shows that the tourist path was placed through the middle of an attractive decoration to give visitors access to the rest of the cave. In general, the features that no longer exist due to tourist track development and vandalism are few.

Acknowledgements

Jenolan Caves Reserve Trust for support. The Jenolan Cave guides both current and former guiding staff who have provided oral histories and identified features in the caves. The Jenolan Caves Historical and Preservation Society members who have contributed to this project. Numerous cavers, both national and international, for their work on this project.

Items sourced from the Jenolan Caves Historical and Preservation Society Collection. Postcards by Charles Kerry and historic photos by Harry Phillips. Jenolan Caves (NSW) 'Nature's Masterpiece' N.S.W Government Tourist Bureau. Rawson G. H. (Manuscript circa 1883), *Guide to and Description of the Fish River Caves,*

Cave	Identified	To be located
Arch	2	0
Devils Coach House	5	2
Grand Arch:	15	0
Chifley	63	2
Lucas	105	9
Nettle	23	0
Orient	85	2
Ribbon	28	7
Imperial	68	2
River	87	22
Pool of Cerberus	25	5
Temple of Baal	34	8
Jubilee	31	31
Total	571	90

Table 2: Number of features identified and yet to be located.

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THE NATIONAL SPELEOLOGICAL SOCIETY MUSEUM: HISTORY, PROGRESS, AND FUTURE DIRECTIONS

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Abstract

The National Speleological Society (NSS) Speleo-Museum developed out of the necessity to preserve the history of the NSS and caving in the United States. The Speleo-Museum collection contains objects, archives, and photographs that highlight the history and ingenuity of the NSS. It began in 1972 as an exhibit for the annual National Speleological Society Convention. Since its inception, the curators of the Speleo-Museum have sought out relevant collections that exemplify the NSS' rich history. With no formal facility, the Speleo-Museum has been housed in various locations by NSS Members.

In 2008, the Board of Governors of the NSS passed three motions to promote the development of the Speleo-Museum. These motions resulted in the Speleo-Museum's relocation to a climate-controlled facility and funding to document and archive the collection. The archival process involves developing a formal collection management policy for the Speleo-Museum, digitizing archival records utilizing Past Perfect Museum Software, and cleaning and re-housing objects using standard archival procedures.

This presentation will highlight the history of the NSS Speleo-Museum and report on the progress made archiving the collection in the Spring of 2009. Emphasis is placed on the development of a collections management policy, items in the Speleo-Museum, and future directions.

CONTRIBUTED PAPERS ON METHODS AND TECHNOLOGIES FOR SCIENCE AND EXPLORATION

BLUNDER DETECTION IN COMPLEX SURVEY NETWORKS

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In the process of surveying a complex cave, there are many opportunities for errors, or blunders, at all stages of the process. This is particularly true in large, complex caves surveyed by many different teams, such as Lechuguilla Cave, New Mexico. The author has developed software to search for the likely blunders, using the principle that multiple survey paths to the same physical point should agree with each other, within the statistical error expected for the three measurements between any given pair of survey stations. The technique is to perform a least-squares solution of the survey grid that minimizes the total adjustments needed to close all of the loops. Then, the sequences of stations that connect one junction to another are removed from the grid (by giving them a very large expected error) one at a time, starting with the one that had the large adjustment needed. Checks are made to see if the sequence in question would then close to the positions determined by all of the other sequences in the grid based on the following possibilities: a) one of the compass readings is reversed; b) one of the inclinations is reversed; c) one of the stations at the beginning or end of the sequence is different from the one in the data base; d) the inclinometer scale was in percent rather than degrees; e) one shot should not be in the sequence (for example because it was a splay shot). This procedure is repeated for all of the other sequences that need large adjustments (with adjustable criteria for "large"). An option exists to either leave the sequences already checked out of the grid, or put them back in again. A report is generated with blunders that are considered "very likely" to be true, where again the criteria for "very likely" can be adjusted to avoid too many possibilities. If the suspected blunder cannot be verified from a careful examination of the survey sketches in the relevant area, then a printout is made of each "bad" sequence in a format that is easy to use for field checking in the cave (including station sequences to get the given area from a major trail, and a list of all shots that tie-in to the stations in question). The field-checking team first checks for the likely blunders, if any are suggested. If necessary, the entire sequence is re-surveyed to find more subtle problems, such as a badly calibrated compass, magnetic cave headlamps affecting the readings, many mislabeled stations, or errors in distance measurements. The first 80 km of survey of Lechuguilla Cave included a very large number of blunders, in part due to the large number of cavers working in a given area, and also due to the lack of back-sights. The software has proven very useful in reducing the number of sequences that needed large adjustments from about 25% to less than 1% in the Western portion of the cave, and less than 3% for the entire cave. The most common blunder was found to be incorrect labeling of survey station flags. Techniques that can be used to minimize the likelihood of blunders are listed.

1. Introduction

In the process of surveying large caves by many different explorers, inevitably there are many blunders made. In the case of Lechuguilla Cave, near Carlsbad, N.M., a frantic pace of exploration and survey from 1988 to 1991 by several hundred different cavers led to a situation where over 30% of the loop closures were bad and likely contained at least one major blunder. This led the author to spearhead a major effort to reduce the number of blunders in the existing and future surveys.

2. Fixing Existing Blunders

The basic method for finding possible blunders is to first write a computer code that simultaneously closes all the loops in a given survey. The basic method is a least-squares fit that minimizes that total corrections (added quadraticly, and called χ^2) to all of the segments, where a segment is defined as a sequence of survey shots that connect one junction to another. The corrections in each case are weighted (i.e. divided by) by the "expected" errors based on station placement uncertainties of 5 cm, and compass and inclinometer readings with random errors of 2 degrees. The author would have like to include a calibration error for each set of readings done with a particular instrument in a given time interval, but this was not possible because the information was not recorded. Different weighting schemes were tried (for example, compass errors that increase for steeper shots), different compass, inclinometer, and station placement errors, which can somewhat change the location of the loop-closed junctions, but had little influence on the segments that were identified as being "bad" (i.e. likely to have one or more blunders).

Once all the segments were closed simultaneously, a search for likely blunders was made by removing one segment at a time, and re-closing the remaining loops, starting with the one with the largest contribution to χ^2. Using the junction locations defined by all other segments, a search is done for the removed segment to see what could make it close with a contribution to χ^2 of less than two units. The following possibilities were examined: reversed inclinometer reading, reversed compass reading, both reversed, compass off by 100 degrees, inclinometer read on percent scale instead of degree scale, digits on distance reversed, and either starting or ending station being different that the one noted in the survey book. If any of these possibilities was considered to be probable, an examination of the survey notes was made to see if there had been a data entry error, or if the notes contradicted the sketch. In about half of the cases, the blunder was found in this manner.

In the case where the problem could not be resolved by an examination of the survey notes, a report was generated for cavers to field check the problem. The report included the following items:

(1) How big the adjustments needed to the given segment are in each of the (x,y,z) coordinates in both the case where the segment is included in the loop closure, and when it is left out. This is helpful in identifying if the error is mostly likely in the vertical or horizontal information, for example.

(2) The sequence of shots in the bad segment (distance, bearing, inclination, and left/right/up/down information).

(3) Likely blunders (if any), such as wrong tie, reversed compass, etc.

(4) A list of all survey shots that tie into any of the stations in the suspect segment. This was done to facilitate finding wrong tie-ins.

5) How to get to the segment from a main trail or well-known area (this was done by hand by the author).

(6) Optionally, the original survey notes for the bad segment, especially if the sketch quality was so poor that a new sketch was needed).

(7) Optionally, a line plot of the area.

Reports for segments that adjoined each other were combined together by hand, and sorted by area of the cave. The net result is a caver-friendly package that can be used to quickly and efficiently identify the problem.

In practice, it was found best to re-shoot all the shots in the suspect sequence, even if one blunder was identified early on. In about half of the cases, there were more than one blunder, and in some cases just about every shot had a problem (for example if the surveyor had magnetized material too close to the compass). It was found to be extremely valuable to check all of the tie-ins, due to the large number of mislabeled or hard to read stations.

3. Findings

The most common blunders were found to be (in order from most common to least common):

(a) One or more stations with the wrong station number written on them (in this project, every station is labeled with flagging tape). Usually, the person marking the station would get off by 1 for two or three shots in a row. In some cases, the sketcher would remember the problem and use the correct number later on, and in other cases not. Another problem is that on many occasions, two teams would pick the same survey letters. The person entering the data in the computer would re-label the stations with new letters, but no-body went back in the cave and corrected the flags.

(b) Front and back sights were reversed, and the sketcher used the reversed numbers to make the sketch. This may seem surprising at first, but the highly complex three-dimensional maze-like nature of the cave, combined with late-night fatigue, or sketching from memory, caused this to happen relatively frequently. Also, until 1993, the sketch scale was 1:600, making it hard to make out stations less than 2 m apart on the sketch.

(c) Compass and/or inclinometer readings were off by more than 2 degrees for many shots in a sequence. This was usually caused by magnetic lights or objects on the surveyor's helmet (for the compass readings), language difficulties (so the sketcher had trouble understanding what the reader was saying, perhaps due to him being Russian and not speaking any English, as happened on one trip this author was on), or simply lack of experience. Until 1993, back-shots were not generally done.

(d) Distance reading was wrong for one reason or another.

(e) Shot simply did not make any sense upon field checking. In at least five cases, the shot seemed to go through a solid wall and the station marker could not be found.

(f) Station maker was moved from its original location. The most common problem was that it fell down a hole. In other cases, it got caught on surveyor's clothing and was dragged to a new location.

4. Lessons learned and recommendations.

Based on 20 years of fixing blunders in Lechuguilla Cave, which is now over 200 km long and has literally thousands of interconnected survey loops, we have learned several things and implemented some of the recommendations below to minimize them in the future.

(a) Take compass and inclinometer readings in both directions, whenever possible. If not, read in one direction twice, trying to forget the first reading while doing the second. While the goal in the Lechuguilla project is currently to get the readings to agree within two degrees, ideally one could use a formula such as 1 degree for shots longer than 20 m, 1.5 degrees for 10 to 20 m, 2 degrees for 3 to 10 m, 3 degrees for 1 to 3 m, and 5 degrees for very short shots less than 1 m long

(b) Do at least three distance measurements, if using a laser device such as a Disto. Make sure to be aware if the distance is from the front or the back of the instrument.

(c) The sketcher should carefully check that each station is labeled correctly in the cave. Ideally, the team would have a detailed map of the area they are working in; to check that the stations they are tying in to match what is on the map.

(d) Correct the labeling of any incorrectly labeled stations, especially if they have been given different labels in the data base due to the use of redundant designations.

(e) Remove any stations that have fallen down or been moved from their original location.

(f) Sketcher read back the readings they have actually written in the book.

(g) Sketch to scale and to a north arrow, and do both plan and profile views.

(h) Label each station on the sketch.

(i) Take a break from time to time to check that the sketch actually matches the cave and the notes, and that front/back shots actually agree.

(j) Have the cartographer of a given section of the cave look over the notes and add them to the map as soon as possible. Blunders in station sequences that are not yet part of the loop closure grid can often be found this way, thus avoiding problems in the future when somebody ties into the sequence and makes it part of the grid.

(k) On camp trips, enter the data into the computer each night and look for problems that can be fixed the next day.

(l) In lava tubes or other caves with magnetized rock, put stations as far from rock as possible (for example, shoot "head to head", even though station placement is less accurate).

(m) Take GPS readings of all entrances.

Some techniques that are not so much designed to reduce blunders, but to give improved survey accuracy are:

(n) Try to do alternate horizontal and dead vertical shots (check carefully that shot is truly vertical) rather than high-angle shots, for which compass readings are especially difficult.

(o) Try to place stations so that both front and back sights can be done, if possible.

(p) Calibrate each instrument on a standard course on each trip. Keep a careful record of which instrument is used for which shots.

(q) Clearly identify the station location within 3 cm (for example by putting a dot of a piece of flagging tape).

5. Conclusions

As we have gradually begun to implement many of the above recommendations, the number of the blunders generated has been going down steadily. By devoting part of most expeditions to fixing previous blunders, the overall loop closure for Lechuguilla has improved dramatically. In one section of the cave (the Far West), the only remaining loops are in areas that cannot be accessed for safety or conservation reasons. In other areas, such as the South, were many hundreds of loops were surveyed in the initial frenzy from 1988 to 1991, considerable progress has been made, but considerably more field checking remains to be done to have a stable survey grid. While faster computers and smarter algorithms make automated blunder finding easier and easier, field work will still be needed. In a cave as warm and beautiful as Lechuguilla, this is far from being a painful endeavor!

The computer code this author has written has also been used for several other caves, such as Lilburn Cave in CA, USA, and Roppel Cave (part of the Mammoth Cave system in KY, USA). There is currently no user-friendly interface, but the author is willing to run it for interested parties (send email to peter@cavepics.com).

LASER SCANNING USE IN CAVE CONTEXTS: THE CASES OF CASTELLANA (ITALY) AND NAICA (MEXICO)

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Survey in caves implies operative and logistic problems due to the position, extension and development of the cavities to be studied. Moreover, it is not possible to measure, with high level of detail, the walls of caves with traditional survey techniques because of their extension and morphological complexity. Virtualgeo, a company working in the fields of geomatics and software development to support the study and valorization of cultural and environmental heritage, has faced surveys in cave contexts several times. For example, in 2006 in Castellana Grotte (province of Bari, Italy) to assist with cave management, and in 2007 in Naica (northern Mexico) in the frame of the multidisciplinary research program organized by the Mexican company Speleoresearch & Films and the exploring team La Venta (Italy). In the Cave of Castellana, which is equipped with tourist facilities, Virtualgeo carried out the survey of the Grave room (100x40 m wide and 60 m high) with a "time of flight" laser scanner and acquired the spatial coordinates (and the RGB color values, thanks to the camera incorporated in the laser scanner) of more than 23 million points. In the giant gypsum caves of Naica, the company carried out the survey of the Cuevas de los Cristales and de las Espadas with a "phase shift" laser scanner and acquired more than 43 million points. In both cases Virtualgeo preferred laser scanning technique (acquisition rapidity, no-contact with the object to be surveyed, data completeness and precision, operational versatility) to traditional survey techniques in order to document the present conditions of the geometry of the caves and speleothems inside them by constructing high precision three-dimensional geometric databases with color information. Laser scanning can also be used as monitoring system, to check possible morphological changes appearing in time, and to carry out large surveys without disrupting work continuity.

The post-processing of the laser scanner data and the three-dimensional modeling of the morphology of the Caves of Castellana and Naica were performed with CloudCUBE, software for managing and three-dimensional modeling point clouds developed by Virtualgeo on AutoCAD® platform. Using the same software it is also possible to extract any linear measure as well as compute areas and volumes from the digital model. The program allows one to automatically produce different graphic representations of the surveyed object (plans, sections, axonometric projections and cutaways). Thus it will be easy not only to study the present conditions of the caves (also by multitemporal analysis) but also to verify research hypotheses and evaluate possible projects.

Laser scanning technology is a practicable solution to document cave contexts in the most possible complete way, limiting risks connected with the insufficiency and/or inadequacy of data acquisition. It is suitable to rapidly survey large surfaces with a remarkable morphologic complexity otherwise impossible to be acquired with completeness.

1 Introduction

Topographical documentation is a fundamental phase to know and preserve environmental heritage. The aim of a speleological topographic survey is producing a topographic cartography that, with descriptive and iconographic information, can construct a reliable precise and complete database for speleologists, scholars, agencies managing territory and environmental safeguard as well as authorities administering caves, etc. Such cartography is not "only" the final result of an exploration aiming at the most complete morphological knowledge of cavities. It has also to be an appropriate base on which all the activities of basic research and research for practical applications concerning caves can be found. A hypogeal topographic survey has to gather the greatest amount of data considering the significance and usability that such information can have for the various scientific or institutional users. In this way the result of the survey is independent of topographer's discretion. Moreover, it has to be considered that hypogeal cavities can get inaccessible for environmental changes or safeguard measures which prevent their use. Speleological topographic cartography "materializes" the "knowledge" of the existence for a newly discovered cave and becomes an essential tool to let future visitors in the conditions to explore and start the study of a new underground environment.

Speleological topographic survey implies a preventive project of the operative modalities to be followed in team working. For hypogeal surveys speleologists commonly use traditional and technologically not sophisticated instruments which nevertheless are strong, humidity and water-resistant and resistant to all the typical hypogeal environmental factors, easy and quick to be read in uncomfortable positions and with little lighting (compass and clinometer for horizontal and vertical angles, altimeter, measures for linear measurements). Precision of surveys in caves is affected by errors during data acquisition due to many factors (technicians' attitude and experience, operative context, instruments and procedures in use). Among them, factors related to environment have great importance.

Representing a speleological topographic survey is traditionally hand drawing the planimetric and altimetric contours of cavities according to acquired data. The completeness of graphic representations (plans, transversal and longitudinal sections) depends on the amount of such data. In the most advanced cases representation has digitally-developed thanks to CAD (Computer Aided Design) with outstanding advantages for the various users in data storing, fruition and sharing.

Management and preservation of hypogeal environmental heritage require a deep and detailed knowledge of it. This is the reason why a precision speleological topographic survey is of primary importance as it constructs a database, which is basic to carry out the relevant activities of each involved subject, and allows, facilitates and increases the knowledge of the underground worlds by means of the most advanced technologies available on the market. In this sense laser scanning, whose application in the geological field has grown much in the last years, can be an alternative to traditional speleological topographic survey. This is an ideal solution when a remarkable morphologic complexity (specific of the natural shapes in caves) has to be surveyed and, consequently, a great amount of data has to be measured and managed. A value-added aspect of laser scanning technology consists of using the acquired data, once they are properly elaborated, not only for technical-operative purposes. As Virtualgeo has already proved for some examples of historical artistic and archaeological value, such technology can foster the access to environmental heritage and scientific contents by means of a series of highly communicative "products" (which can be adapted to different targets of users): virtual animations (which can be also interactive) to use on multimedia platform (also on-line), stereoscopic images and videos for a semi-immersive virtual experience, scale models for a direct sense contact, etc.

2 Three-dimensional Laser Scanning for Speleological Topographic Survey

Virtualgeo has surveyed caves in September 2006 in Castellana Grotte (province of Bari, Italy), in May 2007 in Naica in northern Mexico (Canevese et al., 2008a,b,c) and in December 2008 in Iglesias (Sardinia, Italy). In all such cases laser scanning technology was preferred to traditional speleological topographic techniques for fast rate measurement, completeness and precision of data, non-invasively with the surveyed surfaces and adaptability of use to document the caves present conditions by constructing high precision three-dimensional geometric databases of the structure of cavities and their speleothems. For such characteristics the laser scanning can be used both for monitoring possible morphological variations during the time, carrying our extensive surveys keeping working continuity, obtaining a high productivity survey even in difficult or dangerous working conditions (operative, environmental, logistic, climatic, etc.). Laser scanning is economically advantageous as rapidity and automation assure time saving in campaign phase, also working with a single technician.

Laser scanners are based on different functioning principles (time-of-flight, phase shift, triangulation) and have different ranges (maximum ranges change from few dozens meters up to some kilometers) to acquire high density "point clouds" (X, Y, Z spatial coordinates and, thanks to an associated camera, RGB color value). Such clouds, once they are unified by means of renowned reference points and georeferred to a certain reference system, reconstruct the three-dimensional geometry of the surveyed object or area. The final result of the scans, which are obtained without direct contact with the surveyed surfaces (essential not to affect their integrity, especially when it depends on a delicate balance needing great caution), and their post-processing is a global point cloud, which is a metrically accurate three-dimensional point model of the surveyed object containing also data of chromatic characteristics.

The high speed measurement of a great amount of information, as well as completeness and precision of data, have made laser scanning technique become widespread in the recent years covering, thanks to its extendibility of use, many applications. Laser scanning enters in different kind of working processes (in the fields of geology, engineering geology, engineering, archaeology, architecture, etc.) providing data of primary importance which can be integrated with data obtained with other instrumental survey techniques to interpret complex systems and relationships between their components.

The choice of a laser scanner according to peculiarities of the object/area to be surveyed, their extension and distance, as well as to working conditions, has to be evaluated in relation to its technical specifications: accuracy, field of view, range, measurement speed, pulse wavelength (which is influenced by reflectivity, humidity on surfaces and environmental factors), portable format (weight, dimensions, toughness), power supply, user interface, data storage and transfer, highest operating temperature and humidity levels.

The post-processing and representation of data follow the measurement phase, which is highly automated and quick, and require an important specialized work. The effectiveness of the data post-processing is crucial to optimize laser scanner potentialities. Therefore the support of a dedicated software is focal to use the acquired data into perspective of progressive automation of the representation procedures of surveys. With CloudCUBE Virtualgeo's research and development activity has followed this direction until now as the company is confident of the potentialities of laser scanning, which is destined to a growing spreading as irreplaceable technique for large precise surveys on complex objects in various terrestrial and airborne applications. CloudCUBE software was conceived in fact to allow managing and three-dimensional model point clouds on AutoCAD® platform. Moreover, by means of a special set of commands, it allows to manage surveys carried out with traditional topographic instruments and integrate them with laser scanning surveys.

Virtualgeo used a time of flight technology based laser scanner in Castellana and, for exteriors only, in Iglesias. Such laser scanner measures the distance of the surveyed object by timing the round trip times of the emitted light pulses. In Naica and in all the inner spaces of the mine of San Giovanni phase shift technology based laser scanners were used. They measures the distance of an object "comparing" pulses of different wavelengths reflected back to the instruments (Table 1).

3 The Grave in the Hypogeal Complex of Castellana, the Mine Caves of Naica and the Karst System of Santa Barbara

Virtualgeo works in the fields of geomatics and software development since 1994. It supplies services to support study and advancement of cultural and environmental heritage.

The caves of Castellana were explored for the first time in 1938 and immediately attracted media attention (tourist exploitation started at the end of the Forties). They are an imposing hypogeal formation of karst origin with a 3 km approximately straight planimetric development (included minor branches) in the Altamura limestone. It develops about 70 m below ground level along the main tectonic NW-SE direction while the minor branches develop along E-W and NW-SE directions. The starting phase of the caves evolution dates back to the middle or end of Tertiary period while the stalactites and stalagmites date back to the Quaternary. In the Apulian hypogeal system Virtualgeo performed the survey of the Grave with a time of flight laser scanner. With 10 scans the spatial coordinates and, thanks to the camera incorporated, RGB color values of more than 23 million points were gathered. The Grave is the first of the caves of Castellana, the most wide and indented cavity of Apulia region and among the most important of southern Italy. It is particularly vast: 100 m long, more than 40 m wide and about 60 m high. In such case the great dimensions of the Grave imposed the choice of a medium-long range laser scanner. An acquisition plan of the scans was prepared before starting the survey according to the characteristics of the site and laser scanner. The acquisition plan aimed at reducing "shadows" in the scans and defining the most appropriate scanning angles in order to obtain scans with uniform resolution (by setting the average distance between scanning stations and surfaces to be acquired as well as the scanning point spacing) and good overlapping area. Before scanning, 34 reference targets were placed in the Grave (in significant and visible points) and surveyed with total station for the following operation of georeferencing and registration (union) of the point clouds obtained from the scans. The work took 2 technicians 8 hours (1 working day) to fix and survey targets and execute the complete series of scans. After registering the scans, the post-processing of data was performed by Virtualgeo with the proprietary software CloudCUBE. It implied a careful cleaning and filtering of point clouds to remove "noise" and non significant points. The following elaboration phase of the acquired information consisted of three-dimensional modeling the Grave structure with the specific functionalities of the software.

The mine of Naica is in a semidesertic land about 100 km SE from Chihuahua and opens on the northern side of the Sierra de Naica, which is a low ridge along NW-SE direction composed of carbonate formations developed from the Albian age. In 1910 during mining works a small cavity, the Cueva de las Espadas (Cave of the Swords) was discovered at a depth of 120 meters from the entrance. The small cave is a 87 m long corridor completely covered with gypsum crystals, some reaching up to 2 m in length. Few years ago, 170 m below the mining advancement, workers met with another three natural cavities with huge very transparent gypsum crystals. In the Cueva de los Cristales (Cave of the Crystals) some of them reach up to 12 m in length and almost 2 m in diameter.

Virtualgeo's work in Naica was part of the multidisciplinary "Naica project" leaded by the Mexican company Speleoresearch & Films and the Italian exploring team La Venta. It consisted of laser scanning the Cuevas de los Cristales (Fig. 1) and de las Espadas. The aim of the survey was to document the morphology of the caves and crystals. It was an essential operation as premise of knowledge and any safeguard or advancement action on such ecosystem, unique and unrepeatable, probably destined to be submerged under 170 m of water when the mining activity will cease within 5-7 years. In the Cuevas de las Espadas and de los Cristales 4 scans were executed with a phase shift laser scanner and 40 pictures were taken with the camera associated with the instrument and the spatial coordinates and RGB color values of more than 43 million points were gathered. All the survey operations took a technician (geologist Roberta Tedeschi, who is Technical Manager of Virtualgeo) 3 hours (over 2 working days), of which 20 minutes were needed for scanning. A research phase preceded the choice of the laser scanner to be used in order to test the scanning efficacy of different laser scanner models on gypsum crystals. Virtualgeo tested the laser scanners a on a crystal sample of a good dimensions and thickness and verified the reliability of the obtained data. The chosen laser scanner has a limited range, suitable for the "forest of crystals" of Naica, a more compact size and lower weight than the laser scanner used in Castellana. Such characteristics proved to be useful for moving quite easily around crystals. The survey campaign was carried

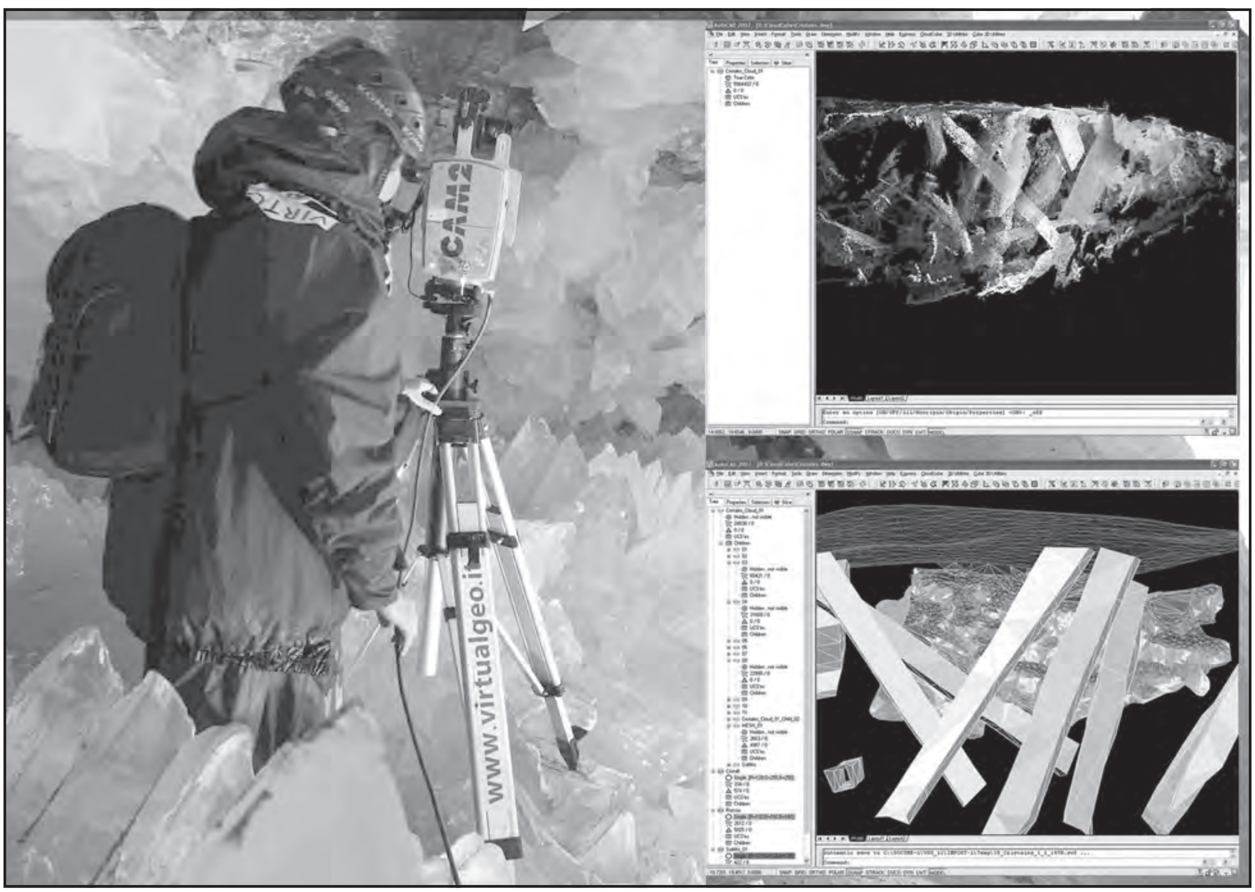

Figure 1: Laser scanning in the Cuevas de los Cristales, Naica, Mexico (photo Speleoresearch & Films©). Upper right side: point cloud of the cave visualized on AutoCAD© platform with Virtualgeo CloudCUBE software. Lower right side: 3D model of the cave and crystals obtained with CloudCUBE.

out in extreme ambient conditions (48°C temperature and humidity close to 100% in the Cueva del los Cristales) both for technicians' physiology and laser scanner functionality (which is guaranteed by the manufacturer to work 5° up to 40°C of ambient temperature and without condensation). Not only the prohibitive microclimate impacted the operations but also the limits set by crystals on moving the survey instruments (laser scanner with tripod, laptop, cables, power supply devices, etc.). The special equipment (suits, breathers and shoes) prepared by La Venta team for the whole expedition was fundamental to safely approach the caves. After registering the scans of the Cueva de las Espadas, the post-processing of the data acquired with laser scanner in the caves of Naica was performed with CloudCUBE. The work implied the importation of the point cloud which was carefully cleaned and filtered. The following stage focused on the Cueva de los Cristales and consisted of organizing the point cloud to obtain an efficient ordered base to work on with optimized time. The work preceded to three-dimensionally model the structure of the cavity and its giant crystals by exploiting the functionalities of CloudCUBE software.

The karst system of Santa Barbara consists of two large subvertical cavities (Santa Barbara 1 and Santa Barbara 2) developed in contact with a sulphides vein in the mine of San Giovanni, 5 km W from Iglesias in south-western Sardinia. The abundant galena in the mine made its exploitation start more than 2,000 years ago. The mine is the largest and most representative area of the Geo-mining Historical and Environmental Park of Sardinia. The whole karst system, whose development started in the Cambrian period, is considered to be one of the oldest. Cave Santa Barbara 1, open to tourist visits since 2002, is one of the most famous mine caves for the euhedral baryte crystals covering its walls.

Virtualgeo, in collaboration with Leica Geosystems S.p.A., surveyed with three-dimensional laser scanner part of the mine complex of San Giovanni. The survey required an acquisition plan due to the complexity of the whole and involved the exteriors at mine entrance level, access and connection galleries, caves Santa Barbara 1 (Fig. 2) and Santa Barbara 2, magazine of explosives and extraction areas. To carry out the whole laser scanning survey, 77 reference

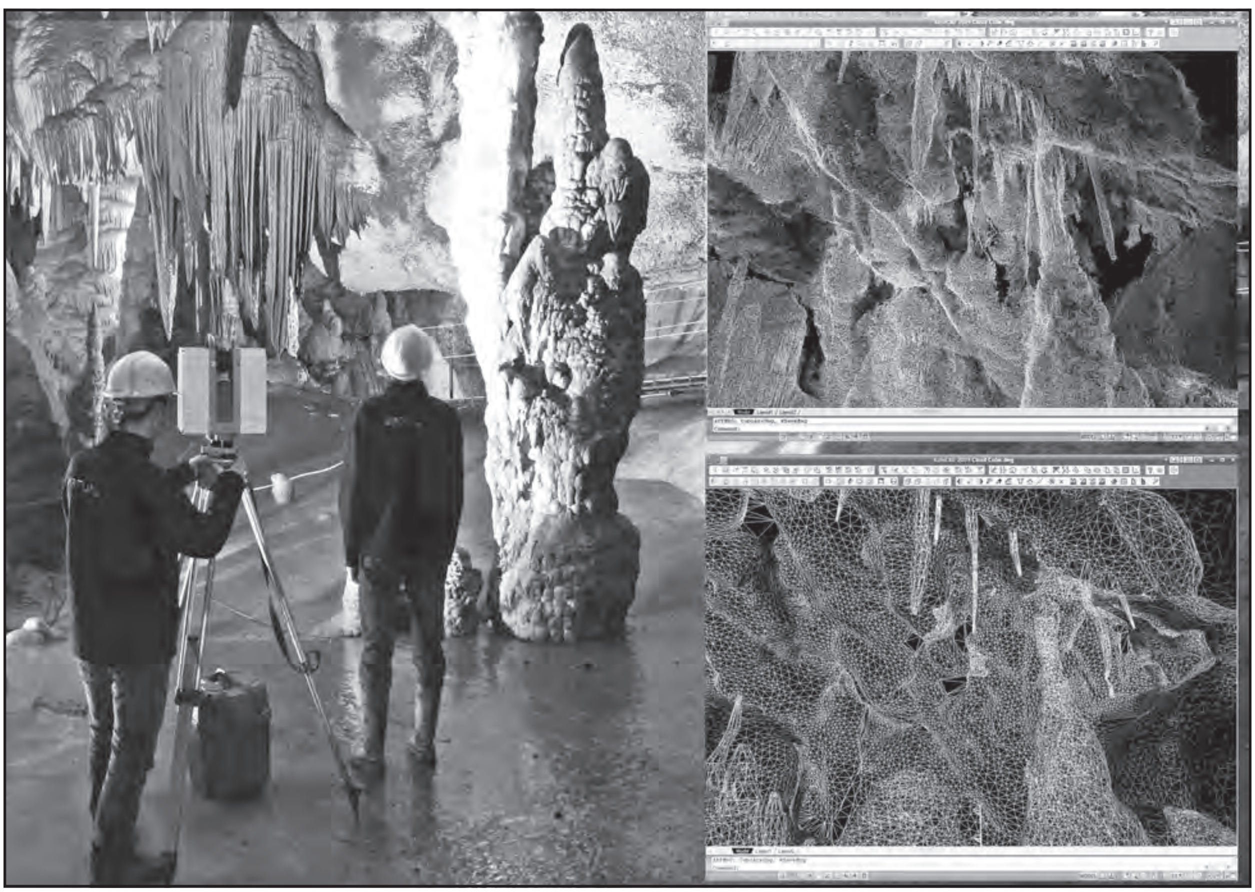

Figure 2: Laser scanning the cave Santa Barbara 1, Iglesias, Italy. Upper right side: a detail of the point cloud of the cave visualized on AutoCAD© platform with Virtualgeo CloudCUBE software. Lower right side: same detail of the 3D model elaborated from the point cloud by using the CloudCUBE 3D modeling functionalities.

targets were placed and surveyed with total station. With the laser scanning survey, topographic works were executed for traversing in order to execute a planimetric and altimetric connection between the two caves and georefer them (the open traverses obtained are globally about 2 km long). In this way the position of the two caves was defined with precision for the first time in their speleological topographic history. Using 46 scans the three-dimensional laser scanner acquired the spatial coordinates and, with the external camera, RGB color values of about 8 billion points. In 4 days, the survey campaign took 4 technicians 8 daily hours for setting datum points, traversing, placing and survey targets, scanning all the interiors and exteriors.

Registration, "cleaning" and filter of the acquired point clouds were performed with Cyclone software of Leica Geosystems. Further elaboration of acquired data is in progress during the preparation of the present paper (January 2009). Virtualgeo is performing it with the proprietary software CloudCUBE focusing on the realization of the three-dimensional model only, for such preliminary phase, of the cave of Santa Barbara 1.

Table 2

4 Conclusion

Virtualgeo has found a feasible solution in the laser scanning technology and reverse modeling methodological approach to document "objects" in the most complete way and limit risks related to lack or inadequacy of data acquisition. Examples of such work modality are the speleological topographic surveys and digital three-dimensional reconstruction of the Grave, Cueva de los Cristales and cave Santa Barbara 1. It is an operative modality that can be extended to other hypogeal contexts where a remarkable morphological complexity and a great amount of survey data have to be managed. Moreover, the rapidity of data acquisition by laser scanning allowed to overcome the ambient conditions in Naica and not to interfere in the flow of tourists in Castellana and Iglesias.

CloudCUBE software provided a set of tools to treat the millions points acquired, manage them in optimized way and elaborate three-dimensional models. Moreover, with the software it is possible to rapidly obtain from the three-dimensional model of the caves any type of dimensional information (linear as well as areas and volumes computing), plans with contour lines, "compound" sections (which are sections combined with line elevations and point clouds images), axonometric projections and cutaways of the present conditions of caves. Digital models can be generated with detail levels to customize according to the specific use they are destined to. Such use can concern basic research and/or research for practical applications (also with "distance" study on caves), educational (for caves equipped for tourist access, documentation centers and speleological museums) or public dissemination purposes. Each specialist can use CloudCUBE not only to study the present conditions of the caves but also to produce digital models to verify study hypothesis or to evaluate projects (e.g. for caves preservation or improvement of caves access and safety, etc.), with the possibility to elaborate graphic representations for the planning phase and verify it with virtual simulations to limit unexpected events on site so saving time, money and reducing the impoverishment of underground environment. Three-dimensional models give not only a basic specialist and operative support but also a possible solution to the conflict between public dissemination and limits set to safeguard underground worlds. Three-dimensional models can make people, wherever they are, virtually explore hypogeal environments to spread caves knowledge, also if caves are not accessible (e.g. for protection measures) or in

Laser scanner model	**RIEGL LMS-Z420i**	**CAM2 LS 880**	**LEICA HDS6100**
Range	2 m- 1,000 m	0.6 m-76 m	1 m – 79 m
Measurement rate	8,000-11,000 points/second	120,000 points/second	500,000 points/second
Accuracy	±10 mm at 50 m	±3 mm at 25 m	±1 mm at 25 m/±2.4 mm at 50 m
Vertical field of view	80°	320°	310°
Horizontal field of view	360°	360°	360°
Weight	16 kg	14.5 kg	14 kg
Dimensions	463x210 mm (LxD)	400x160x280 mm (LxWxH)	244x190x351.5 mm (LxWxH)
Operating conditions	0°-40°C	5°-40°C non-condensing	0°-40°C non-condensing
Camera model	Canon EOS 10D - 6.5 MPixel	Nikon D70 - 6.1 MPixel	Canon 450 D - 12 MPixel

Table 1. Technical specification of the laser scanners, and relevant cameras, used by Virtualgeo in Castellana Grotte and Iglesias (RIEGL LMS-Z420i), in Naica (CAM2 LS 880) and again in Iglesias (LEICA HDS6100).

	Grave – Caves of Castellana Castellana Grotte - Italy	Cueva de los Cristales Naica - Mexico	Cueva de las Espadas Naica - Mexico	Mine of San Giovanni Iglesias - Italy
Number of scans	10	1	3	46
Number of points acquired	23,761,000	13,180,893	30,032,525	about 8,000,000,000
Number of 2D images acquired	54	10	30	322
Amount of laser data acquired	1.45 GB	1 GB	3 GB	15 GB
Amount of 2D images acquired	135 MB	45 MB	135 MB	4.1 GB (raw+jpg)

Table 2. Number of scans and millions points acquired by laser scanners, number of pictures taken by cameras and "weight" of the digital data concerning the Grave of Castellana Grotte, each of the two caves of Naica and the complex of San Giovanni mine.

cases of persons who can not physically visit them. One of the main purposes of Naica Project is to find the best way to safeguard and transmit to future generations a large part of such unbelievable underground world or, at least, leave the most complete and punctual documentation before it disappears submerged. In this sense, the possibility to elaborate digital three-dimensional models with dedicated software as CloudCUBE, to realize products for an effective communication related to scientific information and ecological education is one of the remarkable potentialities of the laser scanning technique.

Acknowledgments

For the survey campaign in Mexico thanks are due to Naica project, Speleoresearch & Films and exploring team La Venta for the collaboration, CAM2 s.r.l.-FARO Technologies Inc. for the laser scanner, Compañía Minera Peñoles for the permission to access the mine.

For the survey campaign in Sardinia thanks are due to Leica Geosystems S.p.A. and to Federazione Speleologica Sarda, Società Speleologica Italiana, Parco Geominerario Storico e Ambientale della Sardegna for the collaboration.

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DIGITAL MODES FOR CAVE RADIOS

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Cave Radios are used to accurately determine the position of an underground transmitter on the surface. They can be used to check the accuracy of cave surveys, as well as to locate positions for drilling and potential entrances. The author has been using cave radios for these purposes for over 25 years. The utility of these radios is enhanced by the ability for two-way communication using manual Morse code. Over the decades fewer cavers have Morse code proficiency. Currently available small personal computers and Personal Data Assistants (PDAs) make it possible to use these same radiolocation cave radios with digital communication modes that are compatible with the narrow bandwidth that is available in these radios.

There are several digital modes that are suitable for cave radios which use a hard limiting transmitter for simplicity and the highest efficiency. PSK-31 which has been developed by the Amateur Radio community is one example. However, on-off keying using Morse code offers some advantages over other modes since it can be sent and received manually in the event of some equipment failure. Also, the low duty-cycle of the on-off keying transmitter helps reduce power consumption which is an important consideration for battery-powered operation. Coherent and quasi-coherent demodulation of the on-off keying waveform provides adequate performance for many caving applications. In this case, a Windows CE based PDA can be used underground to minimize the size and weight, and a small laptop with a higher performance demodulator can be used on the surface.

1. Introduction

This paper describes how digital communication modes can be incorporated into cave radios used for position location. Hopefully the information in this paper and the references provided will encourage others to further the state-of-the-art in cave radio technology.

2. Lessons Learned from Project SIMMER

In 1973 I had an opportunity to participate in Project SIMMER, the Simmons Mingo/Elk River expedition, in West Virginia USA (Robins, 1973). This four-day event included two base camps in the cave and a large surface support team. This was my first opportunity to see a cave radio that was used to locate the surface position of an underground transmitter to verify the accuracy of the underground survey and to potentially help locate entrances. Since the cave had a travel time of 8 hours to get to the extreme sections, finding another entrance was a high priority. Brothers Roy and Jim Charlton used their cave radio for this project. Their surface antenna can be seen in Figure 1. The Simmons Mingo expedition installed field telephone wire and military surplus field phones in the cave for communication. There were enough phone locations that it was necessary to have a telephone operator as shown in Figure 2. The field phones provided excellent communication to coordinate the expedition; however,

Figure 1: The Charlton brothers at Project SIMMER with their surface antenna. Photo by Ray Cole.

Figure 2: Telephone operator at Project SIMMER. Photo by Ray Cole.

most wild caves don't come wired.

3. Development of the Organ Cave Radio

I was very interested in the Charlton's Cave Radio capability since I was co-chairman of the Organ Cave Survey in Greenbrier County, West Virginia USA (Stevens, 1988), and we were ready to start drawing the final map. We wanted to make sure that the position of the underground survey relative to the surface was properly registered and make sure the project co-chairman and our cartographer Paul Stevens didn't have to re-draw the map quads as more cave surveys were added. The first step in properly locating a cave survey with the surface is to do a surface survey that is at least an order of magnitude more accurate than the cave survey. A surface traverse was done using an electronic distance meter and a theodolite. This survey included the entrances and major surface features. The positions of cave radio-locations and depth were then tied into the surface survey and used as constraints to fix those station positions.

Survey indicated (?) that the cave was over 100 meters below the surface, so a cave radio that would give useable results to this depth was needed. The resulting design for the Organ Cave Radio was featured in Issue 3 of Speleonics (Cole 1985). This was a somewhat unique design that was intended to be easy to operate and easy to duplicate with readily available components. The advantage of this design is that the transmit and receive frequencies are accurately determined by a crystal oscillator so no tuning is required. A commutator filter provides the narrow receive bandwidth. The Organ Cave Radios were designed as transceivers capable of two-way communication using Morse code; this worked very well. Several cavers who were also amateur radio operators were anxious to help with the radiolocations. Patrick Moretti is shown in Figure 3 at the intersection of the Humphrey and Lipps passages in Organ Cave. In this figure you can see that a 2-meter diameter antenna is used for the greater depths in this portion of the cave. This antenna can be coiled up and carried in a pack.

Figure 3: Patrick Moretti using the Cave Radio at one of the Deeper Locations in Organ Cave. Photo by Paul Stevens.

4. Use of Manual Morse Code for Cave Radios

Over time fewer cavers have become proficient in Morse code. It is possible to determine radio locations without the benefit of two-way communication by establishing a plan and following it closely. Unfortunately, the lack of two-way communication does not leave any room for contingencies. A better solution was needed, so I have been experimenting with different methods to do digital communication using the same cave radios used for cave radiolocations.

5. Digital Communication using PSK-31

My first attempt at using the amateur radio PSK-31 mode of communication was demonstrated at the 2000 NSS convention. The key to this design was to use the same switch mode transmitter as used in the Organ Cave Radio. However, the audio output representing the PSK-31 frequency shift keying waveform is hard-limited and used to drive the same transmitter. The effect of the hard-limiting strips away the pulse shaping that is important in the use of this mode for radio frequency applications to minimize interface to adjacent channel users. Given the narrow bandwidth of the cave radio transmitter interference is of no concern. The objective is to radiate as much energy as possible and to do so as efficiently as possible.

Two different receivers were tested with this transmitter. One was a simple high gain circuit that used a feedback tap on the receive antenna to create a regenerative effect which further increased gain and reduced the bandwidth. The Organ Cave Radio receiver was found to provide better performance with its narrow bandwidth commutator filter. Figure 4 shows a block diagram of the transmitter and receiver based on the Organ Cave Radio receiver. Since the transmit frequency is determined by the audio frequency from the PSK-31, it's essential that it be on the correct frequency since the receive bandwidth is only about 30 Hz. This narrow bandwidth is important so that the 60 Hz power line harmonics fall outside the receive passband.

Peter Martinez, the inventor of PSK-31 was kind enough to provide me a version of his software without the pulse shaping. There was the potential that this could provide a slight improvement in performance but an A/B comparison didn't show any significant difference. My initial plans were to use small PC laptops but this presented a problem in how to transport these for underground use. More recently a Windows CE based PDA based amateur radio digital program was developed by Vojech Bubnik from the Czech Republic. His program is called PocketDigi . This excellent software includes modes for PSK-31, Morse code, and many other digital modes.

6. Using a Computer to Transmit and Receive Morse Code

In using PocketDigi, it was found that the Morse code mode worked well. This suggested that using the PDA to transmit and receive Morse code was a good option. An advantage to using Morse code over other digital modes is that it provides some redundancy in case of PDA failure; the operator/caver can still transmit and/or receive Morse code manually. Another advantage of Morse code is that the transmit duty cycle can be much lower than constant envelope digital modes which can help reduce the power consumed and prolong battery life. The downside of Morse code is that the actual performance is poor compared to PSK-31, and the data rate is slower. However, the bottom line is that if there is sufficient signal-to-noise ratio for accurate cave radiolocations, then there is more than enough signal level for any of the narrow-band digital communication modes.

A more efficient demodulation technique for Morse code called coherent continuous wave (CW) does exist. Ray Pettit, a colleague of mine in the 1970s, originally developed coherent CW (Petit, 1975). Currently the software available to demodulate coherent CW requires the computational power of a PC. This can be a good match to an underground PDA-based CW transmitter with the more efficient receiver on the surface using a PC where size and power consumption are not necessarily as critical. A Microsoft Windows based Coherent CW program developed by Michael Masterson provides better performance than the PocketDigi PDA based receiver (Masterson). The standard data rate for coherent CW is 12 words per minute.

A block diagram of the Organ Cave Radio with digital mode capability is shown in Figure 4. With a

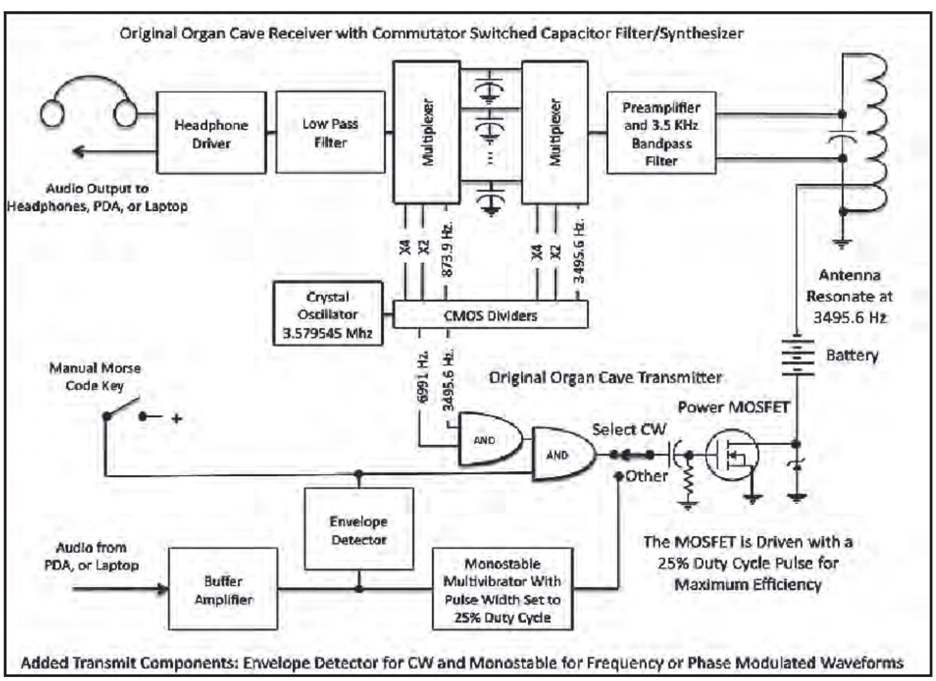

Figure 4: Revised Organ Cave Radio Block Diagram Incorporating Digital Communication Capability.

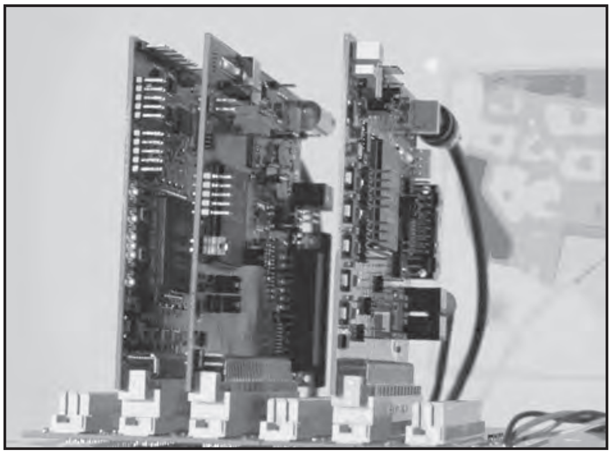

Figure 5: High Performance Software Defined Radio.

small amount of additional circuitry, it's capable of operating with an external PC or PDA for digital modes including Morse code as well as PSK-31.

Figure 6: Display for Software Defined Radio using PowerSDR.

7. Conclusions and the Future of Cave Radio

There is a lot of room for experimentation in cave radios. Other two-way communication needs for cavers, such as an emergency beacon could benefit from digital modes capable of operation at even lower data rates at narrow bandwidths. Currently there is much interest in building high performance radios using digital signal processing techniques (High Performance Software Defined Radio). Figure 5 shows my home high performance HF radio that uses open hardware and software. This radio has a 130 million samples per second 16 bit A/D converter at the receive antenna and a D/A converter which drives the power amplifier. The remaining processing is performed using an on-board field programmable gate array (FPGA) and a Personal Computer, which also serves as the user interface as shown in Figure 6. While this equipment could be used for a cave radio, the low frequencies used for cave radios could be implemented with a lot less complexity, cost, and power consumption. The future of cave radios could be a simple matter of software.

Acknowledgments

The author would like to thank two people that have contributed to this work. The late Frank Reid was instrumental in starting the NSS Communication and Electronics Section. The section has provided a valuable forum for cavers to meet and discuss the application of electronics to caving. All of the issues of the section publication Speleonics ® are freely available on-line to encourage others to experiment and further the art of cave related electronics. The author would like to recognize the collaboration with Brian Pease. His current Double Quadrature receiver provides a high performance design for radiolocation that has been duplicated by many cavers with the help of the printed circuit boards he has made available. Brian also developed a novel Class E Beacon transmitter design for cave radios that uses a series resonate LC antenna.

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THE USE OF GROUND PENETRATING RADAR IN KARST AREAS: METHODOLOGY, FEASIBILITY AND INTERPRETATION

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Abstract

Ground penetrating radar (GPR) is a geophysical technique increasing used in karst areas for speleological and archeological prospecting, detailed hydrogeological studies, and determining foundations in limestone areas. Recently, the installation of wind farms in limestone mountains has caused GPR soundings to be a standard procedure with the aims of preventing destruction of potential existing caves (geological heritage conservation) and avoiding problems in the foundations of wind-power generators.

The main difficulties to perform GPR tests are the roughness of karren fields, the covering of limestone surface with sediments, and the brushwood usual in wild areas. The terrain conditions in wild settings almost interdict the use of ground coupled antennas and compel the use of air coupled dipoles. When the ground is highly irregular or when great depth is to be achieved, continuous acquisition mode must be replaced by stepped mode. This permits to receive a better signal namely at greater depths.

Antennas of 20 MHz to 200 MHz are commonly used. The lower frequencies can reach easily depths of 20 m with good sharpness, while frequencies of 150 to 200 MHz are good to sound the shallow subsurface. Occasionally, they are used together to cover an entire section from ground to depth. When areas instead of lines are to be worked, the best methodology is to draw an evenly spaced net of crossed orthogonal sounding profiles.

The karst objectives are epikarst, empty or filled voids, vadose vertical shafts, dry or water filled karst conduits, paleokarst voids filled with clay or carbonate material, brecciated karstified zones close to faults, and the top of the phreatic level. Not always does each one has its own distinctive signature. In many examples, shafts are hardly detected.

The interpretation of radar profiles has to take in account lithological and textural changes in vertical and lateral characteristics of limestones, such as marly layers, microconglomerate transitions, iron seams, chert nodules, and hard grounds. Also structural and tectonic elements, like intersection of joints with bedding planes, fold structures, faults and calcite veins, are to be considered. Natural and anthropogenic elements to be aware of are positive and negative karren relief, trees, walls, and aerial or buried electric cables. All these features can generate anomalies erroneously interpretable as karst hollows or filled cavities.

THE INTERNATIONAL TRAININGS OF CAVE RESCUE ORGANIZED BY THE FRENCH SINCE 1997

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Abstract

Organized by the Speleo Secours Francais after the UIS congress of La chaux de Fond, 1997 saw the first international training in a new style of cave rescue. Since then, the French, with its commission on cave rescue, has conducted international training for 30 to 40 cavers every two years. All the aspects of the rescue were in the program: Assistance for the casualty, carrying the stretcher (with and without rope), communications underground, removing obstructions (with and without explosives), diving, and operational organization. The teaching was conducted in place: caves, pits, canyons, and cliffs. The courses are conducted in French, Spanish and English. The course starts with simpler techniques and continues to the more difficult. At the end of the training there was an exercise with the cavers of the country and the administrative partners.

We conducted these trainings for more than 200 cavers coming from 24 countries all across the world. Some graduates of the course have become leaders in cave rescue in their own countries.

LES STAGES SPÉLÉO SECOURS INTERNATIONAUX ORGANISÉS PAR LA FRANCE DEPUIS 1997

Résumé :

1997 est le premier stage international d'un type nouveau organisé par le Spéléo Secours Français à la suite du congrès UIS de La chaux de Fond. Depuis la France par sa commission spéléo secours organise tous les deux ans un stage international de secours spéléo pour 30 à 40 participants. Tous les aspects du secours y sont traités : Assistance aux victimes, évacuation avec et sans corde, communications souterraines, désobstruction avec et sans explosif, plongée, gestion de secours. Les enseignements se font sur le terrain en situation : grotte, gouffres, canyon, falaise. Les cours sont dispensés en français, espagnol et anglais. Les notions enseignées vont des plus simples aux plus complexes et les stages se terminent par un exercice incluant les spéléos de la région et les partenaires administratifs.

Ces stages ont reçus plus de 200 spéléologues venant de tous les continents et de plus de 24 pays. Bon nombre d'entre eux sont devenus responsables secours de leurs pays.

ALWAYS READY CAVE PHOTOGRAPHY

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Traditionally, making a cave photograph has been a process of unpacking equipment, setting up lights, cameras, and models, and finally making the photograph. This process is unsuitable for hard, push trips. While it can produce beautiful photographs, unless great care is taken and the models are good actors, the photographs tend to look static and posed.

Modern equipment, including small, waterproof digital cameras, strobes which can be powered for many hours from internal batteries, and transparent, waterproof protective boxes allows a more spontaneous, documentary approach to cave photography. This light-weight equipment can be carried on slings, outside the cave pack, making it "always ready." Photographs can be made during the brief pauses that occur during normal travel through the cave, so even fast-moving parties are not impeded. Combined with digital photographic editing software, the results are beautiful photographs which can show the action of caving, and document the activities of an entire trip.

1. Background

"If camera containers are inaccessible, packed at the bottom of a tackle sack, the time taken to get equipment ready means that few photographs are taken; ensure that your camera is readily available." (HOWES, 1997)

Historically, most cave photographers have carried their equipment in protective cases in their cave packs. In his book on cave photographic techniques, Chris Howes (1997) states, "Protective containers are essential for transporting photographic equipment within the cave." The resulting slow access to the equipment encourages a static style of planned photographs. While many beautiful photographs have been made with these techniques, as can be seen in any cave photographic contest, amateur models tend to look posed and static, and the time needed to make photographs is not available on hard push trips.

Some photographers have experimented with faster techniques. Ron Simmons (personal communication) used small cameras and single flash techniques to make quick photographs on expeditions. Dave Bunnell (personal communication) experimented with "Guerrilla photography" to avoid using a tripod with multi-flash setups. At the Budapest International Congress of Speleology in 1989, Peter Borzsak was using a small camera with attached strobe and a slaved flash in a protective case with a transparent side for fast action photography (BORZSAC 1989). Marc Tremblay (2005) has described a neoprene case for camera with Velcro closures.

2. Always Ready Equipment

Modern equipment makes it possible to use techniques similar to Peter Borzsak's, which allow all of the photograph equipment to be carried outside the cave pack. Pentax has offered a number of cameras, the Optio W60 camera being the most recent, which are water and dust resistant and offer manual focus (PENTAX, 2009). Olympus offers several models which are water, dust, and shock resistant including the Olympus Stylus 1030 SW and the Stylus Tough-8000 (OLYMPUS, 2009). These compact, light-weight cameras

Figure 1: Pentax Optio W30 camera with a neoprene sleeve and neck strap.

can be carried in neoprene sleeves, which provide bump protection and allow one handed operation (Fig. 1). Frequently dive shops are willing to custom-make these sleeves.

A number of companies offer electronic flash units that offer several levels of output, automatic operation, and may be left on for long periods of time without exhausting their batteries. Combined with photographic slave units compatible with the camera used, these flash units can provide off-camera lighting for cave photography. The Firefly 3 photographic slave is compatible with many digital cameras (Firefly, 2009). Otter offers a number of water resistant, transparent cases suitable for holding a strobe unit and a photographic slave (Otter 2009). When combined, this equipment makes a rugged and compact unit which can even be used under water (Fig. 2). In use, the flash unit is turned on at the start of the cave trip. Rechargeable nickel metal-hydride batteries commonly last for over eight hours.

Figure 2: Strobe and slave in a transparent Otter box.

3. Always Ready and Other Techniques

The equipment described above is ideal for a candid, documentary style of photography (Fig. 3). It may also be used for more planned and posed photographs. Since the cameras are all automatic, consumer-grade cameras, they require some specific techniques to get good cave photographs.

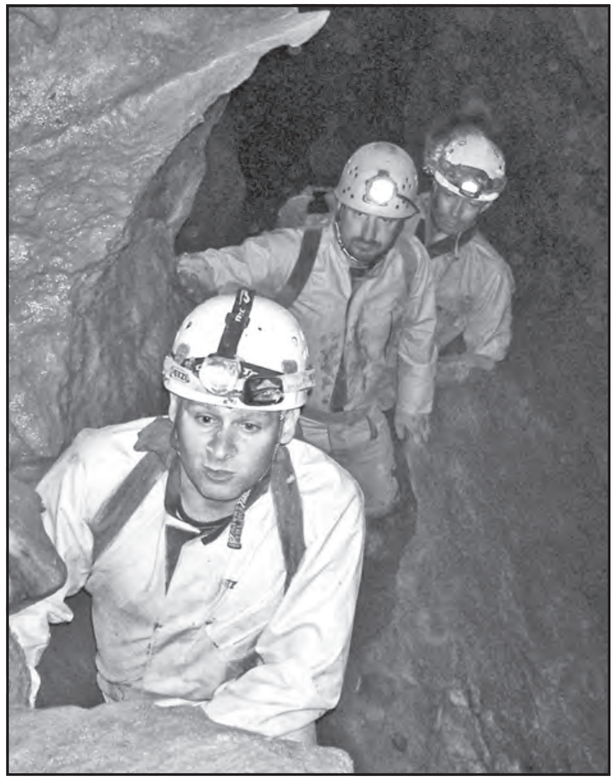

Figure 3: Party traversing the top of a 20 meter drop. Photograph was made while holding on to the cave with one hand, the strobe box hanging from its sling.

3.1 The test photograph

When time permits, a test photograph can check whether focus, exposure, lighting, and framing are correct. These can all be checked in play mode; zooming in to check focus, looking at the exposure histogram, and examining the overall photograph.

When photographing moving people, test photographs can be made before the subject is in place. Sometimes there is not time for a test photograph, so the camera and strobe should be preset for the most likely situations.

3.2 Viewfinder

These cameras use the LCD screen as the only viewfinder. In the dark, there will often be large areas of the picture that are not visible on the screen. Nonetheless, there is usually something to help line up the photo; perhaps a headlamp, or a visible formation. If there is nothing visible on the LCD, take a photo, apply a correction, and take another until the results are acceptable.

3.3 Focus

The auto-focus for many cameras requires a lot of light and contrast. It is usually possible to auto-focus close-ups, with a headlight shining from the side. For more distant scenes, sometimes the auto-focus will focus on people's headlights, but most commonly, it is necessary to use manual focus. Focus can be checked in a test photograph.

3.4 Exposure

Many cameras do not offer any manual exposure controls. However, changing the ISO sensitivity can change the exposure provided by external, slaved flashes. Some cameras can be set up for easy access to the ISO speed menu.

Many cameras offer exposure histograms during play back that show exactly how much of each light level is in the picture. For normal exposures, the peak(s) should be near the middle of the graph, tapering off at the ends. However, the histogram is only an exposure guideline. A dramatic photo, with lots of black, will have a peak at the right end, and may also show the indications of underexposure on parts of the picture. For almost all photos, it is best to avoid overexposure.

3.5 White balance

Letting the camera automatically select the white balance can overly mute the rich colors of some subjects, as the camera will attempt to make the scene "normally" colored. In cave photography, it is best to set the white balance manually. Since strobes closely match outdoor sunlight, use the sunlight setting if there is no flash setting. Alternatively, one could try the indoor settings with uncoated flash bulbs.

3.6 Lighting

There are different approaches for various numbers and locations of the flashes. For a single flash on camera, just use the camera the way the manufacturer intended.

There are two basic approaches to having a single off camera flash. One is to use a slave that compensates for the pre-flash most digital cameras use and cover the camera's flash with a black chip of slide film. The other is to turn off the on-camera flash and use the open flash technique. To use the open flash technique, also known as "on three photography", get everyone in the picture to turn off their lights. Set the camera to a mode which supports long exposures, sometimes called "night scene". Open the shutter on two and fire the flash on three. Covering the lens after the flash can help to minimize ambient light effects. Turning off the on-camera flash has the advantage that the camera does not use power to charge the flash every time it is turned on, preserving its battery.

For two flash photos, with one flash being the on-camera flash, use a slaved flash that compensates for the pre-flash. For quick photography, just hold the slaved flash in the left hand and the camera in the right. For photographing from difficult positions in the cave, the flash box can hang from a sling across the chest and just point in the general direction of the subject. These techniques give some off-camera modeling to the scene, and allow well-lit pictures at a much greater distance than are possible with the on-camera flash (Fig. 4).

Figure 4: Catching a candid photograph of Lisa reaching for an Easter Egg requires a camera system that is ready when she makes her move.

There are several techniques for using two or more off camera flashes: slave all the flashes to the camera, slave them to a master flash, or use the open flash technique described above. The best technique depends on circumstances and available equipment. When slaving flashes to the camera, use several "second flash" slaves. When slaving to a master flash, the on-camera flash sets off a nearby flash with a second flash slave, but the pre-flash must not be bright enough to set off the other flashes in the setup. Getting this technique to work is obviously somewhat setup dependent. When all else fails, use the open flash technique. Either set one flash off manually, and use first flash slaves to fire the other flashes in the setup or have one person hold each flash in the setup and manually trigger it "on three".

3.7 Depth of field control

Many of these cameras do not provide a way to use a smaller aperture, particularly in the dark of a cave. The good news is they have relatively slow lenses and small sensors, so they naturally have a reasonably good depth of field.

4. Conclusions

With these techniques, it is possible to make some really nice cave photos, using equipment that is small enough and light enough to take on hard push trips (Fig. 5).

The equipment is suitable for use in a quick, candid, documentary style as well as in a more planned style. Remember: the camera that is present and ready to use is much better than the one that was too heavy and bulky to bring along.

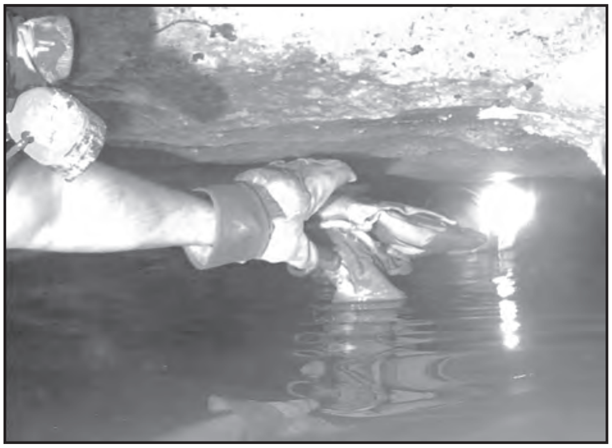

Figure 5: Catching two surveyors passing the book through a low place while neck-deep in water requires water resistant equipment.

Acknowledgments

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TERRAIN MODELING AND GIS TECHNIQUES FOR CAVE EXPEDITIONS IN CHINA

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Cave explorers traverse the globe in search of ever more grand discoveries. The spectacular karst of China comes with many mapping challenges, including limited availability of good base maps. The space shuttle's 2000 Shuttle Radar Topography Mission (SRTM) terrain model data was processed into base maps for these cave expeditions. Substitutes for standard topographic maps were created by contour extraction and automated sinkhole delineation. These layers serve as the base layers for the expedition GIS.

During the project locations of caves, springs, and geologic contacts populate the Geographic Information System (GIS). Daily updates of cave surveys added to the GIS allow team members to see how passages and hydrology relate to surface features.

By creating a karst GIS, intelligent choices for additional surface and in-cave prospecting as well as dye injection and monitoring points are well-supported. The SRTM data analysis approach has been found to be indispensable and has directly led to significant discoveries.

1. Introduction

Cave explorers traverse the globe in search of ever more grand discoveries. These efforts range from targeting the superlatives of largest, longest, and deepest to more science-specific inquiries such as biology, archaeology, and of course, hydrology. Regardless of the pursuit, good topographic maps are a necessity. In addition, cave explorers are increasingly using Geographic Information System (GIS) technology to support both cave and karst documentation as well as follow-on studies. Generally, the cave has to be found, explored, and surveyed before science can follow.

A challenge is presented when standard large scale topographic maps such as 1:50,000 or better are not available. Barriers include cost, supply, logistics of visiting a foreign mapping office, or other restrictions on availability. The space shuttle's 2000 Shuttle Radar Topography Mission (SRTM) data provides an alternative solution in these situations (NASA, 2003; USGS, 2003). Many people already have some familiarity with SRTM but don't realize it. SRTM data is behind the virtual globes, such as Google Earth or World Wind.

By working with the raw data files, we are able to achieve the maximum benefits allowed by the data resolution. Traditionally, field researchers have penciled in features on a paper map and made annotations in the margins. Laptop computers, GIS software, and handheld Global Positioning System (GPS) units have allowed a much more advanced approach to recording field observations. SRTM data supports production of both paper maps and digital base maps for a cave/karst GIS.

2. Data Description

In February 2000, the Space Shuttle collected topographic data for nearly 80 percent of the Earth's land area with a Digital Elevation Model (DEM) grid resolution of 30 m. Areas outside of the US were degraded and made available as a 90 m DEM. The initial 'research grade' data's 90 m resolution was generated by averaging 9 - 30 m cells. A 'finished version' created the 90 m cell by simply selecting the center cell of the 9 x 9 group from the 30 m cells. This paper covers the use of the 'research grade' data from late 2003 to the present. We made first use of these data on a collaborative cave project in China in early 2004.

The most significant problem with the SRTM data is the missing cells or null value holes. These range from a speckle error of one or several cells to large voids. Much has been written about filling the voids from other lower resolution DEMs or topographic sources. Another option is to fill the voids with a derivative of the adjoining good cells in a "smooth across" approach. Since we are trying to push the limits of the data, we will leave most large void spaces as unknown instead of replacing it with something of much lower accuracy. However, the speckling of individual null cells causes problems for most terrain analysis routines so we further process the data to eliminate them and reduce the size of larger voids.

3. Data Processing

Though several versions of the SRTM data are available, the original 'research grade' is the best starting point for the reasons described above. ESRI's ArcGIS software has been used in this project, though other software options are available.

ArcGIS requires a series of steps to convert the SRTM data files into a format it can understand. Tutorials can be found on the web. Once properly converted to the ESRI GRID format, the tiles can be merged or clipped for larger or smaller areas of interest.

The next step is to remove the null value speckles from the grid. A simple averaging of adjoining non-null cells was chosen for this task. In ESRI parlance, this is the focal mean function. The resulting GRID is now our "best" layer. The original is saved for reference. At this point, a hillshade layer is created for later visualization uses (Fig. 1).

Sinkhole delineation is the next step. Depressions are identified and artificially filled using GIS processing tools. Subtracting the starting elevation grid from the starting grid results in a sinkholes-only layer where each cell value is its depression depth. Additional slope analysis may be made here to find sinks with steep headwalls (a likely location for cave entrances), for example. Sinkhole delineation and other watershed related terrain analysis was performed with the TauDEM terrain analysis toolbar plugin for ArcGIS (Tarboton, 2005) (Fig. 2).

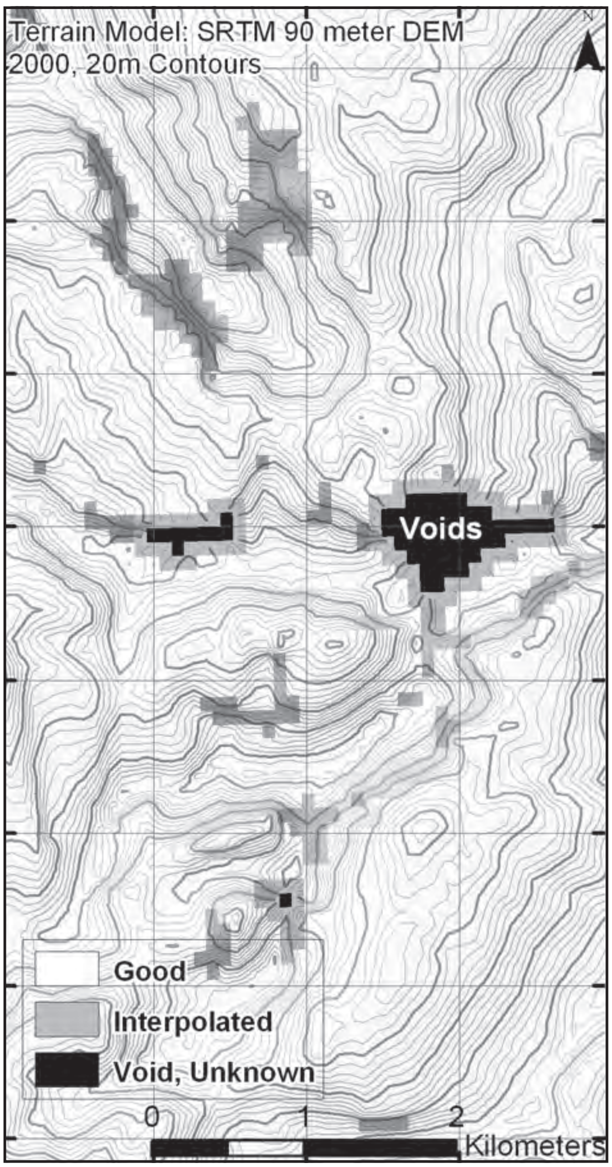

Figure 1: Example of data holes and focal mean fill and processed contour lines.

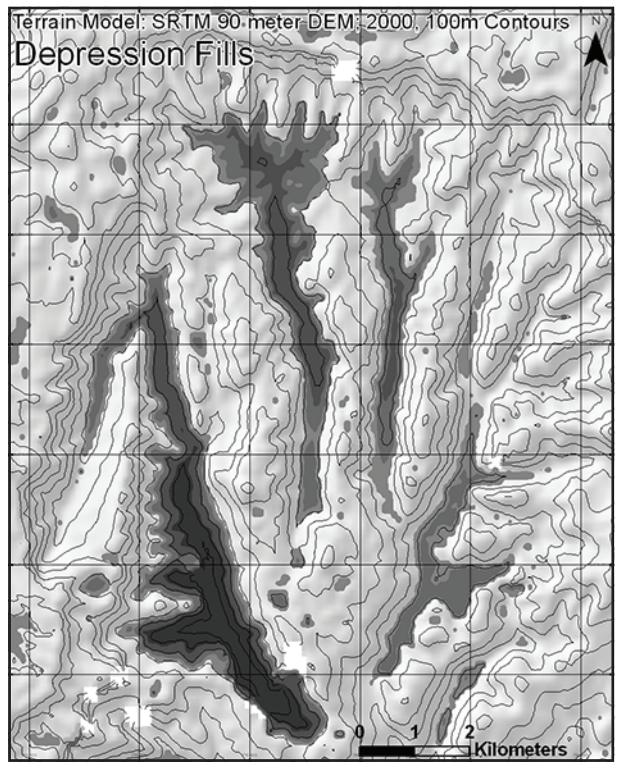

Figure 2: Sinkholes (dark gray colors) delineated from SRTM-derived elevation data. Plotted over contour lines and a hillshade generated from the DEM.

To complete the topographic model contours are generated with goal of simulating a 1:50,000 scale map. A 20-m contour interval was chosen because this is typical on standard maps. Additionally, a dashed 10-m contour interval was added to act more as a visualization aid. This was particularly useful when printing maps at a 1:25000 scale for field reconnaissance. This larger scale is close to the U.S. 7 ½ minute topographic maps. Contours and colored elevation ranges augmented with a hillshade and a 1-kilometer UTM graticule are used to create both digital and paper base maps. Any other available or created GIS data layers are also included.

4. Accuracy

Our SRTM data-derived topographic maps do not meet anyone's definition of map accuracy standards. However, SRTM data-derived maps are much better than nothing and have been adequate for many of our purposes.

Figure 3: Map of the closed depression at Natural Tunnel State Park, Scott County, Virginia as resolved by contours drawn on a SRTM data-derived DEM and on a high-resolution photogrammetricaly-derived terrain model (VGIN).

Verification comparisons have been made with high accuracy terrain models. Anomalies in SRTM sinkhole delineation fall in two classes. False negatives occur when the SRTM data miss a sinkhole due to their size being at or below the resolution of the data. False positives occur when the terrain model derived from SRTM data shows a sinkhole that does not exist. Many of these are also small. However, more problematic are the cases of stream canyons too narrow for the resolution of the DEM grid. Essentially the bottom elevation of a narrow canyon is generalized into the elevation of the top of the canyon (the 90-m cell is too large to "drop" to the bottom of the canyon). The effect is a closed depression that does not exist.

Two case studies of sinkhole detection accuracy verification and proof of concept have been made. The first is a comparison with a high accuracy terrain model. The second is comparisons to georeferenced 1:50,000 topographic maps of several different countries.

The first case is located at Natural Tunnel State Park in Scott County, Virginia. The upper-most depression contours are compared (Fig. 3). The dashed line is the SRTM 10-m contour. The solid line is a 5-foot increment derived from a statewide terrain model based on data acquired in 2002 (Virginia Information Technology Agency, 2002). The background is the standard USGS 7 ½ minute topographic map. This large stream insurgence is well represented in the SRTM-derived terrain model. All similar size and larger karst features are very likely to be represented as well.

The second case is located in the area of Sistema Huautla, Mexico, the second deepest cave in the Western Hemisphere at -1475m. SRTM data-derived contours were overlaid on the 1:50,000 Huautla (E14B87) topographic quadrangle in southern Mexico. The entrance sinkholes to the system are well delineated by the SRTM derived elevation data (Fig. 4).

Similar comparisons have been made with 1:50,000 scale topographic maps from other nations. As expected, fine undulations in the terrain that are captured in an actual 1:50,000 map do not show up in the "generalized" SRTM contours (Fig. 4).

These comparisons illustrate the technical analysis and proof of concept tests performed. They provide general understanding of the level of detail one can expect in real world application. More importantly, comparative analysis demonstrates that we can find large depressions and sinking streams. Conversely, we cannot detect small sinkholes. The smallest possible representation of a sinkhole is 90 m on a side. We prefer to see multiple corroborating cells together, thus we are left looking for sinkholes that are at least hundreds of meters across in the narrow dimension.

5. Field Application

5.1 Identifying promising areas for research

The costs and logistics of field work by 8 to 12 karst geologists for several weeks requires one to select research sites with careful consideration. Terrain analysis of SRTM data allows for pre-trip selection of field sites with an increased probability of finding significant cave systems. The addition of multi-spectral satellite imagery such as Landsat provides additional verification of large streams in addition to a great deal of additional remote sensing information.

In the field, it is hard to argue against an old fashioned folded map in your pocket while hiking. Traditional compass based as well as GPS based navigation is made possible. Like any other map, the SRTM map provides a local reference for "where am I" and "what's over the ridge."

5.2 Karst feature mapping

During the project, karst layers in the database are populated with the locations of caves, springs, and geologic contacts. GPS track logs of local roads, trails, and points of interest augment the base map. Consumer grade handheld GPS units are used for locating the majority of points, however overland surveys are also used to more accurately connect entrances that are in reasonably close proximity.

Surface teams can come back at the end of the day and download GPS track logs into the GIS, recording which areas have been checked as well as the locations of repeatable shareable paths to and from cave entrances. In many instances, GPS coordinates or photos have helped us determine that two different feature reports are the same feature. Locating a cave entrance frequently involves several survey shots from a point of good GPS reception to the entrance datum station.

Cave surveys are entered after each trip. The daily progress can be discussed over a 3D model in cave mapping software such as Survex or Compass. These files are then imported into ArcGIS for additional review.

Daily updates of cave surveys imported into the GIS allow team members to see how cave passages and hydrology relate

Figure 4: SRTM data-derived elevation contours laid over the Huautla 1:50,000 quadrangle topographic map (Mexico).

to surface features. A karst GIS provides information on which to base intelligent choices for additional surface and in-cave prospecting as well as dye injection and monitoring points. Updated maps can be printed as required.

By making daily updates to a master GIS in the field, a more organized and productive expedition results. In the past, much of this work was done after the trip when it was too late to benefit from and react to the insights.

5.3 Data compilation

Our cave and karst database is not as comprehensive as the one proposed by Gao et al. (2005) because our goals are more focused. However we strive to record as much information as possible without getting distracted from our main purpose of finding and surveying caves.

Our typical data layers or tables are:

Base – Roads, Trails, Villages, Points of Interest, Streams.

Cave – Cave entrances, Cave passages, Overland surveys.

Geology – Springs, Faults-Lineaments, Geologic observations, Dye vectors.

Some of the key components in a cave entrance record are:

ID_Number, Name, Description, x, y, z coordinates, GPS_Model, Reading_Accuracy, Date, Photo Report By, Exploration_Status.

5.4 Data presentation

The advent of virtual globes on the Internet has increased audience expectations for animated terrain models in mapping graphics. By having all the data in a GIS these tasks are easily completed. Endless possibilities ranging from posters and report illustrations to PowerPoint slides and virtual globe overlays are easily produced. ArcGIS 3D-Analyst animation tools are used to create video clips.

These tools have allowed us to give on-the-spot presentations during the expeditions as well as formal presentations to local officials at the end of an expedition.

6. Conclusions

SRTM data-derived terrain maps are an excellent substitute for standard topographic maps. The huge scale of the karst and lack of alternate map sources makes this approach particularly applicable in China and in any other frontier areas where map availability is limited. The SRTM data-derived maps have been found to be indispensable and have directly led to significant discoveries while facilitating numerous cave expeditions in rural areas of China.

Taking advantage of daily updates to a master GIS while in the field leads to a smoother, more organized and productive expedition. Using a GIS approach throughout the project makes it easier to write reports and put together presentations after the field phase of the expedition is over.

Acknowledgements

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THE IMPORTANCE OF GEOGRAPHY AND GIS IN UNDERGROUND RESCUE

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Abstract

Geography studies facts and phenomena and their relationship with humans. As this is a multidisciplinary science, geography employs information about the physical environment (climate, rocks, soil, vegetation, etc.) and the social environment (culture, population, economics, routes of transport, services, etc.) for analysis and to obtain relationships that are converted to maps. This application of technology in geography is relatively new in Mexico. The use of satellite images, orthophotos, GPS, vector charts and software have given new insighta 360º turn on the way geographical information is handled. This new management of information is employed in Geographical Information Systems (GIS). GIS) which are data bases that contain physical and social aspects, combined with geographical locations, which permit simple and complex problem solving. The final products of GIS are maps. The use and application of GIS in underground rescue work will permit a better understanding of the physical and social aspects surrounding the area where a rescue may have to be conducted. This makes it easier for rescue groups to see their options for best access routes to the rescue zone, know information about localities, political representatives, vertical and horizontal cave locations, cave characteristics, climate, vegetation, etc. Another important application of GIS is that accident probability models can be made for the residents living in karst areas, including the estimated time it takes to reach each cave in a specific area.

ORGANIZATION OF INTERNATIONAL CAVING CAMPS: THE HUMPLEU EXAMPLE

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Humpleu Cave is the second longest cave of Romania. Because most of the original data were lost, a remapping effort was initiated by Bogdan Onac. Originally started as a Romanian-Swiss collaboration, it grew over the years to an international camp that benefited from financial support from the Fédération spéléologique de l'Europe (FSE). Internationality has several advantages and disadvantages on different levels. For example, an advantage is that specialists (technical speleologists as well as scientists) that are sometimes hard to find in a small country are more easily found. The present paper discusses the advantages and disadvantages of large camps in general and of international camps specifically.

1. History

Humpleu Cave is a 40 km long cave in the Apuseni Mountains in Romania. After discovery of the cave, it was rapidly mapped by several competing clubs, which eventually resulted in at least partial loss of mapping data. In order to make it possible to conduct scientific research, a complete map has to be drawn. The main aim of the Humpleu project is therefore the remapping of this cave – an effort that will take years and a high amount of effort to be completed. It was initially thought that the Romanian-Swiss team, consisting of 4-8 people, would incite remapping and then slowly retire. It soon was realized that this goal could not be reached. So, to quicken the remapping process, people were sought. In the respective clubs of Switzerland

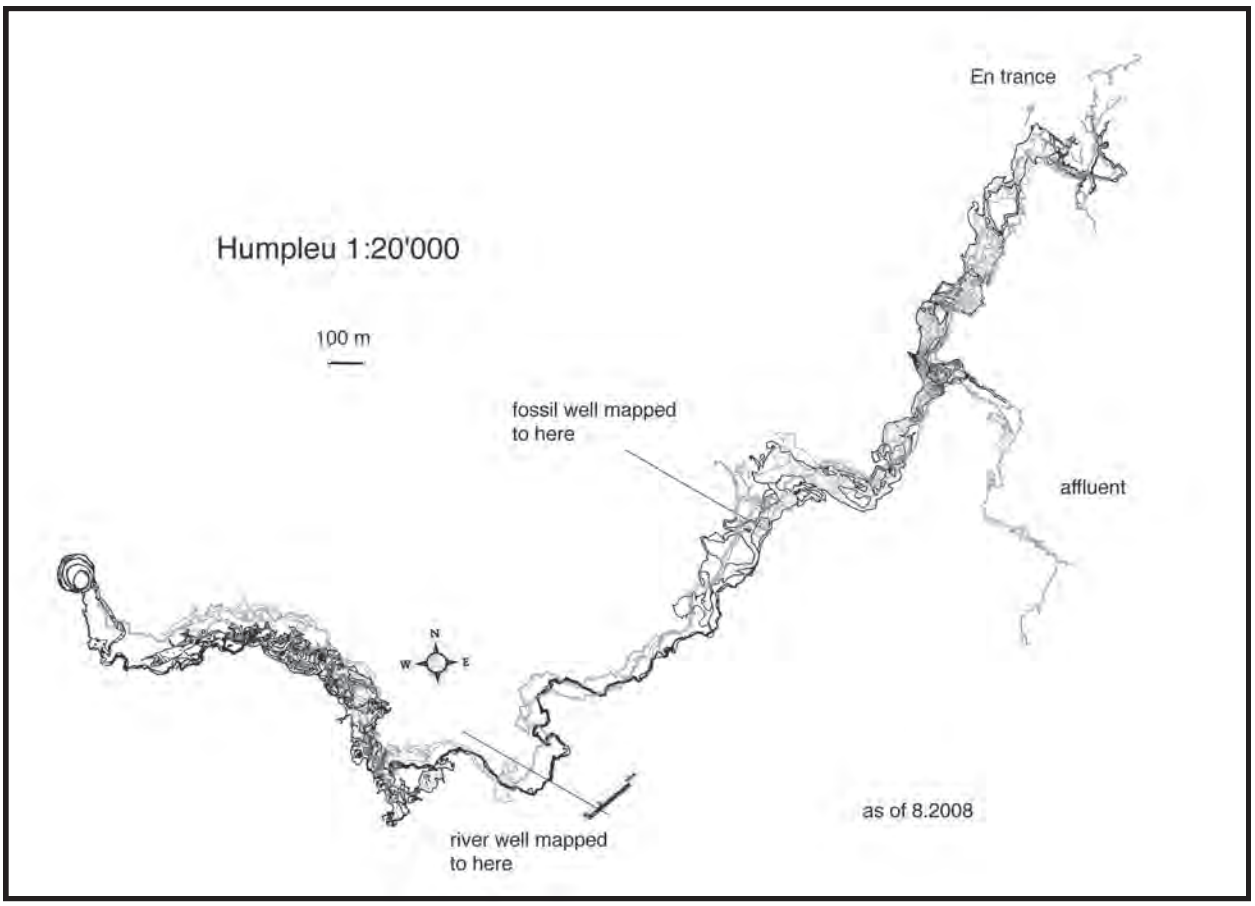

Figure 1: Humpleu Cave. The figure shows the old compiled map as well as the progress in remapping up to 2008. It is expected to remap the remaining parts within the next 5 to 10 years.

and Romania, there were not enough interested cavers, so fellow friends all over Europe were asked. The response was rather large, which lead to camps with 8 different nations participating (and partying), so that in the last two years, the camp was put under auspices and financial help of the Fédération spéléologique de l'Europe FSE. The large participation boosted the yield: While in the first year, about 2 km would be mapped (close to the entrance), the result of the international camps never went below 2.5 km per camp week (up to 3 hours of access) (Fig. 1). However, many people also can be the source of many problems, mostly of an organizational nature.

2. Organization of the Camp

To organize the camp, (Fig. 2), it was first asked the prospective participants when would be the best period in the summer. Then, the date is fixed and communicated to everyone, with the request to announce them as early as possible for planning purposes. Depending on the number and kind of participants (beginners, specialists, generalists etc.), groups with specific tasks was then formed, where the leader is defined, but the participants may change. This way, the leader has the advantage that they can plan their trips from the beginning, and the inconvenience that it is more difficult for them to change groups and objectives. Generally, however, they agreed and were happy. The "normal participants" are tentatively ordered into these groups according to distance from the entrance, task, experience, language (sometimes a quite interesting issue), and personal preferences. They may change groups more easily, most of them, however, chose to stay where they began to work. Group tasks may not only be mapping (horizontal/fossil/in water), but also diving, pole-climbing, geology, and photography. One "group" (consisting mostly of my wife) was the most important one: kitchen, food

Figure 2: The campsite is near the cave, in the spring area of the cave. Photo by B. Wielander (Austria).

organization, shopping (which included stopping at the local baker on their way), and cashing in the money from the participants. This logistics group also had the task not to leave the camp unattended, to prevent theft.

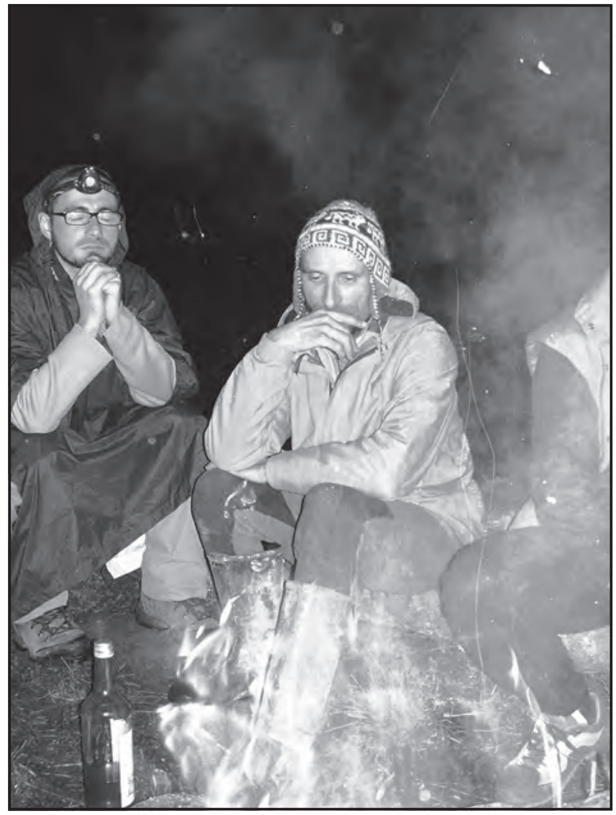

Figure 3: The camp works all day and.all night. Photo by I. Baron (Czech Republic).

3. Advantages of Large Camps

The best advantage of large camps is the availability of different people. Someone indisposed? No problem, they can be replaced. The climbing group needs more people to carry the pole and the drilling machine? We have some cavers for that. The mapping group in the fossil part has to contain six people in order to give sufficient light to the large rooms? No problem. One group wants to make a one-day surface excursion? Feel free, the camp will go on...

Besides the sheer number, the exchange of ideas, techniques, styles, devices is boosting the "art of caving". If the group leader has problems, the chance that one of the participants has an idea to solve it, is much greater in larger camps.

My personal experience is that the spirit of caving (and partying at the campfire, Fig. 3) was seen by all participants as just splendid. The aim to come together in large numbers to contribute to a large project is giving a sense of purpose that boosted energy and confidence in everyone.

4. Disadvantages of Large Camps

The main point is very clear: organization! To organize 30 people into 5-7 different groups with different tasks, some of them depending on good weather conditions (in the active part of the river), others on availability (the "diving" group does nothing if the diver is indisposed), and all this in a way that respects customs, schedules (not all participants arrive at the same day), and personal preferences, is at least tiresome.

This organization can be much less problematic if most of the participants and their desires are known. So, the young woman that just started caving is not put into the group with the mapper that is feared for long and tiresome trips. The caver that just had his leg broken (but insisted in participating) will rather accompany the geologist: lots of looking, less of walking. The guy speaking only Romanian is put with a group where at least another person understands him.

One potential very large obstacle of large camps is inefficiency: If all the camp waits for the last one to have finished his lamp or having repaired his suit, then departure inevitably is an hour before nightfall... One solution would be draconic rules: 7:00 wake, 9:30 sharp departure, or else the guy remains outside. I personally am convinced that this army-style does not work at all with cavers and that the Humpleu camp would not have had the success it had. The better solution consists of giving VERY far-reaching autonomy to the different groups. This leads to more work in organization, but maximizes efficiency. The principle is described below.

5. Functioning of the Groups

As initially said, the group leaders are predefined before the camp begins, and tentatively, some people are assigned to that group. In the first day, the leaders are briefed about the basic objectives for the day as well as for the week. Now depending on work, conditions, and personal preferences, the participants may wish to change group or to have a day off. So, every evening group leaders and participants talk to the camp organizer and tell their needs, the group is then reconstituted following the desires. Then, the group leader again takes responsibility, organizes all material and people according to the job, and in the morning, they leave when they see fit. Therefore, leave of groups can be anytime between 9:00 and 15:00, in complete autonomy. This way, one group does not block the other groups which do not have to wait.

6. Internationality

A large group can consist of only one nation, but in the case of caving camps, it is often international. Now, there are diverse advantages and disadvantages to that, which are basically independent from the points discussed above.

The largest advantage is that an international camp can use much manpower that may not necessarily be available in only one country. In our Humpleu example, it was quite hard to find enough (good) Swiss and Romanian cavers. By opening the camp to international participation, there is no problem to find sufficient people. Moreover, specialists from various disciplines can join, thus bringing expertise that can be very valuable. To reach this aim, the people should ideally be known by the camp organizer, however this is not compulsory.

Another large advantage is the cultural mix. This does not only mean the parties at the campfire, but also the different techniques used by cavers. While some of them may be rather nasty (mapping to the head of the partner instead of using fixed points, for example), the camp also presents opportunity to teach the "how-to-do", and thus it fulfils also a didactic aim that may be difficult to reach with other means. To ensure a happy camp, it also is a benefit that the camp organizer knows the people that may come. Incompatible characters can thus be incited to refrain. The Humpleu example has shown, interestingly enough, that people with divergent views (staunch nationalists of countries that dislike each other) became true friends: their thoughts were not compatible, but their (caving) mind was. I even would go so far as to say that international caving camps should be compulsory for politicians. They would still keep their view, but would have a better understanding for the other side.

While the language is usually not a large problem (most of the people speak English), the organization to ensure a smooth camp is. Internationality means that some people come by car, others by train, still others by plane (and have to be fetched at an airport). To organize such things is not a piece of cake – especially for camps like Humpleu, which are not exactly situated near the main road, and explanation of the path to follow is not very easy.

Experience has shown that it is a benefit to have international camps for large projects. However, there are some limitations to consider. The first and foremost is that you have to have enough work to do for the people coming! This means mapping, climbing, rigging, geology, photo sessions, so that every speleologist present can be of use. It is very frustrating for a, say, Portuguese caver to come to the other end of Europe to discover that... well, sorry, just now you cannot help, it is out of your reach...

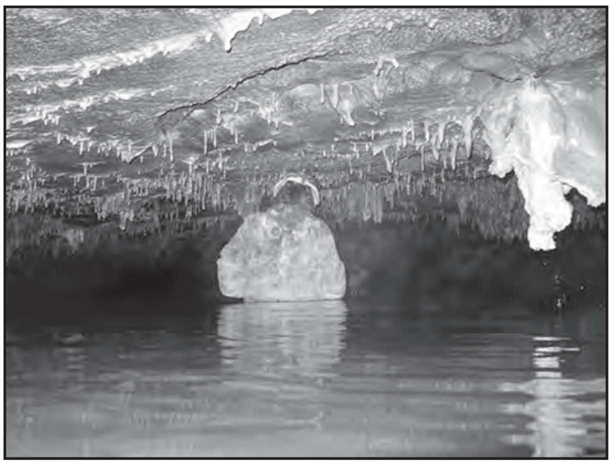

Figure 4: The active part of Humpleu cave is very beautiful, but may pose problems in floods. Photo by Ch. Verdet (France).

Projects where caves are inaccessible in bad weather need special consideration. In my eyes, a true and very important limitation is that people have to do something at all times, even when there are torrential rains. So far, Humpleu always had this possibility, because there was the fossil part to map, and there are still several climbs to be done. They were deliberately "left out" of the previous year when the weather was dry, to push the water parts (Fig. 4) and to leave the dry parts to the periods when the weather is less favorable. This also means that if 2009 will be wet, 2010 will not be a large international camp any more – the uncertainty would be too large to invite people from all over Europe.

To some extent, this is also valid for the mapped percentage. When the fossil part of Humpleu will be completed, the continuation will be after semi-sumps (so only able cavers can go there), and the rooms behind are of restricted access due to their beauty, so only small groups and again ABLE cavers are allowed. Probably, there will be only room for three to four groups (climbing from fossil and river, mapping fossil and river), and the camp has to be restricted to a maximum of 15-20 participants.

There is another possible limit to international camps. The organizer has to be able to cope with last minute changes, and he must not be easily irritable...

If all these conditions are fulfilled, success and a lot of pleasure is guaranteed. These lines should give some hints to prospective organizer of international caving camps about the important things and limitations. If questions persist, I would be happy to assist.

THE UISIC WORKGROUP "TOPOGRAPHY AND MAPPING" AND ITS ACTIVITIES

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The "Topography and mapping" workgroup is a part of the Informatics Commission of the International Union of Speleology. It deals with different aspects of mapping and drawing caves. Besides answering specific questions, the group also tackles some more consequent work. The standardization of the Cave mapping symbols and the Karst surface symbols were done in the last years. An article on sustainable mapping was produced and is currently being published in many different countries. Beginning with the 2009 Congress, the next topic will be a revision and possibly an extension of the BCRA grades. Interested people are welcome to join the discussion.

1. Re-Founding of the UISIC Workgroup "Topography and Mapping"

In the 1960s to 1970s, an UIS commission on mapping already existed. Among others, it dealt with mapping symbols and their unification (Fabre et al., 1978). In the following years, however, the commission ceased its activity and apparently was dissolved later.

However, progress in mapping caves did not stop. In a mapping workshop at the 1991 Swiss Congress of Speleology, the common consensus of the mappers was to revise the symbol set. At the next congress in 1995, a proposition of such a set was presented and subsequently discussed. To make it widely acknowledged, the discussion continued in the 1997 International Congress of Speleology in La Chaux-de-Fonds, where the present workgroup (now under the UIS Informatics commission) was reestablished.

The workgroup consists of a chairman and national delegates. These delegates are not necessarily the official UIS delegates. For matters of general interest, every caver is cordially invited to participate, to propose and to debate. However, in order to maintain equilibrium, voting on the discussed topics is restricted to the delegates. The current list of delegates is appended. For countries or cavers that are not on the list, but want to be, please contact the chairman. Countries or cavers, who feel that their country is not properly represented, please refer to your national federation or directly to the delegate in question. Delegates do not need to be officially endorsed by their federation; but in case of problems, the decision of the federation is binding.

2. Past Projects of the Workgroup

As already mentioned, the first topic of the workgroup was the examination and partial re-adaptation of the cave symbol list. This work was accepted by vote in 1999. Since then, the symbol list is official. It can be found at http://www.carto.net/neumann/caving/cave-symbols/.

Several volunteers worked to have their country language included. If you would like to participate, you are welcome to contact the chairman or the website manager A. Neumann.

During the work on cave symbols, it was found that the geomorphologic symbols used for karst landscapes often differ dramatically not only from country to country, but even among different universities of the same country. Therefore, the next topic undertaken was the revision of the existing symbols for geomorphology of karst landscapes. Because that topic does not specifically touch cavers, but mainly geographers (and geologists as well as hydrogeologists), this work was done in collaboration with different universities as well as with the International Geographical Union IGU and the International Association of Hydrogeologists IAH. The complete symbol set was published in Häuselmann (2006), and has since then also officially approved. The respective weblist is found at http://www.sghbern.ch/surfaceSymbols/symbol1.html.

An article on "sustainable mapping", originally presented at the Slovenian Karst school in 2006, was written and reviewed by the national delegates and other mapping cavers. The article already was published in several journals. However, the long-term aim is to have it published in every national caving journal (in the respective language of the country), in order to inform all possible cavers as to why it is important to map correctly, and what has to be done to produce a correct map. With this article, the workgroup engages in education and formation of cavers. In the future, maps and communications presented at congresses will be judged according to their completeness.

During 2008, some delegates wanted a revision of the cave symbol set. After a long period of discussion and pondering, the majority of the delegates decided to keep the list as it is for the now.

3. Present and Future Projects

Several cavers wished that UIS have a look on the widely known BCRA grades. In some countries, they are used as being "UIS grades" without having been published as such. The 2009 congress now should bring together interested persons in order to begin discussion on that topic. The principal matters of concern are the following: First of all, it was felt strange that a grading system is made, but the explaining text mentions that half of the grades should basically not be used. Then, while the grades express precision in measurement, they do not pronounce about the drawing (and drawing quality).

All interested cavers (and especially BCRA members) are cordially invited to attend the workshop which should be held on Saturday, 25. July 2009.

There is no planning for future projects so far. People interested in topics that should be dealt with are invited to communicate their wish to the chairman.

4. National Delegates (as of 1.2009)

Chairman	Haeuselmann Philipp	praezis@speleo.ch
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USA	Pat Kambesis	pat.kambesis@wku.edu

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MAKING A DIGITAL MAP OF WIND CAVE, WIND CAVE NATIONAL PARK, SOUTH DAKOTA

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Completing a digital color map of the 209 km long Wind Cave was the culmination of a ten-year cartographic project. To our knowledge, this is the longest and most complex cave in the world that has been drawn as a single large-scale colorized digital map. Color was used to show multiple three-dimensional levels on a two-dimensional surface. This process began in 1999, when a digital template for a Wind Cave quadrangle was created in Adobe Illustrator® and printed on Mylar at a scale of 6.09 m/cm. In plan view, each quadrangle covers 457.2 m by 304.8 m of the cave. Each of the 17 quadrangles was then divided into three layers: the upper, middle, and lower layers. Each quadrangle contains an index location map, a legend, and a cartographic history of that quad. Once all of the backlog cave surveys (72 km of survey data) had been drawn by pencil, and added to the 38 new Mylar quadrangle maps, these maps were scanned as single JPEG images. A master quadrangle template was then created in Adobe Illustrator® that was divided into an upper, middle, and lower layer. Each layer was further subdivided into individual cartographic elements (walls, ceiling heights, place names, etc.). Individual scans were then placed into their own layer and turned to 50% transparency, where they were used to trace or place each cartographic element onto its assigned layer. Finally, each of the three major layers was assigned a color (reddish brown for lower, tan for middle, and light green for the upper layer). Once all three layers were completed, all layers were made visible and the interior detail and text were adjusted so that most elements were not covered by an overlying passage. When the 17 master quadrangles were completed, each master quad was stitched to the adjoining quad beginning in the southwest corner of the cave. This resulted in a single 3 x 3.6 m digital colorized map of Wind Cave that can now be used for displays, management, or research.

1. Background

The current digital map project would not have been possible without the efforts of numerous Wind Cave cartographers that drew various versions of quadrangle maps and paved the way for our seven-year project. Wind Cave quadrangle work began in 1959 (Horrocks, 2007), when John L. Haas drew four quadrangle sheets showing 4.82 km (3 miles) of survey from the 1959 NSS Wind Cave Expedition. These maps were drawn at a scale of 3.6 m/cm (30 ft/inch) and covered 309.35 m x 192 m (1,015 x 630-foot) sections of the cave. These maps were drafted with ink and Leroy lettering onto linen. In 1962, Herb Conn was contracted to draw a map at 6.09 m/cm (50 ft/inch) of the tour routes and associated off-trail passages. Conn drew that map oriented so that the main NW/SE passage trend was oriented vertically, with NW upward. This map covered a 571.47 m x 368.8 m (1,875 x 1,210 foot) section of the cave and contained about 4.34 km (2.7 miles) of survey. In 1974, Herb Conn was contracted to draft all of the surveys completed up to that date. He drew 14 cave quadrangle maps at 6.09 m/cm (50 ft/inch). These maps covered 510.51 m x 320.02 m (1,675 x 1,050 foot) sections of the cave and contained about 30.58 km (19 miles) of passages. These maps were drafted with ink on Mylar with Leroy lettering.

In 1975 John Scheltens steered away from the quadrangle approach by drafting all of the known survey onto three large 2 m x 1 m (6 ft x 3 ft) maps, at a scale of 6.09 m/cm (50 ft/inch). He rotated his maps so that north was oriented upwards. These maps originally contained 32.83 km (20.4 miles) of survey and were updated yearly until 63.66 km (39.56 miles) were included by 1984. In 1984, Warren Netherton divided Scheltens map into 18 numbered quadrangles at 6.09 m/cm (50 ft/inch). He then traced Scheltens maps with ink and Leroy lettering onto 0.56 m x 0.91 m (22 in x 36 in) Mylar sheets. Each quadrangle covered 548.61 m x 335.26 m (1,800 x 1,100 foot) sections of the cave that could be subdivided into quarter sections to make photocopying individual sections easier. These quadrangles included about 63.66 km (39.56 miles) of survey. Between 1993 and 1995, Stan Allison, with the help of Colorado Grotto volunteers Doug Kent, Paul Burger, and Jim Wilson, redrew all 18 Wind Cave quadrangles sheets. These working maps were drawn in pencil on large pieces of plotter paper at a scale of 6.09 m/cm (50 ft/inch) and covered 457.18 m x 304.78 m (1,500 x 1,000 foot) sections of the cave, which established the current quadrangle dimensions and naming scheme. Three new quadrangles were also added to the original 18. These 21 quads contained approximately 125.52 km (78 miles) of survey. After many years of failure to update these quadrangles and due to various cartographic problems with those quadrangles, it was determined that new quadrangles would have to be drafted. It was recognized that the easiest way to manage the large volumes of data on the Wind Cave map would be to digitize the quadrangles. However, after analyzing software technology available in 2003, it was determined that it was not quite at the level required to make a digital map of such a large and complex cave.

One of the glaring deficiencies was that any computer drawing software used needed to include a transparency feature to be able to show multiple overlying colorized cave levels for such a complex cave, a feature that was not available at that time in the drawing packages that were evaluated. After deciding it would be necessary to hand draw the maps on Mylar, a decision was made to use Adobe Illustrator®, hereafter referred to as Illustrator®, to design a template that could be preprinted onto Mylar sheets. This new template standardized the quadrangles and included a border, legend, index map, and cartographic history. Because detail was necessary for all passages on each cave level, it was decided that each quadrangle would have to be divided into multiple quadrangles, roughly following the three natural stratigraphic levels found in the cave. Because our divisions did not follow those levels exactly, we named our individual quadrangles the Lower, Middle, and Upper Layers (instead of levels). The nine most complex quadrangles were divided into two or three layers each, which increased the total number of quadrangles from 21 to 37. Between 2003 and 2007, Rod Horrocks, Marc Ohms, Jason Walz, Steve Lester, Evan Anderson, Matt Reece, and Bonnie Curnock redrafted 125.53 km (78 miles) of survey onto 37 Mylar quadrangles while adding an additional 69.20 km (43 miles) of backlogged survey, bringing the total to 194.72 km (121 miles) drawn. These quadrangles were hand drawn with pencil on 0.51 m x 0.76 m (20 x 30 inch) Mylar sheets preprinted with the new template. These Mylar quadrangles were then photocopied for use in the Wind Cave survey project. However, it was soon realized that it was difficult to erase passages on these Mylar maps when a new survey was added or when a closed loop readjusted the cave. Because of the recent availability of a transparency feature in Adobe Illustrator®, it was decided in late 2007 that it was time to digitize the Wind Cave map. The International Congress of Speleology (ICS) being held in the U.S. and the outdated poster map of Wind Cave that was being sold in our bookstore, which only showed 122.31 km (76 miles) of surveyed passages, added additional motivation for this digitization project. Between Horrocks and Volunteer caver, David Lambert, nine of the 37 quadrangles were digitized that year based on a preliminary digital template developed by Lambert. At the same time, Jason Walz added 610m (2000 feet) of new survey to those digitized quadrangles.

2. Development of a Digital Mater Quadrangle Template

In late 2008, Illustrator® was used to update Lambert's template, creating a Master Quadrangle Template that incorporated all elements of the Wind Cave quadrangles into a single, cohesive file. This digital Master Quadrangle Template was designed to help a user visualize all of the levels of Wind Cave at the same time, or individually, depending on the needs of the user.

The digital Master Quadrangle Template was divided into multiple layers and sub-layers for organization and ease of use. By grouping like elements into a specific layer, the entire layer could be selected at any time and universally changed with ease. The primary layers were separated into the following categories: Cartographic Elements, Upper Layer, Middle Layer, Lower Layer, Cross-Sections / Profiles, and Scans. Under Cartographic Elements, various items such as the north arrow, legend, and title were placed into sub-layers. Each of the Upper, Middle, and Lower primary layers were also further divided into sub-layers: walls, place names, ceiling heights, survey stations, station labels, unsurveyed leads, color, and interior detail, which includes such features as breakdown, ledges and other floor detail. Due to the fact that each Wind Cave Master Quadrangle now has the potential to have an upper, middle, and lower level, the original 21 quadrangles could remain combined or potentially be divided into 63 separate quadrangles.

The scanned versions of the original quads were then placed in the digital Master Quadrangle Template and turned to 50% transparency. The digitization process was accomplished by tracing the lines of these scans in Illustrator® at a 6.09 m/cm (50 ft/inch) scale. To speed up the process, a symbol library was created for many of the standard cave cartographic symbols. When digitization was completed, the original scan was turned off, producing an exact digital duplicate of the original scanned hand-drawn quadrangle.

In order to simplify the visualization of all three layers at once, color, transparencies, and gradients were added to each primary layer (upper, middle and lower). A color was chosen for each layer, including: Reddish-brown for the lower layer, tan for the middle, and light gray for the upper passages. Each color was also assigned a transparency of 70%, allowing underlying passages to be visible. In order to create a seamless transition between passage levels, a gradient that merged one color to another was created wherever one level changed to another. This gradient maintained the transparency between levels, and effectively blended two colors together for a more visually appealing look. It also reflected the reality in the cave, as passages tend to transition from one level to the next gradually, not abruptly, except at pits. Once each layer was completed for a quadrangle, all the layers were turned on at once and everything was unlocked so that any lettering that appeared within a passage on another layer, could be moved to a point where it would not conflict.

Due to passage complexity, or lack of complexity in some areas of the cave, the division of passage levels was not automatically applied to all 21 quadrangles. Because these separations were created in some quadrangles and not in others, great care was taken during the digitization process in placing levels under their proper stratigraphic layer in Illustrator®. Since all three layers do not exist on every quadrangle, only 47 separate quadrangles out of the potential 63 have been used in the creation of the digital Master Map.

3. Creation of a Digital Master Map

After all the digital Master Quadrangles had been completed, a new, separate digital Master Map file was created to allow stitching of the 47 finished quadrangles into one, large map at a 6.09 m/cm (50 ft/inch) scale. Each completed Master Quadrangle was transferred to this digital Master Map file by copying and pasting each layer or sub-layer from its corresponding layer into the digital Master Map.

Once all the layers were transferred, each quadrangle was aligned with its adjoining quadrangle using the quadrangle border as a guideline. After each quadrangle was placed in its proper location, the features of each quadrangle were stitched to the adjacent quadrangle to produce a single, seamless map of the entire cave. After stitching, the quadrangle borders were copied to a separate layer and turned off to produce the finished map.

4. Map Updating Procedures

One of the primary motivations for creating a digital map of Wind Cave was to make it easier to add new cave surveys to the existing quadrangles. This process involves going into the cave data processing software that we use to manage our survey data, COMPASS, and creating a metafile of a closed version of the lineplot. This lineplot is then placed under the "Scans" primary layer in the digital Master Quadrangle Template in Illustrator®, where it becomes a base that can be used to align survey stations found on the sketch. The survey sketch scan is then placed on top of the metafile in its own layer and is rotated until the stations are aligned between the two. This layer is then locked and the walls, and each type of feature, are digitized separately into their respective layers. In the future, the stations on the digital sketch will be tied to the lineplot produced from a cave data processing program. This will be accomplished by exporting a file from Illustrator® through a separate program where it is adjusted and then reimported back into Illustrator. This will be accomplished on a quad by quad basis, due to the large size of the map file. By using this round tripping technique, the walls, but not the features within the passages will be adjusted as the loop closure distributes error throughout a loop and adjusts the stations (Allison, 2007). This will allow us to keep the individual quadrangles up to date. However, creating a new digital map of the whole cave will require that each of the 21 adjusted quadrangles will have to be periodically restitched together into one composite master map.

4. Conclusions

Large caves such as Wind Cave typically are depicted as separated quadrangles in order to maintain a scale large enough to be useful and to avoid printing problems and difficulty visualizing the whole cave. However, technology has progressed to a point where much of the complexity, while not completely eliminated, can be "organized" into readable layers that make it easier for users to interface with. It was found that using color and transparencies was one of the most useful methods in visually simplifying a complex cave with multiple cave levels. A black and white map of Wind Cave, where all of the layers are combined, is impossibly complex, while the colorized map that uses transparences is easily readable.

Unique to this map is the depiction of 195.52 km (121.5 miles) of cave passage in an interactive digital map; as whole cave layers can be turned on or off, as can any combination of floor detail or color, depending on the needs of the user. One can see the entire cave and all associated detail at once, or turn off a combination of layers to make things more simplistic and easier to see.

While Technology has advanced to the point that such a digital map is feasible, there are certainly pitfalls and problem areas that still need to be dealt with. One of the largest issues encountered during this project was the problem of loop closures. Wind Cave contains over 1,700 loops, some of which are historic surveys with significant loop closure problems. As a problem loop is corrected, the entire cave shifts, altering each quadrangle, if only slightly. The result is a constantly shifting and changing map. We anticipate being able to resolve these issues on a quad-by-quad basis, using a round tripping method; however, that will be a future phase in this on-going project.

As Wind Cave continues to develop as one of the world's longest and most complex caves, the visualization techniques will need to be changed to accommodate for the increased complexity. In the future, we will likely have to divide each quadrangle into five layers to match the actual number found in the cave, instead of the three currently used. Additionally, more quads will have to be added as surveyed passages continue to expand beyond the current known boundaries of the cave.

Despite the potential problems that may be encountered as the Wind Cave digital map continues to develop, the benefits of digitizing far exceed the problems: explorers now have an accurate, interactive map they can be used to visualize the whole cave, new surveys can be added to the digital quadrangles easily, and interpretive exhibits and displays can be kept up-to-date or changed as needed utilizing this interactive digital technology.

Acknowledgements

The current Wind Cave digital wall map, which contains 195.52 km (121.5 miles) of survey, was made possible by the preliminary work of over 1,000 cave surveyors and numerous cartographers between 1959 and 2006. Dave Lambert not only designed a draft digital Cave Quadrangle Template for the park, but he designed several symbols for our digital symbol library, and then helped digitize several of the quadrangles. Finally, Jason Walz drew 610 m of new cave survey onto the newly digitized quadrangles.

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THE SIERRA NEGRA IN A PDA: EXPEDITION-WIDE ELECTRONIC CAVE SURVEYING

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In 2007, Mexpé, the Société Québécoise de Spéléologie's annual expedition to Mexico's Sierra Negra, celebrated the project's 20th anniversary with exploration results beyond expectations: over 10 km of new passages were discovered and mapped in less than a month. This feat also consecrated the definitive adoption of the Auriga cave survey freeware by the exploration teams for the underground input of survey data. Running on almost any PalmOS PDA, Auriga has since become part of our survey toolbox with the help of classic pocket-sized binders now fitted with a waterproof write-through pouch. The display features provided by the software help in avoiding survey blunders, locating the cause of closure errors, and sketching walls or passage features to scale. With all previous survey data of neighboring caves readily available in the PDA while surveying a new cave or passage, surveyors can see in real time their progress in relation to the rest of the known underground terrain and often anticipate connections. This data availability of the 6000+ survey shots composing the 40+ known caves of the Mexpé area becomes extremely convenient when searching for an old permanent station to connect with a newly discovered passage. Auriga is undergoing a rapid evolution, and the Mexpé test case presents some challenging survey situations that have helped bring about several field-use features like full GPS support, tools for resolving conflicting station names between teams or fixing input errors in bulk, and improved data handling capabilities (IR beaming, memory card securing, and export/merge of cave subsets). Carrying a computer in the cave even inspired features unrelated to surveying, such as a pit sounder where Auriga uses the PDA as a stopwatch to achieve quasi-metric depth precision by timing the fall of a rock. In 2009, the survey process will go electronic all the way, thanks to Bluetooth-connected measuring devices and the on-screen sketching of cave walls and features. Currently in use in several countries, Auriga is freeware, available online in three languages (French, English and Spanish), and comes with a comprehensive user manual, online help, and extensive support (*www.speleo.qc.ca/Auriga*).

En 2007, Mexpé, l'expédition annuelle de la Société québécoise de spéléologie dans la Sierra Negra mexicaine a célébré son 20e anniversaire avec des résultats au-delà des attentes: plus de 10 km de nouvelles galeries ont été découvertes et topographiées en moins d'un mois. Cet accomplissement consacre également l'adoption définitive du gratuiciel Auriga pour la saisie souterraine des données topo. Tournant sur à peu près n'importe quel PDA sous Palm OS, Auriga fait depuis partie de la boîte à outils des topographes, les PDA étant manipulés à travers un étui imperméable installé dans les carnets. Les affichages offerts par le logiciel aident à éviter les erreurs topographiques, à localiser les erreurs de fermeture et à dessiner les parois à l'échelle. Disposant des données antérieures des grottes voisines dans leur PDA pendant la topographie de nouveaux passages, les topographes peuvent constater en temps réel leur progression vers les parties souterraines connues et ainsi anticiper les jonctions. Cette disponibilité des quelques 6000 visées composant la quarantaine de grottes de la zone Mexpé s'avère extrêmement commode lorsqu'il s'agit de trouver une ancienne station permanente pour jonctionner un nouveau passage. Auriga jouit d'une évolution rapide, et le banc d'essai de Mexpé et ses nombreux défis ont permis l'aboutissement de fonctionnalités de terrain telles que le support complet du GPS, des outils pour résoudre les noms de station conflictuels ou corriger globalement des erreurs de saisie et la gestion améliorée des données (transmission IR, sauvegarde sur carte mémoire, et exportation/fusion de sous-ensembles de grottes). Le fait de disposer d'un ordinateur sous terre a même inspiré des fonctionnalités éloignées de la topographie, telle un sondeur de puits où Auriga utilise le PDA pour chronométrer la chute d'une pierre et ainsi déterminer la profondeur d'un puits avec une précision quasi métrique.

En 2009, le processus topo sera entièrement électronique grâce à des instruments de mesure reliés via Bluetooth. Déjà en usage dans de nombreux pays, Auriga est offert en ligne gratuitement (www.speleo.qc.ca/Auriga) en trois langues (français, anglais et espagnol), accompagné d'un manuel complet, d'aide incorporée et d'un support soutenu.

1. Introduction

Through the Mexpé project, members of the Société québécoise de spéléologie (SQS) have been discovering and exploring caves in Mexico's Sierra Negra (Puebla) since 1987. Expeditions are held on a quasi-annual basis, with a base camp initially set just outside the village of Tepepa, and moved in recent years, to Hoya Grande, a huge sinkhole two hours away from Tepepa by mule.

Caves are discovered at a fast pace, and simultaneously explored and surveyed, using common measuring tools (tape, compass and clinometer) and small (14x19 cm) survey binders filled with waterproof paper. In order to avoid the post-expedition laziness, much final map drawing is done at camp on millimetric paper. From the early years, our most modern tool had been a HP programmable calculator used to compute Cartesian coordinates from the survey data, one cave leg at a time. The program was not sophisticated, data entry was tedious, let alone corrections, but we did not know of a better alternative.

2. Turning point

Things started to change in 2002, when a participant decided to bring an old laptop computer, something we had resisted until then for fear of moisture, and to reduce the amount of luggage. With it, we could run Visual Topo, a Windows-based cave survey software able to perform all required computations, as well as loop closure. However, due to the short life of our exhausted laptop battery, its use was deceptively limited. At that time, the village of Tepepa did not have electricity, and recharging the battery required to bring it the next village.

PalmOS PDAs, that could operate for two weeks on a pair of AAA batteries, and which some of us already owned, were another prospect we considered for processing our cave survey data. DocsToGo, an Excel-compatible office suite, could run a homemade spreadsheet and display cave coordinates, much like our earlier programmable calculator, but with a gain in user-friendliness. However, the most promising path for change was open just days before leaving, when a post sent to various online caving forums to find a caving-specific handheld solution received a positive answer. Martin Melzer, micro-electronics designer, had developed Auriga. This PalmOS software helped him to test his prototype electronic compass-clinometer box over a serial (wired) link. The project was now dormant, but he sent me an executable and two sample caves. One night, during the expedition, using Auriga to input into a basic Palm m100 PDA the data of a cave we had surveyed the same day, I realized that such a simple PDA had the capability to perform all the required trigonometric computations and to display a much usable graphic rendition of the line plot.

3. Resuming theAuriga project

From that moment on, the objective of finding a simple cave calculator evolved towards the development of full-blown, yet handheld-based cave survey software that we could bring underground to enjoy the benefits of computer-aided surveying right from the start. Mexpé would be used as a large-scale testbed. In May 2002, I resumed the Auriga project, starting from Martin Melzer's original C code.

The data input interface, sometimes neglected by PC cave survey software, was first overhauled and adapted to underground use: working with a small touchscreen, sometimes in miserable conditions, required a quick and efficient interface, with as much immediate validation as possible (Fig. 1). An input window, handling a single shot at a time, was preferred over the usual spreadsheet-like input method found everywhere else. This window could display all fields at once, without requiring scrolling, and left ample room to write comments, a good practice in every respect. While data is usually written in a PDA by tracing simplified letters with a stylus, a large custom calculator-like keypad was implemented to quickly input data and navigates between fields, even with gloves on, and through a protective pouch (Fig. 2).

Auriga's original version only supported foresights, measured in meters and grads (400 grads = 360°) by invariant instruments, and featured no customization whatsoever. The concept of session was implemented, associating a group of survey shots to a given instruments set, measurement units and interface options. Combined with support for backsights, survey shot direction and various attributes (entrance, surface, lead, etc.); we now had a suitable electronic replacement for our survey notebook.

For Mexpé 2003, we purchased a solar panel to recharge

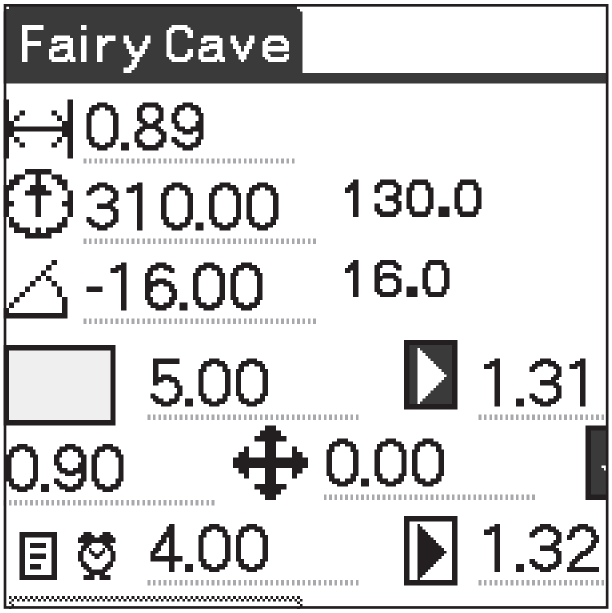

Figure 1: The Survey Shot input window.

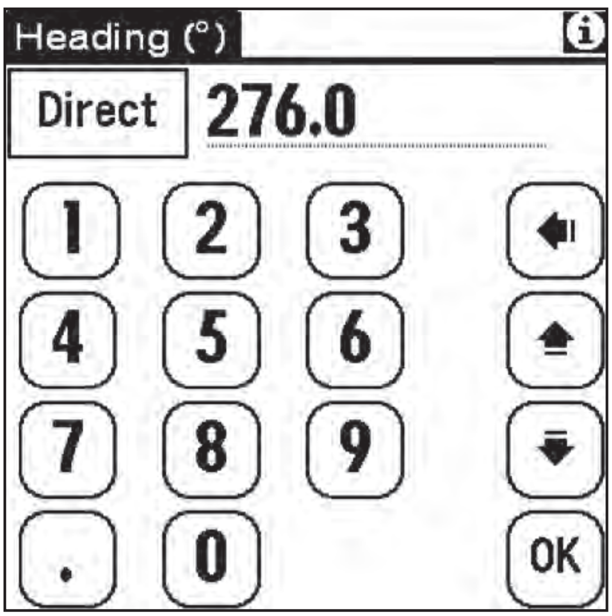

Figure 2: The Auriga keypad.

a few gel-acid batteries used to power the laptop. Eight hours of sunlight gave us at most 1.5 hours of laptop use, after which it would simply turn itself off without warning, its internal battery too weak to sustain it. Although Auriga was not yet stable enough for underground use, it allowed us to save on the slow and power-consuming step of data input: back at camp, exploration teams used a Palm IIIxe mounted on a foldable keyboard (Fig. 3) to transcribe the data from their paper notebook into Auriga. Christian Chénier's "conduit" - PalmOS standard Palm-PC transfer solution - was then used to convert and download the data between Auriga and the PC, in Visual Topo or Compass format. Once computed, the resulting coordinates displayed by PC software could be plotted on paper... unless the batteries died on us prematurely. While Auriga could already compute and draw caves on screen, we still needed the PC to actually display the coordinates in list form for plotting. Moreover, Auriga being based on the rather restrictive Toporobot rules, most notably that of sequentially numbering survey stations as exploration goes, it sometimes stumbled on our caves that mixed legs mapped from the entrance, with others from the end. After lengthy discussions during and after the expedition, a new approach of computing survey shots by scanning them in alternating directions was successfully implemented, thus reducing any software constraint on the survey method.

Figure 3: A Palm PDA mounted on a foldable keyboard. Unknown photographer.

Considering the amount of work invested in Auriga to turn it into flexible software that could adapt to everybody's instruments and work methods, it seemed absurd to limit its use to the sole Mexpé team. Therefore, in December 2003, the first public beta version of Auriga was released at no cost, in both French and English. A Spanish version was added a year later, thanks to Juan Marcos Gomez's initial translation, which I now maintain, reviewed by a few users. To adapt to the multinational aspect of our teams, language switching could be done on the fly, with no re-installation required, a feature unseen before in the PalmOS world.

Mexpé 2004 was cancelled at the last minute due to a speleo-diplomatic incident that hampered caving in Mexico for some time. As for Mexpé 2005, it was a small-scale expedition, mostly aimed at prospecting new areas, where little surveying was done. In the meantime, Auriga kept evolving, both in features and reliability.

With several teams exploring contiguous zones, sometimes leading to connections, data sharing would soon become another priority: all PDAs would have to be updated on a daily basis with the most recent survey data. Building on the PDAs' built-in infrared hardware, selective beaming was added to Auriga, where each team could send, in seconds, its latest survey data to others, with the software neatly merging survey shots and reporting duplicate station names, if any. Compared to a paper survey notebook, this was superior to a backup photocopy.

4. Auriga Goes Underground

It is during Mexpé 2006 that Auriga came back in full force in the Sierra Negra. With an investment firm giving us over 50 Palm PDAs deemed obsolete for their business needs, we could fit every participant of our first Computer-Aided Surveying class, and every field exploration team. Survey binders were fitted with a waterproof pouch to store the PDA and input numeric data on one side, while sketching the cave walls and details on the other side in a classic fashion, using waterproof sheets (Fig. 4). While it had been customary to take GPS coordinates at cave entrances, Auriga made things easier by accounting for surface legs we had to survey between the deep foliage cover of entrance areas and a distant unobstructed sky view. Georeferencing entrances gained in interest, as we could now see our cave passages in relation to surface features such as sinkholes, and other caves, thanks to a "network" view of neighboring caves, each properly geolocated. This once coaxed a team to cross a rather uninviting muddy crawlway which resulted in a connection with another cave, Auriga displaying in real time the progress towards that connection from the base of a pit several hundreds of meters before. And with the survey data of this neighboring cave readily available in the PDA, a permanent station to connect with was quickly located. This ability to anticipate connections had been sadly missing in previous years, when teams exited a cave after a long day of exploration, only to find out the next day they had stopped a hundred meters short of the expected connection, something Auriga could have helped prevent.

Back at camp, survey data was transmitted at once to the

Figure 4: The Auriga binder in action. Photo by Guillaume Pelletier.

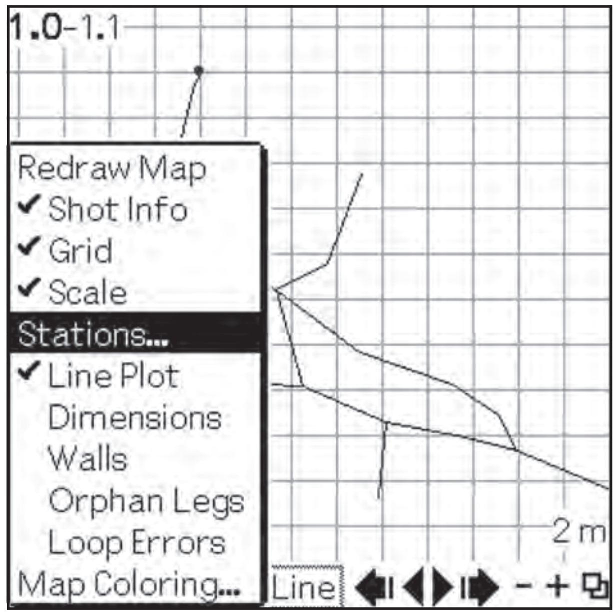

Figure 5: The Map display.

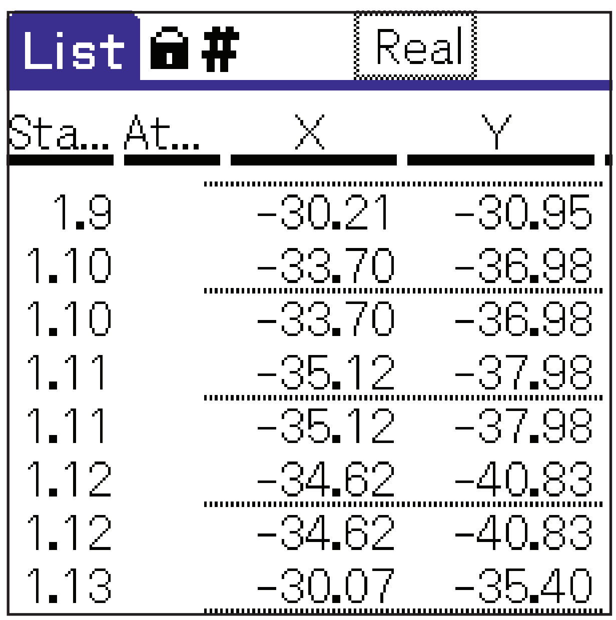

Figure 6: The List display.

"Camp" PDA using the devices' built-in infrared link. This PDA never left camp and served as a safety repository for all survey data. While the final Illustrator drawing was only done once back home, notebook sketches were first assembled in camp on millimetric paper with the line plot Auriga provided (Fig. 5) Thanks to Auriga's new List display of computed station coordinates, we could now do away with the PC (Fig. 6).

Now that survey data was wholly handled on the PDA, a maintenance feature was added to allow editing station names in bulk before merging caves after connections, thus avoiding conflicts. And for added safety, SD card support was implemented, even though no survey data was ever lost due to using Auriga or the PDA

5. An Enhanced Toolbox

By Mexpé 2007, no one would ever question the relevance of using Auriga, and its impact on the quality of our survey work. All the survey data from previous expeditions was imported in Auriga format into the "Camp" PDA, now a Tungsten T3, with enough memory and processor power to compute and simultaneously display all known caves of the Sierra Negra. Each time a survey team went to work on a new found cave, they would load their field PDA with the neighboring caves in case they connected. Mexpé 2007 turned out to be an exploration and electronic survey success with 10 km of new passages, half of it surveyed with Auriga underground, the other half entered at camp by notebook data transcription when surveyors were not familiar enough with the software. Underground users much appreciated the various passage sketching help such as the Sketch to Scale feature reporting station locations in paper grid coordinates, a cross-section view and especially the continuous display of the horizontally projected length of survey shots. Exploring vertical caves, the extended profile view was also most useful. Thanks to the display of the cave line plot in real-time, we could detect survey errors as they occurred, and orient our explorations towards the most promising areas. Lastly, the implementation of geodesic conversions (latitude/longitude⇔UTM) allowed connecting a GPS to the Palm to automatically input the location of surface features or to follow on the surface the current position relative to known cave passages mapped underneath.

Nowadays, as Auriga is used to map even larger and more complex cave systems such as Lechuguilla and its 30,000 survey shots, several options have been implemented for searching survey shots and selectively handling or displaying a map subset for easier navigation despite a small PDA screen. Coloring by depth is also much useful in 3D mazes or wherever passages at different levels intersect in plan view.

In 2009, teams now enjoy full loop handling, starting with their automatic detection as they occur, along with the display of their relative closure error, the ability to specifically zoom on them in the map, all the way to the global, yet selective closure process, where loop closure errors are spread over the entire loop path. With minimal CPU and memory requirements, this operation can be performed on even the most basic PDA. Auriga being a field tool, blunder detection tools are now being designed to help surveyors find erroneous survey shots while still in the cave.

Once back home, survey data is transferred to the PC in minutes, currently to the Compass, Visual Topo, GH Topo or Toporobot, and soon Walls formats.

6. Conclusion

Such advances on the software side are now matched by novelties on the hardware side of data measurement, with the development of survey instruments connected over a wired serial link or a wireless Bluetooth link. Auriga now supports the Disto A6 laser distance meter, the combined compass-clinometer SAP and 3-in-1 devices like the TruPulse and more notably the Disto X, thus going full circle with the initial development started 10 years earlier.

With over 70 km of surveyed passage in some 40 caves, and new connections occurring every year, the Sierra Negra area explored by the Mexpé project has represented a formidable real-life field test. This close link between Mexpé and Auriga development has been beneficial to both projects.

A METHOD FOR DETECTING CAVE CONNECTIONS BY INDUCED AIR FLOW

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Cavers have used many different techniques in trying to discover where and how to tie smaller caves together into a cave system. These include, but are not limited to: exploration, mapping, stream dye tracing, digging, and air tracing. The admonition "follow the air" is always good advice to explorers but often this proves to be impossible because of passage size or lack of strong air flow. Air scent tracers such as ethanethiol and smoke tracers like white phosphorus have been used with very limited success. This paper discusses a promising (and less polluting) new technique using mechanical methods of generating air flow and micro meteorological instruments to measure the results.

The authors demonstrate that mechanically changing the airflow at one entrance will rapidly affect the rate of airflow at other entrances as measured by sensitive anemometers. The authors also discuss a simple mathematical technique to enhance the sensitivity of the airflow measurements.

Our method involves directing a fan, with a 480 watt motor, in and out of a cave entrance in a periodic fashion. The in and out reversals of the fan are recorded on a datalogger. At the same time an anemometer, recording to a datalogger, is placed in another remote entrance location. The anemometer signal and the fan reversals are recorded over a period of time. This is repeated between entrances with known connections to each other and between those with no known connections. The result of the measurements shows that the induced airflow causes a measurable change in the rate of the airflow in delayed synchronism with the fan reversals at the connected remote entrances and between some cave entrances where there is no known connection.

Although the technique demonstrates an air connection between caves, it does not guarantee that the connection is humanly accessible.

1. Introduction

"Follow the Air" has certainly been the creed of cavers, rewarding them in many instances. The feel of a cave breeze blowing from some unknown source is intriguing and exciting. Can the source be from some vast cave system not yet discovered? Is it possible that a "far distant blowhole" is somehow connected to a known cave? The possibility of finding such a connection becomes an exciting prospect especially if it might lead to the discovery of virgin cave passages. But air flow can be elusive and trying to follow a tantalizing, barely discernable draft, can be exasperating. Many times the question is raised "Are we on the right track or is this just a local circulation?" "Should we dig here?" or "Is that dome worth a bolt climb?" To have the knowledge of the source or ultimate destination of air flow can be very useful. To determine that a cave is connected, at least by air currents, to another cave six kilometers down the valley is an exciting prospect.

In the past various methods have been used to attempt to trace air currents. These range from injecting some type of smoke into the air stream such as white phosphorus, burning wood, leaves or even tires. Ethanethiol, an air scent tracer producing an "essence of skunk" odor has been used with limited success. But none of these methods has proven to be effective in detecting a cave's air flow over long distances.

The method described in this paper is simple. It is based on the premise that under certain conditions if two entrances are connected, then mechanically blowing air into (and out of) one entrance will rapidly change the air flow velocity at the other entrance.

The following will show the arrangement of devices, instrumentation and how this premise was determined to be true. All the cave entrance locations discussed in this paper are located in the Burnsville Cove, a significant karst area in the Virginia counties of Bath and Highland. All the large caves in this karst area have strong air flow. It is believed that convection air currents between entrances (or any entry points for outside air) of different elevations is the primary mover of air.

2.Instrumentation and Equipment Used

1. One 10.16 cm wind run meter modified to act as an optically detected bidirectional anemometer with associated electronics. Startup wind speed 0.27 m/s and a maximum wind speed in or out of 4 m/s.

2. Four 10.16 cm optically detected bidirectional anemometers with associated electronics. Startup wind speed 0.36 m/s and a maximum wind speed in or out of 4 m/s. This instrument was designed and constructed by the authors.

3. One 480 watt 5 blade fan (76 cm. diameter) modified to reverse direction every 65sec, 100sec. or 200sec. which includes a 9 sec. off period while reversing.

4. Five HOBO U12 4-Channel Data Loggers

5. One ultrasonic bidirectional anemometer with associated electronics. The anemometer is able to measure wind speed as low as 0.045m/s with no practical limit on the high end. The output is recorded on two channels of a data logger. The math necessary to calculate a wind velocity is preformed in an Excel Spreadsheet. This instrument was designed and constructed by an author.

3. Butler Cave–Nicholson and Sofa Entrances

Butler Cave has 27 km of passages much of which is large in volume. It has two known entrances. Its Nicholson entrance is located 144 meters to the north and 41 meters higher from its Sofa entrance. The two entrances are separated by about 478 meters of passages generally large in volume (6 m by 15 m) but with many turns and several restrictions (crawlways). The upper Nicholson entrance has an air current consistent with the direction of a convection flow. However the Sofa entrance generally has a neutral or an oscillating air current indicating it is an intermediate (in elevation) entrance and that a lower, presently unknown entrance, exist elsewhere. Figure 1 shows a 480 watt reversing fan (76 cm. diameter) placed in the Sofa entrance (a rectangular opening reduced to the fan's dimensions). Power was supplied by a generator. A signal is sent from the fan to a recording data logger when the fan changes direction. For redundancy an anemometer is also placed at the fan to record the air flow and direction. Part of the Nicholson entrance is a small opening that allows bats access. The anemometers were placed in this opening during the testing (Fig. 2). All anemometers were connected to data loggers and the air velocities recorded at one second intervals.

Figure 1: The rectangular doorway Butler Cave's Sofa Entrance has been sealed around a fan. The fan blows alternately in and out of the cave in even intervals. A signal is sent from the fan to a recording data logger when the fan changes direction.

Figure 2: An ultrasonic anemometer (left) and a mechanial anemometer (right) recording data are located in the bat access hole to measure the rate of air flow.

Figure 3 shows the air velocity at the Nicholson Entrance. It includes a 500 second period before the fan operation (base-line) and the next 500 second period during the fan's operation of alternately blowing in and out of the Sofa

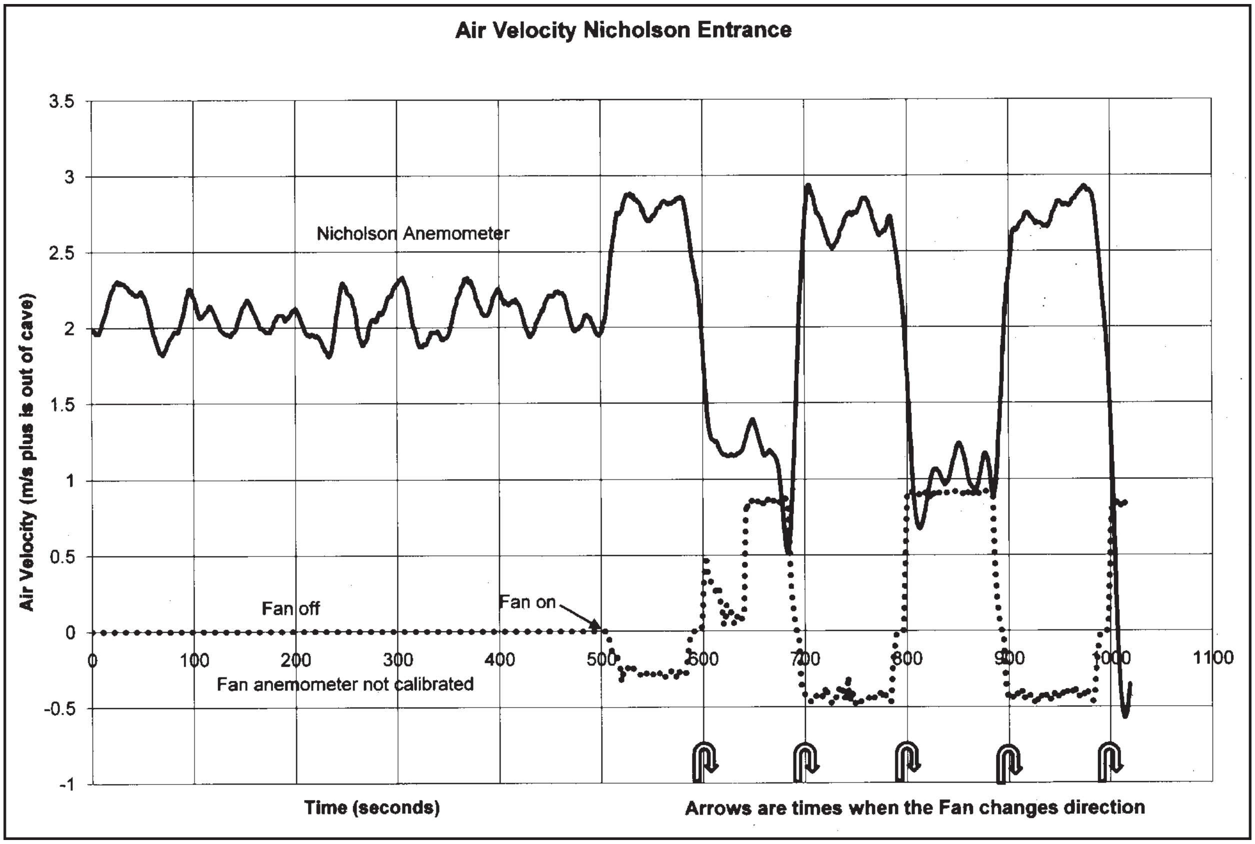

Figure 3: Butler Cave entrances air flow test. With the fan placed in the Sofa Entrance and an anemometer placed at the Nicholson Entrance, this chart shows the result of changing air velocities before and during the fan's operation. When the fan begins running for each 100 second interval there is a distinct signal (change in air velocity) measured by the anemometer. At the end of each interval, the fan stops for 9 seconds and begins rotating in the opposite direction.

Entrance. The measurements are summarized as follows:

- The "base-line" air flow is blowing out from the cave (the direction of a convection air current) but with small variations. These variations are assumed to be caused by small changes in barometric pressure (atmospheric waves). They are referred to as "noise" in this paper. Much of the noise is caused by surface winds and it increases with increasing surface wind speeds.
- With each fan reversal there is a corresponding change in the air velocity at the Nicholson entrance.
- The change in air flow takes place three seconds after the fan is reversed.

Note that during the period of 600 seconds to 650 seconds, the anemometer was being re-aligned. Being out of the main air stream the blades anemometer slowed their rotation and the effect is seen as lower velocities during that 50 seconds.

4. Big Bucks entrance, Buckwheat Cave, Backyard Cave, and Basswood Cave

Barberry Cave about 5.5 km in length has a large passage extending roughly along a small valley trending northeast. Big Bucks Pit, its northern most entrance, is unusual in that it is located in a small building used as an apple shed. The entrance is a 43 meter pit that extends down from the floor of the apple shed. The building is sealed to the top of the pit. The fan was placed in the apple sheds door which provided the same sealed fan attachment as site 1 (Figure 4). There are three cave entrances that lie to the northeast of the Big Bucks Pit entrance, Basswood, Backyard, and Buckwheat.

Basswood Cave entrance, a 76 cm. metal culvert, is located just 524 m. northeast of Big Bucks Pit. There is only moderate air flow at the entrance. The cave is formed in upper limestone units above Barberry Cave so a connection to Barberry Cave seemed unlikely. Backyard cave is a 61 cm. metal culvert located 772 m. northeast of Big Bucks Pit. Although it has strong air currents and is in upper limestone units it was not suspected to be connected. The Buckwheat

Figure 4: Inside this shed used for apple storage is Big Bucks Pit, a 43 m. drop into Barberry Cave. The pit is sealed to the floor of the building. The door to the building has been reduced to the size of the fan. Accordingly, as the fan blows in and out of the building the air is exchanged in the cave.

Figure 5: Cardboard has been placed over the entrance (a vertical culvert pipe) to Basswood Cave. The anemometer placed over a hole in the cardboard records the rate of air flow.

entrance is a 61 cm. metal culvert and is located 773 m. to the northeast of Big Bucks Pit. Prior to this investigation it was suspected that Buckwheat Cave might have some connection to Barberry Cave through an area of breakdown but no human sized opening has been found despite digging.

The test consisted of anemometers being placed in each of these three cave entrances to record changing air velocities when the fan at Big Bucks Pit was in operation. At Backyard and Buckwheat the anemometers were placed inside

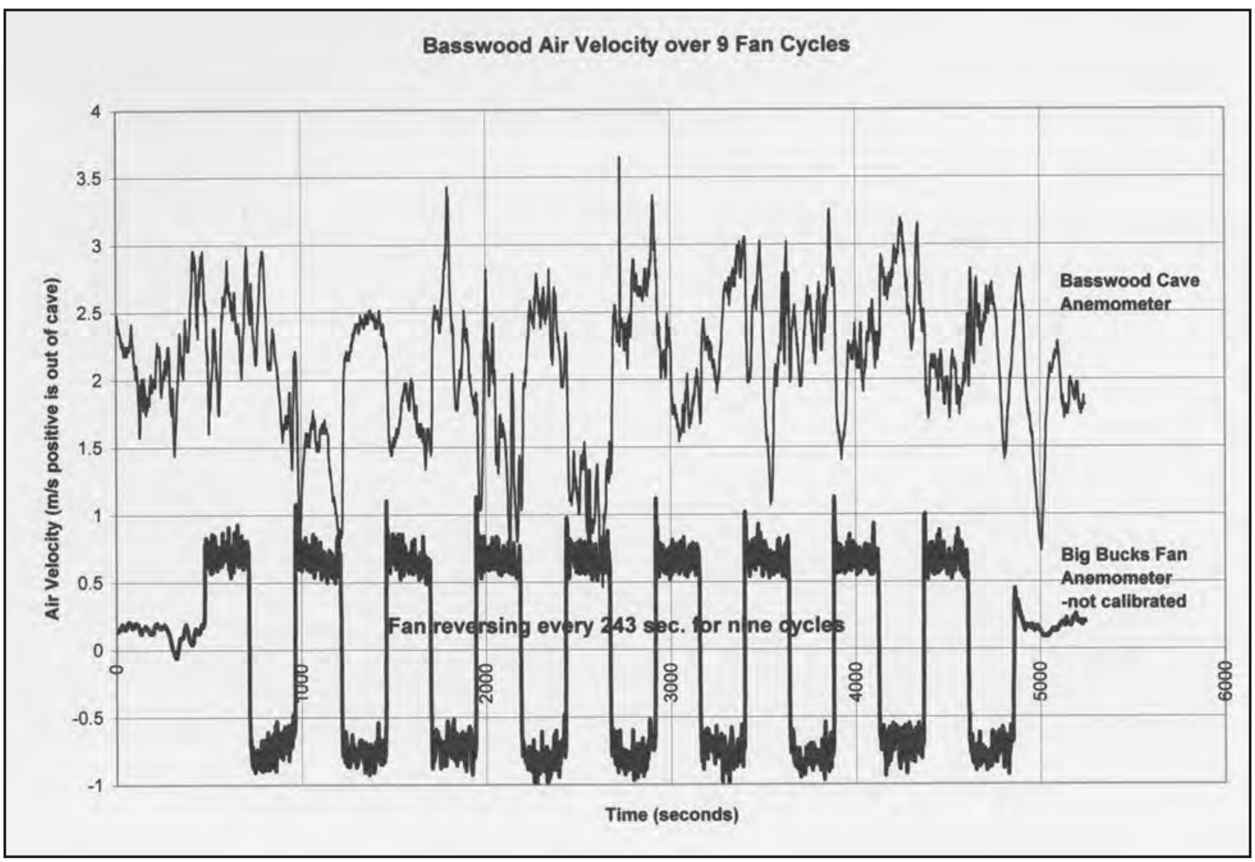

Figure 6: Big Bucks to Basswood Cave air flow test. This shows nine cycles with the fan placed at Big Bucks Pit and anemometer at Basswood Cave. In this instance the signal was much weaker than at Butler Cave entrances.

the metal culvert entrances that had strong air currents. However at Basswood where air flow was weaker, cardboard was placed on top of the entrance pipe. A small hole in the cardboard accommodating the anemometer concentrated the air flow. Figure 5 shows this arrangement.

Figure 6 shows the result of an air flow test between Big Bucks and Basswood where the signal is present but being weaker than shown in the Butler entrances test. Shown are nine cycles of the reversing fan operation and the resulting air velocity as measured at the cardboard restriction in the Basswood Cave entrance. Identifying the weaker signal against the background "noise" is still possible with this chart but it demonstrates that weak signals can become buried in the noise. There is a simple mathematical method of suppressing the random noise in a signal when the period of the repetitive signal, the fan, is known. If we add the periods together, first second to first second, to next second, over all nine periods (in this case), the signal will be enhanced and the noise, being random, will be suppressed. We can make an average out of this by dividing by the number of periods. Figure 7 shows the effect of this method. It shows the nine cycles of the air flow velocity combined to show the maximum effect from any changes from the fan operation. A dark line representing the overall average air velocity for the entire test separates the periods for the fan blowing in each direction. This simple method clearly shows that the velocity is significantly altered from the overall average by the fan's influence and demonstrates the two entrances being connected.

Results of all the air flow tests at these three entrances show that all are connected to Barberry Cave (Big Bucks Pit). Buckwheat's anemometer/logger recorded the strongest signal from the fan's operation at Big Bucks Pit. The delay time was 13 seconds. Backyard Cave had a weak but definite response and had a 13 second delay time. Basswood Cave had a definite response but one that was delayed by 12 seconds. This curious delay might mean that the connection is a long route despite the two entrances being only separated by 524 m.

5. Helictite Cave to Subway

Helictite is a compact maze cave with over 11 km of canyon passages averaging 6 meters high by 2 meters wide. The cave has only one known entrance. At this site the fan was placed directly into the 76 cm. steel culvert entrance to Helictite Cave. The anemometer was placed at an entrance to the Subway (a major section of the Water Sinks Cave). The two entrances are only 159 m. apart but are on opposite sides

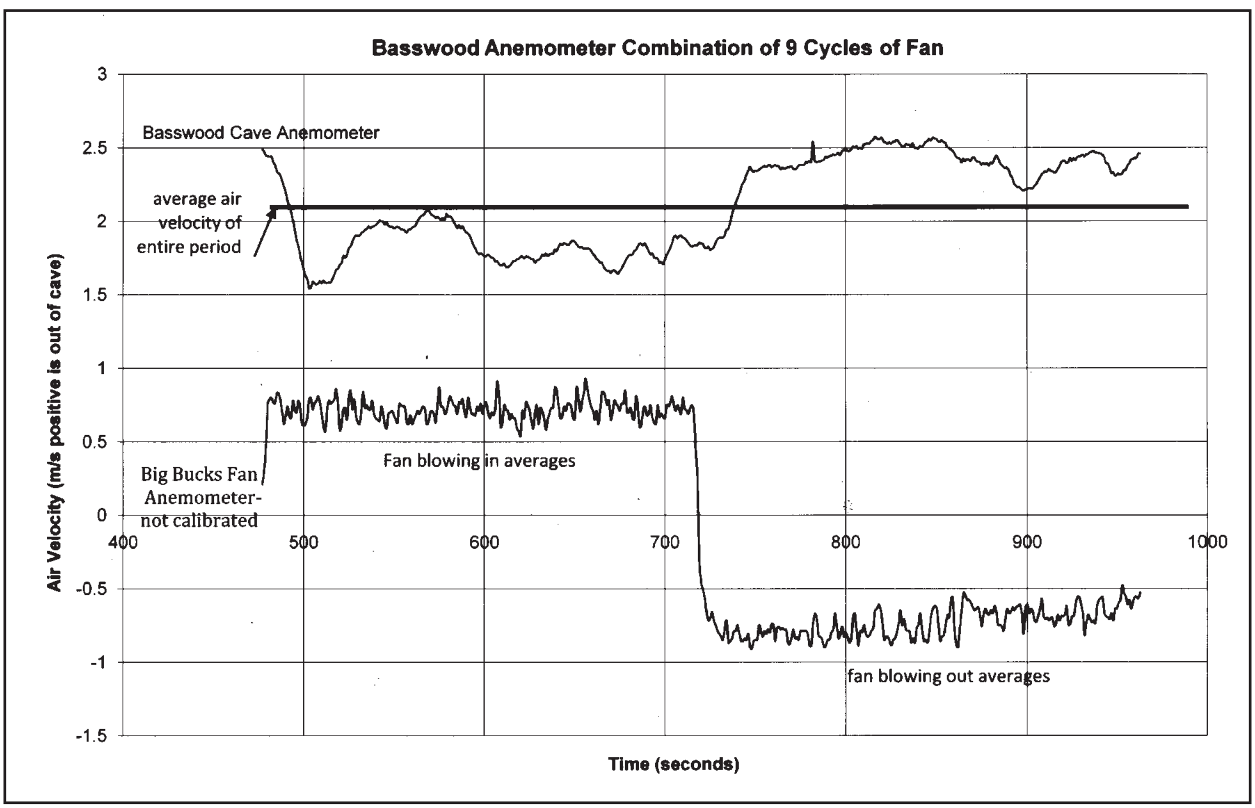

Figure 7: Big Bucks to Basswood average. This shows the combined average air velocity for the nine cycles of fan operation compared to the overall average. This calculation produces a clearer signal by cancelling much of the background noise.

of a large sinkhole. The air flow testing shows no detectable signal between entrances.

6. Helictite to a blowhole

With the fan placed in the Helictite entrance, an anemometer was placed at a surface blowhole 880 m. to the north. Previously some digging has taken place at the blowhole in an attempt to find a possible cave. As a result of the digging the air flow was coming up through an area of broken loose rock measuring about 4 square meters on one side of the excavation. To concentrate the air flow, a tarp was placed over the loose rock with the anemometer placed in a small hole cut in the tarp (Fig. 8). The result of this test shows a connection exists between Helictite Cave and the blowhole. The effect at the blowhole was slight and delayed by 40 seconds.

Figure 8: A tarp was fastened to one side of an excavation to cover an area where air was passing through a zone of rocks. Cardboard was taped to the tarp to provide a rigid surface and a hole was cut in the cardboard and tarp. An anemometer was placed in this hole where the air flow was then concentrated.

An interesting observation was made during the Helictite tests. A strong outflow of air would follow after the fan had been blowing into the cave for a ten minute period. Even though the entrance displays a convection air flow, the fan's operation was enough to create increased pressure within the cave that it far exceeded the outflow for the convection air flow.

7. Conclusion

The results from these tests vary from strong changes in air flow to weak changes or no detectable changes. The time it took for the effect to occur changed from just a few seconds to nearly 30 seconds. As this method of testing was being developed and preliminary testing was performed, it was apparent that testing done on windy days was not satisfactory. Gusty winds over hills and ridges create many pulses that tend to be amplified at entrances and this "noise" overwhelmed the signal the fan introduces. Also the clearest signals were obtained when the outside temperatures and cave temperatures are close to each other thereby creating only weak convection currents. All of the caves tested with possibly one exception are thought to have convection as the primary energy driving the air flow. Helictite Cave's airflow might have a strong barometric component as determined by another test (not described in this paper). Accordingly additional testing using this method between barometric caves entrances will be interesting. Although, these tests reveals a connection between some cave entrances it does not provide information about the nature of the connection or its location. It does not say whether this connection is humanly traversable. The different time delays suggest that some connections are more distant, longer in length or more restricting than others but a more examination of this is needed. This testing requires some preparation of the placement of the equipment, fan, and anemometer/loggers along with a power source. But the outcome can provide a valuable insight about the relationship of caves in a karst area. This method of air tracing is certainly less polluting to the cave than past methods.

THE HISTORY OF CAVING PACKS

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Abstract

The search for caves and exploring hidden passages has forced cavers to search and explore better ways to carry stuff in caves. Born of necessity, caving packs (tackle bags) have seen a fascinating evolution. From woven satchels to army surplus bags to caving specific packs, the innovation and adaptation of materials and gear has spawned an entire industry.

What worked and what did not? What inspired and what frustrated? How new materials and techniques have influenced development. How different caves forced innovation. How different types of caving trips made certain types packs a requirement. Strange packs, innovative packs, ridiculous packs and what we may be carrying in the future.

THE SWAYGO GEAR RACK TRAP

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Abstract

A demonstration and explanation of the Swaygo Gear Rack Trap–a top bar for an SMC rappel rack. The Rack Trap serves several purposes. First, it makes the rack longer–allowing from more room to spread the bars apart. Second, it provides a place to loop the rope over the top of the rack, similar to a hyperbar, for locking off. Third, it streamlines the rack by removing the long bar that sticks out and the pin that sticks up.

DIGITAL PHOTOGRAPHY IN SUPPORT OF THE LIDAR PROJECT, EDWARDS COUNTY, TEXAS USA

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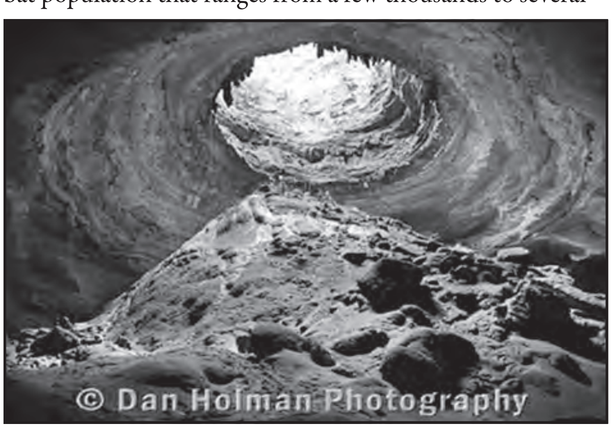
To create a photo real image of the Devils Sinkhole for inclusion in the LIDAR digital model of the cave, the entire interior of the cave needed to be photographed. This included the walls of the cave, the breakdown mountain formed by the collapse of the cave, the 50-m deep entrance shaft, and two lake rooms containing the formations and pools of water. Thousands of high-resolution digital images were collected using various flash systems and exposures. The entrance shaft and large room of the cave have some levels of natural light which made photography more difficult. Flash photography was required to obtain the correct texture and detail of the walls and floor. However, natural light also provided the shadows and color play that could be washed out or distorted. The changing light conditions in the shaft required extensive post processing of the photos. The photography in the shaft hanging from ropes at three different locations provided additional complexity to an already difficult process.

1. Introduction

The Devils Sinkhole is located southeast of the town of Rocksprings in Edwards County, Texas, USA. (Fig.1) It was discovered by European settlers in 1876. The pit was purchased by the Texas Parks and Wildlife Department as a State Natural Area in 1985. The entrance is 18 to 24 m across and drops down about 23 m, before opening up about 21 m above the breakdown mound. Entering the cave requires a 45 meter rappel to the top of the breakdown mound. (Fig.2) There are two major lake rooms at the lowest levels of the cave. The South Lake Room is at the base of the breakdown mound, where the dome slopes down to the floor and is open to the entrance chamber. Visiting the North Lake Room requires approximately 50 m of hiking and climbing from the top of the mound. It is a precarious crawl and climb down past crumbling walls and large loose breakdown. The Devils Sinkhole is home to a bat population that ranges from a few thousands to several million, depending on the time of year. The cave was mined for guano until about 1950. The size and beauty of the sinkhole has enticed explorers and scientists alike for more than 100 years. Texas Parks and Wildlife closed the sinkhole to the public because it is considered dangerous and also to protect the bat colonies that inhabit the cave between April and October.



The sinkhole property is open to the public to view bat emerging from the entrance. To view the cave, visitors must peer into the depths from a steel platform that overhangs the lip of the pit. There is a direct view down to the top of the breakdown mound but the viewers do not see the main chamber. Access in the cave is only allowed for approved scientific studies. Currently, there are ongoing studies in water flow and biology.

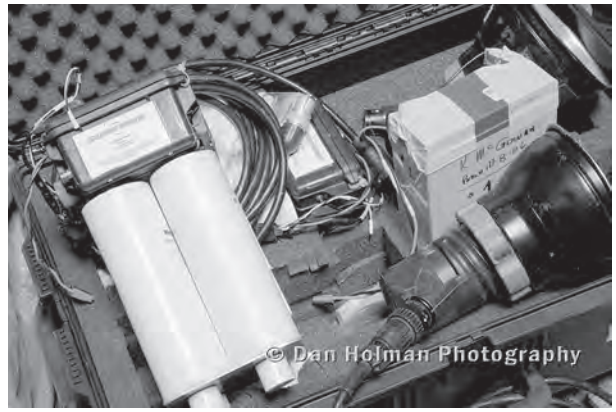
The cave has always held a fascination to visitors and locals of south-central Texas and many wild tales of exploring the cave exist. In an effort to give visitors a better understanding of the size and beauty of the sinkhole, The Devil's Sinkhole Society, the town of Rocksprings, and the Texas Parks and Wildlife Department coordinated with Texas Cave Management Association to produced a 3-D map with overlaid photography to create a "bat's eye" view of the cave. Using LIDAR technology, a highly accurate 3-D map was created that can be used for education, resource management, and scientific studies.

2. Cave Photography Component

Photography in any cave can be a daunting task. Most cave photography is oriented toward creating aesthetically pleasing photos. This project required photographing large sections of wall with complicated areas such as jutting rocks, under cut walls and the great distances that had to be evenly lit. These requirements seemed a bit overwhelming at first. Kevin McGowan was asked to assist with the technical part of the photography. Not only did he have more than 20 years of experience as a commercial photographer with studio and location experience, he had the required vertical caving expertise.

The first obstacle to overcome was locating a flash system that was not only battery powered, but was able to light the large areas while being sturdy enough to withstand the cave environment. We did not have a budget to speak of. McGowan contacted a cave photographer who is an electrical engineer by trade named Willie Hunt. He loaned us his strobe equipment. This provided us with two 2400 w/s power packs and 2 Speedotron Black Line® 2400 w/s heads. Hunt had custom built these systems for his own use and on occasion would allow cave photographers to use his system for special projects. (Fig.3)

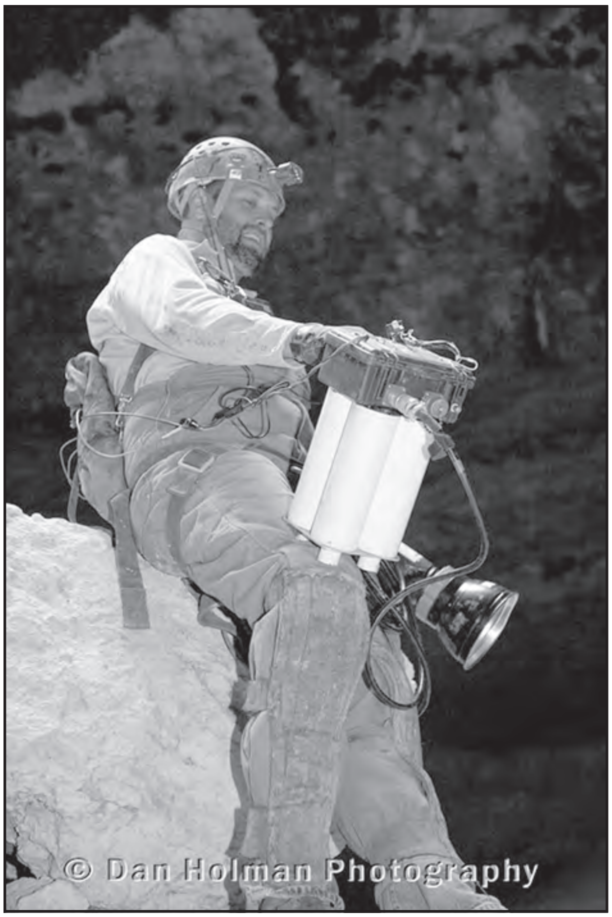
Cave photography is usually about lighting the darkness to



illustrate the underworld. Most still photographers of the sinkhole would use the available light from the large shaft opening. On a bright day, the light streams in and bounces around the walls, creating a gorgeous scene. Our process depended on every photo having consistent exposure and color balance edge to edge. Natural lighting, albeit beautiful on its own, was too inconsistent for our needs. The exposure at the top of the cave, in direct daylight, might be f8 @ 1/250th of a second. The exposure at the bottom of the breakdown mound, in the shadows, would be close to f8 @ 30 seconds. This exposure latitude was well outside the range of digital technology. We needed to keep the images exact no matter how the natural light affected the cave walls.

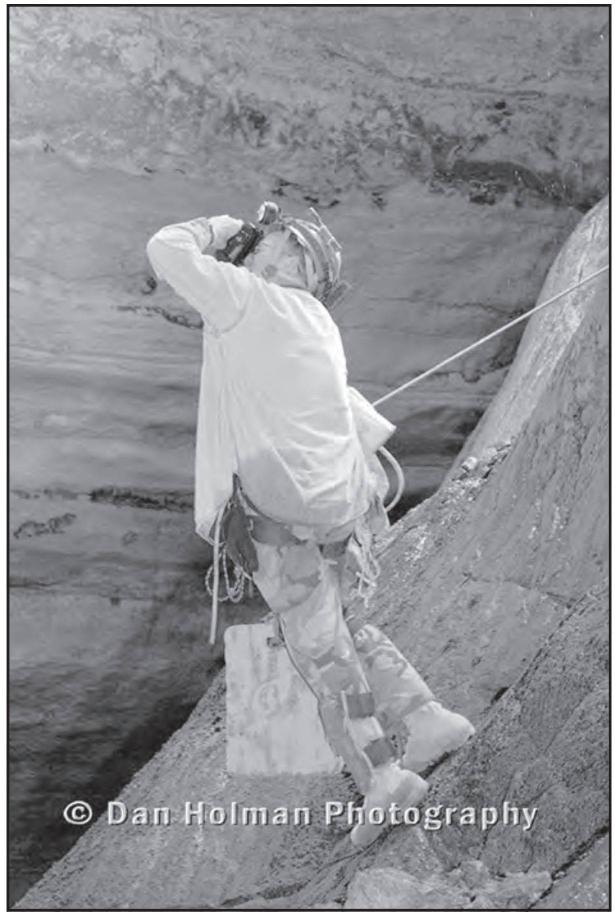
3. Equipment and Safety

The project organizers gave us an orientation on safety procedures regarding vertical work and individual assignments. McGowan briefed the team regarding the strobe system. Each strobe pack was powered by a 12 v sealed lead-acid battery. Hunt used small waterproof Pelican® cases to house the sensitive electronics. Each pack had 4 large capacitors that connected to the bottom of the case and were sealed in PVC tubes. The packs were relatively safe but for extra safety the settings were adjusted inside the cases then used nylon wire ties to prevent an accidental opening of energized packs and to keep someone from changing the settings. The procedure to turn off the power to the pack was critical so as not to discharge them while being handled. We drained the capacitors by manually firing the strobe with a button on the outside of the case. Then we could unplug the strobes from the packs. We always made sure the packs were off, the power was purged, and the power cord was disconnected from the battery before we plugged in or unplugged the lights to avoid the flashtube or strobe head. The flashtubes cost about $210US each and the strobe head was valued at about $300 each. A large reinforced, padded equipment case was used to transport the equipment in and out of the cave. Once we started shooting, the battery and pack traveled in the assistant's cave pack. We were very careful with it but the main concern was the safety of the assistant. The photographer would direct them where to stand and what to light. It was the assistant's job to determine if he was safe there. We would adjust as needed. There was normally one assistant. They would carry one strobe pack and battery for a combined weight of about 25 lbs. The Speedotron® head used a 5" silver lined reflector and gave a very wide and even light (Fig.4).



4. Photographing the Inside of the Dome

Photography started near the top of the dome, about 3.3 m down from the top, shooting from where the dome intersected with the floor up to the bottom edge of the shaft. There was normally about a 75% overlap between successive photos. The overlap was more than required for the project but it gave us visual confirmation that we were not missing an area. We shoot in an up and down pattern. We would move to the right then repeat until we were almost shooting 90 degrees to the left and right. We would continue this pattern until we made a compete circle around the mound. Then we moved about 8 m down the mound and repeated the pattern. In places, there were wet areas from water running from the shaft walls above. These wet and slick areas would have to be avoided. In one area, we rigged a safety line so the photographer could be out of the falling water on a slope that was too slick and steep to stand on. We rarely used a tripod because it was quicker and easier to follow our photography patterns manually. (Fig.5)



Photographing the undercuts in the dome was a necessary part of our project. The scans had covered the underside of the dome and our initial photography had missed some of them. We kept to the bottom of the mound or close to it. Our goal was to shoot the underside and still have enough of a visual reference points in the photos to orient them to the side shots from the mound. We did not have use of the powerful strobes when we shoot in the dome area. Instead of the large strobes, we used a commercially available system made by Lumdyne® for this part of the project. We had 3 batteries and used a 600 w/s pack and one strobe head with a small reflector. Again, an assistant carried the equipment.

5. Photographing the Lake Rooms

The lake rooms were the most complicated and troublesome areas to photograph. The South Lake room was easier but our camera-to-subject distance would vary greatly because of low ceiling being almost too close. The distance was about 1.5 m compared to the walls past the water which were about 6 or more meters away. We used small strobes in this area, Vivitar 283 flashes powered by four AA batteries. These on-camera strobes have proven to be a hardy caving flashes, are affordable, and readily available. Synchronized firing of several flashes, in a cave, can be a problematic. Standard flash slaves are usually not sensitive enough in a cave environment as the cave absorbs the light to such a degree that they do not seem to see it. I used a flash sync specifically designed for cave photography made by FireFly®. They utilize infrared light and are ultra sensitive. This became problem when we photographed too close to the LiDAR scanner. It seemed to fire the flashes off many times and using up the power from the AA batteries. Many times, we would have to wait for the LIDAR scanner to finish and move far enough away so he did not affect our flash syncs.

We needed a larger team to photograph the lake rooms. The terrain was more complicated due to the many layers of rocks, ledges, and rooms that needed to be lit. At times, it was hard to hide the assistants behind the rocks. In some places, it took numerous attempts to make sure the light was not too bright and over expose the details or not bright enough and under expose areas. I would have to move my assistants as I moved my camera lens. I was able to indicate where my assistants needed to point their lights with my use of a laser pointer. I would appoint each assistant an area and outline the area with the laser pointer for them to aim toward with their flash. This technique also allowed me to show them areas that they needed to avoid.

The North Lake Room was the most difficult part of the sinkhole to photograph as it was the most complicated and layered area of the cave. The floor was very unstable and most of our handholds would give way under light stress. The floor was steep and slick that would send a person into the lake.

That was the photographer's fate when he lost his footing and slid down a gravel and flowstone embankment, landing in the water. He was able to stop himself but not before dunking a gear case and having the water up to his waist. Cave pools can be very deceptive in their apparent depth. The water is usually very clear and still. It may seem 1 m deep but in reality it may be 3 m deep. This lake had a short shelf that ran along the edge of the "shore" about 1.2 m deep. It quickly went to 6 m beyond the shelf. After that, you could see it slopes down into the darkness.

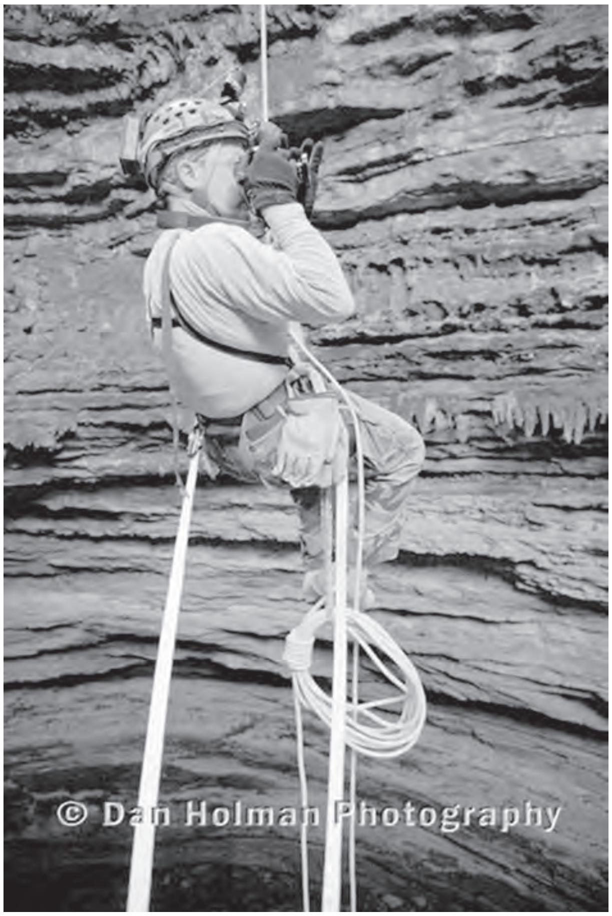
In the lake rooms, we had to light the rocks under the water for the photography. The LIDAR scans do not record data under the water's surface so they appear as black holes in the LIDAR point cloud. Our photography needed to overlap those areas. The photos would show the rocks under the water but they would not appear in 3-D in the final map.

6. Photographing the Shaft

Our initial attempt at photographing the shaft was from a single rig point. This resulted in photos that would vary greatly in camera-to-subject distance, from 24 m to 23 cm. Unfortunately, this would cause gross visual errors in the final product.

Our solution was to photograph the shaft from three separate rig points, about 120 degrees apart from one another. Three points were needed since our ropes were rigged close to the wall. The photography would merge together better if we kept the camera to subject distance more consistent. WEshot about a 220 degree angle left to right. To steady the photographer, we had to rig two ropes no more than 1 m apart. An assistant help with the gear and keep me in the proper direction we needed to shoot. The shaft has a travertine ledge that visually separates it from the dome of the chamber. It made an obvious dividing point for the shaft and the chamber. We started from the bottom of the shaft and worked upward. We started at that ledge and shot a 270 degree turn from the left to the right. Then we would shoot up about 40 degrees to record the many overhangs that formed the shaft walls. We would climb up the rope about 6 m or so and repeat that process. We would adjust that distance when we were hindered by foliage, dripping water, or if there was a ledge that needed special angles to properly document it. We would repeat this process until we reached the lip of the pit. Once we were above the travertine dividing point, we would photograph down about 45 degrees to record a view that would be closer to what the scanner would see. We were unable to scan the shaft except from inside the sinkhole angled up or topside near the ledge angled down.

We always tried to err with too much data and too many photos. This again gave us the visual confirmation we needed to make sure we were not missing anything. The exposure in the shaft was a balance of available light and electronic flash. The photographer made a judgment while on rope as to the shutter speed and aperture needed to get the best balance. He had to adjust the ISO of the camera to 200 in the shaft. We used a Nikon D300 for this part of the project. It was hard to keep a steady shot while hanging from a rope in varying lighting conditions. The assistant helped greatly in keeping the photographer as steady as possible. He used the strobe as the main light and would adjust the shutter speed to adjust when direct sunlight was an issue. The natural light was good on the day we photographed the shaft. There was a high layer of clouds that softened the harsh sunlight and made the balance of available light and flash easier to maintain. (Fig.6)



7. Camera/Lens Calibration, Orienting Photos toSscan, Post Production of Photos

Xueming Xue with Real Earth Models did the LiDAR scanning of the sinkhole. Xueming photographed a checkerboard chart at numerous angles. Each camera/lens combination had to be calibrated. The original camera used in this project was a Nikon D100. We used a Nikon D100 at the start of this project, also a Nikon D200 and D300 in the end. Most of the wall shots were with a Nikkor 24mm f2 lens. We repeated those shots with a Nikkor 18mm f3.5 lens.

There were a few false starts when we tried to orient our photography with shots taken from the LiDAR scanner's digital camera. One problem was the D100 did not record lens changes and we had to experiment to find which lens we had used. The photography from the scanner camera was not shot with flash so the images varied drastically in color and detail. We found that taking the scanner images that were easily calibrated to the scans and overlapping the files from the flash photography gave us good reference points. We shot all the files in RAW format and used Photoshop CS3® to process them. Photoshop CS3® has a program called Bridge® that can take dozens of images and process them together. It can sync the color, value, contrast, saturation, and other adjustments of the file and save them in non-compressed TIF format.

Caves can be very disorienting. When you can travel through a cave and when you turn around it can look completely different. To work around this problem, we used the most obvious geologic features as landmarks. The flash photography would expose areas in such a way that they would be hard to relate because there was so much detail that we again would have to seek obvious geologic features and formations to orient the images. For example, there is a distinct geologic layer that shows completely in a 360 degree around the cave. Cracks in this geologic formation were useful to help with the initial orientation of the photos. When properly oriented, one photo other photos would quickly come into line. In some cases, the images from the camera would be distorted differently from the LiDAR scanner's camera and that would lead to some identification problems but eventually we were able to identify and correlate the photography to the scans.

The end product of this part of the project was to deliver digital photos as tiff files to Xueming Xu for overlaying on the point cloud data from the LIDAR scanner. Throughout this project approximately 2500 digital images were taken and about 150 of these images will be used in the final 3-D map.

Acknowledgements

This project was coordinated by the Texas Cave Management Association with contributions from Texas Parks and Wildlife Department, the Devils Sinkhole Society, Real Earth Models and the Bureau of Economic Geology,

VERY LONG ZIP-LINE WITH SPELELOGY TECHNIQUES: MODELIZATION AND MEASUREMENTS

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In August 2008, during the European Caving Congress that took place in Vercors, France, the world longest zip-line named *Tyrolienne Pierrot Rias,* with a rope has been installed by the French caving rescue association. Its horizontal projected length was 1,096 m and the difference in level from the two anchors was 245 m. For such a long crossing, it was necessary to predict and measure the physical parameters of the rope in order to choose the appropriate site and the appropriate tension to ensure security and the travel of cavers down to the near end.

1. Introduction

In August 2008, during the European Caving Congress that took place in Vercors, France, the world longest zip-line with a rope has been installed by the French caving rescue association under coordination of Bernard Tourte (for history and practical aspects see *Spéléo Secours Français* (collective) 2009, and videos given in references, and for detailed calculations see Lismonde 2008, Morel & Chambat 2009,). Its horizontal projected length was 1096 m and the difference in level from the two anchors was 245 m (Fig. 1). One of the goals was to prove the efficiency of the caving rescue techniques. For such a long crossing, it was necessary to predict and measure the physical parameters of the rope (www.cordescourant.com) in order to choose the appropriate site and the appropriate tension to ensure security and the travel of cavers down to the near end.

Figure 1: Global view of the zip line from the top anchor.

We present in that paper the mechanical modelization and the various physical measurements achieved before and during the installation. In the absence of elasticity and of a caver on the rope, the shape of the rope is well-known. It is a catenary (hyperbolic cosine). It is a much more difficult task to estimate the shape and the tension when a mass rolls on the rope. We have written the corresponding dynamical equations and numerically solved the resulting differential system with a least-square matching method. The speed of the caver is then evaluated, taking into account the shape of the rope and the various frictions. A number of measurements were tested in order to constrain the various unknowns of the problem. Central to these experiments are two dynamometers continuously measuring the tension, a distant temperature measuring the temperature of the pulley and a rev counter the speed of the pulley (Fig. 2).

We first review the modelization principles, and then the measurements are compared to the modelization.

2. Mechanical Modelization

The modelization of the evolution of a rope between two anchors (Fig. 3) and of a caver rolling on it needs to write the momentum conservation of an element of rope and of

Figure 2: The top anchor and the dynamometer.

the caver (Figs. 4 and 5). The rope is elastic, weighted and flexible.

2.1 Momentum conservation of the caver

Let M be the mass of the caver, the caver is submitted to its weight M**g**, the friction in the air **F**, the force of the rope upon the pulley that we decompose into a part **f** aligned with the absolute velocity **v** of the caver and a part **R** that is normal to the velocity. The momentum conservation then reads:

$$M\, d\mathbf{v}/dt = M\mathbf{g} + \mathbf{R} + \mathbf{F} + \mathbf{f}.$$

Let us neglect the velocity and the acceleration of the rope itself and the normal part to the rope of the caver acceleration, note $\langle\theta\rangle$ the angle (negative on Fig. 4) between **R** and the vertical direction, then last equation can be projected onto the normal and tangential parts as (in that paper vectors are noted in bold, their algebraic parts in non bold):

$$Mg \cos \langle\theta\rangle - R = 0, \quad M\, dv/dt = - Mg \sin \langle\theta\rangle - F - f.$$

2.2 Equilibrium of the rope

The forces exerted on an element of rope of length ds are the tension **T**(x+dx) on the side that is at position x+dx, the tension -**T**(x) on the side at x, the weight $\mu\mathbf{g}$ ds of the rope where μ is its linear mass density, and the action of the pulley -**f** . Since the acceleration of the rope is neglected the momentum conservation reads:

$$0 = \mathbf{T}(x+dx) - \mathbf{T}(x) + \mu\, \mathbf{g}\, ds - \mathbf{f}.$$

Let us neglect the effect of the friction of the pulley upon the tension of the rope, the projection of the last relation upon the horizontal and vertical directions then read, with the usual notation df = f(x+dx)- f(x):

$$d\,(T \cos \theta) = 0, \qquad d\,(T \sin \theta) = \mu\, g\, ds.$$

At the very point where the caver is, the tension and the angle encompass a jump. Note [[f]] = f(x+)-f(x-) a jump of a function f, the equilibrium of the rope implies (fig.42 and 5):

$$[[T \cos \theta]] = R \sin \langle\theta\rangle \qquad [[T \sin \theta]] = R \cos \langle\theta\rangle.$$

A relation between $\langle\theta\rangle$ and the other parameters is needed. We will suppose that the direction of the velocity is close to the mean direction of the rope i.e. that

$$\langle\theta\rangle = (\theta\,(x+) + \theta\,(x-))/2.$$

To those dynamical relations must be added the geometrical and kinematical ones:

$$dx = ds \cos \theta,\ dz = ds \sin \theta, \quad v=ds/dt.$$

2.3 Elasticity and friction

We chose here to relate the linear mass density in charge μ to the density at rest μ_0 with a linear élastic relation:

$$\mu = \mu 0\ (1 - e\, T / Tr\ ),$$

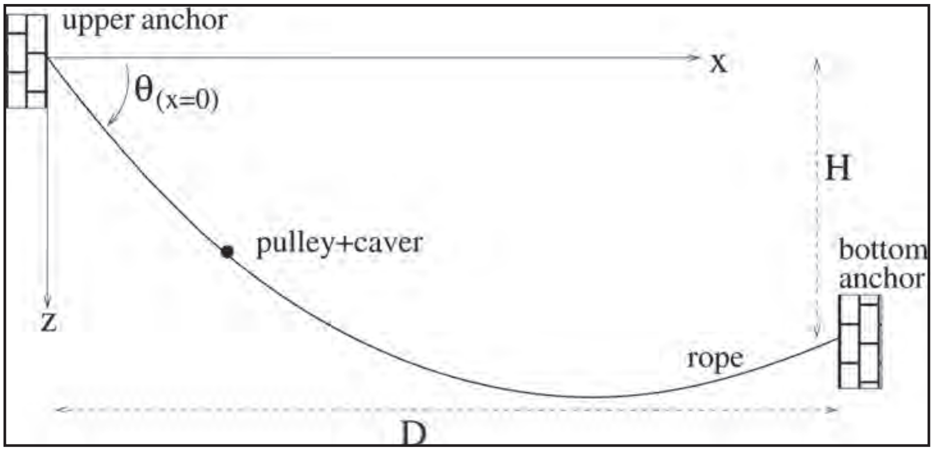

Figure 3: The zip line, the upper anchor on the left, the down anchor on the right. D and H are horizontal and vertical distance between the anchors.

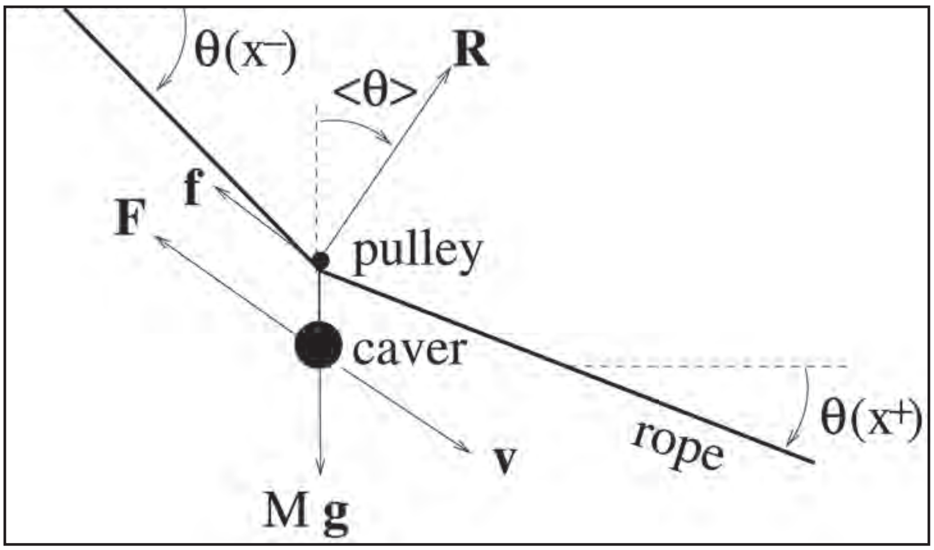

Figure 4: Forces acting on the system 'caver+pulley': weight Mg, frictions of the air F and of the rope f and reaction R of the rope. The angle of the rope with the horizontal has a jump [[❑]] =❑(x+) - ❑(x-).

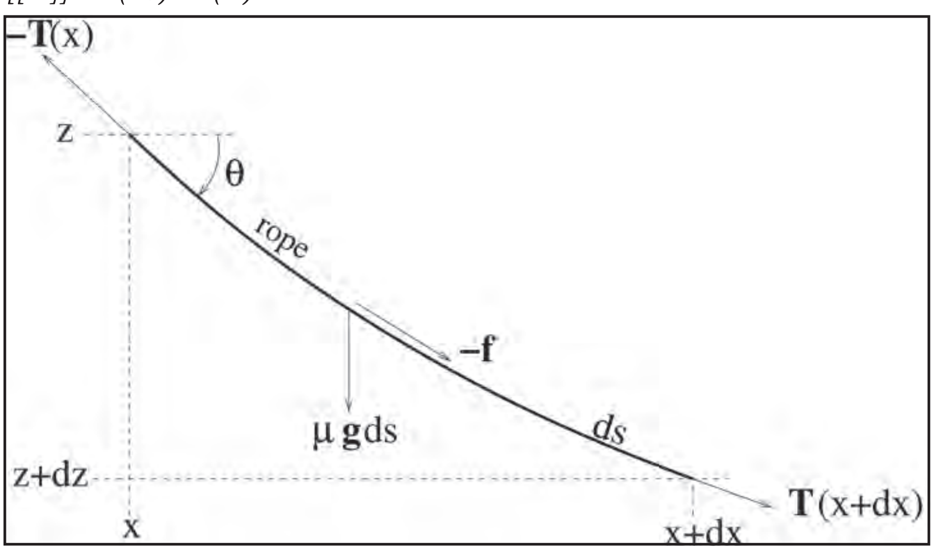

Figure 5: Forces acting on an element of the rope of length ds: the tension T on each side, the weight μg ds and the friction of the pulley.

where e is the strength for a reference difference of tension Tr. The conservation of mass then relates the length of the element in charge to the length at rest:

$ds0 = ds (1 - e T / Tr)$.

Friction in the air is supposed proportional to the squared speed c of the caver:

$F = - 0.5 \rho CxS v v$.

where C_xS is the product of the drag coefficient by the reference area of the caver. Friction of the pulley is taken as $f = - kv - k_1$.

2.4 Numerical integration

The mathematical form of equations to solve is an order one differential system with four variables T, θ, s and z, which reads, at every point of the rope where the caver is not:

$d(T \cos \Theta)/dx = 0$
$d(T \sin \Theta) /dx = \mu g/\cos \Theta$
$ds/dx = 1/\cos \Theta$
$dz/dx= tg \Theta$

At the point where the caver is, there is a jump:

$[[T \cos \Theta]] = Mg \cos <\Theta> \sin <\Theta>$,
$[[T \sin \Theta]] = Mg \cos2 <\Theta>$,
$[[s]] = 0,[[z]] = 0$.

The independent relation $ds_0/dx= (1 - eT/T_r) / \cos$

θ is also integrated in such a way that the boundary conditions can be applied:

s0(0) = 0, z(0) = 0, s0(D) = L0, z(D) = H.

where L_0 is the initial length of the rope (at rest). In the absence of elasticity and of a caver on the rope, the solution is well-known; it is a catenary (hyperbolic cosine). In the present general case the system must be integrated numerically, for every possible position of the caver on the rope, with a usual o.d.e. solver like Euler or Runge-Kutta solver. The solution gives the tension T(x) in the rope, the angle θ(x), the shape of the rope(x), and especially the height z(D), the length in charge s(D) and at rest s_0(D). One must find the initial parameters $T_{(x=0)}$ and $\theta_{(x=0)}$ in such a way that y(D) equals H and that s_0(D) keeps equal to L_0. We determine these parameters with a least-square method (we search for $T_{(x=0)}$ and $\theta_{(x=0)}$ that minimize $(H-y(D))^2+(L_0-s_0(D))^2$). The length at rest L_0 is arbitrary and depends on the tension at an anchor. That tension is the parameter to adjust at the beginning of the experiment and that determines the values of the other parameters. Once the shape of the rope is determined for every possible position of the caver the dynamical equation (1, right) can be integrated numerically. Figure 6 shows some such rope shapes and the caver's trajectory.

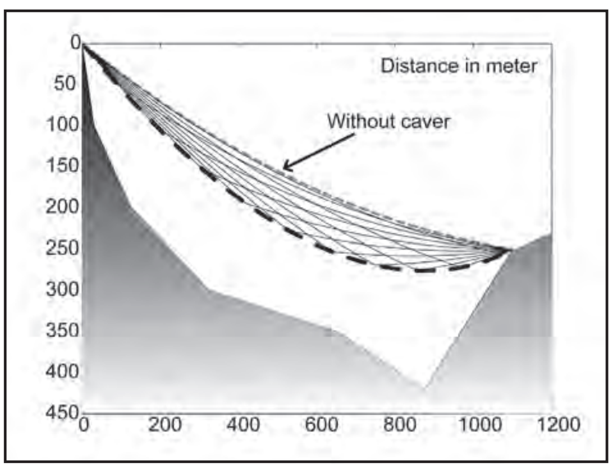

Figure 6: Shape of the rope without caver (grey dashed curve), in charge (plain curve) as a function a the horizontal caver's position. The black dashed curve represents the trajectory of the caver.

3. Measurements and Comparison with Modelization

The zip-line was instrumented to validate calculations and assumptions. Let us give some results with the values of the real experiment: H = 245 m, D = 1096 m, μ_0 = 74 g/m, M = 80 kg, g = 9.81 m/s^2, ρ = 1.1 kg/m^3. Some parameters are not well known and have been estimated in such a way that the calculated curves of velocity and tension fit the observations the best: we used e = 0.9% (for T_r = 100 daN), C_xS = 0.45 m^2, k = 1.5 kg/s, k_1 = 15 kg m /s^2.

The force was measured continuously at the top anchor of the zip-line with dynamometer sampling at a 0.1 s interval, the temperature heating of the pulley was measured every second, and the rotation speed of the pulley was also recorded. All the geometrical parameters of the rope trajectory were measured by using a theodolite.

3.1 Pulley temperature

Difficult information to predict is the pulley temperature rising during the test; this is why it was important to measure it. Two phenomena produce an increase in temperature. The first one is the losses in the ball bearing of the pulley due to the rotation. The rotation speed of the pulley is about 14,000 revolutions per minute on average, with a maximum at about 22,000 rpm (the pulley diameter is 2.8cm).The second source of heating is the friction of the pulley on the rope. We have installed an infra red sensor without contact to measure the pulley temperature every second at the pulley groove. The heating did not exceed 30°C during the whole descent.

3.2 Influence of rope elasticity and cavers mass

The maximum tension during a descent depends mainly on the rope elasticity (Fig. 7) and the caver weight (Fig. 8). A deformation of 3% for a tension increase from 50 daN to 150 daN is given by the manufacturer data sheet (www.cordescourant.com). For higher tensions this elasticity becomes smaller. The elasticity for which the calculated curves of velocity and tension fit the observations the best has been found to be around 1%.

Figure 8 shows a slight correlation between the maximum tension and the caver's weight. he linear regression of the points is represented in grey line. The dispersion around the straight line is due to the caver's Cx, its body position, and especially the initial starting condition.

3.3 Tension

At the beginning of the experiment the rope has been stressed up to 260 daN at the top anchor. After some cavers descents the tension without caver then stabilized at about 220 daN. The rope tension during a descent is represented in Figure 9 as a function of time. The tension grows from 2600 to 3800 daN during the crossing of the caver. At the end

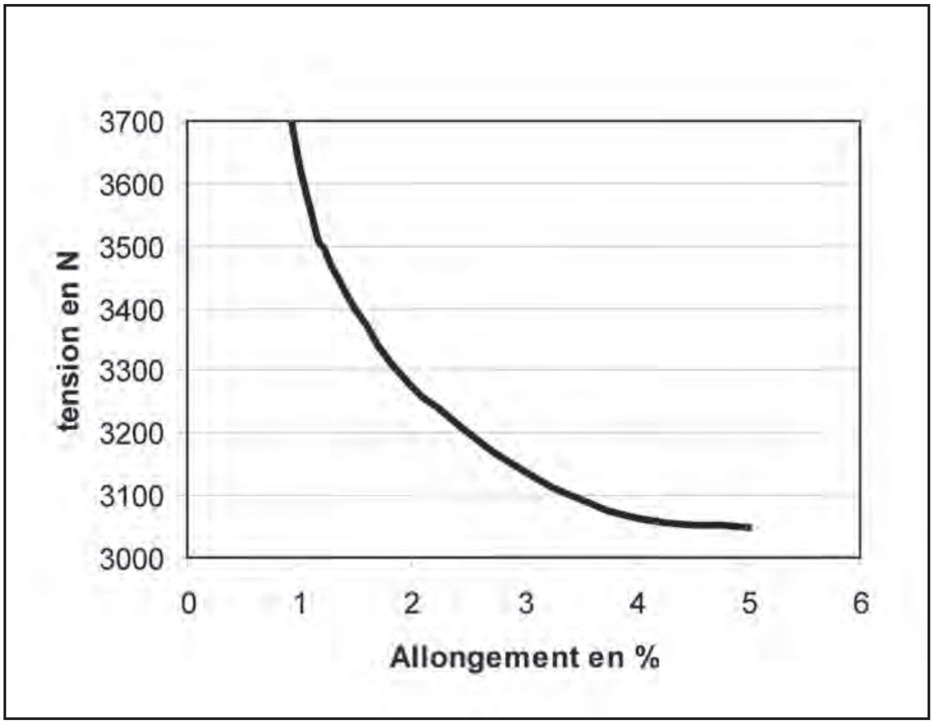

Figure 7: Calculated maximum tension during a descent as a function of the elastic coefficient of the rope (unit : deformation under 100 daN stress increase).

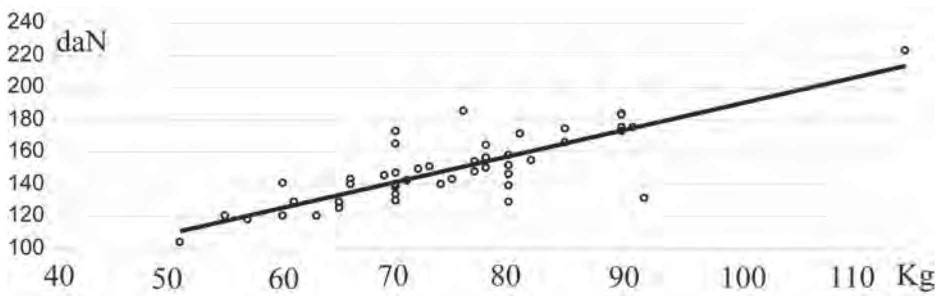

Figure 8. Maximum tension recorded during the crossing minus tension without caver according to the caver's weight recorded for 50 descents.

of the crossing the tension decreases until the caver stops, rolls back on several meters. Oscillations appear due to the shock of the retrieving system with the caver. The modeled tension agrees quite well with the observation.

3.4 Caver's velocity

The velocity measurement has been achieved with a revolution counter. A black painting mark is painted on the pulley flask. An infra-red diode lights this flask and a phototransistor detects the attenuation of light at the passage of this mark. Every second the number of revolutions is recorded. It is then easy to trace the profile speed and distance covered according to time, (Fig. 10). The velocity reaches 120 km/h and again the modeled velocity agrees quite well with the observation.

4. Conclusions

The shape and tension of a very long zip-line and the velocity of a caver rolling on the rope has been calculated taking into account the acceleration of the caver but neglecting the acceleration of

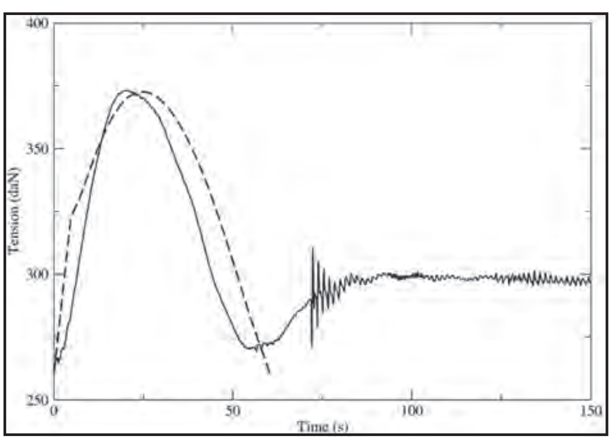

Figure 9. Tension measured at the top anchor (plain curve) and calculated with the parameters given in the text (dashed curve).

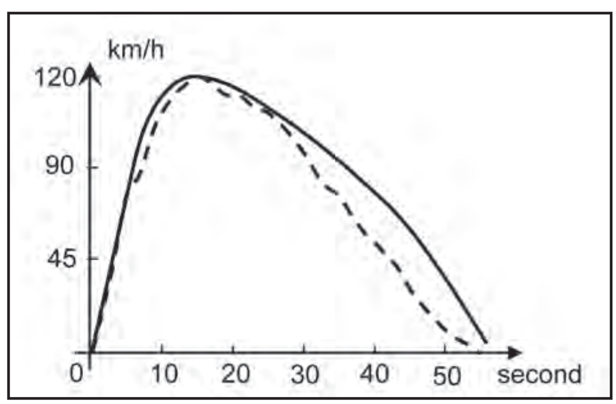

Figure 10. Velocity of the caver as a function of its position: measured (plain curve) and calculated (dashed curved).

the rope. The observed and calculated tension and velocity curves mostly agree. However when the caver begins its travel the observed tension increases slower that predicted. That discrepancy is probably due to the fact that the rope 'falls' with the caver and does not support the weight of the caver as if it was quasi-static. We were not able to take into account the full dynamics of the rope yet; that should be a next step.

The zip-line was named *Tyrolienne Pierrot Rias* in honor of that great caver passed away in June 2008, who among his achievements founded the French caving rescue association and explored the *Gouffre Jean-Bernard*. We dedicate the paper to Pierrot, a guide and a friend in the *Groupe Spéléo Vulcain*.

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LIGHT-EMITTING DIODES IN THE ILLUMINATION OF SHOW CAVES

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Abstract

The cave lighting equipment is one of the most important technical aspects of a show cave. In addition to enabling visitors to observe the beauty and dimensions of rooms and the variety of natural colors and shapes, adequate and appropriate lighting equipment is essential in allowing safe movement through the cave. Preparing a wild cave to become a show cave is quite complicated and always affects the cave's ecosystem to some extent. To avoid destruction of the cave environment, great sensitivity must be exercised to prevent damage from poor lighting choices.

Aspects of lighting a show cave include the following: ecology (minimal modification to the natural cave, avoidance of continuing degradation of the cave environment by the heat and the qualities of the light produced by the equipment), safety of visitors and personnel (correct installation of equipment, adequate illumination of passage hazards, emergency lighting); esthethc considerations (retaining natural colors and sounds, adequate and appropriate lighting to allow appreciation of objects and passage shapes, unobtrusiveness of installed equipment); cost (initial installation and maintenance, the latter being affected by characteristics such as tolerance of temperature extremes and frequently being turned on and off); ease of operation of the lighting equipment; and the establishment of operational guidelines (hours of operation per day, number of visitors per party, supervision of visitors, emergency procedures). The choice of LED lighting in a show cave, powered by an adequate number of switchable circuits, affects every one of these aspects and has many positive features in comparison with other options.

While there is no "wizard light" that excels in all areas with no cost, damage, or other disadvantages, LEDs may be the "light of the future" for show caves.

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