16th INTERNATIONAL CONGRESS OF SPELEOLOGY

Proceedings

VOLUME 2

Edited by

Michal Filippi
Pavel Bosák

16th INTERNATIONAL CONGRESS OF SPELEOLOGY
BRNO 2013
CZECH REPUBLIC
WHERE HISTORY MEETS FUTURE

16th INTERNATIONAL CONGRESS OF SPELEOLOGY

Czech Republic, Brno

July 21–28, 2013

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Produced by the Organizing Committee of the 16th International Congress of Speleology.
Published by the Czech Speleological Society and the SPELEO2013 and in the co-operation with the International Union of Speleology.
Design by M. Filippi and SAVIO, s. r. o.
Layout by SAVIO, s. r. o.
Printed in the Czech Republic by H.R.G. spol. s r. o.

The contributions were not corrected from language point of view. Contributions express author(s) opinion.

Recommended form of citation for this volume:
Filippi M., Bosák P. (Eds), 2013. Proceedings of the 16th International Congress of Speleology, July 21–28, Brno. Volume 2, p. 507. Czech Speleological Society. Praha.

ISBN 978-80-87857-08-3

KATALOGIZACE V KNIZE - NÁRODNÍ KNIHOVNA ČR

International Congress of Speleology (16. : Brno, Česko)
16th International Congress of Speleology : Czech Republic, Brno July 21–28,2013 : proceedings. Volume 2 / edited by Michal Filippi, Pavel Bosák. -- [Prague] : Czech Speleological Society and the SPELEO2013 and in the co-operation with the International Union of Speleology, 2013
ISBN 978-80-87857-08-3 (brož.)

551.44 * 551.435.8 * 519.86/.87
- speleology
- karstology
- modeling and simulation
- proceedings of conferences
- speleologie
- karsologie
- modelování a simulace
- sborníky konferencí

551 - Geology, meteorology [7]
551 - Geologie. Meteorologie. Klimatologie [7]

Cover photos (some photos were adjusted/cropped)
Top left – A gallery along the "Rio de los Venezuelanos" in the Imawarì Yeuta Cave system in quartz sandstones, Auyan Tepui, Venezuela. Photo V. Crobu. For details see the paper by Sauro et al.
Top right – The 15th siphon of Ramo Nord in the Grotta del Bue Marino, Sardinia. Photo by R. Husák. For details see the paper by D. Hutňan.
Bottom left – Using an Xbox Kinect equipment to survey a cave. Photo by J. Gulley. For details see the paper by Covington et al.
Bottom right – Inclined workings of the Voskresenskyi Mine, Ural Mountains, Russia. Photo by A. Gunko. For details see the paper by A. Gunko.

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Contents

Preface

Dear readers, the Proceedings volumes you are holding in your hands were issued within the 16th International Congress of Speleology (hereafter 16thICS) on July 21–28, 2013 in Brno, Czech Republic. Let us welcome you to its reading.
In total, over 320 contributions (over 250 oral presentations and over 70 posters) by more than 750 authors have been received to be included within the Congress Proceedings. This represents over 2,300 received e-mails and a similar number of responses during the last 6 months, approximately 4,300 electronic files and over 1,450 printed pages of the text. To put it simply, "really, really much interesting stuff concerned with cave and karst subject". The author's guidelines stipulated that the particular contributions should not exceed 6 pages of text and we were delighted to find that most authors prepared contributions close to this upper limit. Only very few contributions did not exceed one page of text. This illustrates a clear willingness of the cavers and karst scientist to share their discoveries and research conclusions.

The presented contributions (abstracts/papers) stand for both oral and poster presentations as indicated in the headings. Contributions in each session are arranged alphabetically by the last name of the first author. All contributions were reviewed from the viewpoint of technical quality and scientific content by members of the scientific committee and invited reviewers. The authors had the opportunity to revise their papers in response to reviewer's comments and we were pleased to see that the reviews have improved the clarity and readability of the contributions. However, profound improvement of the English language could not be arranged due to the shortage of time and insufficient human resources; the authors themselves are therefore responsible for the linguistic level of their contributions.

Thirteen thematically different sessions and six special sessions were scheduled within the call for your contributions to cover the whole range of subjects to be discussed within the wide scope of the 16thICS. The low number of contributions for some of these "detailed" sessions necessitated their merging with others. As a result, eleven original and three joint sessions are presented within the Proceedings. The contributions were grouped into three separate volumes. The purpose of this arrangement was that each particular Volume is filled with a certain logical hierarchy of topics, and that related topics are presented together. It was also the intention that the content of each Volume is topically balanced and contains both generally interesting (popular) topics with rich photographic documentation and hardcore scientific topics dominated by tables and plots.

Volume I starts with three plenary lectures representing three global topics related to 16thICS subject. Further it contains papers concerned with history of research (session "History of Speleology and Karst Research"), archeology and paleontology (sessions "Archaeology and Paleontology in Caves"), topics focused on management and preservation of caves and karst areas and other social-related aspects (sessions "Protection and Management of Karst, Education"; "Karst and Caves: Social Aspects and Other Topics"). In the last mentioned session you can also find a small part devoted to extraterrestrial karst. Volume I is ended by a relatively large portion of biology-oriented papers placed within the session "Biospeleology, Geomicrobiology and Ecology".

Volume II contains the traditionally heavily attended session "Exploration and Cave Techniques" and by the related session "Speleological Research and Activities in Artificial Underground". These exploration topics are, we believe, logically supplemented with contributions from the field of "Karst and Cave Survey, Mapping and Data Processing". The content of the second Volume is completed with a somewhat more specialized session "Modelling in Karst and Cave Environments" and with session "Cave Climate and Paleoclimate Record". The last mentioned session probably better fits to the end of Volume III, but it was placed into Volume II in order to reach balance in the extent of the individual volumes.

Volume III also starts with traditional, heavily attended topics organized in two sessions: "Karst and Caves in Carbonate Rocks, Salt and Gypsum" and "Karst and Caves in Other Rocks, Pseudokarst". These topics are supplemented by the related session "Speleogenesis". This last volume of the Proceedings is ended by the study of cave minerals, included in a specific session "Cave Minerals".

It is clear already from the previous ICS meetings that the range of the published topics becomes wider and wider, including localities in the whole world but also – owing to the access to high-quality spacecraft images – from other planets. The range of the instrumental, analytical and software methods employed in cave and karst research is remarkable and shows that the topic of "cave & karst exploration" attracts an ever increasing number of researchers even from already established scientific disciplines.

Let us also say a few words about the selection of the cover photos for the Proceedings volumes. The idea was to select such photos which would best represent all topics (especially those enjoying the highest interest) in each particular volume and be of high technical quality. Since we believe the cover page is a place for a serious presentation of the inner content, we made our selection from photos used in the presented papers. In one case the additional photo was requested to get a better representation of the topic. For our purpose, we decided to place several photos on the cover page of each volume. We hope that you enjoy them.

We wish to take this opportunity to apologize for the all mistakes which might have possibly originated within the operations with different versions of the manuscripts and other related files and e-mails which passed through our computers. We believe that everybody find their interesting reading in the Proceedings and we wish that the whole publication (Volumes I–III) becomes a valuable record of the 16th meeting of enthusiasts addicted to the fascination of the underground world.

Finally we wish to thank all the authors for their contributions. Enormous thanks belong to the reviewers and especially convenors (members of the scientific committee) of the particular sessions for their time and effort in the improvement of the overall message of the texts. We also wish to thank Michal Molhanec who significantly helped with the on-line form for the contribution submission, to Jiří Adamovič who repeatedly helped us with the improvement of our English, and to Jan Spružina, Zdeněk Motyčka, Jana Holubcová, and Renata Filippi who contributed to the preparation of the Proceedings.

After the few introductory words, let's now enjoy the papers from localities all over the world, presenting all forms of activities in karst, caves and other related surface and subsurface environments!

Michal Filippi and **Pavel Bosák**
Proceedings editors

Session:

Exploration and Cave Techniques

RECENT INVESTIGATIONS IN THE GÁLAPAGOS ISLANDS, ECUADOR

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The Galápagos Islands are an archipelago of volcanic islands, created by a hot spot, some 1,000 km off the coast of Ecuador. Initial explorations of Besson (Besson et al. 1982) and also investigations led by the Museo de Ciencias Naturales (led by J. J. Hernandez), suggested that a systematic effort to document the caves of Gálapagos was warranted. In 2006, Addison, Osburn and Toulkeridis conducted a successful reconnaissance trip to assess the potential for caves. Starting in 2010 yearly expeditions began to locate and document the lava tubes and magma chambers of Galapagos. These data are being used as a solid foundation for scientific investigation on these largely unknown enviornments. Efforts to date include the discovery and survey of Triple Volcán, the deepest known cave (conduit) in the islands at -101 m and documentation of numerous giant tortoise sites within lava tubes. Initial measurements of gas emissions in caves indicate an enormous natural rate of important greenhouse gases, some of which have been measured at untolerable levels for human health. Evaluations of biospeleology and paleontological potential are also being conducted. Fieldwork in 2010 revealed the presence of several undescribed cavernicoles on Isla Isabela, including a trobobiont ground beetle. In addition, varied microbial communities observed in the caves remain unstudied. Current efforts are focused on organization and field trip support for the Sixteenth International Symposium on Vulcanospeleolgy to be held in Gálapagos in 2014.

1. Introduction

The Galápagos Islands are an archi-pelago of volcanic islands some 1,000 km off the western coast of Ecuador. The islands were first discovered by adrift Spaniards in 1535. Various attempts were made at colonizing the islands during the 1700s and 1800s. Accounts of these attempts and a good overall history of the islands can be found in Curse of the Giant Tortoise by Octavio Latorre. Charles Darwin made the islands famous in The Origin of the Species by documenting specialization of fauna on the various islands. While there is much known about the wildlife of the islands, only a handful of research projects have focused on the caves of the area. Within the limited attention given to the caves, only the French (Besson et al. 1982), and two expeditions by the Museo de Ciencias Naturales de Tenerife (led by J. J. Hernandez) are of much significance in relation to exploration. The latter is well documented in their report published in the proceedings of the 6th International Symposium on Vulcanospeleology.

In the spring of 2006, Bob Osburn and Aaron Addison participated in a Washington University field trip to the islands. While the main purpose of the field trip was to study the volcanoes of Galapagos, it became clear that we should use the trip to do a bit of field reconnaissance for the potential of lava tubes. During that trip we visited Cuevas de Bellavista, a > 2 km segmented tube on the island of Santa Cruz. Bellavista (aka Cueva de Gallardo) turned out to be a 5 m wide × 10 m tall rectangular tube with some small lava shelves and scattered lava formations. It was enough to convince us that we should return to Galapagos.

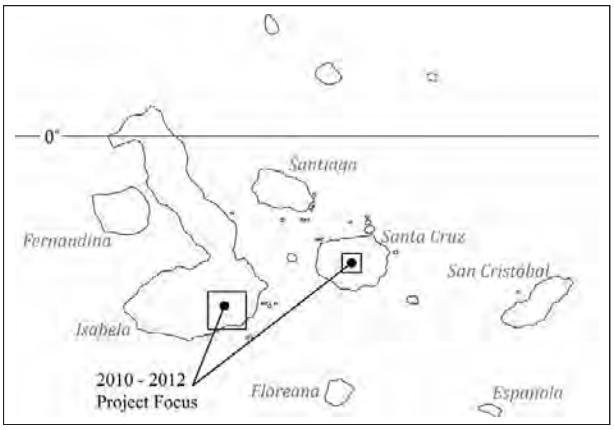

Figure 1. 2010–2012 Study Area.

2. Geography and geology

The Galápagos Islands are a product of hot spot volcanic activity. A hot spot is a region of intense heat within the Earth's mantle. Hot spot theory, states that there is a "mantle plume" of intense heat remaining relatively stationary, deforming the oceanic plate moving above it. These crusts or plates ride over the "long-living" hot spot and are occasionally perforated by the molten rock that rises from the earth's mantle. The region of the upper mantle above the stationary plume is partically melted, and migrates to the surface as magma. The final result is a shield volcano protruding above the ocean. The most prominent and voluminous types of volcanoes are the shield volcanoes, as their profiles resemble that of a Roman warrior's shield having a gently sloping, convex-upward landform. Such shield volcanoes can clearly be seen in the younger western islands of Isabela and Fernandina. These features are also locally referred to as "inverted soup-bowls" due to the morphological similarity.

The shield volcanoes in the Galapagos consist largely of thin lava flows, with minor pyroclastic (mainly ash) layers. Their subaerial slopes generally range from 4–8 degrees, and are characterized by steep-walled summit calderas. Several also have pit craters that are similar to calderas in form but are much smaller scale. The gentle slopes are the result of the low lava viscosity, which characterizes those volcanoes having regularly high production rates that drive lavas quickly and long distances. The lava flows (pahoehoe and aa) commonly initiate their path from flank vents and fissures rather than from the summit. These flank vents are the result of the widening and/or subsidence of the volcano. Eruptions and lava flows occur also along collinear rift zones, which can extend very far from the summit. Eruptions are concentrated at the active rift zones. Above and close to these zones one encounters also ash cones, cinder cones and spatter cones. Some of which remain empty after their eruptive activity and represent ideal areas to study magma chambers and lava tubes of such volcanoes.

Recent investigations of lava tubes and volcanic conduits have been focused on Santa Cruz and Sierra Negra volcanoes. The volcanically young but very active shield volcano Sierra Negra is 60 to 40 km wide, and with 7 to 10 km caldera, the largest and simultaneously the shallowest (elliptical) caldera of all volcanoes of the Galapagos. Although commonly related as fact, Sierra Negra does not have the second largest caldera in the world, but still ranks in top fifty largest shield volcano calderas on the planet. Eruptive centers and different lava fields have been subdivided into five distinctive age groups all being younger than 6,000 years old. These are alkaline to tholeiitic lava flows that erupted from east to northeast trending circumferentially and radial fissures situated on both sides of the summit caldera on the upper flanks and on the western and eastern lower flanks. The caldera itself has undergone several episodes of collapse, upheaval and deformation. Ten historic eruptions occurred and several have involved a frequently visited (by tourists) caldera rim fissure zone called Volcan Chico. These explosive phases of the past have given rise to frothy pumice, which was followed by the formation of agglutinate cones and voluminous lava flows. The last eruptive activity took place in end of October of 2005 and lasted a just seven days, after 26 years of silence.

The most central island of the Galapagos (Santa Cruz) is a 1.3 Ma old large shield volcano with a high abundance of parasitic cones, large lava tubes and pit craters (e.g., Los Gemelos). The volcano is subdivided into two main units. The older unit is the platform unit, while lavas of the shield series represent the younger unit. The plagioclase and olivine phenocrysts bearing tholeiitic lavas of the platform series include faulted and uplifted parts that appear today as independent islands such as Baltra, Seymour and Las Plazas. The latter was formed evidently below the sea surface due to the almost entire composition and occurrence of pillow basalt. These older and therefore lower units show intercalations with marine carbonates with a precipitation depth of < 100 m. Based on their morphology and the lack of vegetation, the younger overlying lavas of the shield series appear to be as young as a few thousand years old. These lavas, which mainly flowed from the summit but also from the flank of the volcano, are composed of a range of different volcanics but mainly exhibiting olivine tholeiites and transitional alkali basalts besides some hawaiites.

One of the most fundamental issues and questions in volcanology comprises the meticulous anatomy of a volcano, from the eruptive system starting at great depths up to the conduit and the final surface structure with the corresponding volcanic edifice. Scientific aspects of this subject can be gained by various direct and indirect methods such as the study of xenoliths, by tephrastratigraphy or the exhibition of eroded parts of extinct volcanoes in addition to the usually dangerous sampling of active lavaflows etc. Commonly, following eruptive activity, craters and conduits close or fill with crystallized material and are unavailable for direct observations. In this respect, based on a recent detailed mapping of different volcanic cavities of volcanoes above (active) shield volcanoes in the Gálapagos Islands, two open vents of different depths have been mapped. The first vent is named "The Pyramid" and is located on the lower highlands of Santa Cruz Island (Figure 2).

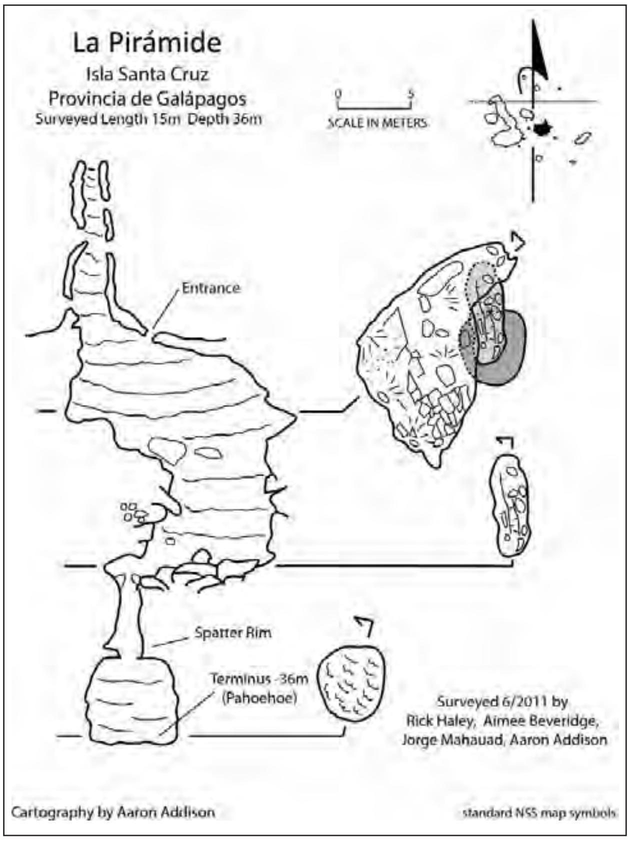

Figure 2. "The Pyramid", a volcanic vent.

The open conduit is situated in a small crater with the entrance being a quite unusual, and very dramatic spire rising some 8 m from the surrounding terrain. This terrain is made up of a 60–70 m wide crater of a cinder cone. The spire is situated on an elevated central part of the crater. Several pahoehoe flows, up to several meters long, are directed towards lower parts of the crater. The spire has numerous openings above the surrounding ground level, but access to the cave is via a small window at ground level. Accessing the inner, vertical and therefore deeper parts of the conduit required specialized equipment and techniques. Upon entry, there is a short 3 m drop to a ledge, leading immediately to a 15 m drop to the floor of the largest room in the conduit. This room appears to be a vacated magma chamber, measuring 15 m along a north/south axis and 10 m east/west. Several bones were observed scattered on the floor at this level, including a mostly intact tortoise shell. The open conduit continues down a 6 m drop to a small offset room along a fissure. Moving along the fissure for 5 m south, a large splatter rim guards the final drop in the cave. This drop of 12 m is narrow and unstable in places. The floor of the terminus room is smooth pahoehoe, and the final observable magma level in this location.

The second vent is situated along the main route between Puerto Villamil in Isabela Island and Sierra Negra caldera and is called “Triple Volcán”. (Figure 3)

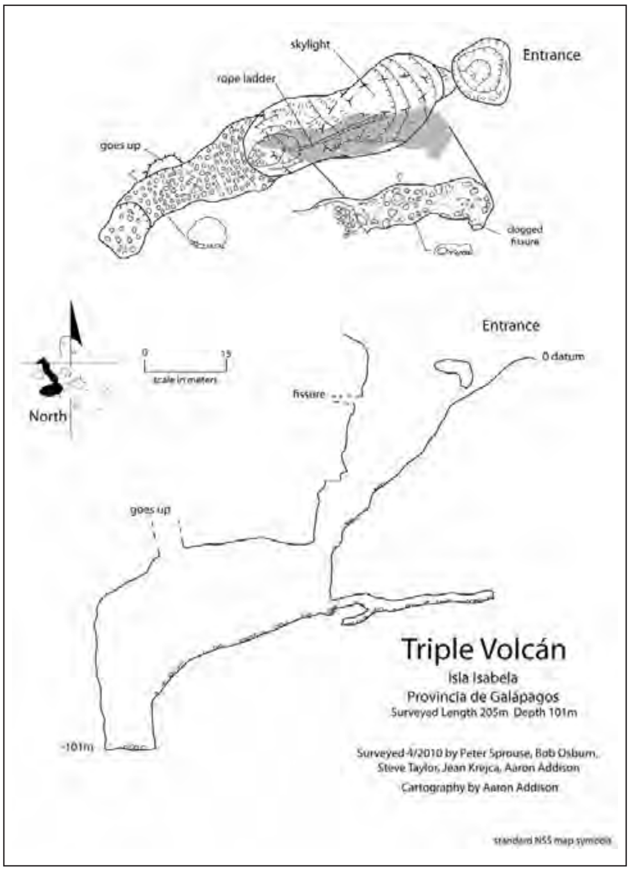

Figure 3. Surveyed extent of Triple Volcán.

The surveyed horizontal extent of this spectacular and multi-colored open conduit has been of 205 m with a total depth of 101 m, making this the deepest so far documented conduit in the Galápagos. The steeply sloping entrance pit narrows to a small throat, and then drops free for 15 m to the floor below. The floor is a cinder mound scatter with debris (rocks, cinder, bones etc.). At the base of the slope, the passage drops an additional 10 m to a terminus.

The cave has some small side passages, including an intersected small tube with aragonite, and patches of calcite. Numerous small caves have been also surveyed downslope from Triple Volcán, which indicates the continuation of the magmatic system of this vent. Similar to the Thrihnukagigur volcano in Iceland, it appears that Triple Volcán forms a rare exception where the magma in the chamber seems to have withdrawn, allowing a direct access to the walls of a previous shallow magma chamber. The magma in the chamber may have withdrawn or drained via lower elevation vents. Further focused mapping inside of such volcanic caves may also allow to understand complex geochemical and hydrothermal processes occurring underground, which are usually unobservable by the human senses, while a volcano is still active.

3. Exploration

Occasional exploration and use of the caves in Gálapagos dates to the first visitation by whalers and pirates that first mention discovery of the archipelago. A French led team conducted the first serious exploration of the caves in 1982 as a part of a larger effort focused on the caves of Ecuador (Besson et al. 1982). Their expedition documentented several locally known tubes, pits and fissures, generally located in proximity to populated areas. This is understandable given their likely limited time available and the difficult logistics of moving from island to island and navigating the unforgiving terrain. J. J. Hernandez et al. report on just over fifty caves on five different islands. Thirty five of the reported caves are located on Santa Cruz island, while only five caves are reported on Isabela island. As with the French expedition, this appears to be largely attributable to the difficulty of transportation and logistics of locating caves on Isabela. Santa Cruz is also a more populated island, leading to greater local knowledge of cave locations.

The first expedition in 2010 focused on the southern flank of Sierra Negra, the largest volcano in all of Gálapagos. As with previous exploration expeditions, we relied heavily on local knowledge of caves and access routes to lava tubes. Although we attempted to arrange access to Parque Nacional Galápagos areas on the island, it became clear that this would not be possible during the expedition. Teams focused on privately held lands along the southern edge of the summit. Full details of the expedition are reported by Addison (2011). Significant discoveries included survey a reported “pit”, named Triple Volcan, located approximately 200 m below the summit of Sierra Negra. The owner of the pit had rigged a primitive handline and rope ladder in to the pit and reportedly led past (adventurous) tourists into the pit. The team determined the ladder to be unsafe and rigged a rope for exploration. The pit was determined to be a vacated magma chamber and led to a small side tube with a small area of secondary mineral deposits. The overall depth of the cave was surveyed at -101 m, the deepest known cave in the islands. (Figure 4)

Another important discovery was of Caverna el Garancha Barral, a 450 m lava tube segment ~1.5 km to the east of Triple Volcan. Garancha Barral, is a segment of a braided tube system that has undergone several modifications from flows subsequent to the orginal tube formation. Giant tortoise remains documented in the cave. It is not possible that the tortoise entered using the modern day pit entrance, and indicates that at least one entrance able to accommodate giant tortoises previously existed. This discovery may yield new insight to age and range of toroises in areas where they are no longer found on the surface.

In addition to the new discoveries, two known Park caves were surveyed, Cueva Sucre, and Túnel del Estero. Sucre is a 340 m long braided tube segment open to visitors on a self led trail within the National Park. Estero is located on the coast, literally in the surf. The tube is entered via a roof collapse on the beach and the tube extends < 100 m in to the ocean. Unusal for cave exploration, it is possible to hear the surf impacting the outer shell of the tube while inside. Observations also revealed that water levels within the cave are tidal. Estero also represents a dark shallow and calm

Figure 4. Cinder mound in Triple Volcán. (Peter Sprouse).

saltwater environment that could yield interesting biological discoveries.

The 2011 expedition team returned to Isabela island to continue pushing leads, with permission to explore caves within the boundaries of Galapagos National Park. Additionally, we were able to work with Park guides familiar with Sierra Negra, and caves in the area. Several new caves were added to the database, including additional caves with giant tortoise remains in areas where tortoises are no longer found on the surface. Bad weather prohibited travel along the coast to investigate a new caving area, so teams relocated in mid expedition to begin working on Santa Cruz Island. Teams began the survey of Caverna La Llegada, a large tube segment high on the northern slope of Santa Cruz. Over 500 m were mapped in this "stacked tube", where evidence of at least three different flows was observed along a common path. A second important discovery was "The Pyramid" a pit conduit described earlier in this paper.

4. Science

4.1. Volcanic gas measurements

Geochemical and also isotopic gas investigation have been conducted since 2000 in the Galapagos, focused at well known and very particular (tourist) gas emission sites such as Volcan Chico and Minas Azufres at Sierra Negra volcano as well as at the sulfur area of Alcedo volcano (Goff et al. 2000). More recently, work has included a fumarole/plume and diffuse gas emission mapping of the Sierra Negra caldera at Isabela Island (Padron et al. 2012). Measurements of visible and diffuse gas emission were conducted in 2006 at the summit of Sierra Negra volcano, Gálapagos, with the intent to better characterize degassing after the 2005 eruption (Padron et al. 2012). However, no previous work has been done in order to determine the gas levels of lava tubes and set a base line for various gases. Such as baseline would not only establish rates and concentrations of some specific gases, but also to understand whether the gases contribute (indirectly) to the greenhouse effect. Lastly, direct measurement and monitoring of such gases will be helpful to scientists and land managers reviewing concentrations representing any danger for the health of tourists, cavers and wildlife that may be using the caves.

Measurements were performed in October–November of 2012 with a RAE-3000 instrument. Such insturmentation allows measurement of gases in the range of ppb´s. Measurements in caves in Santa Cruz (Gallardo´s cave and Premicias) as well as in Isabela Island (Cave of Sucre and open gas emissions sites like Volcan Chico and Minas Azufrales) were taken every five seconds and averaged every minute. Typical observation times ranged from 20–45 minutes.

The data obtained in our preliminary measurements were much higher than the data obtained in limestone caves in the Amazonian lowland (September–November 2012). Limestone cave data determination reached ranges of 5–380 ppb for H_2S and 500–1,400 ppb for NO_2. Data for Santa Cruz island caves reached levels of around 460 and 830 ppb for H_2S as well as 2,600 and 4,600 ppb for NO_2 respectively. Sucre Cave, a cave open to tourists, on Isabela Island reached higher values than other gas sites having up to 560 ppb for H_2S and above 6,200 ppb for NO_2. H_2S and NO_2 are both highly toxic and even lethal with certain concentrations. Both gases are heavier than air, and tend to accumulate at the bottom of poorly ventilated spaces such as lava tubes and magma chambers. Nonetheless, all data except the NO_2 data obtained in Sucre Cave are below any health risks. The data range obtained for NO_2 in the Sucre

Cave however is more than 1.5 times higher than the level, which will anesthetize the nose, thus creating a potential for overexposure. Levels six to seven times higher (measured in this location) would potentially decrease lung function and increase the risk of respiratory symptoms.

4.2. Biospeleology

Biological studies in the islands extend back most famously to Darwin's (1860) early observations of the unique flora and fauna. Indeed, Darwin noted the the flanks of the volcanic isalnds "are studded by innumerable smaller orifices". Darwin also described "steep walled" pits and lava tubes with collapsed roofing. This is the extent to which he studied the caves and cave life. Some 220 years later, the only rigorous studies of the cave fauna of the Gálapagos Islands was led by Stewart Peck (Peck 1990; Peck and Finston 1993; Peck and Peck 1986). Their work was focused on entrance areas of caves and did not extend in to the dark zone.

The cave fauna of the Gálapagos is relatively unusual, though similar situations exist in the Canary Islands and Hawaiian Islands (Juan et al. 2001; Peck 1990). Peck (1990) compared the eyeless terrestrial cryptozoans (ETCs) of Gálapagos to both Hawaii and Canary islands. This analysis suggests that both the number of caves and ETCs within the Gálapagos archipelago is only beginning to be revealed.

Expeditions in 2010–2011 have doubled the number of known caves on Isabela. While there are surely errors in any extrapolation, data suggest that numerous discoveries await in realm of biospeleology. 2013 expeditions will focus on biological inventories of known caves.

5. Discussion and future work

Our understanding of the caves of the Gálapagos archepelego has only scratched the surface. Despite being a world famous location, little is known about the geography, geology, and biology of the caves thoughout the islands. Our efforts will continue to document the caves of Gálapagos through primary exploration, geological and biological studies and support for scientists interested in understanding these unique cave resources.

Expeditions in 2013 will continue exploration and science on Isabela, and Santa Cruz. Team members will also support fieldtrip activities for the Sixteenth International Symposium on Vulcanospeleolgy to be held in Gálapagos in 2014.

Acknowledgments

Expedition support has been provided by a grant from the National Speleological Society, International Exploration Fund, Escuela Politécnica del Ejército, the Subterranean Ecology Institute, and individual expedition members. In addition, we wish to thank Parque Nacional Galápagos for their support and cooperation.

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QUARTZ SANDSTONE CAVES ON TABLE MOUNTAINS OF VENEZUELA

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The turning point in the discovery of sandstone caves occurred in 2002. Czech and Slovak members of hiking expedition visiting Roraima tepui in Venezuela discovered and explored first meters of the cave system called Crystal Eyes (Sistema Ojos de Cristal). In early 2004, a team led by Charles Brewer Carias discovered a massive sandstone karst spring on top of mesa Churi tepui in Masizo Chimantá in Venezuelan state Boliviar. In the following years a team of international scientists has documented over 30 km of horizontal caves on this mesa. Caves Colibri, Muchimuk and Brewer were connected in 2009 into one cave system called Sistema Charles Brewer. The Czech team played very important role in 9 speleological expeditions into the "Lost World". During expeditions the endemic cave fauna has been described, but several spider species are awaiting detailed research due to their significant contribution to the development of secondary opal fills, so called Spider stalactites created by capture of aerosol saturated solution of SiO_2 on cobweb fibers. Other unique secondary fillings are opal stromatolites. These white spherical bodies with a diameter up to one meter or the coatings on the wall are created by single-celled microorganisms.

1. Introduction

Exactly a hundred years ago, science fiction writer Arthur Conan Doyle introduced his famous novel "The Lost World". He was probably inspired by lecture by Sir Everard im Thurn – the first conqueror of the top of Roraima tepui plateau. The plot of Doyle's novel has been placed on similar mesas (table mountains) in Guayana highlands. By the mid 20th century it was known that the world of the Mesozoic dinosaurs is only a fiction of the writer. Nevertheless thanks to the uniqueness of the habitat of endemic life it has been accepted even by the scientific community under the name "Lost World".

The Table Mountains of the Guyana highlands consist exclusively of quartz sandstone in places metamorphosed to quartzite. When we simplify the geological processes, we can say, that the sand was deposited 1.5 billion years ago in a shallow freshwater sea. Only roughly 65 million years ago the entire area of the Guayan shield was raised approx. 4 km above the sea level.

There are several hypotheses about the formation process of the mountain.

One of them is a collision of Earth with a smaller planet. The actual formation of the table mountains and pinnacles is then easily explained by erosion processes on which all geologists agree. The erosion process continues to this day.

2. History of exploration

The cave in Guyana sandstone mountains was first time mentioned by the Jesuit missionary Filippo Salvatore Gilii in 1782. He placed the cave on the Carivirri today known as Autana. The first expedition to explore this cave was led by Charles Brewer Carías from Venezuela in 1971. The entrances can be seen in a perpendicular wall of rock towers thousand meters above the ground. The researchers were unloaded from a helicopter at the top of the mountain. The Cueva Autana, the name the researchers gave to the cave, was graded in terms of genesis in the category of river caves. Ten years later Brewer, was the first to descend into the world's mightiest abysses Sima Mayor and Sima Menor on the mesa Sarisariñama. The diameter and depth of the bigger and deeper Sima Mayor exceeds 350 meters! Although he did not discover any further underground caves in either Sima Mayor or Sima Menor, in his book he published in great details the hypothesis about karst drainage of Sarisariñama table mountain.

In the following years, the Brazilian and Venezuelan cavers tried intensively to find another cave in the sandstone. Since the global onset of the Single-rope technique, speleoalpinists focused on crevice abyss. These tectonic faults are hundred meters deep and often stretch several kilometers along the full length of the mesas. Today we know that these tectonic fissures can actually cut through a large cave system, or even drain into it water out of part of the plateau. The probability of pinpointing the exact place where the source of horizontal cave river starts is very small. Speleologist is tied to rope not only figuratively but also physically. Movement or rather traverse on the bottom of tectonic fissures through rubble and boulders the size of small houses, also covered with dense vegetation, is at a distance virtually impossible. Yet in the brazilian abyss of the Gruta do Centenario in the Serra de Caraca mountains has been documented 4.7 km of such fissures into the depth of 481 m. This fissure abyss held the first place in charts in the world for the longest and deepest quartzite cave for 20 years.

The turning point in the discovery of sandstone caves occurred in 2002. Czech and Slovak members of hiking expedition visiting Roraima tepui discovered and explored first meters of the cave system called Sistema Ojos de Cristal (Crystal Eyes). The following year members of the Czech and Slovak Speleological Society expedition measured several kilometers of tunnels in Ojos de Cristal cave system. In the immediate vicinity of the cave were discovered and documented additional underground locations. Cueva Gilberto, Cueva El Hotel Guacharo and Cueva Asfixiadora.

In 2005, the Venezuelan Speleological Society continued in our work, added to our mentioned caves and extended the

Table 1. The longest quartzite caves of the world.

Sistema Muchimuk Cueva Brever, Diablo, Colibrí, Muchimuk	17.8 km/±230 m	Venezuela	Churí tepui	SVCN-ČSS-SSS-SOPDS (2009)
Cueva Ojos de Cristal	8.2 km/± 85 m	Venezuela	Roraima tepui	ČSS-SSS, SVE (2009)
Gruta do Centenario	4.7 km/-481 m	Brazil	Serra do Caraça	Gruppo Bambuí (2009)
Sistema de la Araña Cueva Cortina, Araña, Eladio (Auchimpé)	4 km/±120 m	Venezuela	Churí tepui	SVCN-ČSS-SSS (2009)
Cueva Zuna	3.5 km	Venezuela	Churí tepui	SVCN-SSS (2009)
Sistema Dal Cin-Maripak	3.5 km	Venezuela	Akopán tepui	LAVENTA (2009)
Gruta da Bocaina	3.2 km/-404 m	Brazil	Serra do Caraça	Gruppo Bambuí (2005)
Sima Auyán-tepuy Noroeste	2.9 km/-370 m	Venezuela	Auyán-tepuy	SSI-SVE (1996)
Gruta das Bromélias	2.7 km	Brazil	Ibitipoca	Augusto S. Auler (2002)
Sima Aonda Superior	2.1 km/-320 m	Venezuela	Auyán-tepui	SSI-SVE (1996)
Magnet cave	2.0 km	South Africa	Northern Transvaal	Martini J. (1990)
Bat's, Giant's, "Climber's" System	1.63 km	South Africa	Cape Peninsula	Tim Truluck (1996)
Krem Dam	1.3 km	India	Meghalaya	Tony Oldham

SVCN – Sociedad Venezolana de Cincias Naturales
ČSS – Czech Speleological Society
SSS – Slovak Speleological Society
SVE – Venezuelan Speleological Society
SSI, Laventa – Speleological Society Italiano
SO PDS – Croatian Speleological Federation

measured length of Ojos de Cristal cave up to 8.2 km. The system Ojos de Cristal cave became for a short period of time the longest cave in the world in the quartz sandstones. (In literature there was even mentioned length over 10 km. This error happened by misinterpreting the results of our and Venezuelan expeditions and especially by combining the measurements of all caves in Roraima tepui into one single number, which are not part of the Sistema Ojos de Cristal.)

In early 2004, a team led by Charles Brewer Carías discovered a massive sandstone karst spring on top of mesa Churí tepui in Masizo Chimantá in Venezuelan state Bolivar. In the following years a team of international scientists has documented over 30 km of horizontal caves on this mesa. Caves Colibri, Muchimuk and Brewer were connected in 2009 into one cave system called Sistema Charles Brewer. And so the primacy of the Ojos de Cristal was doubly defeated.

During these expeditions the endemic cave fauna has been described: Grasshopper Hydrolutos breweri (Derka and Fedor 2010) and nearly blind beetle Dyscolus sp. (Moravec et al. In press). Several spider species are awaiting detailed research due to their significant contribution to the development of secondary opal fills, so called Spider stalactites created by capture of aerosol saturated solution of SiO_2 on cobweb fibers.

Other unique secondary fillings are opal stromatolites. These white spherical bodies with a diameter up to one meter or the coatings on the wall are created by single-celled microorganisms. By using the Th/Uh dating it was established that the age of stromatolite with the diameter of 10 cm is 408 thousand years (Lundberg et al. 2010).

3. Summary

The Czech team played very important part in 9 speleological expeditions into the Lost World. In the coming years members of the Czech Speleological Society are planning to continue the research of sandstone caves in Venezuela.

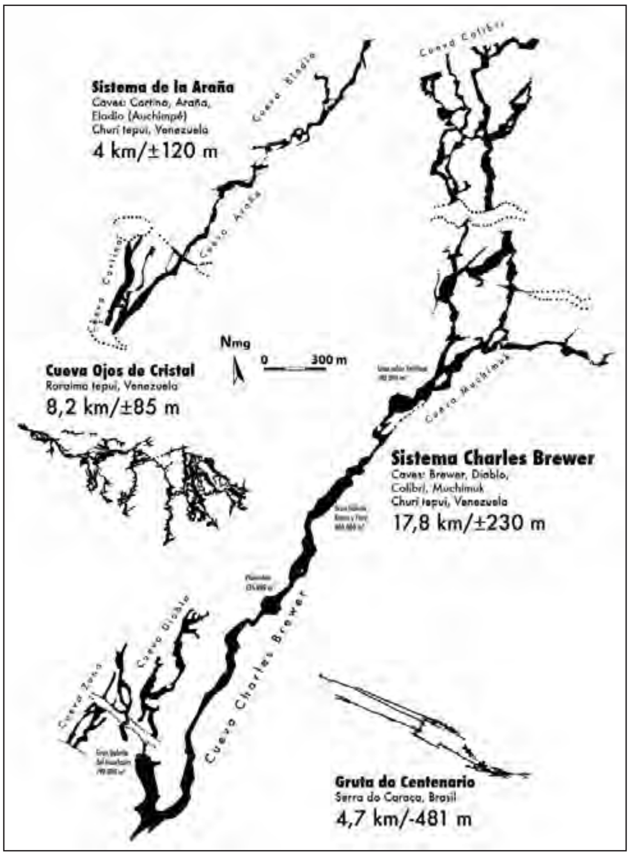

Figure 1. Map of caves on Churí tepui.

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Figure 2. The river flowing through the vast spaces of the Sistema Charles Brewer has a variable flow. During the rainy season the water surface may rise in a few minutes to a few cubic meters per second.

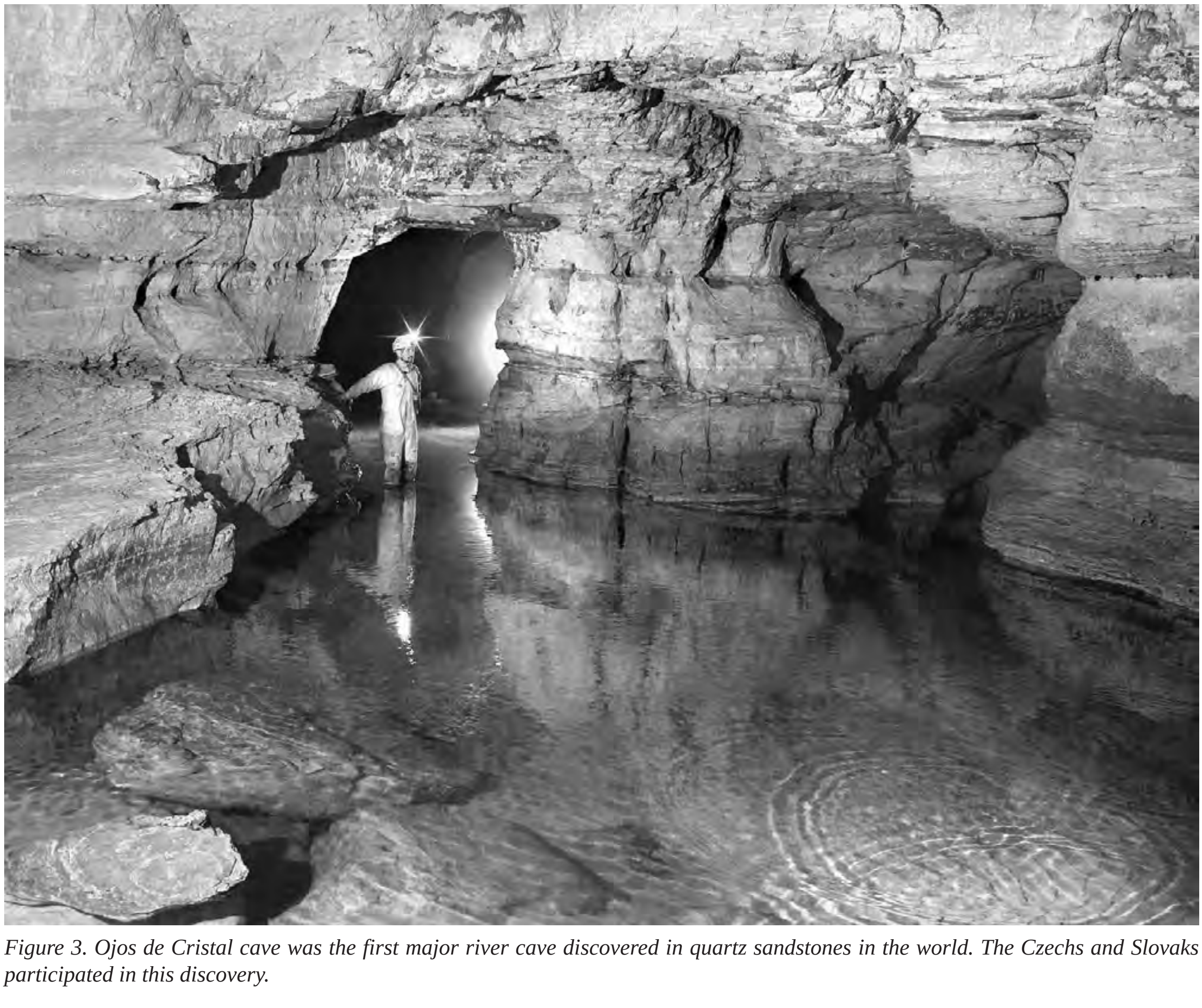

Figure 3. Ojos de Cristal cave was the first major river cave discovered in quartz sandstones in the world. The Czechs and Slovaks participated in this discovery.

Figure 4. Roraima tepui – the mesas of Guyana highlands consist exclusively of quartz sandstone (photo by Charles Brewer Carías).

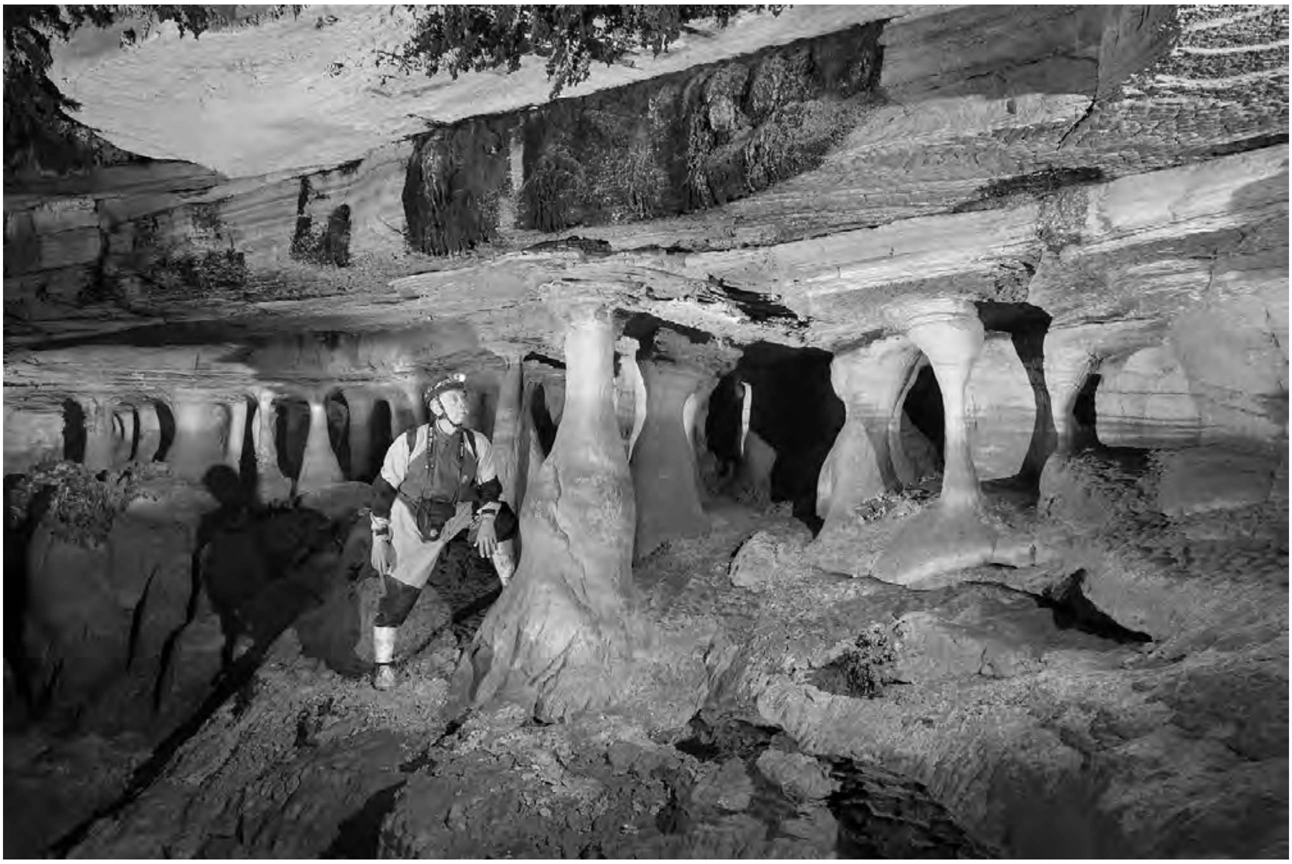

Figure 5. The columns of strengthened parent rock are characteristic feature of sandstone caves. Cueva Eladio – Churí tepui.

NORTHERN VELEBIT DEEP CAVES

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Research of Northern Velebit started in the early 90s by Slovak cavers. From then on, each year at least one caving expedition is carried out in the Northern Velebit. In 22 years in the Northern Velebit area a total of 348 caves were explored of which three caves are deeper than 1,000 m, five caves are deeper than 500 m, nine caves deeper than 200 m, and 27 caves deeper than 100 meters. Other explored caves do not reach 100 m of depth. Most of cave entrances are located at an altitude between 1,400 to 1,600 m.

Basic morphological features of Velebit caves are verticality and the incidence of major verticals. The biggest discovered verticals are located in Patkov gušt (P553), Cave systemVelebita (P513), Meduza (P333) and in Cave system Lukina jama (P329). Five verticals are deeper than 200 m and 100 m verticals are quite common.

The majority of Croatian caving associations participated in the cave research but the most of those expeditions were organized by the Speleological Committee of Croatian Mountaineering Association. During all these years of research an excellent international cooperation was formed with cavers from Slovakia, Hungary, Belgium, Polish, Lithuania, France, Italy, Switzerland, Great Britain, Slovenia, Spain, Bulgaria, USA and Serbia.

In the last four years, there were four expeditions. In the summer of 2009 Lubuška jama was resurveyed and some new parts was explored. During summers of 2010 and 2011 Cave system Lukina jama was resurveyed and also some new parts was explored and in the summer 2012 in Cave system Velebita exploration were continued. Expedition leaders were Luka Mudronja and Ronald Železnjak. Results of these expeditions are presented in this article.

Figure 1. Mt. Velebit position.

1. Introduction

Mount Velebit, with its 145 km in length, is the longest Croatian mountain (Figure 1). Its strike is NW-SE direction, and it spreads over three Croatian regions: Lika, Dalmacija and Hrvatsko primorje.

Northern Velebit is a mountainous region between the Adriatic Sea and the Ličko-Gacko Polje. It begins at the saddle of Oltari in the north and spreads over to the saddle of Veliki Alan in the south with a length of 17 km and a maximum width of the massif of 30 km. The middle part of the massif reaches a height of almost 1,700 m (Mali Rajinac, 1,699 m). Despite being only several kilometres away from the sea, the area of Mount Velebit is influenced by the mountain climate. The mean annual precipitation in Northern Velebit is around 2,000 mm. In the highest parts of the massif, the snow cover remains on the ground for over 100 days in a year. The mean annual temperature is about 4 °C.

Velebit has always attracted people, not only with its valuable flora and fauna, but also with its natural beauty on the border between the mountains and the sea. Ever since the beginning of systematic speleological surveys in 1990, Velebit has constantly surprised cavers.

2. Geology of Northern Velebit

The area of Northern Velebit is composed of lithostratigraphic units ranging from Middle Triassic to Paleogene Age (Mamužić et al. 1969, Sokač 1973, Velić et al. 1974). The Middle Triassic deposits are predominantly composed of limestone. Tuff and tuffite occur laterally in the uppermost part. The lower part of Upper Triassic is

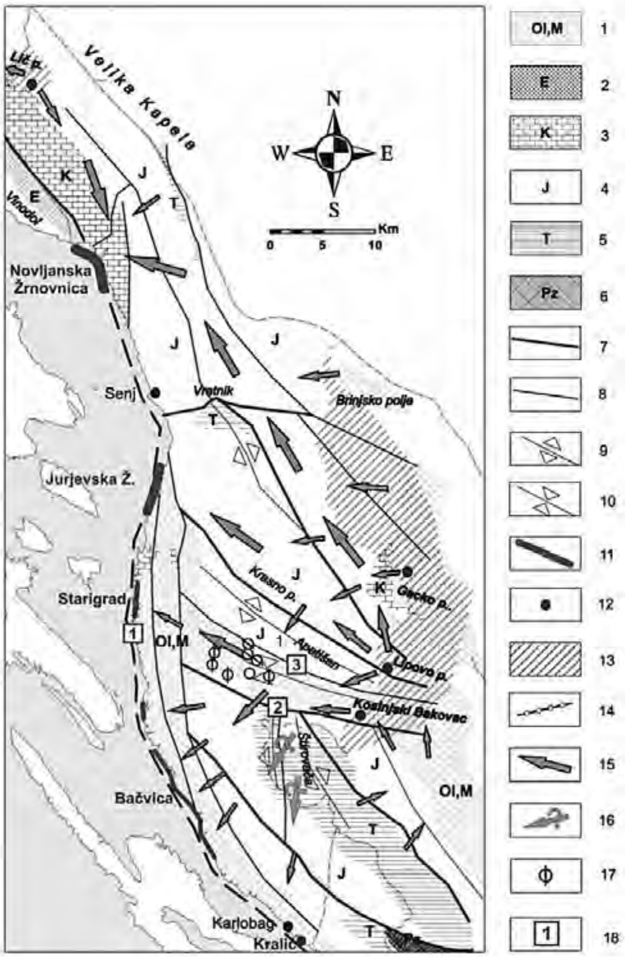

Figure 2. General groundwater flow directions tested by tracing and according geological structure (Prelogović 1989, Prelogović et. al., 1998, Blašković, 1998, Velić and Velić, 2009, Stroj, 2010) 1) Tertiary calcareous breccias; 2) Eocene flysch sediments; 3) Cretaceous carbonate rocks; 4) Jurrasic carbonate rocks; 5) Triassic carbonate and clastic rocks; 6) Paleozoic sediments; 7) Regional fault/fault zone; 8) Significant fault; 9) Anticlinale axis; 10) Sinclinale axis; 11) Regional significant spring zones; 12) Traced sinlholes; 13) Sinking area; 14) Hydrogeological watershed; 15) Groundwater flow direction; 16) Assumed groundwater flow direction; 17) Deep caves main orientation 18) Most important faults.

characterized by the sequence of clastic rocks up to 200 m thick represented by shale and sandstones. Carbonate sedimentation proceeded with 250 m thick dolomite deposits. Due to a lower permeability as the consequence of lithological composition (clastic and dolomites), and structural position in the central part of an anticline structure, the Triassic sediments form the complex hydrogeological barrier of Mt. Velebit. The largest part of Northern Velebit is composed of Jurassic sediments, which have deposited continuously under almost identical conditions and which contain carbonate rocks only. Limestone prevails in the composition of deposits, but dolomites are also present. Generally, Jurassic sediments are very permeable units, but in some locations dolomite inhibits groundwater flows and acts as a relative barrier (the Apatišan area) (Pavičić, 1997). The thickness of Jurassic deposits is approximately 2,850 m. However, speleological explorations have revealed a more complex geology of Northern Velebit. For example, Lukina Jama contains deposits of carbonate breccias from -450 to -700 m and from -750 to -950 m. A similar situation occurs in Slovačka Jama as well. This poses a number of questions related to their stratigraphy and tectonic movements (Lacković 1994, Šmida 1999).

In the investigated area, the well permeable Cretaceous sediments have not greater importance. At a narrow belt along Adriatic coast they are represented by limstone-dolomite alteration. In the Lika region on the side of Mt. Velebit (Lipovo polje) deposits are composed of limestones intercalated by dolomite and calcareous breccias.

The significant part of the area concerned is covered by Jelar formation of Upper Paleogene age. Its origin is closely related on strong tectonic movements, which effected the area during that time (Bahun, 1974). In the hinterland (Lika) they are partially permeable but in the higher positions on Northern Velebit calcareous breccias are highly permeable.

This can best be seen in the spectacular landscape of Hajdučki and Rožanski kukovi area (*Figure 3*), as well as the numerous karstic phenomena and the deepest caves of Croatia among them. The thickness of calcareous breccias is up to 300 m (Kuhta and Bakšić, 2001).

The geological structure is the consequence of two main periods of tectonic activity. During the Tertiary tectonic cycle, which lasted from Eocene to the end of Miocene, compressive movements oriented NE-SW reached their cumulative maximum with orogenesis of the Dinarides. As the consequence of mentioned regional tangential stress, the deep nappa structures, folds and regional faults of Dinaric strike (NW-SI) have been formed. During the later, Neotectonic period, the main stress changed to N-S, resulting in further uplift and transpressive deformation of older structures, which were broken in the smaller structural units and tectonic blocks.

On the basis of geology of the studied area and the basic tectonics involved, distinctive areas, structural units and

Figure 3. Rožanski kukovi on Northern Velebit.

faults that influence the hydrogeology of the terrain and karstification processes development presented on *Figure 2*. Numbers mark the most important faults that effected the development of numerous deep caves in the investigated area.

The regional longitudinal reversal Velebit fault (1) located in the coastal area, on the surface manifested as 4–6 km wide faulting zone, represents the boundary between Dinaricum and Adriaticum megastructural units. The tangential movement is estimated on 6–8 km.

The Bakovac fault (2) is very strong normal fault. The horizontal movements along it are not observed but the vertical displacement is estimated on about 1,500 m (Prelogović, 1989). After Blašković (1998) this fault is reversal whitch means different hidrogeology interpretation. The fault interrupted extension of the Velebit complex barrier and significantly effected the hydrogeological relations in the area. In geomorphologic sense, the Bakovac fault represents the boundary between Middle and North Velebit.

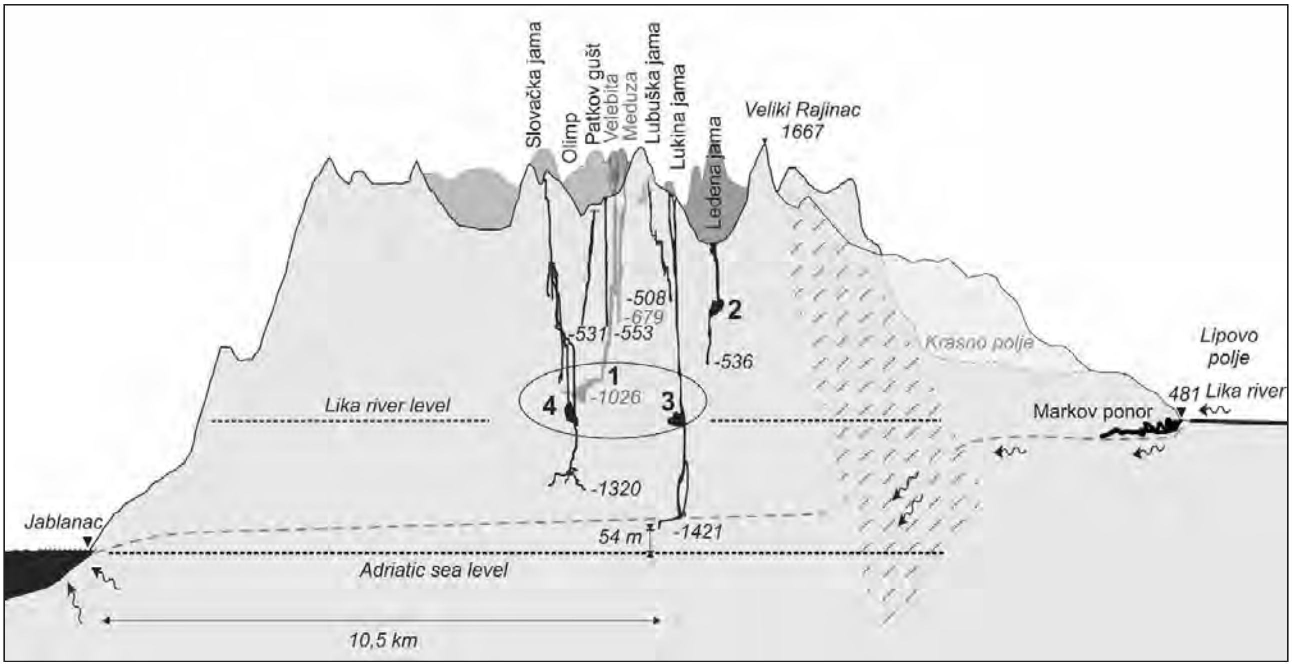

Figure 4. Cross section of Northern Velebit massif with profiles of deep pits. Big Halls are shown with numbers: 1 – in Cave System Velebita – 253,260 m^3; 2 – in Ledena jama – 192,000 m^3; 3 – in Cave System Lukina jama – 118,750 m^3; 4 – in Slovačka jama – 72,000 m^3.

The Lomska Duliba fault (3) is located on the northern boundary of the investigated area. The vertical displacement is estimated on 150 m.

All mentioned faults have been very active during Neotectonic period. The vertical neotectonic movements were estimated on the basis of deformations of the Jelar formation, position of the Pliocene and Quaternary deposits, comparison with neighbouring areas and disposition and deformation of geomorphologic elements. In the area concerned, the summary amplitudes of these movements reach 1,600 m.

Speleological exploration of deep caves on the Northern Velebit show a very deep vadose zone within the central part of the carbonate massif. Considerably higher underground water level in the sinking areas indicates a sudden fall of the water level in the east part of the massif.

One of the reasons for this can be the hydrogeological function of active fault zones which might act as partial barriers for underground water flows. The active faults partially direct underground water flows parallel to their own strike (toward NNW) in the upstream area, but also dispersing and allowing the restrained flows to pass directly toward the Velebit channel at the same time (Figure 2).

Another reason is sought in the process of retrograde karstification caused by uplifting of mountain massif, i.e. lowering of the erosion basis. Influence of active fault zones and advancement of the karstification process are not mutually exclusive, but probably act together. The karst areas upstream (Lika hinterland) and downstream (Velebit Mountain Massif) from the zone of sudden water level fall are hydraulically mutually separated, and can be analyzed as separate parts of the cascade system. This enables significantly different directions of underground flow within different parts of the system (Stroj, 2010).

Mentioned tectonic activity, the emergence of concentrated flows of water which descend to the bottom of deep sinkholes in times of climate change and melting of glaciers. Tertiary carbonate breccia resistance to mechanical erosion enabled remarkable development and preservation of corrosion landforms (ledges), inside of which the entrances of the most important caves are situated. Smaller glaciers of the peak segments of the relief did not have enough ice mass and pronounced horizontal movement that would destroy karst morphology of the terrain below. Finally an important factor and is a very deep vadose zone within the carbonate massif.

3. Northern Velebit pits

Research of Northern Velebit started in the early 90s by Slovak cavers, members of the Speleology Club of Comenius University. From then on, each year at least one caving expedition is carried out in the Northern Velebit.

In 22 years in the Northern Velebit area a total of 348 caves were explored of which three caves are deeper than 1,000 m, five caves are deeper than 500 m, nine caves deeper than 200 m, and 27 caves deeper than 100 meters. Other explored caves do not reach 100 m of depth. Most of cave entrances are located at an altitude between 1,400 to 1,600 m.

Basic morphological features of Velebit caves are verticality and the incidence of major verticals (Figure 4).

The biggest discovered verticals are located in caves: Patkov gušt (P553), Cave system Velebita (P513), Meduza (P333) and in Cave system Lukina jama – Trojama (P329) (Bakšić 2006). Five verticals are deeper than 200 m and 100 m verticals are quite common. Vertical morphology of the pits is most distinct in the parts built of massive tertiary breccia that is why after entering the older stratified deposits, probably of Jurassic age, this morphology is partly alleviated.

The reason is unbedded breccia, for which the karstification relates solely to systems of steep to vertical cracks. Great persistence and low incidence of cracks in the breccia favors the development of extremely deep and spacious verticals, which typically occur at the intersections of cracks. Concentrating of flows towards the most permeable parts of the rock mass mechanisms of epikarstic zone is the most important factor in the development of large underground vertical dimensions.

Verticals formed that way are beneath the surface, without an external entrance (example is the large vertical in Cave system Velebita) and due to denudation of the surface ground external entrance for some pits was subsequently opened (Patkov gušt).

In older carbonate beds, under the influence of higher density discontinuity and slightly inclined layer surfaces, canals are generally somewhat less steep, with smaller pits and narrower meanders. It must be noted that the lower parts of these caves are also very vertical.

Vertical morphology of caves in vadose zone of Northern Velebit massif indicates the abrupt rise of this terrain, whereby there was probably not enough time for the formation of significant horizontal phreatic and epiphreatic channel systems at different altitudes in the massif. Interesting phenomena are large halls (Figure 4 – Velebita 253,260 m^3, Ledena jama 192,000 m^3, Lukina jama 118,750 m^3) and smaller halls and fragments of the horizontal channels (Slovačka jama – hall 72,000 m^3), whose formation is associated with vadose flows within the massif, and are in the range from 494 to 563 m above the sea level, high above the present phreatic zone, but 13 to 82 m above Lika river sinkhole.

Only the hall in Ledena jama is at slightly higher altitude between 924 and 957 m. These subterranean spaces are traces of the earlier stages of karstification, which were largely disintegrated and fragmented in more recent tectonic movements. Figure 5 shows plans and dominant direction

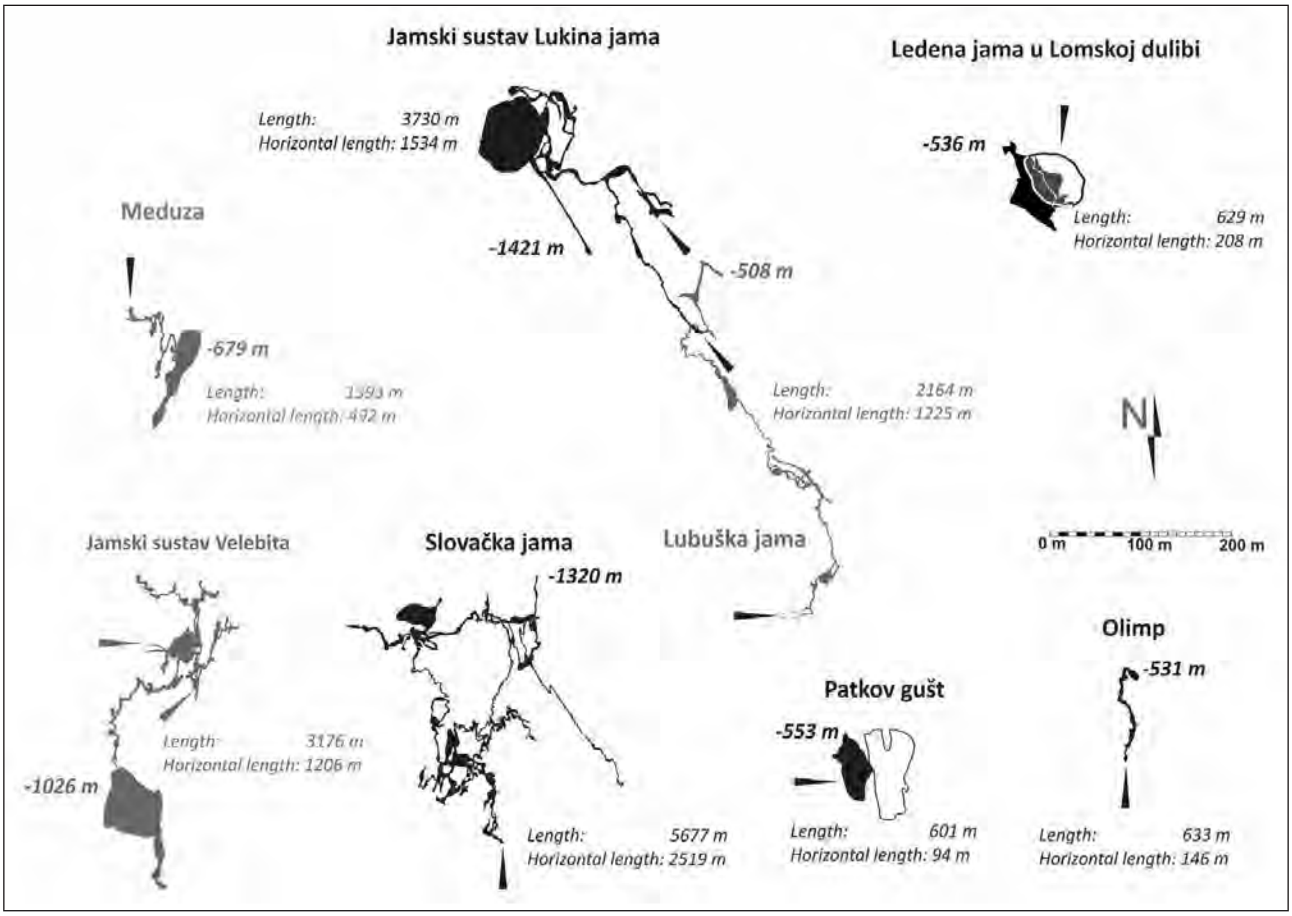

Figure 5. Plans of Northern Velebit deep caves.

of channels of most significant caves in the Northern Velebit. According to the directions of channels dominant orientation discontinuity by which the karstification occurred can be well observed.

Lukina jama and Lubuška jama channels (both located in Hajdučki kukovi partially overlapping in plan) are dominantly oriented in NW–SE direction, and subordinatly in NNW–SSE and SSE–NNW. Slovačka jama (Rožanski kukovi) formed to an equal extent by orientation systems NW–SE and NNE–SSW and is less pronounced in NE–SW.

Cave system Velebita (located in the westernmost part of Rožanski kukovi) predominantly oriented in NNE–SSW direction and subordinately in WNW–ESE and NE–SW. In Meduza cave, also located in the western part of Rožanski kukovi orientation of the channels are very similar to those in Velebita, with even more pronounced dominance of channel oriented in NNE–SSW direction.

Directions of the channels are largely in line with structural features. From directions of channels increasing importance of discontinuity of orientation NNE–SSW is noticeable in the Northern Velebit in a westerly direction, probably as a consequence of approaching the zone of Velebit fault. At the direction of east, the greatest influence on the direction of development of karst channels are gradually taken over by discontinuities oriented in NW–SE.

In caves occurrence of snow and ice is relatively common. In 118 pits (34 %) snow and ice was recorded. Usually if forms at the depth of 50 m and goes even up to a depth of over 500 m. The deepest recorded occurrence of snow and ice was in Patkov gušt cave at a depth of -553 m and it was the snow and ice that fell mainly in the higher parts of the pit. Increased melting of snow and ice over the past 20-odd years was observed (opening passages in the depth).

The majority of Croatian caving associations participated in the cave research of Northern Velebit but he most of those expeditions were organized by the Speleological Committee of Croatian Mountaineering Association. During all these years of research an excellent international cooperation was formed with cavers from Slovakia, Hungary, Belgium, Polish, Lithuania, France, Italy, Switzerland, Great Britain, Slovenia, Spain, Bulgaria, USA and Serbia.

4. Resuls of new caving expeditions

In the last four years, during summers, there were four expeditions: "Lubuška jama 2009", "Lukina jama 2010", "Lukina jama 2011" and "Velebita 2012". Expedition leaders were Luka Mudronja and Ronald Železnjak.

Entrance to Lubuška jama was found on 11/09/2000 by Polish cavers from Bobry Žagan ans Gawra Grozow associations accompanied by cavers from SO PDS Velebit from Zagreb. During two expeditions they explored Lubuška jama to a depth of -521 m. Possibility of further progress and connection to the Cave system Lukina jama encouraged the organization of expedition 2009 to try to find a passage to the Cave system Lukina jama.

Expedition in the Cave system Lukina jama was made for resurveying and because of the dive into a siphon at the bottom of the cave, while the expedition at Cave system Velebita was made to explore promising parts of the cave.

4.1. Expedition "Lubuška jama 2009"

During expedition to Lubuška jama in 2009 a new map of the cave was drafted M 1:500. According to the newly created map, depth of the pit is smaller and amounts to -508 m and the length increased to 2,164 m.

The most important finding of this expedition was, most likely, a new species of stigobiontne leech currently on DNA analysis.

4.2. Expeditions "Lukina jama 2010" and "Lukina jama 2011"

A new map of Cave system Lukina jama" from the entrance Trojama (Manual II) to the bottom of the cave was made. However, drawing of the Cave system Lukina jama from the entrance Lukina jama to the junction of Trojama could not be repeated because at 60 m of depth in Lukina jama an ice-snow cap prevented the passage.

Newly determined depth of the Cave system Lukina jama is -1,421 m (poligon was made to a depth of -1,409 m). Length is 3,730 m and the volume is about 313,000 m^3.

By comparing the map of Lukin jama made in 1993 and 1994 with the one made in 2010 (Figure 6) it was concluded thet the maps differ for 0.94 %. According to UIS Mapping Grades (Häuselmann 2012) the mark would be UISv2 5-4-BF.

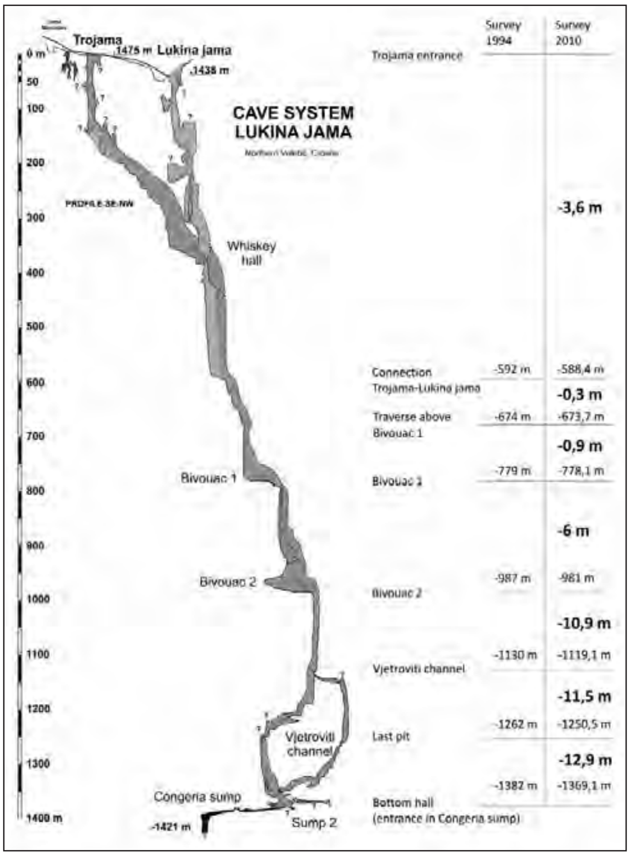

Figure 6. Comparison of two surveys of Cave system Lukina jama from 1994 and 2010.

Junction of "Vjetroviti channel" with the bottom of the pit was proven.

During 2010 expedition two dives were made in Congeria siphon at the bottom of Lukina jama. The first dive in the length of 135 m and depth 20 m were made by Ivica Ćukušić and Robert Erhardt, and the second dive in length from 135 to 40 m depth was performed by Branko Jalžić.

On this occasion living specimens of cave *bivalves (Congeria kusceri)* were found in the siphon, which determined the second known populations of shellfish in Lika, and fourth in Croatia. Unexpected finding was so far the only known underground cave sponge *Eunapius subterraneus* (Bilandžija et al. 2012; Bedek et al., 2012). There is significant biospeleological finding of one new springtails species *Disparrhopalites* sp. nov. provisionaly assigned to genus *Parisotoma* (Čuković and Lukić 2012).

During expeditions 2010 and 2011 scientific research of Cave system Lukina jama was conducted on 20 measuring points from the entrance to the bottom. Cave geology, microclimate parameters, radon concentration, water quality and dynamics were investigated.

4.3. Expedition "Cave system Velebita 2011"

The main goal of this expedition was to continue previous scientific research (Paar, 2008) of geological, physical, chemical and biological properties of the cave (scientific project "Investigation of deep pits of North Velebit National park"). There is significant biospeleological finding of one new springtails species of the genera *Tritomurus* (Čuković and Lukić 2012).

Cavers was continued in promising and open channels in Velebita vertical shafts, but they failed to go further. During the expedition, 43 new caves were found. Their exploration will continue in 2013.

5. Conclusion

Cave research of Croatian deep caves spurred the development of the Croatian caving, scientific research, development of cave rescue and enabled international cooperation.

Acknowledgments

We thank the Northern Velebit National Park for their cooperation and support in speleological research.

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BEST-PRACTICE TRAINING APPROACHES FOR MITIGATING CAVING HAZARDS AND ENHANCING CAVE EXPLORATION TECHNIQUES FOR SMALL GROUPS OF CAVERS

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Close calls, a.k.a. near misses, were studied to identify environmental conditions and human behaviors associated with root cause hazards that could lead to mishaps during cave exploration. Subsequently, training approaches were examined to establish best practices that could be used to inform cave explorers about major caving hazards, thus helping to mitigate potential for hazards becoming undesired events. Online questionnaires were completed by an international audience of cave explorers to determine environmental conditions and human acts related to close call events experienced or observed during cave exploration. As reported by survey participants, close calls were associated with vertical exposure, rockfall, cave surface integrity, lack of attention, misestimation of the integrity of the cave surface, and physical exhaustion. Interviews were conducted with caving experts to ascertain perceptions of best-practice training techniques for optimizing training curriculum development in order to better inform cave explorers about cave hazards. Based on the findings of this study, a focused training technique is proposed for the audience of smaller group, less-experienced cave explorers to effectively inform and prepare them to overcome hazards in caving as well as to enhance their overall cave exploration experience.

1. Introduction

Caving for recreational and scientific purposes is a very fulfilling and worthwhile endeavor. Many thousands of people safely visit caves each year to engage in scientific, physical, and personal exploration. However, for those who are not adequately prepared, great risk may be taken by entering a cave. Caving is known to be a dangerous activity. There have been numerous injuries and deaths in caves that could have been avoided had the individuals involved taken action to prepare for hazards associated with cave exploration. While it is impossible to address or prepare for every situation in a cave, it is fully possible, and a collective responsibility, to take whatever actions we can to avoid adverse situations and overcome hazards that could lead to injuries, illnesses, or deaths of individuals. Hazards in caves are known to include darkness, poor contact with surfaces, water, temperature, rock fall, and inattention. In addition to these, Sparrow (2009) includes biological hazards and Burger (2006) adds bad air. Both authors also discuss cave complexity as a hazard. However, hazards alone represent only the potential for what may occur. In reality, it is the combination of undesirable human acts and adverse environmental conditions that allow a hazard to become a mishap.

Training is used to inform about hazards and to prepare for safe and effective exploration. Through training and education, cavers' awareness of the hazards associated with caving increases, thereby reducing likelihood of injuries, illnesses, and fatalities. Training and education also can have the benefit of enhancing the experience of visiting the cave. Thus, through adequate preparation, the cave explorer will become knowledgeable of the hazardous cave environment and skillful in the traverse thereof, making the experience positive and beneficial.

2. Methods

Data were obtained through an online questionnaire available to cave explorers from May 2011 through January 2012. In addition, interviews were conducted with caving experts in February and March 2012. The online questionnaires consisted of sixteen questions designed to reveal information about the environmental conditions and human acts associated with close call events that occurred during cave exploration (see Table 1). The US-based National Speleological Society assisted with questionnaire distribution via emails to Society members. In addition, URLs linked to the questionnaire were posted on the Cave Chat (US) and UKCaving.com online discussion forums. It is likely that subsequent distribution of the questionnaire URLs occurred through personal and group emails.

Table 1. Categories in close calls questionnaire.

Category	Questions in category
Characteristics of cave explorers involved in the close call	3
Characteristics of the cave in which the close call event occurred	4
Conditions present in cave when close call event occurred	3
Human acts and behavior associated with close call event	4
Specifics of close call event	2

Individual interviews were conducted by email with eleven caving-skills training experts from Austria, United Kingdom, and United States (see Table 2). They were each asked ten questions related to caving-skills training, hazards in caves, and perceived impacts of training.

3. Results and discussion

A total of 181 responses were received for the online questionnaire on close call events in cave exploration. Respondents were from the US (81 %), UK (9 %), Mexico (4 %), Austria (1 %), and Spain (1 %). The remainders were individual responses from Afghanistan, Belize, Canada, New Zealand, and Ukraine. Among the respondents, 56 % reported having had formal caving-skills training, 37 % reported having informal caving-skills training, and the remainder reported having none. Responses revealed that vertical exposure, rock fall, and poor contact were the most prevalent environmental hazards leading to cavers experiencing a near-miss event. Responses also revealed lack of attention, overestimating quality of contact with the cave surface, and exhaustion as the three most prevalent human acts related to near-miss incidents in caves.

Table 2. Experts interviewed for this study.

Name	Organization
Christian Berghold	Austrian Speleological Association, AUT
Christopher Binding	Association of Caving Instructors, UK
Jansen Cardy	National Speleological Society, National Cave Rescue Commission, US
John Harman	West Virginia University Student Grotto, NSS, US
Patricia Kambesis	International Projects, Cave Research Foundation, US
Allen Maddox	Philadelphia Grotto, NSS, US
George Plant	Carlton Lodge Outdoor Centre, ACI, UK
Philip Rykwalder	Cave Now, Inc, US
Geary Schindel	Edwards Aquifer Authority, US
Gregory Springer	West Virginia Association for Cave Studies, US
George Veni	National Cave and Karst Research Institute, US

The eleven caving skills experts interviewed for this study were asked to choose just one hazard of caving. Four of eleven selected falls and/or gravity, two indicated water, two selected hypothermia, two selected misestimation and lack of attention, and one selected rockfall. While it is not possible to directly compare near-miss events to mishaps resulting in injury or death, it is useful to look at the more-prevalent hazard occurrences in both categories. Among mishaps, falls occur most frequently in US caves (Keeler 2011). This corresponds with accidents at home and at work, where falls are also the highest prevalence mishap. The second most-prevalent mishap occurring in US caves involves equipment issues. Rockfall is next, followed by being trapped or stranded. Finishing the list for mishaps is being lost. For close calls, however, the list is somewhat different. Most prevalent among close calls is vertical issues, followed by rockfall, slippery surfaces or other poor contact conditions, water-related hazards, and being trapped or stranded. Tables 4a and 4b contain complete response information from the close calls portion of this study.

The interviewed experts responded to a number of questions about caving-skills training. Of the responses, six of the eleven indicated that training would be more effective if it was conducted in the cave environment. Three believe it is most effective if first conducted on the surface then underground and two believe it is best conducted in a classroom setting. Questions were also asked about potential negative outcomes of caving-skills training. Six of eleven indicated that overconfidence could be a negative outcome, two reported that there would be no negative outcomes, and one each indicated poorly designed curriculum, inflexible training requirements, and increased impact on the cave environment.

Table 3. Top five most prevalent mishaps and close calls in US cave exploration.

Mishaps*	Close calls
Falls	Vertical
Equipment issues	Rockfall
Rockfall	Slippery, poor contact
Trapped/Stranded	Water related
Lost	Trapped/Stranded

*Keeler, R. (2011), American Caving Accidents.

The interviewed experts were asked for their definitions of formal caving skills training. A majority indicated that formal training is equivalent to courses that are designed and structured. Others commented that passing of experience and knowledge in a structured way would also constitute formal training. Regardless of the nuances, all but one expert agreed that formal caving-skills training is effective for reducing the chance that cave explorers could be injured or killed while traversing caves. Patricia Kambesis, states, "*Training…is the most proactive means for providing cavers with a toolbox of techniques, skills, mindset, and philosophy*." Jansen Cardy suggests that training can reduce chances of mishap through teamwork because "*…students are taught to communicate and work together to achieve a common goal.*" Christopher Binding states, "*…formal training is a distillation of the experiences and techniques of many hundreds of person-years of caving knowledge* (that) *massively advances the trial-and-error approach*." Lastly, George Plant adds that because formal training brings together people with experience and qualification, "*…we can avoid making the same mistakes*" that others may have already made. Collectively, it is clear that those with extensive knowledge and experience of caves and caving value training.

This outcome is consistent with research findings by Bird, Sawa, and Wiles (submitted, in review) in which over 90 % of UK and US cavers (n = 133) responded to a questionnaire and indicated that both formal and informal training allows them to more safely explore caves. This research further established that informal caving-skills training is very prevalent, and appears to be effective. Philip Rykwalder notes, "*…the injury/death rate among skilled cavers is low – surprisingly low – for the amount of risk we take and the number of trips that we go on weekly.*"

Informal training may be likened to the mentor-apprentice model where growth in knowledge and skill occurs

Table 4a. Hazardous conditions associated with close calls in cave exploration.

Of the hazardous conditions listed below, which do you feel were associated with the close-call event (near miss) you experinced or observed? (Select all that apply.)	
Hazardous condition	**% Responses (n = 165)**
Vertical exposure	45.1
Rockfall or rock-shofting potential	36.1
Slippery or other poor contact conditions	29.9
Water, other than high or deep water	18.8
Tight cave passage	16.7
Temperature too high or too low	14.6
High or deep water	7.6
Bad air	4.9

Table 4b. Human acts associated with close calls in cave exploration.

Of the human-related acts listed below, which do you feel were associated with the close-call event (near miss) you experienced or observed? (Select all that apply.)	
Human Acts	**% Responses (n = 111)**
Not paying attention	46.9
Did not check integrity of contact point	23.4
Became exhausted	16.2
Did not inspect equipment	14.4
Entered cave beyond current abilities	12.6
Tight cave passage	13.5
Chose incorrect clothing or footwear	12.6
Attempted movement (climb, squeeze, descent, etc.) beyond abilities	12.6
Misestimated water depth	2.7
Inadequate lighting (batteries not charged, lack of backup lights)	1.8

gradually over time, usually through on-site learning and practice. Many regard this approach as more desirable than formal training. Informal training is certainly more personable, as it is likely conducted in one-on-one settings or in small groups. Trainees may feel more comfortable in this learning environment and thus may receive guidance more readily, as well as more freely provide feedback about their current status, which the trainer can use to further enhance the learning experience. However, informal training is possibly conducted with fewer rigors than formal training, which means that important materials may not be covered in great enough detail or may be missed altogether. Informal training is further contrasted with formal training in the settings where learning occurs. Formal training is usually conducted in a designed environment, such as a classroom. Trainees are then walked through exercises in a controlled environment above ground and then guided through the exercises in a relatively controlled environment in the cave. While a large number of research participants have indicated that informal training is preferred and effective, one of the key upsides of formal skills training is that it can be delivered to larger groups of people. Furthermore, because it is a designed teaching approach, it will necessarily have established learning objectives, a means for delivering the curriculum, and metrics for measuring learning outcomes. However, there are downsides, as well. In particular, people who prefer to be taught in smaller groups or who have slower learning paces may have more difficulty retaining the delivered information in a structured environment.

With informal, apprentice-style training, – assuming a qualified and experienced mentor – the learning and demonstration of outcomes usually happens at the student's pace. It has been shown that a reflection period after introduction of new material helps to enhance learning (Bleakley 2000). With formal training, this may or may not occur, depending on the design of the curriculum. For informal training, this likely occurs naturally and may indeed be the reason why informal training appears to be so successful.

Whether training is formal or informal, for most-effective teaching and learning, the training should be designed. Learning objectives should be established up front and from there different teaching approaches would be applied, as appropriate, to address the needed topics of instruction. Having structure, Geary Schindel states, is more effective because it "…*allows you to cover more issues more quickly.*" In addition to the structure of the course, knowledge and skill of the instructors or mentors is also essential. John Harman suggests, "…*the best way to learn is to do serious caving with people that have advanced skills and lots of experience*." Thus, by combining some structure through the establishment of learning objectives with extensive knowledge and skill of highly experienced individuals, the training can be conducted more efficiently and the result can be more effective.

Quality of instructors is paramount to successfully bring others to a high level of cave exploration functionality. Even so, on the receiving end, the learners' capabilities to absorb information and understand concepts, techniques, tools, the cave environment, and their own behaviors in the cave are

Table 5. Questions to consider for designing caving-skills training.

Questions
Training goals established by mentor and trainees in concert?
Mentor/Instructor knowledgable, skilled, and experienced for helping trainees to achieve goals?
What are the trainees' learning styles?
What are the trainees' experience levels?
What are the learning objectives that flow from the overall training goals?
What are the ideal/desired training locations?
What specific teaching and learning tasks need to be accomplished to achieve learning objectives?
How will trainees' learning be measured?

just as important. Previous research conducted by the authors revealed that cavers are generally of post-college ages and thus could be classified as adult learners.

For most effective caving-skills training, it is especially important to develop strategies that cater to the needs of the adult caver. A preferred method of teaching adult learners is with "hands-on learning" which is a concept used quite frequently in informal, apprentice-mentor style for training because there is an opportunity for trainees to practice and receive constructive feedback (Olivero, Bane, Kopelman 1997) and reflect on their experiences (Bleakley 2000).

Focusing on "discovery learning" optimizes adult-style learning. In this approach, the individuals are motivated to learn through their desire to understand in detail what they are learning (Knowles et al. 1998). George Veni shares, "*Using a cave* [for training] *also tends to create a better respect and appreciation for caves than I've ever been able to relay in a classroom,*" and adds that "*caving conditions can be simulated on the surface, but do not simulate the psychological element found in the natural environment.*" A plurality of experts interviewed for this work indicate that if a single learning environment must be chosen, it is to conduct training in the cave. It is known that adult-style discovery learning is best accomplished in the environment where the work will be conducted. Even so, a caution may be in order. Christopher Binding notes, "*…trainees tend to be distracted from listening by being keen to get hands-on with the shiny bits of kit nearby.*" This comment emphasizes the importance of maintaining the learners' attention before engaging in active components of the training.

Several experts recommend that a combination of training locations, such as classroom followed by in-cave, hands-on training can be very effective. The structured classroom setting with few distractions will allow for clear delivery of instructions, which can then be followed by discovery learning shortly thereafter in the cave environment. This very model has been used by a number of organizations that routinely conduct training and education related to caves and caving, namely the Association of Caving Instructors, the Austrian Speleological Association, and the Hoffman Institute at Western Kentucky University. Schindel suggests that the classroom lecture may be better suited for facilitating discussion of hazards associated with caves in general, while "*…in-cave training may work work well for hazards associated with the cave…*" in which the learning is taking place. Gregory Springer adds that during in-cave exercises, instructors or mentors "*…can point out specific hazards and correct mistakes as they see them.*" Allen Maddox states, "*For the novice, I like classroom type followed by in-cave activity*." Christian Berghold agrees, "*…that exercises alone won't suffice,*" and adds, "*…a combination of classroom lectures…and in-cave training*" in addition to dry, outside-the-cave exercises are best for delivery of content. Binding recommends that after information is delivered in a classroom-like environment, the hands-on experience in the cave will allow cavers to "*immediately define and apply specific dynamic examples with compelling relevance*." He further makes the recommendation that training should be limited to small groups of a few people at a time, especially for single rope techniques.

Based on outcomes of the expert interviews, several clear themes emerge: (1) training should be designed and conducted in a step-by-step manner, (2) training should be conducted by those with appropriate levels of knowledge and experience, (3) learning environments should be optimized for best retention of material, (4) curriculum should be specific for the hazards and topics being addressed, and (5) class sizes should be small. Further, based on literature research, (6) the learning styles and experience levels of the trainees should be assessed to determine best delivery of content for the audience being trained. It should be noted that the above numbered themes are areas where training bodies such as ACI, NCRC, ASA, etc. have for some time successfully applied best-practice caving-skills training approaches. These groups have curriculum development and review committees who vet content so that it is up-to-date and pertinent to the training being conducted. However, research by Bird, Sawa, and Wiles (submitted, in review), revealed that informal training conducted at the level of caving clubs and among individuals is very widespread and thus the benefits of the larger caving-skills training organizations may not be felt by many cavers and potential cavers. Further, a review of injury and fatality reports shows that lack of experience and lack of effective training are often causes for mishaps (Keeler 2011). Following from this, the tailored training approach presented here is focused toward smaller groups of less-experience cave explorers and incorporates guidance for developing checklists (Seifert 2009) in order to ensure that important aspects are covered. Table 5 proposes a number of questions that may be helpful in the initial design of the training curriculum.

Answering the questions in Table 5 requires knowing the cave conditions and human actions that will be addressed through training, hence the importance of the mentor being knowledgable and experienced for the caves and caving regions for which training is being prepared. For novice-level cave explorers, referencing the most prevalent caving hazards and close calls provides a good starting point. For example, Table 3 lists falls as a common mishap or close call in caves, so a primary training objective could be to successfully move through the cave without falling or stumbling. The learning objective in this case is for the trainees to develop balance and movement strategies that allow them to remain in control of their bodies as they move through the rocky, slippery, and otherwise uneven surfaces of the cave. After answers are established for the questions

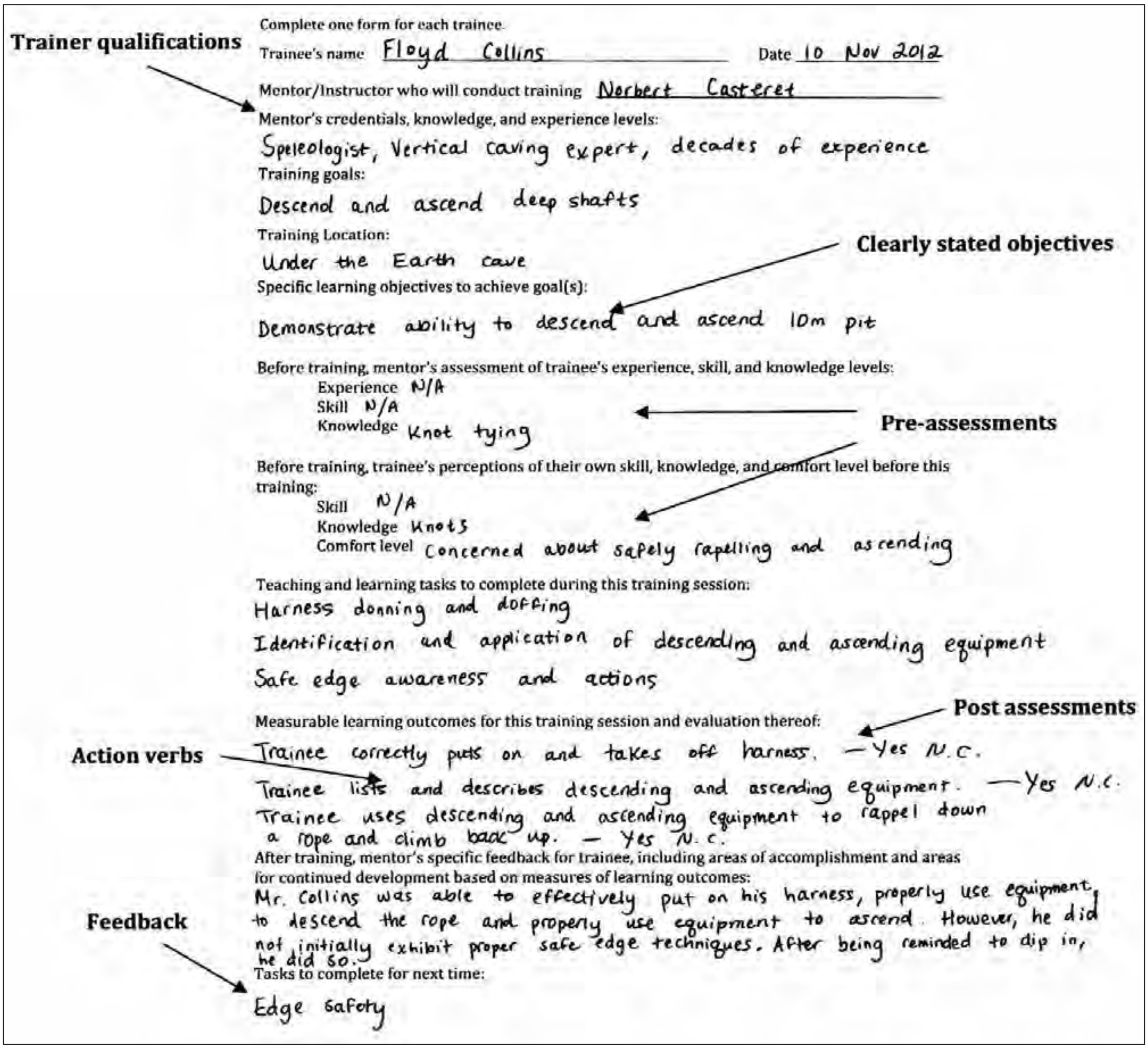
Trainer qualifications
Complete one form for each trainee.
Trainee's name Floyd Collins Date 10 Nov 2012
Mentor/Instructor who will conduct training Norbert Casteret
Mentor's credentials, knowledge, and experience levels:
Speleologist, Vertical caving expert, decades of experience
Training goals:
Descend and ascend deep shafts
Training Location:
Under the Earth cave
Clearly stated objectives
Specific learning objectives to achieve goal(s):
Demonstrate ability to descend and ascend 10m pit
Before training, mentor's assessment of trainee's experience, skill, and knowledge levels:
Experience N/A
Skill N/A
Knowledge Knot tying
Pre-assessments
Before training, trainee's perceptions of their own skill, knowledge, and comfort level before this training:
Skill N/A
Knowledge Knots
Comfort level Concerned about safely rapelling and ascending
Teaching and learning tasks to complete during this training session:
Harness donning and doffing
Identification and application of descending and ascending equipment
Safe edge awareness and actions
Post assessments
Measurable learning outcomes for this training session and evaluation thereof:
Action verbs
Trainee correctly puts on and takes off harness. — Yes N.C.
Trainee lists and describes descending and ascending equipment. — Yes N.C.
Trainee uses descending and ascending equipment to rappel down a rope and climb back up. — Yes N.C.
After training, mentor's specific feedback for trainee, including areas of accomplishment and areas for continued development based on measures of learning outcomes:
Feedback
Mr. Collins was able to effectively put on his harness, properly use equipment to descend the rope and properly use equipment to ascend. However, he did not initially exhibit proper safe edge techniques. After being reminded to dip in, he did so.
Tasks to complete for next time:
Edge safety

Figure 1. Sample training form for preparing a caver descend and ascend a 10-meter pit.

in Table 5, a more-specific form (Figure 1) can be used to clearly state the components of the training that will be conducted to address the particular hazard.

Another example could be vertical issues, which is the first close call listed in Table 3. This hazard is significant as it could lead to serious injury or death. Figure 1 is a sample form completed for a training scenario to descend and ascend a 10-meter pit. It is important to establish measureable learning outcomes for which a clear evaluation can be made. For example, in the given scenario Mssr. Casteret evaluates Mr. Collins' ability to identify and apply vertical caving equipment. The learning outcomes are as follows: list and describe equipment used for ascending and descending a 10 m pit; demonstrate ability to use ascending and descending equipment to safety rappel into and ascend out of a 10 m pit. At the bottom of the form, Mssr. Casteret provides feedback to Mr. Collins about actions he can improve upon. The form used in the example scenario is just one way of keeping track of small-group training learning objectives, learning outcomes, and feedback to trainees. Mentors and trainees are, of course, free to use whatever approach they would like for the specific training they are conducting. However, it is important to establish the goals, measure the outcomes, and provide feedback, regardless of which training design or record-keeping formats may be used.

It has been mentioned previously in this paper that the classroom makes for an ideal distraction-free learning environment. However, an educational classroom is, of course, not necessarily required for small groups. Instead, "classroom learning" can take place in the living room of a participant's home, in an office or a coffee shop, on a park bench, or any other comfortable environment, provided it is distraction free. Even the mountainside where the cave is located can be a "classroom," although greater care may be needed to ensure the beautiful surroundings do not become distracting. On the receiving end, the students and trainees must practice what they've learned. At the appropriate time, and before embarking on a challenging caving trip, the trainees should demonstrate their knowledge and skill to the more-experienced and higher-skilled mentors. This is the measure of learning achieved, i.e. of progress made. Direct measures of learning can include a range of options from written exams to physically demonstrating to the instructor or mentor that the student can accomplish the task at hand.

4. Conclusions

Respondents to the online questionnaire indicated that the top five close call events in cave exploration included vertical, falls, rockfall, water hazards, and becoming trapped/stranded. Previously conducted research, reports from caving accidents, and review of the literature shows that the top five mishaps in cave exploration include falls, equipment issues, rockfall, becoming trapped/stranded, or becoming lost. While there are many more hazards in caving, preparing to overcome those listed here among mishaps and close calls will help intrepid cave explorers avoid most of the undesired situations that may be encountered during caving. Research on close calls shows that mishaps can be avoided if environmental conditions in caves are well understood and if detrimental acts can be avoided. Training, of some kind, is universally agreed to be essential for preparing cave explorers to overcome hazards and practice proper behaviors while caving.

The panel of experts interviewed in this research indicate that designed training delivered by qualified and experienced cavers to small groups of people in optimized learning environments is most effective for preparing people to safely and conscientiously explore the cave environment. In particular, training should focus on human acts and environmental conditions that lead to mishaps. In addition to the primary hazards already listed above, human acts that should be prepared for include paying attention to surroundings, assessment of integrity of cave surface, physical fitness, and equipment inspection. Preparation should be made for in-cave environmental conditions including vertical exposure, rockfall or rock-shifting potential, slippery and poor-contact conditions, water, tight cave passages, temperature, and air quality. The hazards, human acts, and environmental conditions described in this paper are generalized to all cave exploration, whereas the specific ones that should be prepared for are dependent on the caves and regions where exploration will take place. Mentors, instructors, and/or curriculum designers will select topics appropriate to the conditions for which training is being designed. Further references are available to ensure proper techniques are being taught. In addition to the texts by Sparrow (2009) and Burger (2006), *Alpine Caving Techniques* (Marbach and Tourte 2002) and *On Rope* (Smith and Padgett 1997) provide excellent information for developing caving skills.

The passing of information in a controlled, structured, and documented manner from those with more knowledge and experience to those who are developing their knowledge and skills will help to reduce injuries and illnesses, as well as to hopefully eliminate fatalities that occur in cave exploration. This process has the additional benefit of giving cave explorers greater ability to make the most of their underground exploration, thus enhancing the overall caving experience.

Acknowledgments

The authors wish to acknowledge the eleven caving-skills experts who participated in the research interviews, the 181 cave explorers who participated in the online close-calls questionnaire, and the organizers of the 2013 International Congress of Speleology for providing a venue in which this research could be shared with the international caving community. The authors also acknowledge the Oakland University Insitutional Review Board for guidance and oversight in this research and the reviewers for their thoughtful comments. The authors wish to thank the NSS Safety and Techniques committee members for their ideas, feedback, and guidance over the past two years that this research has been conducted, and in particular Dr. Rane Curl for his continued guidance and long-standing commitment to safe caving, worldwide. Finally, the authors are grateful to Gary Bush and Bruce Smith for their reviews of this paper.

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CAVING IN THE ABODE OF THE CLOUDS – MEGHALAYA, NORTH EAST INDIA

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Meghalaya in North East India is blessed with good limestone and a warm, wet climate that results in many fine caves. In the last 21 years 24 mostly multi-national expeditions have explored/partially explored 892 caves yielding over 398.6 kms of cave passage. The caves are found in a band of limestone/karst that runs along the southern fringe of the Meghalaya plateau. Exploration from 1992 to 1999 took place in many locations across Meghalaya and developed a productive collaborative partnership with local Indian cavers. From 2000 to 2009 the main focus of exploration was on the Shnongrim Ridge in the Jaintia Hills where over the years 157 kms of cave passage were explored. During this period the Krem Liat Prah Cave System, discovered in 2002, was extended, linked into other systems and eventually connected to Krem Labit Moolasngi and Krem Rubong in 2008 to create a cave system of 30.9 kms in length – India's longest cave and first cave system in the Indian Sub-continent to have in excess of 30 kms of passage. In 2009 the focus moved away from the Shnongrim Ridge to the Pala Range and the Kopili River Valley where exploration has remained until 2013. In this area some 53 kms of cave passage has been explored including the Krem Tyngheng – Dieng Jem system that at 21.3 kms is currently India's 3rd longest cave. From 1999 onwards several of the expeditions have undertaken small scale Bio-speleological investigations utilising skills and interest within the expedition team. In the last three years (2011 to 2013) this element has had a more substantial presence with more in-depth and systematic studies and recording taking place. This lecture gives an overview of the limestone and caves of Meghalaya, the exploration from 1992 to 2013 looking in more detail at the more recent 2012 and 2013 expeditions and the tensions between the economic exploitation of the limestone resource and cave conservation.

1. Introduction

The Caving in the Abode of the Clouds Project takes its name from the Sanskrit meaning of the word "Meghalaya" which literally translates to "Abode of the Clouds". This is in recognition of the fact that, because of its geography, Meghalaya is often enveloped in cloud, which results in world record rainfall. This feature, added to a warm climate and extensive areas of limestone, has created many fine caves, making Meghalaya of great interest to the International Caving fraternity. In 1992, a small team of four European Cavers were able to visit Meghalaya and the Khasi, Jaintia and Garo hills, finding many caves and, more significantly, realising the huge caving potential of the region. In 1994, contact was made with Brian D. Kharpran Daly and Donbok Syiemlieh of the Shillong based Meghalaya Adventurers Association and since that time the systematic exploration of caves across Meghalaya has been undertaken as a partnership between Indian, European and American Cave Explorers. This productive collaboration is known as the Caving in the Abode of the Clouds Project.

The State of Meghalaya lies between 25.47 degrees to 26.15 degrees of latitude north and between 89.45 degrees to 97.47 degrees of longitude east. It extends for about 300 kilometres in length from west to east and about 100 kilometres in width from north to south covering an area of 22,429 square kilometres.

Meghalaya is composed of three ranges of hills, which have given their names to the three main tribes. The Khasi and Jaintia Hills of central and eastern Meghalaya present a panorama of a plateau of grasslands, hills and river valleys. The height of the plateau is generally between 1,500 metres and 2,000 metres above sea level. The southern edge of the plateau drops steeply to the plains of Bangladesh and is noted for its waterfalls and deep jungle clad north to south valleys.

The Garo Hills to the west are lower in elevation, with an average height of 450 to 600 metres above sea level and are more deeply dissected. The limestone is found in a more or less continuous band that runs along the entire southern fringe of the state. This band of limestone is approximately 300 kms in length east to west and between 10 to 25 m in depth, north to south. Despite 25 expeditions being made to Meghalaya since 1992, significant areas of Limestone remain unexplored.

2. Recent Cave Exploration

1992 – A small team of four European Cavers were able to visit Meghalaya and the Khasi, Jaintia and Garo hills, finding many caves and mapping just over 9 kms of new cave passage. In the Khasi Hills, Krem Mawmluh was explored and mapped for 3.7 kms becoming (November 1992) India's longest cave and Krem Dam also in the Khasi Hills for 1.2 kms. In the Garo Hills, the well-known Krem Siju Dobhakol, partially explored by Kemp and Chopra from the Museum of Natural History in Calcutta in 1922 was extended from 1.2 kms to 2.9 kms. This initial expedition paved the way for access to Meghalaya and established that there was indeed considerable caving potential.

1994 – Contact was made with Brian D. Kharpran Daly and Donbok Syiemlieh of the Shillong based Meghalaya Adventurers Association and visits the Khasi, Jaintia and Garo Hills by a small European Team of 8 cavers saw another 14 kms of cave passage explored and mapped. In the Khasi Hills, Krem Mawmluh was extended from

Figure 1. Square Passage – Siju Dhobakhol, Garo Hills.

3.7 kms to 4.5 kms in length and Krem Dam from 1.2 kms to just over 2.0 kms becoming India's longest cave formed in sandstone (March 1994). In the Garo Hills, Tetenkol was explored and mapped for 5.1 kms over taking Krem Mawmluh as India's longest cave (February 1994).

1995 – A small Multi-National Expedition (9 cavers, including 2 Indian cavers) visits the Khasi, Jaintia and Garo Hills and explores and maps 10+ kms of new cave passage. In the Jaintia Hills, the sizable Krem Pubon Lashing was explored for 1.7 kms and in the Lumshnong area (Jaintia Hills) Krem Kot Sati was explored and mapped for 2.6 kms and left very much ongoing.

1996 – A small German/Indian expedition based itself at Lumshnong in the Jaintia Hills and explores and maps 9+ kms of new cave passage with Krem Um Lawan partially explored and mapped for 6.3 kms.

1997 – A larger Multi-National Expedition (16 cavers, including 5 Indian cavers) returned to Lumshnong in the Jaintia Hills and explores and maps 25+ kms of new cave passage connecting Krem Kot Sati to Krem Um Lawan to create a 19.2 km long system becoming (February 1997) India's longest cave. Just to the north of Lumshnong in the Musianglamare area Synrang Pamiang was explored and mapped for 1.7 kms. Krem Lymput in the Nongiri Area for 2.7 kms and Krem Pubon Lashing extended from 1.8 kms to 3.0 kms in length.

1998 – A Multi-National Expedition (18 cavers, including 4 Indian cavers) visits the Khasi and Jaintia Hills explores and maps 26+ kms of new cave passage. At Nongiri in the East Khasi Hills, Krem Lymput was extended from 2.7 kms to 6.5 kms. In the Lunshnong Area Krem Kot Sati/Um Lawan was extended from 19.2 kms to 21.2 kms and Synrang Pamiang from 1.7 kms to 4.8 kms. In the Lukka Valley lying to the east of Lumnshnong, Pielkhlieng Pouk, a massive river cave was partially explored and mapped for 2.5 kms.

1999 – A Multi-National expedition (17 cavers, including 4 Indian cavers) visits the Khasi and Jaintia Hills and explores and maps 27+ kms of new passage. In the Lumshnong Area (Jaintia Hills) the impressive river cave of Synrang Pamiang was extended from 6.2 kms to 14 kms to become India's 2nd longest cave (February 1998). In the Lukka Valley the even more impressive Pielkhlieng Pouk was connected to Seilkan Pouk to create a 9.7 kms long system to become (February 1999) India's 3rd longest cave.

1999 – A small reconnaissance expedition by members of Wells Catheral School visits the Shnongrim Ridge in the Jaintia Hills and explores and maps 4+ kms of new cave passage.

2000 – A Multi-National Expedition (14 cavers, including 4 Indian cavers) visits the Khasi Hills and the Shnongrim Ridge in the Jaintia Hills and explores and maps 20+ kms of new cave passage. Exploration and mapping on the Shnongrim Ridge includes Krem Mawshun at 3.3 kms in length, Krem Wah Ryngo at 3.3 kms, Um Sngad at 2.4 kms and Krem Shrieh with its massive 97 m deep shaft at 8.7 kms. The latter becoming (February 2000) India's 4th longest cave.

Figure 2. Key Hole passage, Krem Mawshun.

2001 – A large Multi-National Expedition (26 cavers, including 4 Indian cavers) visits the Khasi Hills and the Shnongrim Ridge in the Jaintia Hills and explores and maps 35+ kms of new cave passage. At Borsora in the West Khasi Hills, Krem Khlieh Kherthang is explored and mapped for 2.8 kms and Ronga for 1.9 kms. On the Shnongrim Ridge in the Jaintia Hills, Krem Umthloo is explored and mapped for 12.4 kms becoming (February 2001) India's 3rd longest cave. In the same Area Krem Shynrong Labit is explored and mapped for 5.7 kms and Krem Risang for 4.5 kms.

2002 – A large Multi-National Expedition 923 cavers, including 3 Indian cavers) visits the Khasi, Shnongrim Ridge in the Jaintia and Garo Hills explores and maps 22.5+ kms of new cave passage. In the West Garo Hills (Asakree area) 5.5 kms are explored and mapped in a variety of caves. In the south Garo Hills 2.6 kms are explored and mapped and on the Shnongrim Ridge (Jaintia Hills), the impressively proportioned Krem Liat Prah is explored and mapped for 5.9 kms.

2002 – A small USA led Expedition (13 cavers, including 4 Indian cavers) visits the Lum Lawpaw plateau near to Nongjri in the West Khasi Hills and explores and maps 6+ kms of new cave passage. Krem Mawtynhiang is explored and mapped for 3.0 kms and remains as India's longest Sandstone Cave.

2002 – A small Italian/German Expedition (9 cavers, including Indian cavers) visits the South Garo Hills and in the Asakree area and explores and maps 2.7+ kms of new cave passage in Sang Kni Ikgilram, which remains the longest cave in the Asakree area.

2003 – Large Multi-National Expedition (33 Cavers, including 9 Indian Cavers) based mainly on the Shnongrim Ridge in the Jaintia Hills, but with satellite teams visiting the West Khasi and Garo Hills, explore and map 25.7+ kms of new cave passage. On the Shnongrim Ridge Krem Liat Prah was extended from 5.9 kms to 8.3 kms in length and Krem Umthloo from 12.6 kms to 13.4 kms to become (March 2003) India's 3rd longest cave. The exploration team included a number of Biologists that undertook Bio-Speleological investigations in some of the caves.

2004 – Large Multi-National Expedition (24 Cavers, including 7 Indian Cavers) based on the Shnongrim Ridge in the Jaintia Hills explores and maps 17.1+ kms of new cave passage. Krem Liat Prah was extended from 8.4 kms to 14.6 kms taking it from India's 6th longest cave (February 2004) to India's 2nd longest. Krem Krang Wah (Tigers Mouth Cave) with its 93 m deep shaft entrance was explored for 2.2 kms and Krem Tyngheng in the nearby Samasi (Pala Range) area partially explored for 3.75 kms along fine river passage.

2005 – Large Multi-National Expedition (28 cavers, including 6 Indian cavers) based largely on the Shnongrim Ridge in the Jaintia Hills and also visiting the West Khasi Hills explores and maps 19+ kms of new cave passage. On the Shnongrim Ridge Krem Liat Prah was linked to Krem Um Im to create a system of 15.9 kms in length, India's 2nd longest in 2005. In the adjacent Samasi Area (Pala Range) Krem Tyngheng was extended from 3.75 kms to 5.3 kms.

2006 – Large Multi-National Expedition (28 Cavers, including 5 Indian Cavers) based on the Shnongrim Ridge in the Jaintia Hills explore and map 15.4 + kms of new cave passage. The 2006 expedition anticipated the completion of the exploration on the Shnongrim Ridge and in Samasi. However, it saw an existing cave system (Krem Liat Prah/Um Im) linked to (Krem Labit Khaidong) and extended to create a 22+ km system which at that time (February 2006) was India's new longest cave. In the adjacent Samasi Area Krem Tyngheng was extended from 5.3 kms to 7.7 kms in length. During the course of the expedition yet more huge relic and river passage was explored, indicating the Shnongrim Ridge was far from finished.

2007 – A large Multi-National Expedition (33 Cavers, including 3 Indian Cavers) based on the Shnongrim Ridge and the adjacent (Lukka) area in the Jaintia Hills explores 15.9+ kms of new cave passage. The Krem Liat Prah/Labit/Um Im System was extended from 22.2 to 25.2 kms in length, Pielklieng Pouk/Sielkan Pouk, a huge river cave, was extended from 10.4 to 12.4 kms in length and yet more cave systems on the Shnongrim Ridge were linked together.

2008 – A large Multi-National Expedition (40 cavers, including 3 Indian cavers) based on the Shnongrim Ridge and visiting the nearby Pala Range in the Jaintia Hills explores 14 kms of new cave passage. The linking of the Liat Prah Cave System to Krem Labit (Moolasgni) via a 3 m sump free dive and the connection of two other potholes plus the resurgence cave Krem Rubong into the system along with surveying of new side passages created a cave system of 30.9 kms in length. This firmly established this system as the longest cave known to date (May 2013) in the Indian Sub-continent and more significantly made it the first Indian Sub-continent cave to exceed 30 kms in length. The extension of Krem Tyngheng in the Samasi area from 9.8 kms to 12.9 kms in length, via some long swims, to make it (February 2008) Indian Sub-continent's 5th longest cave and the partial exploration and surveying of two other caves in the Kopili area; Krem Labbit Kseh at 0.9 kms in length and Krem Bylliat at 0.6 kms in length. Krem Umthloo, was extended to 18.1 kms in length maintaining it as the 3rd longest cave (March 2008) in the Indian Sub-Continent. The extension of several existing caves in the area including: Um Sngad River Sink, extended from 1.25 km to 2.15 km in length and ongoing; Krem Kdong Thloo extended from 1.18 km to 1.58 kms. Krem Synrang Ngap was extended from 4.5 kms to 4.9 kms and Krem Mawshun from 3.3 to 3.6 kms. Additionally the discovery and exploration of several new caves in a previously blank NE section of the Ridge near to the Liat Prah system including Krem Lumthymme at 1.1 km in

Figure 3. River passage in lower section of Krem Tyngheng/Diengjem System.

length, that unfortunately failed to connect into the Liat Prah system. The discovery and exploration of two new caves on the south flank of the ridge, Krem Thapbalong Sim for 0.3 kms in length and ongoing and Krem Shyrong Shrieh is 1.39 kms in length and on-going. In addition to the cave exploration, an International Conference entitled 'Discover Meghalaya – The Caving Experience' was held at the Pinewood Hotel in Shillong on the 22nd to the 23rd February. The Government of Meghalaya Tourism

Department and the MAA (Meghalaya Adventurers Association) hosted this with a significant input being made by the European team members. The conference was attended by some members of the expedition, the MAA and over 60 delegates drawn from the Meghalaya Government and its various departments along with representatives from the coal and limestone extraction industry and Adventure Travel Agencies from across India and Bangladesh. The aim of the conference was to raise awareness of the great cave resource within Meghalaya; highlight the threats to the caves posed by the recent increases in the limestone and coal extraction industries and try to identify a ways of addressing this issue; and to develop strategies to promote the use of caves for tourism and local economic development

2009 – A large Multi-National Expedition (28 cavers, including 13 Indian cavers, 10 of which were from the Indian Navy) based on the Shnongrim Ridge in the Jaintia Hills explore and map 12.6 kms of new cave passage. In the SW end of the Shnongrim Ridge, Krem Thapbalong Sim (Humming Bird Cave) was connected to Krem Shyrong Shrieh (Monkey Skull Cave) to create a system of 5.48 kms in length. In the Kopili River Valley, Krem Labit Kseh was extended from 0.88 kms to 1.65 kms. Krem Tyngheng in the nearby Samasi (Pala Range) area was extended by 0.4 kms to 12.8 kms in length. Exploration of several caves in the new Umkyrpong area saw Krem Dieng Jem (believed at this time to be the resurgence for the Krem Tyngheng) partially explored for 1.3 kms. 2009 was the last of the large Shnongrim Ridge camps that had become synonymous with the Caving in the Abode of the Clouds Project. In the period from 2000 to 2009 the Shnongrim Ridge had yielded 157 kms of cave passage and become the area of Meghalaya (and the Indian Sub-continent) with the greatest concentration of known caves.

2010 – A large Multi-National Expedition (35 cavers, including 9 cavers from the Indian Navy) based in the Umkyrpong/Kopili Area of the Jaintia Hills and at the start of the expedition a satellite camp in the West Khasi Hills explored and surveyed 25.1 kms of new cave passage. In the Mawsynram Area in the East Khasi Hills, Krem Mawphun was explored for 1.6 kms and Krem Lymbit for 0.8 kms along with several other smaller caves. At the main expedition area in the Umkyrpong/Kopili Area in the Jaintia Hills, Krem Dieng Jem was extended and connected to Krem Tyngheng to create a sink to resurgence system of 21.1 kms in length becoming (March 2010) India’s 3rd longest cave and the third cave in the Indian Sub-continent to exceed 20 kms in length. Krem Labit Kseh in the Kopili River Valley was extended from 1.6 kms to 4.7 kms. New caves: Krem Man Krem was partially explored for 4.7 kms and Krem Shalong (Misty Cave) for 2.6 kms and both left ongoing.

2011 – A Multi-National Expedition (22 cavers, including 3 Indian cavers) based in the Kopili/Pala Range Area in the Jaintia Hills explores and maps 10+ kms of new cave passage. The Krem Tyngheng/Dieng Jem system was extended to 21.2 kms maintaining it as India’s 3rd longest cave (March 2011). Krem Shalong was extended from 2,61 kms to 4.7 kms in length and a new cave Krem Labit Mynlin explored for 1.6 kms. In addition to the cave exploration there was significant bio-speleological investigation undertaken in some cave sites with a particular focus on bats – this bat survey, undertaken by Manuel Ruedi of the Geneva Museum of Natural History, led to the detection of a species of Murina bat – new to science. It was later named Murina Jaintiana to honour the tribe of the Jaintias who had given their warm and welcoming hospitality to the expedition for so many years.

Figure 4. Krem Khung, main passage.

2012 – A large Multi-National Expedition (Two separate teams with a total of 25 cavers, including 3 Indian cavers) based in the Kopili/Larket Area in the Jaintia Hills and in the Mawsynram/Balat Area in the East Khasi Hills explores and maps 6.8+ kms and 6.1 kms of new cave passage respectively. In the Kseh/Larket Area the main focus of the exploration was in the new Krem Khung system where 5.1 kms of very large passage was explored. In the Mawsynram/Balat Area Krem Mawphun was extended from 1.7 kms to 2.5 kms in length becoming India’s 2nd longest known cave to be formed in Sandstone. In addition to the cave exploration in the Kopili/Larket area there was on-going bio-speleological investigation undertaken.

2013 – A more modestly sized Multi-National Expedition (17 Cavers, including 2 Indian Cavers) based in the Kopili/Larket Area in the Jaintia Hills explores and maps 9.1+ kms of new cave passage. Krem Khung was extended from 5.1 kms to 7.3 kms in length to make it India’s 7th longest cave and Krem Labit Kseh, on the banks of the Kopili river, was extended from 6.4 kms to 7.2 kms to make it India’s 9th longest cave. Alongside the cave exploration the two associated Romanian biologists, the expedition team biologist and their Indian counterpart from the Lady Keane College in Shillong that were part of the exploration team continued with the study the documentation of various cave fauna in the area. On return to Shillong members of the expedition and the Meghalaya Adventurers Association attended the inauguration of the Bio-speleology Section of the Zoology Museum at Lady Keane College, Shillong, Meghalaya (India). The link between Lady Keane College, the Meghalaya Adventurers’ Association (MAA) and the Caving in the Abode of the Clouds Project will further enhance the study and understanding of the bio-speleology of Meghalaya. Building upon the bio-speleology investigations that have been part of many Caving in the Abode of the Clouds expeditions since the late 1990’s.

3. Conclusion

As a result of these explorations, the whereabouts of over 1,500 caves are known, of which 892 have been explored to yield almost 399 kilometres of surveyed cave passage, with much more still awaiting discovery. Much of the cave passage that has been explored to date is impressive river cave, deep shafts and large ancient relic passage. These features form cave systems equal in size and beauty to those found anywhere else in the world, thus putting Meghalaya firmly on the world-caving map as a significant Cave and Karst Region.

In the achievement of the above the Caving in the Abode of the Clouds Project is indebted to the help and support it has received over the years from; the Meghalaya Adventurers Association, the Government of India Tourist Office (East and North East India) Kolkata; the Meghalaya State Tourism Department; Officials and Government Departments within Meghalaya; and, very importantly, the People of Meghalaya. Acknowledgement must also be given to the Ghar Parau Foundation, the Grampian Speleological Group, the Mount Everest Foundation of the UK and the NSS (USA) for their financial support at various times.

However, the abundance of limestone and coal in Meghalaya makes the state not only of interest to the caving fraternity but also of interest to the commercial world, as limestone and coal are valuable economic resources. The initially small-scale extraction of limestone has in recent years been replaced by large commercial operations seeking to fuel economic growth in the region. To protect the environment, the unique landscape, the natural history and particularly the wonderful caves that are to be found within the Khasi, Jaintia and Garo Hills. It is vital that the limestone and coal is extracted in an environmentally sensitive and sustainable manner otherwise irreversible damage will be caused and these unique natural features will be lost forever.

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CAVE EXPLORATION IN IRAN

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In the early 1970's Iran was one of the British overseas expedition areas of choice with Ghar Parau becoming the best known Iranian cave because it was the focus of two major UK Expeditions in 1971 and 1972 that were striving for a world depth record. Using the funding left over from these expeditions the Ghar Parau Foundation (GPF), a UK Overseas Expedition Granting body that has supported many UK overseas expeditions ever since, was set up, immortalising the cave name Ghar Parau in the UK. This paper gives and overview of the Karst and Cave in Iran and then describes the history of cave exploration by both Iranian and Foreign Cave Explorers. The paper then gives an overview on the multi-national expeditions to Iran that took place in Oct/Nov 2006, October 2007, October/November 2008 and most recently in November/December 2011 that have offer training, explored and mapped caves alongside Iranian cavers in many areas across Iran. As well as touching on the exploration history of Ghar Parau (Iran's deepest and most well-known cave) and reviewing the rapidly developing caving scene in Iran the paper provides an insight to this fantastic county and its people.

1. Overview and early cave exploration in Iran

The Islamic Republic of Iran has an area of 1,648,000 sq kms which is equivalent to 3× the size of France or 1/5 the size of the USA. Of this land 11 % is Arable, 8 % Forests, 47 % Pasture and the remaining 34 % Deserts and Mountains. Iran has a rich and complicated Geological structure with many natural resources. Limestone comprising of Cretaceous, Jurassic, Triassic and Mesozoic is present across many areas with the greatest concentrations being found in the Alborz Mountains in the North of Iran and the Zagros Mountains that run down the SW flank of Iran. Within this limestone many caves are to be found and to date there are in excess of 2,400 known caves in Iran.

Iran is a very well developed country with a strong oil based economy. Tehran, Iran's capital city is very modern and vibrant and the Iranian People generally enjoy a good standard of living that involves many cultural, social and sporting activities. Iran has a population of over 70 million people with around 70 % of the population being under 30 years of age. Iran's geographical spread and geology mean that within the country there is a great variety of landscapes. These range from sub-tropical forests in the north, further south and on the west, high mountain ranges and temperate areas, and huge deserts and semi-arid areas in the south.

Systematic cave exploration began in Iran in 1945 when members of clubs such as the Damavand Club from Tehran and the Hamadan Mountaineers from Hamadad began visiting, exploring and mapping caves. Early pioneers included; Manocher Mehran, Marafat, Changiz Shelkli and Yousef Nejaei. In 1995 a publication "Caves and Mountains of Iran" listed over 250 caves.

In the early 1970's Iran was a popular overseas expedition area with Ghar Parau becoming the Iran's best known cave because it was the focus of two major UK Expeditions in 1971 and 1972 that were striving for a world depth record. Following this the cave became the namesake of the UK Overseas Expedition Granting body (the GPF) that has supported many UK overseas expeditions ever since. In 1974 a Polish Team reached the bottom of Ghar Parau where they confirmed that the cave had indeed finished. In 1973 Napier College Hydro-geological Expedition surveyed 1,700 m in Ghar Sarab near to Hamadan. In 1979 major political change in Iran made the country largely inaccessible for foreigners and exploration activities ceased until the mid 1990's. However, from 1976 through to 2003 numerous Iranian caving and mountaineering groups visited Ghar Parau with many reaching the bottom and some new passages and a second entrance being discovered. In 2004 a team from Kermanshah Mountaineering Club succeeded in getting a diver into the terminal sump which appeared to quickly close down and become impenetrable.

In the mid 1990's a Czechoslovakian team began exploring the Salt Karst of Qesam Island in the far south of Iran where they discovered Namakdan 3 which has subsequently been extended to become the world longest Salt karst cave with a length of 6,580 m. Regular on-going return trips to this area have seen many more caves explored and mapped. In 2000 and 2001 a German-Iranian and then a German-British-Iranian team explored and mapped Ghar Alisadr, Iran's most popular show cave, yielding 11,400 m of passage. In 2003 a German-Swiss-Iranian team explored and mapped the majority of Katalehkhor another of Iran's fine show caves that at 12,860 m is currently Iran's longest known cave.

2. Recent cave exploration in Iran

A return to Ghar Parau – October/November 2006.

In late October through to early November 2006 a team of 21 cavers lead by Yuri Evdokimov from Russia on a visit to Iran as part of the "Parau 2006 Expedition". The team consisted of 19 cavers from various parts of Russia and Shary Ghazy an Iranian caver who then lived in Germany and Simon Brooks from the UK. The Russians were a strong and well-equipped team with good experience of deep caves at high altitude, including participants from the deep Krubera-Voronja Project. The main aim of the expedition was to reach the bottom of Ghar Parau, dive the terminal sump and climb avens etc in an attempt to extend (deepen) the cave, and, if time allowed, visit and extend Ghar Sarab in the Hamadan Area.

Prior to joining the main team Simon Brooks and Shary Ghazy travelled down to Hamadan, meeting up with Yousef Nejaei from the Hamadan Mountaineers (Sina) Club. Two days were spent in the Hamadan Area visiting the Ghar Alisadr Show cave and Ghar Hizch (Hizch Cave, AKA Ghar Hezej) where in excess of 520 m of dry horizontal passage were mapped and photographed.

The Russians had been travelled overland from Moscow in three very well laden vehicles and on the 29th October arrived in Kermanshah where they set up a base camp. Shary and Simon joined them, equipment was sorted, and the following day the team began the ascent to Ghar Parau. The weather in Kermanshah had been getting gradually worst, cold with heavy rain and low cloud enveloping the mountain tops. Laden with huge amounts of equipment packed into massive rucksacks the team set off up the mountain accompanied by Yousef Sornynia from the Kermanshah Mountaineering Club.

Despite worsening weather, within two days, a forward camp was set up on the Kul-e-Parau Plateau (Altitude 3,100 m) just 50 m from the entrance of Ghar Parau. The team then began rigging the entrance pitches. Progress was slow with pitches having to be re-bolted due to the excessive amounts of water entering the cave rendering the traditional (Those used by the 1971 and 1972 Expeditions and apparently still used in the more recent visit by Iranian teams) pitch hangs unsuitable. For the next few days the Russians pushed onwards deeper into Ghar Parau as the weather worsened, the temperature dropped to minus five and it began snowing heavily. At a depth of around -400 m the need to re-bolt/re-rig virtually every pitch and the weather conditions indicated to the Russians that they were quickly running out of time to reach the bottom of the cave, dive the sump and climb avens. Somewhat disappointed and frustrated they decided to cut their losses, de-rig Ghar Parau and turn their attention to the many other shafts/entrances on the plateau. Over 30 entrances a shafts were located, some explored, with one reaching a depth of -100 m.

Meanwhile Simon Brooks and Shary Ghazy had descended from the plateau and arrived back in Hamadan on 3rd November 2006 only to find the expected trip to the new cave (Dodza Ghar/Smoking Cave) had been called off due to a disagreement over ownership of the cave. As an alternative a visit to Ghar Alisadr had been arranged to assist the Hamadan TV Company in making a documentary about the cave and about Yousef Nejaei who was one of the original explorers of the cave in the 1960's. The next day the Hamadan TV Crew went to Ghar Sarab where yet more filming was done. Ghar Sarab looking somewhat different than it had in 2001 as a recently constructed irrigation scheme taking water from the cave had succeeded in lowering the water table in Sarab by over two metres.

On 5th November Simon returned to Tehran and then the UK. Shary, Yousef and the Russians made a trip into Ghar Sarab with the Hamadan TV Crew where they spent a further two days exploring and filming, concluding that there was a significant amount of un-surveyed and un-explored passage remaining.

Iran 2007 – Caving with the Damavand Club and the Hamadan Mountaineers.

Between the 10th October to 28th October 2007 Simon Brooks (Orpheus Caving Club, UK) and Shary Ghazy (DAV Frankfurt Germany) returned to Iran and joined members of the Damavand Mountaineering Club in Tehran and the Hamadan Mountaineering Club in Hamadan on a small caving expedition. Building on the contacts made in 2006 the expedition had two aims; the first being to conducting more cave exploration in Iran and second being to support and train Iranian cavers to survey and record caves.

The training element ran throughout the expedition and involved several aspects. These varied from lectures and training workshops delivered to audiences of Iranian cavers at the start, middle and end of the expedition. To back up the training session the Iranian Team members put their new skills into practice by actually surveying the caves that were being visited/explored during the expedition. At the end of the expedition a gift of a Compass, Clinometer, Tape and Survey Book were made to the Damavand Club, both as a thank you, and to enable the Damavand Cavers and caving members of the Hamadan Mountaineers to continue to practice and develop their surveying skills.

For the first part of the 2007 expedition Simon and four members of the Damavand Club drove North of Tehran to the town of Chalus on the Southern Coast of the Caspian Sea where they spent three days visiting caves in this area. On the way to Chalus, about one and a half hours North of Tehran, Ghar Yakhmorad (Cave of the healing Ice) was visited and 295 m of passage surveyed. This cave is well known to the Iranian Cavers who use it as a site to introduce people into the sport of caving. In the winter the cave contains much ice and in the chambers in the lower parts of the cave this remains throughout the year as green coloured ice floors. Regretfully there was not time to complete the survey of this cave but on subsequent visits Damavand Club members have explored and surveyed it to over 700 m in length. In the Chalus area itself the excellent Danal Cave was explored. This fine resurgence cave was found to contain over two kilometres of excellent streamway, many side passages, one large chamber and one smaller but well decorated chamber. During the visit to the cave some new side passages were explored and many photographs taken. Returning to Tehran a visit was made to the 400 m long Ask Cave. This cave is again is well known to the Iranian Cavers as a beginners cave and for its spectacular entrance that looks squarely onto Damavand Peak, Iran's highest mountain.

After the visit to the Caspian Sea area, Simon returned to Tehran and then he and Shary travelled to the North West of Iran to the City of Mahabad where they were joined by four members of the Hamadan Mountaineering Club. Here accommodation and food was being provided by the management of Sahoolan Cave, another of Iran's fine show caves, in return for accurately mapping the cave. Two days were spent mapping, fully exploring and photographing the cave that proved to be 771 m in length. It contained many fine lake chambers which where surveyed using the boats that take visitors through the cave. Leaving Mahabad the Hamadan Mountaineers went directly to Hamadan whilst Simon, Shary and Yousef Nejaei took a more leisurely two day cross country route in order to visit the Kraftu Caves and the Katalekhor Show Cave. The Kraftu Caves are well known as an important archaeological site with the caves multiple cliff entrances having been modified and adapted

Figure 1. Looking out of the entrance of Ask Cave.

as homes in times past. However, what was not expected was that behind the many cliff entrances lies a large and very spectacular phreatic cave with many passages and large chambers. Ghar Katalekhor is both Iran's longest cave at 12.8 kms in length and also a very beautiful and well visited Show Cave. Accompanied by a cave guide many of the main areas of the cave were visited and photographs taken.

Arriving in the Hamadan Area a base was established in Sarab Village and four members of the Hamadan Mountaineering Club and one member of the Damavand Club (Tehran) joined Simon, Shary and Yousef. The plan was to re-survey the nearby Ghar Sarab where recent extraction of water for irrigation had dropped the cave water level revealing new passage in addition to those that had not been fully explored by the Napier College expedition in 1973. Over the period of the next five days two thirds of Ghar Sarab was re-surveyed along with a significant amount of new and uncharted passage, yielding around 2 kms of surveyed passage, leaving the cave far from finished. Whilst in the Sarab Area, Shary and Simon, accompanied by a group of cavers from Hamadan's Azad University, went to visit Dodza Ghar (Smoking Cave). Dodza Ghar proved to descend very steeply through boulders and down steeply inclined chambers to reach a large and beautiful lake chamber where the cave is likely to continue. 406 m of passage was surveyed with the cave reaching a depth of 154 m. (In 2011 another 400 + m was added to the cave by an Iranian team) Returning to Tehran the final two days of the expedition were spent visiting friends and caving contacts.

Iran 2008 – Exploration, Mapping and Training with the Damavand Club and the Hamadan Mountaineers. Between the 16th October to 2nd November 2008, Simon Brooks (Orpheus Caving Club, UK) returned to Iran and joined members of the Damavand Mountaineering Club in Tehran and the Hamadan Mountaineering Club in Hamadan to visit, explore and survey caves in the North and Central West of Iran. This visit built on the contacts made on visits to Iran in 2006 and 2007 and followed shortly after an International Speleological Expedition to Iran (ISEI-2008) that took place between 23rd September and 6th October 2008.

The objectives of this trip were to survey and explored Ghar-e-Danial (Danial Cave) in the Mazadaran Karst Area on the southern edge of the Caspian Sea and to complete the exploration and surveying of Ghar Sarab (Sarab Cave) that is in the Hamadan Province in Central West Iran. The second (and arguably the more important) objective was to explore caves in Iran with the Iranian cavers and continue the training and support of them in the skills of surveying and recording.

Saturday 18th October saw the first day of surveying in Ghar-e-Danial where 274 m was surveyed in the entrance passages and into the large Talar-e-khoffash (Chamber of the Bats) that lies some 200 m into the cave. The following day another 300 m of cave passage was surveyed including the Talar-e-khoffash chamber. This large breakdown chamber (60 m by 110 m) rises steeply from the streamway over a mass of boulders which are descended on its far side to join the streamway again. By the end of the third day of surveying another 380 m of excellent river passage, cascades and streamway were surveyed from Talar-e-khoffash to just beyond the "duck" at Gozar-e-Javaanshaad. Gozar-e-Javaanshaad is a very significant point in Ghar-e-Danial as it is the point where the cave was originally thought to end. However, a caver by the name of Ali Javaanshaad passed this obstacle many years ago to reveal a substantial amount of cave beyond. To an experienced caver the significance of what lies beyond this obstacle is all too apparent by the howling draught that greets you as you prepare to pass through this classic "chin-in-the water" duck. The following day another 364 m of yet more magnificent and varied stream passage was surveyed to reach the beautifully decorated Talar-e-Rizan (Rizan Chamber/Chamber of fallen blocks). Wednesday 22nd October saw a brilliant 11.5 hour long trip surveying from Talar-e-Rizan to the small chamber that marks the known end of the cave. This yielded another 833 m of surveyed passage, but due to shortage of time left several side passages un-surveyed. In four days Ghar-e-Danial had

Figure 2. Talar-e-Rizan Chamber, Danal Cave.

yielded 2,158 m of excellent passage and when the remaining side passages are surveyed is likely to be in excess of three kilometres in length. It is a superb, varied and spectacular river cave and more significantly is likely to be one of many in this part of Iran.

On the morning of the 25th October Simon Brooks travelled down to Hamadan on the bus for the second part of the trip which was to continue the exploration and surveying of Ghar Sarab. Meeting up with a team consisting of; one member of the Damavand Club: six members from the Hamadan Mountaineers and a caver from Esfahan, the rest of the day was then spent in Hamadan meeting friends, discussing plans and making preparations for the on-going exploration and surveying of Ghar Sarab. The following morning the team left Hamadan and arrived in Sarab Village to establish a comfortable, albeit unusual, expedition base in the village Mosque.

Over the period of the next five days the nearby Ghar Sarab was photographed, surveyed and extended adding 1,176 m of new passage to the cave taking it to 2,959 m in length. Surveying was done in two teams with Eshan Jabbar leading one and Simon Brooks the other and the Iranian team members putting the surveying skills they had acquired in 2007 into practice by surveying the cave. The Iranian team member quickly gained competence in cave surveying, proving they were fast, accurate and enthusiastic.

On Thursday 30th October the team packed, tidied the Mosque and took a car back to Hamadan. Over the next two days Simon Brooks gave lectures and ran workshops on cave exploration, recording and surveying to group of caver in both Hamadan and Tehran.

Before leaving Iran a set of surveying equipment consisting of a Suunto Compass and Clinometer, Tape and a Survey Book was given to both the Damavand Club and to the Hamadan Mountaineers. This was to say thank you and most importantly enable them to continue to practice and develop their surveying skills. Reports and surveys from Iran indicate that they are making good use of this equipment.

During the course of the 2008 expedition 2,158 m was surveyed in Danial Cave (Ghar-e-Danial), 13.6 m in Ghar Danial Kuchik (Small Danial), 9 m in Ghar-e-estakhr Danial (Pool Danial) and 1,176 m in Ghar Sarab taking the latter to 2,959.8 m in length.

3. 2001 Expedition to Iran

Between 17th November and 3rd December 2011 Simon Brooks and Shary Ghazy returned to Iran where they visited numerous karst areas in the vicinity of Nisaboor, Mashad, Kerman, Esfahan and Hamadan, met Iranian caving groups and assisted them in exploring, recording and mapping caves.

The first area visited was the Chah Nasar Area that lies to the south of Nishaboor in NW Iran. Here contact was made with a local caving groups and a small cave, Ghar Chah Nasar, was surveyed yielding a modest 62.8 m of passage with a vertical range of 20.8 m. To the north of Nishaboor a cave known as Ghar Shakh was explored, surveyed and photographed to yield 195.5 m of passage with a vertical range of 48.5 m. This cave situated near to the summit of a mountain contained 3 pitches and some very well decorated chambers. Travelling onward to the Mashad contact was made with local cavers and Ghar Kardeh that lies near to Kardeh Village to the north of Mashad visited. In this cave the team split into two groups that together surveyed 336 m in Kardeh's labyrinth of passages. Subsequently return visits by the Iranian teams have more than doubled its length.

Figure 3. Formations in main chamber of Ghar Shakh.

Leaving Mashad and traveling by bus to Berjand another caving contact was met and using his car the impressive Dasht-e-Lut (Iran's largest desert area) was crossed to reach Kerman. Here contact was made with a local caving group and the following day the team drove to the town of Sirjan and then made a 1.5 hour desert crossing to reach Ghar Uta which had been found and partially explored by the group within the last year. Here the 33 m entrance pitch of the cave was descended, photographs taken and a small amount of surveying undertaken in the large dry breakdown chambers that form the bulk of the cave. Moving on from Kerman to Esfahan contact was made with a group of Esfahan cavers and a cave known as Ghar Kalaroud that lies some 1.5 hour drive north of Esfahan, near to the village of Kalaroud visited. Surveying over period of two days saw 521 m of passage surveyed in this fine cave. This cave has subsequently been extended by over a kilometre.

In Hamadan contact was made with members of the Hamadan Mountianeers and another caver and a camp established in a house in the village of Sarab. From here Ghar Sarab was accessed and the remaining sections of the cave un-surveyed by the 2007 and 2008 visits were mapped taking Ghar Sarab to 3,250 m in length. Returning to Tehran a party to celebrate Mr Chengis Shelkli's 84th Birthday and

60 years since the establishment of Iran first caving group was organised. This also served as a goodbye event for Simon and Shary.

4. More recent exploration

The 2003 Iran Cave Directory (1st Edition – Berliner Hohlenkundliche Berichte) listed 850 caves and around this time interest in caving and cave exploration by Iranian cavers started to increase. In 2011 the "Iran Cavers and Speleologist Association" (ICAS) was established and more importantly a plethora of small independent caving groups were becoming increasingly more active. The 3rd edition of the Iran Cave Directory (2012) listed over 2,000 caves with the actual number of known caves being in excess of 2,400.

The rise in the number of small independent caving group and the availability of more cave related information and equipment has meant that caving is becoming a more popular activity in Iran. This is putting increasing pressure on some of Iran's most accessible and popular caves which are being sullied by discarded rubbish consisting of bits of clothing, food and drink containers and most significantly kilometres of plastic string which many groups use to find their way in and out of the caves. To address this situation and to encourage groups to care for the caves one of the very positive spin-offs from ICAS has been the promotion of the Annual "Iran Clean Caves Day", now in its 4th year with the recent 2012 event taking place on 23rd September. This was again very successful in all respects involving over 50 groups who removed rubbish and other discarded items from various caves all across Iran.

In November 2012 the Naghshe Jahan Caving Club from Esfahan located and explored Ghar Do-Sar (Two Heads Cave). Descending and initial 19 m entrance shaft and a final 90 m pitch into a huge chamber. This was carefully surveyed and confirmed that with a length of 385 m and a width of 265 m giving a floor area of over 81,000 m sq. it is currently (May 2013) ranked as the world's 4th largest chamber. Both the quality of the survey and the photographs are testament to rapidly developing competence of the Iranian caving fraternity.

Acknowledgement

In the above visit to Iran in 2006, 2007, 2008 and 2011 proved to be excellent with some fine cave passage explored and surveyed and many new contacts made. Iran on all occasions proved fascinating, the scenery was beautiful and spectacular, the cities busy and modern and the Iranian people hospitable, welcoming and friendly. The links made with the cavers from the various clubs and groups has grown from strength to strength and the enthusiasm and energy of both the young and older members is impressive. The opportunity of spending time caving with the Iranian cavers and share skills and knowledge were possibly the most enjoyable and rewarding aspect of these trip.

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CAVE EXPLORATION IN PAKISTAN

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Pakistan's rich and varied culture, sometimes-sensitive geo-political situation and variable infrastructure can make the search for caves within its extensive areas of limestone a challenging experience. With regular systematic cave exploration only taking place from 1990 onwards and most recently in April/May 2006. The 2006 Expedition saw a total of 14 caves explored and surveyed to yield 531 m of cave passage that took the total number of surveyed caves in Pakistan to 127 with a combined passage length of 6,230 m. This lecture gives an overview of the karst and caves in Pakistan and describes the exploration that has taken place within this fine country from 1990 to 2006.

1. Introduction

Pakistan's rich and varied culture, sometimes-sensitive geo-political situation and variable infrastructure can make the search for caves within its extensive areas of limestone a challenging experience.

Pakistan, covering an area of 803,944 sq. kms, stretches from the Arabian Sea up to the high mountains of Central Asia. Much of the country is mountainous with the mountain belt stretching from the Karakorum Range in the north to the Sulaman Range in the south/south west of the country. Within this long chain of mountains are some significant areas of limestone and karst that ranges from Triassic through to Eocene in age. In the Karakorum Range in the very north of the country, between the villages of Passu and Sost, very hard and highly marbleised limestone have yielded some small caves, seldom more than a few tens of metres in length. The Chitral District also in the north has limestone but only a few very small caves. Immediately north of Islamabad are the limestone Margella Hills in which just over a dozen small single chamber caves have been found whilst to the north of Islamabad, between Muree and Abbottabad, is a large block of limestone that also contains some small caves. To the north and south of Peshawar lie the tribal areas of Karran and Waziristan, both of which contain extensive tracts of limestone and some caves. Small caves have been recorded in the Khyber limestone that form the walls infamous Khyber Pass. The largest areas of limestone and karst are found in the semi-arid state of Balochistan. This comprises of limestone surrounding the former hill station of Zairat, mountainous limestone's surrounding the provincial capital of Quetta and the limestone's of the Kalat Plateau further to the south. It is here the largest and deepest caves are to be found. Pir Ghaib Gharra situated in the Bolan pass being the longest with 1270 m of passage and Kach Gharra near to Zairat with a passage length of 353 m and a depth of -127 m. The latter at an elevation of over 2,200 m asl, near the top of limestone that is well in excess of 1,000 m thick give an indication of the depth potential that may exist in Pakistan.

2. Cave exploration 1990 to 2006

Much of the systematic cave exploration in Pakistan has been conducted from 1990 onwards by British Groups (Orpheus Caving Club, Derbyshire, UK) working in Partnership with Pakistani Cavers and Mountaineers based in Quetta (Brooks 2001).

The first 1990 expedition was a reconnaissance that visited all the major karst areas in Pakistan and made some useful contacts with officials and groups in Pakistan. In the Karakorum Range in the very north of the country, between the villages of Passu and Sost, very hard and highly marbleised limestone have yielded some small caves, seldom more than a few tens of metres in length. In North West Frontier Province to the north of Peshawar the impressively sized Kashmir Ghara. In Balochistan the Pir Ghaib Ghara caves were located and explored for 90 m and the exploration of Bartozai Ghara begun.

Figure 1. Siygazi Ghar, Balochistan, Pakistan.

This was followed by another expedition in 1991 when a small group of three British Cavers made contact with local Pakistani Cavers/Mountaineers from the Quetta based Chiltan Adventurers Association along with good contacts in the Tribal Area's of Balochistan in Western Pakistan. In North West Frontier Province several caves were explored in the Khyber Pass Area. In the Margella Hills to the North of Islamabad Mohra Muradu Cave was explored for 148 m. In Balochistan Pir Ghaib Ghara was extended from 90 m to 250 m, several small caves were explored in the Ziarat Area and Bartozai Ghar explored for 250 m.

November 1994 saw a small team of three British cavers return to Balochistan and the Margella Hills to the North of Islamabad. These early expeditions had identified the main caving areas, which between them had yielded some 2.2 km's of cave passage divide between 43 separate caves. Significant discoveries in Balochistan on this trip the extension of Pir Ghaib Ghara No 1 its previous 1991 surveyed length of 250 m to 512 m and the exploration of Bartozai Ghara to 330 m in length. Whilst in the Margella Hills several small single chamber caves were explored none of which were more than 100 m in length.

October/November 1997 three British and one German caver joined forces with members of the Quetta (Pakistan) based Chiltan Adventurers Association as part of the 5th Pakistan Joint Mountaineering and Cave Exploration Expedition. Over a three week period 30 new caves were explored and Pakistan's longest cave (Pir Ghaib Ghara No 1) was extended from its previous 1994 surveyed length of 512 m to a significantly longer 1,270 m. This has firmly established it a both Pakistan's longest cave and the first Pakistan cave to exceed 1 km in length

November 2000 a team of five cavers from the UK (mostly from the Orpheus Caving Club, Derbyshire) joined with members of the Pakistan based Chiltan Adventures Association (Balochistan) to participate in what was described as the "7th Pak-Britain Mountaineering and Cave Exploration Expedition 2000" during which the expedition explored over 20 new caves in the mountains of the tribal areas of Balochistan (Western Pakistan). Over the three weeks of the expedition over 1.7 km's of new passage was explored and surveyed. Significant finds of the expedition included the impressive Murghul Ghul Gharra (Cave of the Bats Shit) located in the Harnai District that with a large chamber measuring 40 m wide by 90 m long and 580 m of surveyed passage became Pakistan's second longest cave. Other significant finds included Kach Gharra (Kach Cave) located on the Peil Ghar Mountain (Elephant Mountain) that contained a 35 m entrance pitch and an impressive 70 m second pitch. With 350 m of passage and a depth of 127 m it is Pakistan's deepest cave to date. In October 2000 the Pakistan Cave Research Association was formed to further cave exploration and research in Pakistan. Based in Quetta this organisation has very close links with the department of Geology at the University of Balochistan and Geological Survey of Pakistan also based in Quetta.

The most recent expedition in April/May 2006 saw a total of 14 caves explored and surveyed to yield 531 m of cave passage. Significant finds on this visit included Lamboor Cave situated in the Aghbaragh Mountains to the west of Quetta that is truly unique in Pakistan being the only known active resurgence cave that has been found to date. Although only having 48 m of passage the cave begins as a chest deep canal that opens into a chamber containing a waterslide and a short section of vadose streamway.

Figure 2. Vadose Streamway, Lamboor Cave, Balochistan.

North of the town of Sharigh that lies on the Southern side of the Ziarat (Khalifat) Mountain range two small dry caves were explored, Ghwa Ghara (Cow Cave) at 50 m in length and Sharigh Ghara (Sharigh Cave) at 34 m. At a location to the North of Sharigh two more caves were explored, Killi Parri Ghara (Cave) at 94 m in length of passage and many with fine formations and a second cave, Farishta Wazzar

Table 1. Pakistan Longest and Deepest Caves – May 2013.

	Cave Name	Location/State	Surveyed Length
Longest			
1.	Pir Ghaib Ghara	Balochistan	1,270 m
2.	Murghul Ghul Ghara	Balochistan	580 m
3.	Kach Ghara	Balochistan	353 m
4.	Bartozai Ghara	Balochistan	330 m
5.	Mohra Muradu Ghara	North West Frontier Province	148 m
Deepest			
1.	Kach Ghara	Balochistan	127 m
2.	Maraan Ghar Ghara	Balochistan	52.2 m
3.	Siyazgi Ghar	Balochistan	48.9 m
4.	Shabaz Sah Ghara	Balochistan	33 m
5.	Thaan Ghara	Balochistan	32.2 m

Ghara (Angles Wing Cave) began with an 11 m pitch and again had many fine formations, one of which provided inspiration for the caves name. In the Loralia Area six small caves were explored in the remote Draggi valley whilst near to Loralia itself Pathan Coat Ghara (Cave), AKA Shipana Ghara (Shepherds Cave) proved to be somewhat larger with 87 m of passage an impressive entrance and a good sized chamber. On the summit of the impressive Siygazi Ghar (Siygazi Mountain) Siygazi Mountain Siygazi Pot was explored and surveyed to yield 102 m of passage. At 2,470 m altitude this is the highest known cave in Balochistan to date.

3. Summary

To date there are 127 recorded caves in Pakistan with a combined passage length of 6,230 m. The sometimes-sensitive geo-political situation and variable infrastructure will continue to make the search for caves within its extensive areas of limestone a challenging experience. However the positive collaboration that has been formed between the Orpheus Caving Club (UK) and the Pakistan based Chiltan Adventurers Association (Balochistan) and various government agencies is likely to lead to more discoveries and a better understanding of the Pakistan Karst and Caves.

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CLUB OF CLIMBERS AS A BASIS FOR TRAINING PROCESS OF CAVERS

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Abstract. An exploration of Altai and Sayan (Russia) karst massifs by efforts of our Club was began in 1978 and has given a discovery of the most technically difficult cave in Siberia (Altaiskaya Cave, almost 3 km of a vertical section to climb up or descents) and the deepest one (Kektash Cave, -350 m), as well as a result in a significant contribution to the Big Oreshnaya Cave (totally about 50 km length), the longest in the world and complicated, various in structure labyrinth in conglomerates. All discoveries were possible to perform owe to a special climbing preparation and trainings on a base of the Club of climbers of Novosibirsk State University. For the exploration needs a geophysical prospecting method was elaborated to benchmark near surface cavities.

Абстрактная. Исследование карстовых массивов Алтая и Саян (Россия) усилиями нашего Клуба началось в 1978 году и дало открытие самой технически сложной пещеры в Сибири (пещера Алтайская, почти 3 км протяжённость лазания вверх или спусков) и самой глубокой пещеры (пещера Кёкташ, -350 м), а также внесло значительный вклад в пещеру Большая Орешная (общая длина около 50 км), самый протяжённый в мире, сложный, разнообразный по структуре лабиринт в конгломератах. Совершить все открытия оказалось возможным благодаря специальной скалолазной подготовке и тренировкам на базе Клуба скалолазов Новосибирского Государственного Университета. Для исследовательских нужд был разработан разведывательный геофизический метод для отсечки близповерхностных пещерных пустот.

1. Introduction

Peculiarity of caves in Siberia consists in a necessity of either free or aid rock climbing. Our Club members appeared to be one of the first in the world who had been practicing in 70th an aid technique of sheer wall ascents inside caves (Bulychov 1999). To get to the large sub-horizontal storeys discovered one has to climb up as high as 40–180 m hanging walls using a serious mountain skill.

2. Geography and geology

Altaiskaya and Kektash caves are located in 15km to the north-west from village Kamlak on Seminsky range of mountainous Altai on the plateau "Clean Swamps". Altitude of an entrance is 800 m; basis of erosion is 380 m. Rocks in caves are presented by dense limestone of low Cembriy of blue color. Abundant net of faults results in many leveled complicated system of galleries, passages, former ancient streams and contemporary rivers.

Big Oreshnaya Cave is located in 3 km to the east from village with the same name in Mansky region of East Sayan. Altitude of an entrance is 590 m; basis of erosion is 350 m. The cave is developed in brown-red conglomerates of Lower Ordovician with significantly contained limestone and dolomite pebbles filled in gravelites of quartz-calcite-dolomite material. There are lots of lakes, streams with temporary or continuous water flow, several sumps, a number of gaps, shafts, huge faults, many places with beautiful draperies and stalactite cascades. Much clayey-sand-aleurite material is located everywhere on a floor of cave passages and grottos (Tsykin 1985). There are no distinct storeys in the cave. Labyrinth is very intricate, tangled and too complex. A reason of rare karstification of conglomerates may be in a high porosity of rocks as well as a net of cracks and faults significantly developed (Цыкин 1990). Geomorphologic position of cave massif is favorable for penetration and movement of underground waters.

3. Premise

Our Club was organized as a large group of scientific researches of Academic institutes of famous Academic town and students of well-known University who were infatuated in rock-climbing and cross-country skiing. We preferred to climb outdoor, so once found out caves in Siberia to be a perfect object to enjoy a long pitching climbs (one of the best training ground occurred to be Torgashinskaya Cave situated near the border of the city Krasnoyarsk). We noticed having a good climbing skill makes passing of a sportive route in a cave much faster.

4. Training routine

Cycles of our training process are conditioned by local weather. In Siberia usually there is 6 months snow cover, so a year is commonly divided to a winter season and not winter one. That's why we are fond of cross-country skiing as there is nothing to do else in a sense of moving activity but in turn, we live among marvellous forest and still can enjoy a transparent clean air, fir-trees, pines, cedars, lovely prepared ski treks. Skiing is incentive for endurance and stamina. So in winter all of us are going for race skiing at least 3 times a week, least 15–20 km every time, and 1 time a week is dedicated to indoor rock climbing (2 hours of pleasant training). In not winter season, contrary, only 1 time a week is devoted to a race cross-country running and 3 times (3 hours every) are disposed to outdoor rock climbing. Supplementary, every day morning and evening exercises (half of hour every) are certainly compulsory. The schedule of trainings is the same for any age of a Club member (no matter, 16 or 55 years old he/she is), intensity and loading are relevant to a rank of functional readiness (usually it depends on an age but not strictly correlated). If one is a sportsman it is mandatory to pass current medical reviews and a deep medical exam before every expedition. Regularity, permanency, execution of prescribed tasks of a coach appears to be an irrefutable statement of a training process.

Determined daily regime (sleep, work, training, relax), nourishment (correct and balanced), neither harm habits nor bad addictions are also necessary to follow.

As a rule we proceed mostly a free climbing either leading or top belay. But recently more aid climbing is demanded. In cave to ascend 40–180 m hanging face is mandatory to use a wide range of mountaineering technique such as storm climbing stairs, telescopic platform, cams, nuts, rock-fifi, rurks, sky hooks, pitons, bolts, etc. Experienced Club members are generally prepared to lead on rocks 6c+, 7a, A2/C2, to ascend in mountains V, TD.

5. Geophysical method

To benchmark emptinesses situated close to a surface (5–10 m depth) the seismic-electric effect method was elaborated (Bulychov 2000). The source of elastic waves is repeated blow of a heavy sledge-hammer. The working frequency is 200–500 Hz. The receiver consists of grounded electrodes and sensitive magnetic film. Compared with other methods the advantage of the treatment of a signal of reflected waves in terms of our method is that the signal is distinctly traced on a receiver in such field conditions (Sorokina and Bulychov 2000).

6. Results

Our climbing skill allowed us to make the first significant success in 1978 in Big Oreshnaya Cave. We overcame up the waterfall “Adventure” against a water flow and found spacious system of galleries with rare calcite flowers. In 1988 the author climbed up 70 m sheer wall with a help of Struchkov Igor and discovered three tremendous systems “Strem-Lotos-Siberian”. In 1994 the author climbed up 40 m hanging face above the bottom Sump with an assistance of Badazkov Dmitry and discovered the large system “Overlake”.

The mentioned seismic-electric effect (Bulychov 2002) geophysical method used helped in Big Oreshnaya Cave to predict from a surface the system “Zastrem” that 1 year later, in 1993, was discovered by Shundeev Sergey. Some grottos of this system are located very close to a surface, in some places in 2.5–3 m.

The most appreciable discoveries were made in Altaiskaya Cave in 1982, 1986. 1988, 1996, 2008, 2010, etc. This cave is outstanding for its high (40–180 m) sheer or hanging face ascents in order to get upper storeys from lower ones. Aid climbing, the most one, combines with free pitching. To make a complete sport route a strong group is demanded at least 10 days to spend inside the cave. Huge shafts climbed up are definitely memorable – Giants (110 m), Birth day (170 m), named in memory of Olga (180 m), Tube (70 m), 4th Sump (30 m), Sphinx (30 m), Red-White (25 m), Merry river (several 30 m), Old river (several 40 m), etc.

In Kektash Cave in 1997 the final mud sump was overcame by upper gallery, as a result the deepest point in Siberia was achieved (-350 m).

7. Ethics, philosophy

A sense of caving (and any sport) is implied in our Club to gain bright colors of life, to be wise and wealthy (spiritually, of course not to context of money), to sustain a healthy way of life.

Cruelty in usual sports can result in bruises, damaged joints, tendons, knuckles, broken bones. We suppose a cruelty (even meanness) in caving (and mountaineering) is believed to jeopardize mates or one by instigating to stamped to do insane brave exploits for vanity. A cost of a mistake made here can be a lost life.

We advise our young members to never prevail upon themselves, no heroism but to be sober, prudent and to enjoy a training process and being on nature. In expedition one has to be courageous to retreat if ominous danger is evident or already foreseen. We appeal to overcome a route not due to a desperate audacity but according to a skill and experience that are being improved by regular and persistent trainings.

8. Conclusions

We have performed a school of cavers as far as our followers in face of young generation have continued our life’s work. They have discovered in Altaiskaya Cave by means of climbing up the new large system “Through blackthorns to the stars”, found out and explored the new large “Kat-Shu Cave” near the Teletskoye Lake (Shwarts 2012), investigated many other (not so large yet) caves.

In general speleology and caving have a boundless potential to bring up young generation in harmony with a peace, to enhance a social cognition, self-perfecting, feeling a balance and serenity on nature and in daily life.

Acknowledgments

We have been training a caving since 1978 and mountaineering since 1993 and during all the time are faithfully grateful to our fraternity, particularly to V. Sorokin, A. Lelyak, V. Shikhov, A. Zdanov, V. Chub, P. Minenkov, and Dm. Rogozin for a human support in life.

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EXPLORATIONS AND DOCUMENTATION ON THE ATEPETACO KARST SYSTEM (HUEYTAMALCO, PUEBLA, MEXICO)

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Since 1998, ongoing exploration in the Hueytamalco area (State of Puebla, Mexico) was carried as a joint collaboration between Italian and Mexican cavers. The results of these activities are summarized in the following paper. In time, several caves have been explored, the biggest of which have been recognized as belonging to a single karst system, called "Atepetaco karst system".

At present the system reaches 12,100 m of total surveyed length and 222 m of depth. However the total length of the system could be further increased by finding new connections with other caves which shows hydrological connections to the main system and with new explorations.

The caves referred to the "Atepetaco karst system" are carved in the San Pedro Fm. limestones of the Upper Jurassic, affected by orthogonal fracture systems and reverse low-angle faults.

Topographic surveys, photographic and cinematographic documentation were collected during each expedition including geolithological and hydrological analyses in the area (15 km^2). Preliminary archaeological and biological observations of the explored caves were also obtained. Some archaeological findings have been delivered to the University of Mexico City.

Several conferences were organized for the public opinion in order to show the features of the different caves of this area, and to highlight the issues related to the vulnerability of karst aquifers.

1. Introduction

In this work, we intend to summarize the main results achieved during 5 speleological expeditions in Hueytamalco area, (State of Puebla, Mexico) occurred in 1998, 2002, 2008, 2010 and 2012, in the frame of a project called Tláloc. During these expeditions, thanks to the joint efforts of cavers from Sicily, Lombardy and Mexico, many cavities were discovered.

These cavities were initially explored as independent caves but subsequently extensively connected to each other, allowing to delineate a single complex, named "*Atepetaco system*". This system is 12,100 m long and 222 m high. In 1998, *Resumidero de Miquizco* was explored, discovering 3 entrances with a total length of 1.5 km. In 2002, the *Cueva de Los Cochinos* was also explored (500 m of total length).

In 2008, the entrances of *Cueva del Viento* and *Cueva de Mama Mia* were discovered and during the exploration, the two caves were connected. The length of the system reached 5.5 km with 4 entrances (Iemmolo et al. 2008). In 2010 *Cueva del Camarón* (600 m), partially explored in 2002, was connected to *Resumidero de Miquizco*, the system then reached 2.3 km with 5 entrances. The *Resumidero de Miquizco* and *Cuevas Viento – Mama Mia* (up to 6.9 km) systems were only 25 m apart (Rossi et al. 2012). In 2012, the *Cuevas Viento – Mama Mia* was connected to *Miquizco* system, by overcoming a landslide and a sump. Few days after, *Cueva de Las Lagartijas* up to 800 m long was connected to the same system (Rossi et al. 2012).

The latest explorations allowed to better define the extensions and characteristics of the "*Atepetaco karst system"*. Surveys, photographic and cinematographic documentation were collected including the realization of geolithological and hydrological analyses of the area (15 km^2).

Preliminary archaeological and biological observations of the explored caves were also obtained. Some archaeological findings have been delivered to the University of Mexico City. In addition, a remarkable sensitization campaign of the public opinion (on issues related to the vulnerability of karst aquifers) was conducted.

2. Geographical and geological settings

The site studied is located in the north-eastern zone of the Puebla State (Mexico) in the proximity of the village Atepataco, in the Municipality of Hueytamalco. The area is included between the UTM zone PT 0674000 – 0677000 E and UTM 14Q PT 2205000 – 2209000 N. It is part of the tectono-stratigrafic system of the Cuenca Sierra Madre Oriental of the Terreno Maya. Surface and underground explorations allowed to recognize the sequences of the outcropping and sub-outcropping litho-stratigraphic units (Confortini and Marsetti in press).

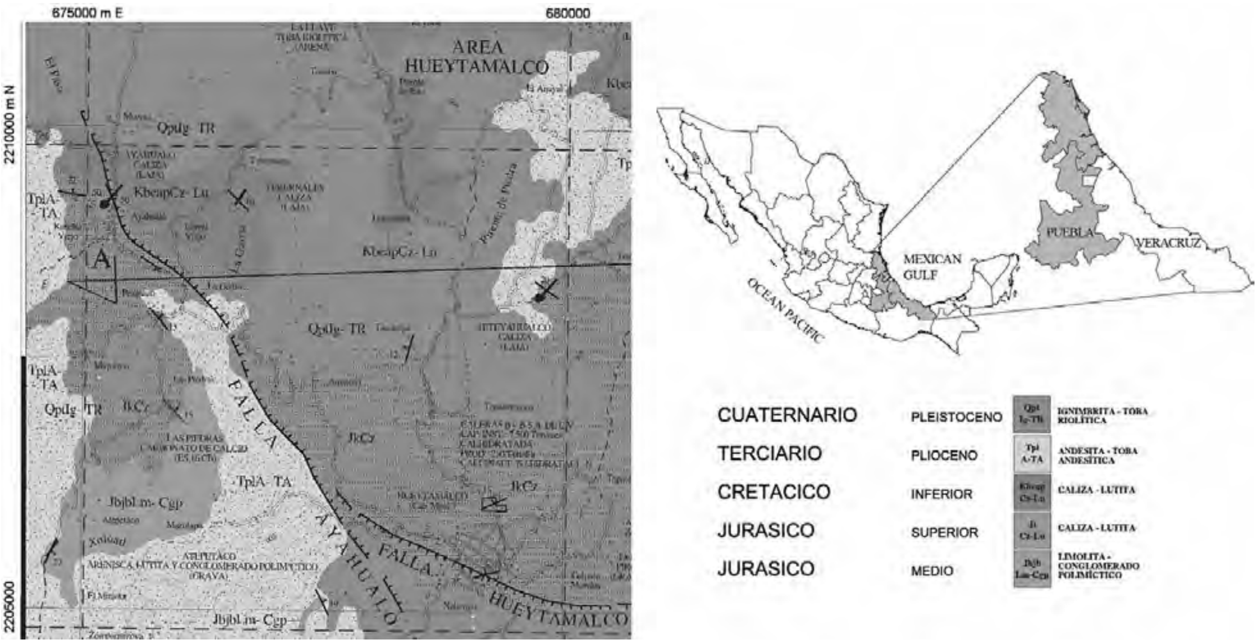

Figure 1. Location and geological map of the investigated area (after SGM – Servicio Geologico Mexicano).

The oldest unity of the stratigraphic sequence is the Cahuasas Fm (Middle Jurassic, JbjbLm-Cgp in Fig. 1) which irregularly outcrops in the investigated area. It is composed of non-karstifiable terrigenous rocks with fine and massivily bedded pinky-beige sandstones, with clasts of quartz. The sandstones gradually evolve into reddish marls with thin beds dipping towards NNE and average value of 15°.

The following unit, hosting the karst system, is composed of carbonatic rocks with two distinct comformable formations in gradual transiction. The lowest formation, San Pedro Fm, (Upper Jurassic, JkCz in Fig.1), is composed of a sequence of grey-beige compact layers of calcirudites with metric thickness. In some isolated cases, white bio-calcirudites with gasteropods and broken coral fossils can be found in the San Pedro Fm. These corals are occasionally substituted by iron oxides. Decimetric nodules of grey or black chert can be found at the bottom of the sequence.

The Atepetaco and Las Piedras villages are located on the tabular relief belonging to the San Pedro Fm. This relief is characterized by pinnacular karst. In the estearn sectors, in the proximity of the Rio La Garita river, the carbonatic outcrop is delimited by morphoselective scarps ten of meters high.

The upper part of the unit, which is not indicated in the geological map because of the little extensions of the outcrops in the area, is part of the Pimienta Fm. (Upper Jurassic). This formation is composed of a sequence of dark grey calicilutites, blandly stratified in parallel beds, with an alternation of thin marly limestone layers, with lens and nodules of chert. Occasionally, it is possible to find in the sequence, layers rich in ammonoids, echinoids, bilvalves and corals. This formation, is generally sub-outcropping and visible along road trenches, (e.g., in the proximity of the Rancho Viejo sink cave).

The complex of carbonatic rocks is eroded on the top showing a unconforbable contact with the above volcanic unit. The unit is located on the central part of the studied area dipping towards NE with average values between 5 and 10°. The monoclinalic setting of the carbonatic rocks can be associated to the uplift of the East Cuenca Sierra Madre occurred during the Cenozoic.

The youngest formation is formed of Cenozoic vulcanites mainly composed of andesitic tufa and breccias of the Andesita Teziutlan Fm. (Pliocene, TplA-TA in Fig. 1), and of ignimbrites with rhyolitc tufa of the Ignimbrita Xaltipan Fm. (Pleistocene, QpgtIg-TR in Fig. 1).

The contact with the underlying units is erosional confirming the existence of a long phase of subaereal remodelling of the sedimentary sequence. Highly alterated pyroclastic deposits, with cineritic matrix and centimetric pomice, can in places overly the summit of the limestone relief with discontinuous and thin covers. These deposits can partly fill some entrances of the karst system.

2.1. Water analyses

The water analyses (temperature, Ph, conductivity) were carried out during the surveys of the caves, along the resurgences located in the proximity of the Rio La Garita river. The temperature of the air circulating into the caves varies between 19–21 °C, influencing the temperatures of the internal waters which vary from 18 in the deepest part of the caves to few degrees higher, closer to the surface. The Ph values vary from 6 in the proximity of the surface where the waters circulate around volcanic rocks overlying the carbonatic rocks, to a value of 7.5 in the subterranean waters of the deepest part of the caves and in correspondence of the resurgences. The electric conductivity changes from 30 mS for the superficial waters, to 50 mS in the deepest part of the cave, reaching a value of 170 mS in the resurgences. A decrease of the ph and conductivity values can be attributed to water inputs from the surface to the underground system circulating through the sink caves and/or dolines.

3. History of the explorations

The expeditions of the Tláloc prject in the Puebla State (Mexico) started as a collaboration between cavers from Sicily (Speleo Club Ibleo, SCI) and Mexico City (group Union de Rescate e Investigaciòn en Oquedades Naturales, URION). In 1998, the area of Teziutlan (Puebla), in the municipality of Huyetamalco (Puebla) became of interest for the expeditions. In this area the entrances of two caves, the *Cueva de Las Lagartijas* and the *Resumidero de Miquizco,* were already known and the latter one, was already explored for a initial length of 1.5 km (see Table 1 for up to date total length and depth values of the explored caves).

In 2002, new activities were organized along with continuing the expeditions into the already known caves. The caves of *Cueva del Cocinero* (190 m of total length L, -57 m of depth D) and *Cueva de Los Cochinos* (500 m L, -80 m D), were discovered and explored. Several new entrances were located among which the entrance of *Cueva del Camarón* (Pannuzzo et al. 2003). In 2008, two new caves were discovered, these caves were named *Cueva del Viento* e *Cueva de Mama Mia*, in a short lapse of time these cave were connected reaching a total length of 5.5 km (Pannuzzo et al. 2008; Dominguez-Navarro et al. 2009).

A continuous exploration activity was carried out in 2008, especially focussing on the *Resumidero de Miquizco* and on the *Cueva de Los Cochinos* (explored for a further kilometer in depth and reaching -80 m). Meanwhile three new small caves were discovered (*Huertas Tri*, *Cueva Gloria*, *Enchonada*). In 2010, the new-born system, *Cueva del Viento – Cueva de Mama Mia* reached 6.9 km of total lenght with 4 entrances. A distance of 25 m divides this system from the *Resumidero de Miquizco* which, thanks to the junction with the *Cueva del Camarón* and new explorations campaigns, reached a total of 2.5 km and 5 entrances. Surface search activities allowed to discovered new minor caves such as the *Cueva de Victor*, the *Cueva de la Pequeña Agonia*, the *Embudo de Rancho Viejo*.

In 2010, the *Sotano del Sendero*, discovered in 2002, was explored again. Last expedition occurred in April 2012, when the exploration of the *Embudo de Rancho Viejo* (-75 m D) and the *Resumidero de Miquizco* was completed with the latest being connected with the *Viento – Mama Mia* system. In addition, the exploration of the *Cueva de Las Lagartijas* (L 800) was completed and connected to the above mentioned system. The connections of the different systems and caves allowed to delineate a new system called Atepetaco which reaches a total length of 12 km and depth of 200 m (Fig. 2; Tab. 1).

Table 1. List of the explored caves with total length and depth indicated. The stars mark the caves referred to the Atepetaco system.

Cave	Length (m)	Depth (m)	Year of exploration
Cueva de las Lagartijas *	800	173	1998
Resumidero de Miquizco*	2,109	120	1998
Cueva de las Cruces	48	13	2002
Cueva del Cocinero	190	67	2002
Cueva de Los Cochinos	983	125	2002
Cueva del Camarón*	672	59	2002
Cueva del Viento*	4,192	111	2008
Cueva de Mama Mia*	4,103	94	2008
Huertas Tri	62	33	2008
Cueva Gloria	53	13	2008
Enchonada	188	29	2008
Cueva de Victor	–	–	2008
Cueva de la Pequeña Agonia	57	6	2008
Sotano del Sendero	173	22	2008
Embudo de Rancho Viejo	250	101	2010
Ojo Escondido	49	36	2010
Embudito de Rancho Viejo	32	27	2010
Pozo Ostia	62	42	2012
Cueva Don Alfredo	363	99	2012

4. Brief archaeological notes

During one of the explorations (2010) of Tláloc project, several rock shelters were discovered in the surroundings of a river. Petroglyphs and paintings were founded inside the shelters. These archaeological discoveries were analyzed for the first time resulting of great interest for the studied area. During the last campaign (2012), a cave with entrance of large dimensions, named "*Cueva Don Alfredo*", was explored. In the interior remains of pottery, corresponding to pots and cajetes, were founded in proximity of the entrance. These potteries are associated to rituals, probably occurring inside the cave, intended as a prayer to the God Tláloc, for water and rain. It is nowadays known that these kind of rituals were a common practice in Mesoamerica. However no proofs of the occurrence of such activities in the Huyetamalco area were previously anywhere reported. The cultural group who inhabit these caves is still not known. The only evidence is that these findings can be attributed to periods previous to the Spanish conquest, between 1000 and 1500 A.D.

5. The caves

The Atapetaco karst system (Fig. 2) is located along a monocline blandly inclined towards nord-east in correspondence of the contact between the carbonatic rocks and the non-karstifiable substratum. This system was divided into three main sub systems of major caves spreading on two main levels and characterized by large rooms (*Resumidero de Miquizco, Cueva de Mama Mia e Cueva del Viento*). Along with the main system, several minor caves have been explored and occasionally connected with other caves previously explored.

Figure 2. 3D view of the Atepetaco karst system.

5.1. Resumidero de Miquizco

Il *Resumidero de Miquizco* is a sink cave located at the end of a blind valley which is characterized by a vertical wall 70 m long. This active cave is fed by a river with a capacity that, even in the dry seasons, reaches few hundred meters per second.

Figure 3. Resumidero de Miquizco. Large chamber in correspondence of the Sotanos de los Ojos (Photo M. Vattano).

The main branch of the cave shows a series of large breakdown rooms, one of which characterized by the presence of two twin shafts (*Sotanos de los Ojos*), 70 m long from the surface (Fig. 3). The junction with the *Cueva del Camarón* is located in the eastern sector of the cave, while along the main branch and following the underground river, it is possible to reach the sump which is in connection with the *Cueva de Mama*.

5.2. Cueva del Viento

The *Cueva del Viento* is located at the bottom of a rock scarp 20 meters high. The main passage is a gallery with large dimensions and the floor, along which a small stream of water flow, is covered with thick clay (Fig. 4).

Figure 4. Cueva del Viento. Gallery showing an orthogonal fracturation system on the roof (Photo A. Corna).

Below the gallery a more recent systems of branches are located showing a pattern strongly influenced by the fracture systems of the host rocks. These branches are active, with the waters coming from several secondary branches which often show a loop pattern.

The secondary branches are connected with several cavities located upwards of the *Viento* portion as shown by the discovery of the junction between these branches and the

Cueva de las Lagartijas and *Resumidero de Miquizco*. Several small passages connect the lower active conduits to the upper inactive galleries. Between these galleries, the *Pomice*, is characterized by a pond with floating pumice fragments and connected with the *Asuncion* shaft (50 m, connected with the external surface). Another gallery, called the *Puzzone* lake, feed the stream that converges towards the resurgences, and a sump which is presumably connected with another small resurgence located between the entrance of the *Cueva de Mama Mia* and the *Cueva del Viento*. A gallery of large dimensions is located along the main passage (12 m long, 8 m high). This gallery is characterized by a roof showing a clear system of fracturation of the host rock (Fig. 4). At the end of this gallery it is possible to reach smaller passages among which, the one in connection with the *Resumidero de Miquizco*, can be found. A large room, (Salon Pack, 30 m wide, 15 high and 70 m long) opened along the main passage, is in connection with the *Cueva de Mama Mia*.

5.3. Cueva de Mama Mia

The *Cueva de Mama Mia* is the main resurgence of the Atepetaco system. The cave is characterized by imponent rooms created by waters flowing inside the caves, which in period of flood, reach considerable capacity. From the entrance, characterized by breakdown deposits, it is possible to walk through large galleries entirely carved by scallops. Contrary to the *Cueva del Viento*, the main passage is active and located at lower altitude. Large inactive rooms and breakdown chambers are located, in the southern sector of the cave.

Figure 5. Cueva de Mama Mia. Main active flooded gallery (Photo A. Corna).

In the active passage towards the west, smaller passages and ponds with shrimps and small fishes coming from outside the cave, can be seen. This sector of the cave is characterized by large chambers until reaching a vertical jump which gives access to the water (Fig. 5). Here the passage is blocked by a breakdown which does not allow any further prosecution precluding the possibility of finding another connection with one of the branches of the *Resumidero de Miquizco*.

5.4. Cueva de los Cochinos

The entrance of the *Cueva de los Cochinos* opens on the side of the deepest zone of a collapsed doline. This entrance is characterized by a narrow passage which gives access to a shaft 33m deep (Pannuzzo et al. 2005). A gently dipping gallery is located at the base of the shaft. This gallery follows the same tectonic direction towards which the galleries of entire Atepetaco System inclined (NNW-SSE and NNE-SSW). From the base of the shaft it is possible to go upstream, and downstream into the cave. In both directions, a small underground river can be found.

The upstream portion of cave is composed of a series of potholes and small climbs becoming impracticable, after about 100 meters from the base of the shaft. The downstream portion is longer and more complex and, as the upstream, characterized by small jumps and potholes. The initial part leads to a chamber with breakdown blocks which almost completely block the room. These chaotic deposits can be overcome only passing through small passages after which the gallery continues with its trend of short jumps and water flows. After a small passage, the cave changes its appearance and the gallery tends to go low and wide until reaching a 15 m deep shaft. After the shaft, greater amount of waters can be found in the rooms of the cave. These water flows can be bypassed following a path composed of a sequence of jumps followed by a chamber filled with breakdown deposits. After these deposits the galleries continues until it ends up narrowing. The water flows enter through a narrow slot in the proximity of which two small not practicable passages can be found. The total length of the cave reaches about 1,000 m with a depth of 80 m. The topographic surveys of the cave show that the *Cueva de los Cochinos* is connected to the Atepetaco system, with only a few meters missing to be connected with the *Cueva del Viento* in the *Rio Negro* branch. This part of the Atepetaco karst system is the closest to the scarp which constitutes the eastern boundary of the carbonatic outcrop.

5.5 Cueva de las Lagartijas

Not far north from the Atepetaco village, a stream enters a small blind valley, forming the *Cueva de las Lagartijas*. The first part of the cave, about 165 m, was already explored in 1998, up to a narrow passage impossible to overcome. This portion of the cave is characterized by a slightly dipping gallery, interrupted by small vertical jumps of a few meters of depth. The gallery follows the stratigrapich bedding. The water flows modelled the gallery which nowadays show a section with width larger than the height. The eastern portion is also characterized by a short secondary branch in which the water still flows. During the 2012 explorations, the narrow passage that had stopped the previous exploration, was exceeded. After these passages the general patter of the caves follows a wide and low conduct even if occasional wider rooms can be found along the path. The cave is characterized by homogeneous forms until reaching a fissure between speleothems after which there is crossroads. After few meters, the section of the eastern branch of the cave becomes non practicable because of the significant narrowing of the section. The western branch instead continues with portions of different width, until a narrow horizontal passage called "*paso de los 60*". Only petite cavers (those who weight less than 60 kg) were able to overcome the passage. This ends in an 8 m shaft, the only one in the cave that requires the use of ropes. From there forward, the dimensions of the gallery increase, because of the confluence of several water flows and thanks to tectonic discontinuities that have forced a vertical development of the rooms.

The stream, flowing on an inclined plane, ends up in a striking waterfall and generates one of the most remarkable sector of the cave. Passing the waterfall, numerous speleothems (e.g., stalactites, columns, stalagmites and white flowstones) can be found (Fig. 6).

Figure 6. Cueva de las Lagartijas. Gallery characterized by white speleothems (Photo G. Gurrieri).

The gallery leads to a last room where a narrow downward fracture is in communication with one of the branches of the *Cueva del Viento*. The total depth is 173 m and the total surveyed length is 800 m. Several other secondary branches will be explored in future expeditions

6. Discussion and Conclusions

Years of explorations enabled us to identify, although still in a non-definitive way, the structure and features of the "Atepetaco karst system". This system is entirely developed in the limestones of the San Pedro Fm. (Upper Jurassic) with passages slightly inclined, and parallel to the main discontinuities of the host rock, (i.e. fracturation, bedding and low-angle reverse faults).

The "Atepetaco karst system" reaches about 12 km of total surveyed length and about 200 m depth. It is composed of a series of sink caves located at different altitudes, which intersect, from SW to NE, the carbonatic relief, and form a complex network of active and inactive galleries.

The evolution of the karst system, which represents an exposed karst system, led to the formation of multiple storey in response to the geomorphological evolution of the area.

At present many galleries of the whole system, are inactive, while others are activated only during intense rainfall. The latter are responsible of the formation of a series of different heights waterfalls formed along the eastern scarp of the limestone outcrop.

The pattern of the karst system, the in-depth knowledge acquired thanks to the explorations of the Tláloc, together with the analysis of the waters, allowed to classify the "Atepetaco karst system" as a system characterized by active galleries sized by the maximum flood and with a rapid circulation of waters.

During the 2012 expedition, a paper was written in collaboration with some exponents of the local villages, and subsequently distributed to the municipal authorities and rest of the population. The text, aims not only to illustrate the caves of the karst system, but also suggests norms and behaviors to adopt to safeguard the caves when accessing them. For the protection of these environments, in order to minimize pollution of both surface and karst systems, the exploration team has also tried to organize campaigns of sensitization for the local population.

The activities in the Atepetaco area have yet to be continued in order to complete the exploration of the secondary branches of several caves already known and also to connect different caves for which the connection is, at present, only hypothesized. These explorations will allow us to obtain a complete knowledge on the system, which will be used in future surveys in adjacent areas.

Acknowledgments

The authors would like to thanks the following caving groups for their active participation to the explorations: Speleo Club Ibleo (RG), Gruppo Speleologico CAI Belpasso (CT), ANS Le Taddarite (PA), Speleo Club Orobico CAI Bergamo (BG), Gruppo Grotte Milano CAI Sem (MI), Gruppo Grotte CAI Busto Arsizio (VA), Gruppo Speleologico Prealpino (VA), Gruppo Speleologico Bergamasco Le Nottole (BG), il Gruppo Grotte I Tassi CAI Cassano d'Adda (MI), Gruppo Speleologico "Urion" (Uniòn de Rescate e Investigaciòn en Oquedades Naturales), I.P.N. (Instituto Politecnico National, sezione speleologica, Ciudad de Mexico).

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DISCOVERY AND EXPLORATION OF EVKLIDOVA PIŠČAL, JULIAN ALPS, SLOVENIA

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During the fall of 2010, we discovered a small blowing hole in the forests above the plateau Pokljuka in the Julian Alps of Slovenia. The air flow was impressive, but it appeared that a lot of work would be needed in order to make it human size. A little less than a year later, we returned to the site to try a bit of digging and see what we could find. On five different days during fall of 2011 we returned to the blowing hole to dig. Most of the work simply required removal of loose rocks and debris that had likely filled the hole as a result of frost shatter. Our biggest challenge was that the unstable walls of debris were frequently collapsing back into the dig, requiring us to remove much more material than would otherwise be necessary. We were beginning to wonder whether the effort was sustainable, when on the fifth digging effort we made an initial breakthrough into a small chamber and a narrow meander passage beyond. The cave continued as a narrow meander with a few small free climbs for about 100 m before we reached the first pitch. From there, the cave began to descend rapidly, but at the bottom of every pit we found another narrow meander that we had to negotiate before reaching the next shaft. Over a few months of exploration, the cave reached a depth around 150 m, where it became more horizontal. Exploration beyond this point was initially quite challenging due to narrow passages, but eventually we found a way through to a nearly kilometer-long fossil meander passage that gradually descended into the mountain. Currently, the cave is 429 m deep and 1,731 m long, making it both the longest and deepest cave on Pokljuka. The current bottom of the cave is at a sump, and ongoing efforts are attempting to follow the airflow and find a bypass. Many side passages and upper levels remain unexplored. In addition to efforts in the main cave, time was spent searching for other caves in the area. In particular, the direction of airflow suggests that the main entrance is a lower entrance, and many possible cave entrances have been located on the plateau above the cave. The depth potential of the area is approximately 1,000 m.

Figure 1.California Dreamin', the deepest pit in the cave. Photo by Matic Di Batista.

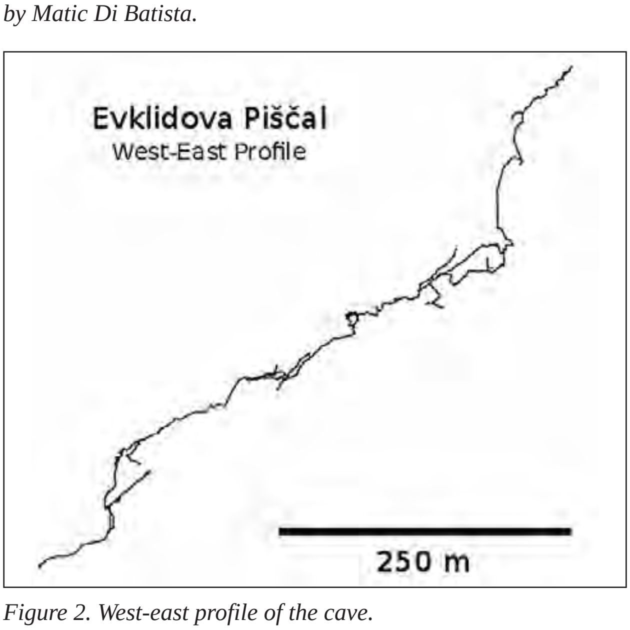

Figure 2. West-east profile of the cave.

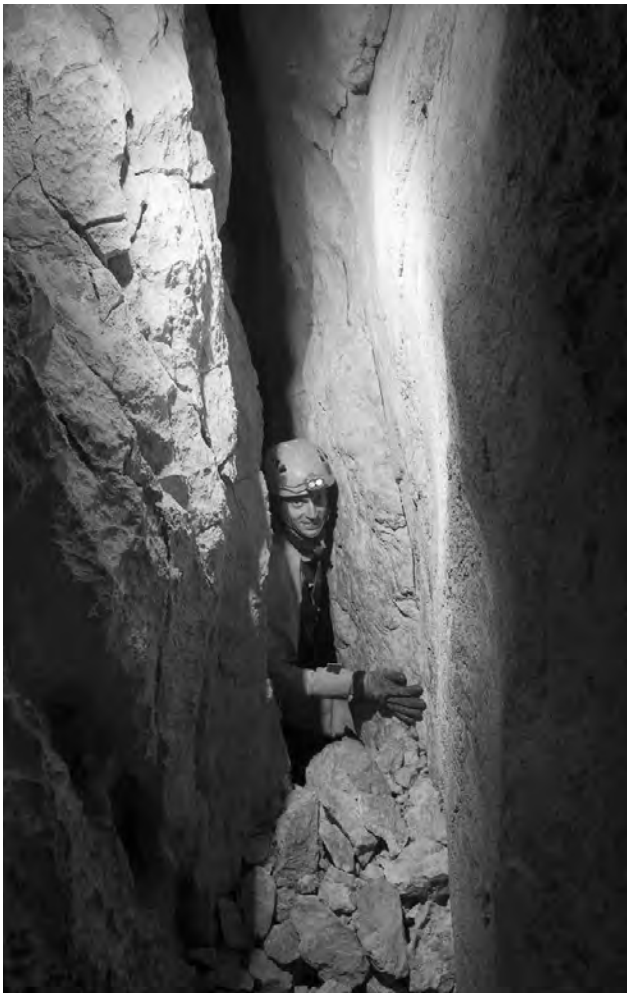

Figure 3. Squeezing through narrow passages at -150 m. Photo by Matic Di Batista.

GLACIER CAVE EXPEDITIONS 2012: NEPAL AND SVALBARD

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This exploration report combines a brief introduction to glacier caves and their relevance to glaciology with summaries of recent expeditions in the Arctic (Svalbard) and the Himalayas (Nepal). In the fall of 2012, as part of multi-year research efforts, team members undertook caving expeditions to caves in the glaciers of Svalbard and in the Ngozumpa glacier in the Khumbu region in Nepal. A number of caves were explored and mapped. The main objective was to collect data to better understand the formation of such caves and how they relate to the glacial hydrologic system.

Figure 1. Sitting in front of a cave entrance on the debris-covered Ngozumpa glacier. Photo: David Ochel.

1. Background

Glacier caves are formed by glacial melt water draining along fractures, into moulins, and along the beds of glaciers. Frictional heating within the water leads to melting of the ice, enlarging passages to form an efficient flow system. Glacier caves play an important role in determining the sliding speeds of glaciers, since they are one of the factors that control water pressure at the bed of the glacier. Large pulses of melt water can lead to water backing up within the system, building up large pressures beneath the glacier. These large water pressures can lead to faster glacial sliding. On the other hand, once glacier caves form an efficient flow system, melt water can be routed through the glacier without creating such high pressures, and glacial sliding rates will decrease. Therefore, understanding the patterns and timescales of glacier cave formation is important for predicting the response of earth's glaciers to future climate change.

2. Svalbard Expedition

Ken Mankoff, a PhD student from the University of California – Santa Cruz, organized the expedition to Svalbard. Jason Gulley and Matt Covington assisted with the field work and logistics.

The main objective of this expedition was to construct a 3D model of a cave system for later use in fluid flow simulations. The field site was Jaskinie Ptasiego Mozdka, a cave near the Polish Polar Research Station that reforms

Figure 2. Vertical cave entrance on the Fugle Glacier in Svalbard. Photo: Jason Gulley.

annually on the Fugle Glacier. In addition to a traditional cave survey, data was collected to construct 3D models of the cave using two different, recently developed techniques. One technique employed an Xbox Kinect as an inexpensive 3D scanner. This allows millimeter-resolution data to be collected and later stitched together into a single model.

Figure 3. Using an Xbox Kinect to survey a cave. Photo: Jason Gulley.

The second technique employed an algorithm called Structure-from-Motion, which combines large sets of photos using pattern recognition techniques and weaves them into a 3D model. Several thousand photos were taken in the cave for this purpose, and the technique produced stunning results.

3. Nepal Expedition

In November 2012, Jason Gulley led an expedition to the debris-covered Ngozumpa Glacier in the Khumbu (Everest region) of Nepal. The objectives included:

1. Perform reconnaissance on the glacier to determine how recent expansion and deepening of supraglacial lakes had affected cave formation processes. Additionally, we sought to determine how many caves that had been mapped on previous expeditions in 2005, 2006 and 2009 had survived lake basin expansion.
2. Identification of a cave suitable to support the development of a roughness model for the calculation of water flow rates.

The team of four cavers (Jason, David Ochel, Vickie Siegel, Pati Spellman) spent two weeks in the Sherpa village of Gokyo (4,790 m elevation), which offers easy access to the southern part of the glacier. About a dozen potential cave entrances were identified and checked during that time, leading to the exploration of four caves.

One cave was confirmed to have been surveyed in 2009, and had experienced multiple modifications since then (development of a new passage, plugging of a previous entrance). Another cave, well decorated, is pending confirmation as to its existence in 2005 and 2006. Two new caves were found – one insignificant in size, but well decorated; the other with more vertical development than had been previously experienced on the glaciers in the Solukhumbu district.

Figure 4. In a cave on the Ngozumpa. Photo: Jason Gulley.

In addition, the team assisted the non-profit organization GlacierWorks (http://www.glacierworks.org) in their video and photographic documentation of the scientific relevance of glacier caves. Videos and photos from the trip will be used to create educational material about research on Himalayan glaciers.

Acknowledgments

Klättermusen (http://www.klattermusen.se) provided both teams with superior salopettes and coats suitable for glacier caving. The expedition to Hornsund would not have been possible without the help and hospitality of the researchers at the Polish Polar Research Station and logistical and financial support from the Institute of Geophysics of the Polish Academy of Sciences. Funding for research in Svalbard was provided by the US National Science Foundation (EAR # 0946767 – to Gulley) and a Svalbard Science Forum Arctic Field Grant (to Mankoff).

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SPELEOLOGICAL EXPEDITIONS TO THE SHAN PLATEAU IN MYANMAR (BURMA)

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The extensive and virtually untouched karst of the Shan plateau is well known from literature. Access is very difficult due to common regional unrest causing travel restrictions in combination with a very limited road network. Few investigations have been carried out since independence in 1948, notably those by Dunkley (1988), Mouret (1995–98), Bence (1998) and La Venta (2004–05). This series could be continued by four expeditions from 2010–12 within the Myanmar Cave Documentation Project in cooperation with Myanmar authorities. Caving areas near Hopon, Ywangan and Pinlaung were visited confirming the presence of larger river cave systems. In total 44 caves with an overall length of 16.9 km were documented and new longest and deepest caves of the country discovered. These are Khau Khaung (Ywangan) with 2,355 m length and Mai Lone Kho (Pinlaung) with -160 m depth.

1. Introduction

Only a few regions on Earth are more unknown than Myanmar with regard to their speleological potential. This is due to the long chosen international isolation of the country, the absence of local speleologists and the difficult access to the mostly remote karst areas. First knowledge about caves originates from British colonial times where caves were used for weekend outings. Kusch (1987) provides a very good summary based on literature from this period. A significant step was the discovery of prehistoric paintings and excavations in Pindaya (also Pindah-Lin) cave in 1960 by geologist U Khin Maung Kyaw.

The first modern investigations were by small teams in reconnaissance style and took place from 1988 onwards: Dunkley succeeded to use a window of opportunity for a five day visit (Dunkley 1989) before the country closed again. Mouret did intensive scouting while living in Yangon in 1995 and Bence followed up by a systematic expedition focusing on the Shan plateau (Bence 1998). Afterwards visits by bat researches from the Harrison institute in the UK (Bates 2004) enhanced the knowledge about the extent of karst in Myanmar. These contacts were later used for two expeditions of the Italian La Venta team to the Shan plateau in 2004 an 2005, but these stopped afterwards since permission could not be regained. The findings of these groups were encouraging and indicated that Myanmar possesses potential for long and deep caves comparable to its neighboring countries.

The slow opening up of Myanmar with the intention to promote tourism has created a favorable situation and lead to a first contact at the International Tourist Fair in Berlin in 2008. A personal introduction of a cave documentation project followed in September by J. Dreybrodt based on the experiences of the Northern Lao – European Cave Project in the neighboring country Laos. This triggered the first speleological reece to Hpa-An in Kayin state project a few month later in January 2009. Afterwards several expeditions lead by the authors focused on to the largest karst area of Myanmar – the Shan plateau. The Myanmar Cave Documentation project was then formed in its current state to guarantee well documented expedition results as base for future research activities of other groups and institutions.

The table below gives an overview of the ten longest caves of Myanmar. It shows that only few caves of significant length are known despite the addition of several new caves over the last years.

Table 1. Longest caves of Myanmar with year of survey.

No.	Cave	Location	Length (m)	Surveyed
1	Khauk Khaung	Ywangan	2,355	2012
2	Mondowa Gu	Taunggyi	1,770	1998
3	Hopon Spring Cave	Hopon	1,655	2011
4	White water Buffalo and Tiger Cave	Hopon	1,343	2010
5	Happy Monk Cave	Hopon	975	2010
6	Leikte Gu (active)	Kalaw	960	1998
7	Maung Nyunt Sinkhole	Pinlaung	900	2005
8	Naung See cave 2	Kutkai	859	2011
9	Sadan Gu	Hpa-An	800	2009 (1995)
10	Barefoot Cave	Hopon	718	2011

The objective of this article is to summarize previous findings and report the results of speleological expeditions to the Shan Plateau from 2010–2012. A geological overview is followed by descriptions of the major caving areas and conclusions with an outlook on the further caving potential.

2. Geography and Geology

The Shan Plateau, in the east of Myanmar, is approximately 600 × 500 km, and has the most extensive area of karst in the country (Fig. 1). It consists of a complex series of mountain chains and plateaus with an average height of 900–1,200 m. It rises abruptly from the central Myanmar plain and comprises granite and gneiss with limestones, clays and alluvium covering the bedrock. The limestone, often called “Plateau Limestone” or the “Shan Dolomite Group” has a thickness of more than 2,000 m in places. It is mostly from the Carboniferous to Lower Triassic period, with some earlier Ordovician elements and has underlying

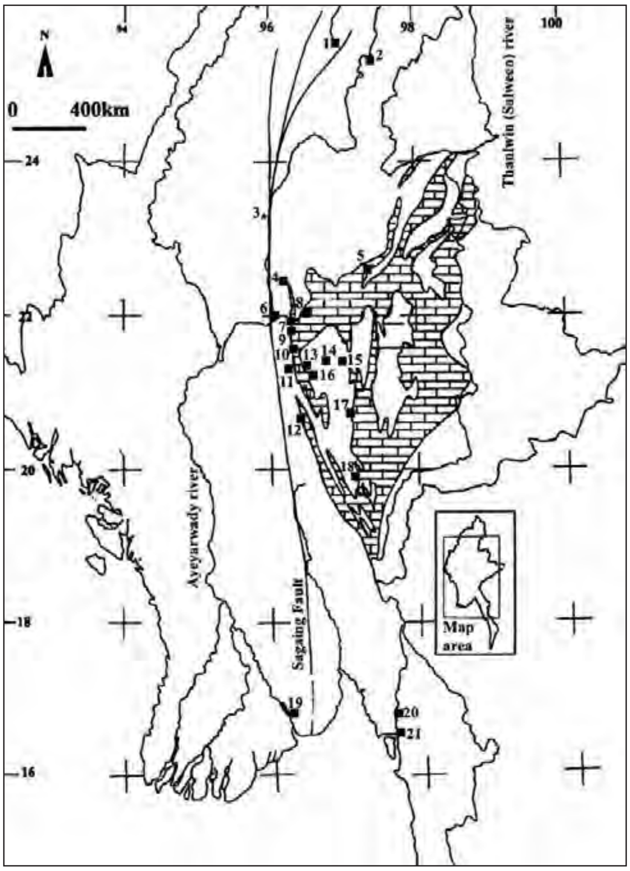

Figure 1. Limestone area of Shan States in Myanmar.

Devonian strata. Recently, a more detailed stratigraphic assessment has been made (Oo et al. 2002), which divides the carbonates into two main units: the Thitsipin Limestone Formation (with five main sub-facies) passing transitionally upwards into the Nwabangyi Dolomite Formation (with four sub-facies). The presence of these abundant carbonate beds has a major impact on the scenery in the Southern Shan States, leading to "dramatic scarp and ridge scenery and with spectacular karstic features" (Fig. 2). It is characterised by a series of rounded ridges, N–S oriented along the dominant structural trend, which separate different basins flowing southward. The ridges are made up mainly of carbonate rocks where a well-developed karst landscape occurs.

The Shan plateau shows many of the typical geomorphic features of tropical countries. Topography is controlled mainly by lythology: 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. The carbonates that form the Shan Plateau also form a natural geographic break between the elevated and cooler plateau states and the hotter lowlands to the east. The Salween river limits the area to the east though it is not proven if further areas of lime stone are present. British expeditions to the Myanmar border in Yunnan confirmed the presence of regional well developed lime stone areas with large river caves and Tiankengs (Talling 2012).

3. Karst Areas

Access to the vast area of the Shan plateau is one of the limiting factors in obtaining an overview of the potential

Figure 2. Karst landscape east of Taunggyi with N-S facing ridges visible on the horizon.

for caves. Few roads cross the plateau, mainly linking major cities like Mandalay or Taunggyi with important Myanmar-China border crossings for intensive trade. These roads are only partially tarred and road works are common. Side roads are dust roads and travel speed can be very low; taking considerable time (measured in hours) for only few 10's of km. In addition overnight stays are permitted only in foreigner licensed accommodation, which are scare in remote caving regions and therefore special permits are required.

The Shan region is divided in three administrative states: Northern Shan with the capital Lashio, Eastern Shan with Kentung and Southern Shan with Taunggyi. These are again divided in town ships that were historical ruled by local leaders called Saopha. This local hierarchical structure persists until today and large areas are self administered and restricted for foreigners. Accessible are the roads from Mandalay to Lashio and Taunggyi and the tourist area around Inle lake. Most of South and East Shan state areas require special permissions. The following sections give an overview of visited areas, their regional settings and presence of caves (Fig. 3). These areas are:

- Kalaw, the most visited caving area
- Pinlaung, 40 km south of Kalaw in the same ridge (restricted).
- Nyaungshwe, east of the Inle lake
- Hopon, 25 km east of Taunggyi (restricted)
- Ywangan, north of the famous Pindaya caves (partial restricted)
- Lashio and Kutkai (restricted)

3.1. Kalaw

The significance of the area comes from its relatively easy access for the first expeditions of Mouret, Bence and La Venta. Historically it is a well known British hill top town for escaping the hot summers in the plain. The town sits at 1300 m altitude on the northern end of a large limestone ridge with scenic hills and deep valleys in the south and west. Several small caves are located in easy reach of town and were the first visited (Leikte Gu ie.). They vary from fossil caves with conglomerate ceilings to sink holes with active streams. Several river caves were found mostly south and west of the town by the La Venta expeditions which require steep descents of about 400 m down to the valleys (Fig. 4). Due to the difficult access by road and trail the

Figure 3. Geographical map of the Shan states. Visited caving areas are marked by black circles: 1 Kalaw, 2 Pinlaung, 3 Nyaungshwe, 4 Hopon, 5 Ywangan, 6 Lashio, 7 Kutkai.

caves are not fully surveyed, mostly the entrances have been recorded and the first hundred metres checked.

Figure 4. Hiking west of Kalaw down to the river cave Twin ii Gu. The next N-S facing ridge is clearly visible.

Two caves were revisited near Pinwon 12 km south east of Kalaw close to the rail way tracks in 2012. The Twin ii Gu fossil and river cave were surveyed to a length of 282 m and 490 m stopping in a wide open river passage with wind. A train ride confirmed the assumed further potential for caves especially near Sindaung station about 10 km south of Kalaw.

3.2. Pinlaung

A large sinkhole was seen during the domestic Yangon to Heho flight by the 2005 La Venta expedition. This seems to be the same sink hole already mentioned by Dunkley (1998) near Pinlaung. It was immediately visited by a sub-team. Geologically the area is in the same N-S ridge as Kalaw. The city of Pinlaung is nestles nicely in a karst valley and offers a convenient base for exploration (Fig. 5). It is known for its cold weather at 1,400 m altitude. Large river caves were found near the village of Phinton partially traversing one of the ridges (The Shwe Cave). The main sinkhole is reached by few hours walk and the disappearance of a major river confirmed. However the 50 m pitch with a waterfall and porous walls could not be descended and remains a challenge.

Figure 5. View over Pinlaung towards the main lime stone ridges in the west.

The 2012 team focused on the immediate surroundings of Pinlaung. Six caves of a few hundred meters length were surveyed. These are the caves 5 km north-west of town near the village Minbu: Nanpa Gu (322 m), Bilu Chaung Ye Hwut Gu (340 m) and Kyan Lin Gu (277 m).The visit to the eastern hills with a communication station on top proved also successful. A large entrance of 40 m height and 80 m width was spotted from its top and visited (Fig. 6). A large day light chamber slopes down followed by two pitches until the cave ends in a lake at -160 m. With all side passages Mai Lone Kho Cave is 545 m long and is now the deepest cave of Myanmar (Fig. 7). Similarly Zee Yauk cave is just close by along the same ridge with a depth of -110 m. The nearby village Hti Hwali has two other cave entrances with immediate pitches which were not descended.

The whole area requires a more systematic investigation, including exploration of known open leads.

3.3. Nyaungshwe

Nyaungshwe is the main tourist town on Inle lake. The caves are commonly known and used by monasteries for religious purposes. The area is on the border to the self-administered restricted Pa-O area were other caves are mentioned by local guides. In 2012 six caves 10 km east of Nyaungshwe were surveyed with the longest being Hta Ein Gu (260 m) and Ye Htout (235 m).

3.4. Hopon

The project became aware of this area by a travel related article in a domestic in-flight magazine. The impressive pictures of large well decorated halls triggered two expeditions in 2010 and 2011. It is the most systematic investigated and best documented region in the Shan states. The reason is a mystic cave called Tham Sam that is converted into a budddist shrine of the Pa-O tribe about 35 km east of Taunggyi near Hopon.

Figure 6. Descending to the large entrance of Mai Lone Kho.

Figure 8. Approaching the karst hills near Parpant.

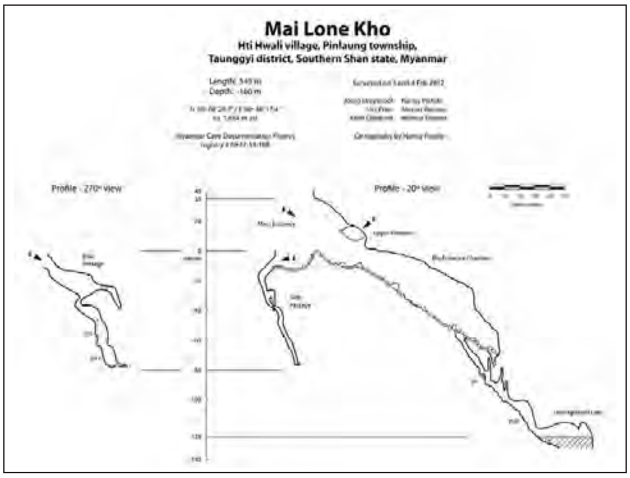

Figure 7. Map of Mai Lone Kho.

Two areas are distinguished: a.) the Parpant area 8 km north east of Hopon and b.) the Htam Sam area 15 km along the main road. The Parpant area is at 1,200 m on the plateau and consists of round shaped hills with fields in the plain (Fig. 8). The well decorated passages form through caves limited by the extension of the hill. The longest are White Water Buffalo and Tiger cave (1,343 m), Happy Monk Cave (975 m), Htam Kong Kiamg (654 m) and Hopon Spring Cave (1,655 m). Hopon Spring Cave is well known from its resurgence near the main road and public bathing and washing place. A larger portal of 30 m width and 10 m height opens up after a steep climb of 10 minutes. At the bottom of the entrance chamber is a river passage that has to be swum for 120 m until a dry water fall is reached. After a technical climb of 5 m the main passage of about 10 m width with strong wind is reached. It has a cascading active stream which had in January a discharge of 2.4 cbm/s. After about 1 km a surface shaft of 45 m depth connects. The passage becomes narrower and sumps after 600 m.

Tham Sam cave is located in a valley close to the main road to Tachilek. It is made accessible by a new side road directly in front of the entrance providing access to the Buddhist pilgrims who come to pray at the cave (Fig. 9). The cave is surveyed to a length of 584 m until an artificial lake.

The further passage is blocked by a brick wall and access is restricted (Fig. 10). It is said the cave continues beneath the mountain for few more hours. The floors and walls have been extensively modified and levelled to accommodate Buddha Statues and mystic animals. Nearby is beautiful decorated Kyauk Sa Gu (Stone Scripture Cave, 313 m) which has its name from sinter columns appearing through a sky light like frozen stone slabs. Barefoot cave on the opposite side of the valley is an active river cave of 718 m length with two entrances. The resurging river enters into Tham Sam Cave after a short distance.

Figure 9. The entrance of Tham Sam in 2011.

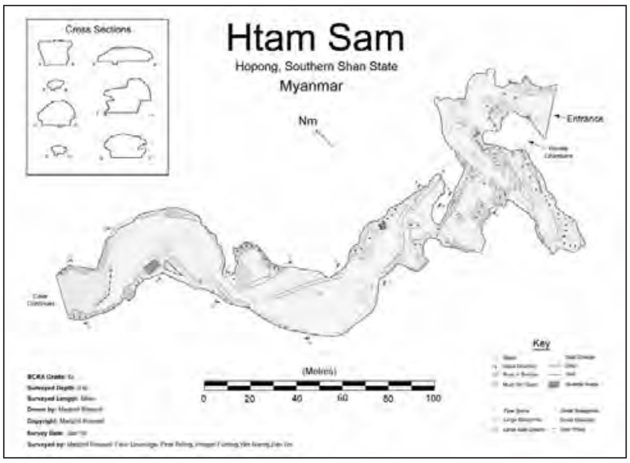

Figure 10: Map of Tham Sam with the end lake on the left.

3.5. Ywangan

The Project first visited this area when on route to Lashio from Taunggyi in 2011. Views from the expedition vehicle suggested the region was karstic, which was substantiated by subsequent geological research (Garson et al. 1976). As a result this became the main focus of an expedition in 2011/2012. Fifteen entrances were located during the trip, the highlight of which was Kyauk Khang (Fig. 11), currently the longest known cave in the country at 2,355 m.

Ywangan is situated near a seasonal lake. This is reported to fill up following the rainy season but with a slight lag. This is interpreted to be a feature similar to the Irish term "turlough", being a karstic seasonal lake. However, it is possible that there are superficial quaternary sediments in the fertile basin around Ywangan which complicate the local hydrogeology. Apart from the lake there are few surface water features. In a number of small caves a shallow local water table was encountered with the appearance of cave adapted fish species. These areas do not appear to have extensive large cave passage development, although underlying rock is karstic.

The main cave explored during the expedition, Kyauk Khaung, is a river sink in the Thitsipin limestone. Strangely, the flow of water gradually reduces through the cave. It is also not known where the water from the cave resurges, although a closed basin of 5 km to the north is one possibility. Kyauk Khaung contains extensive, large and well decorated fossil galleries (Fig. 12). There are a number of locations at which the cave is ongoing.

The majority of the other caves explored around Ywangan appear to be within the Ordovician Doktoye Limestone formation and are not so well developed.

Figure 11. The entrance to Kyauk Khang cave.

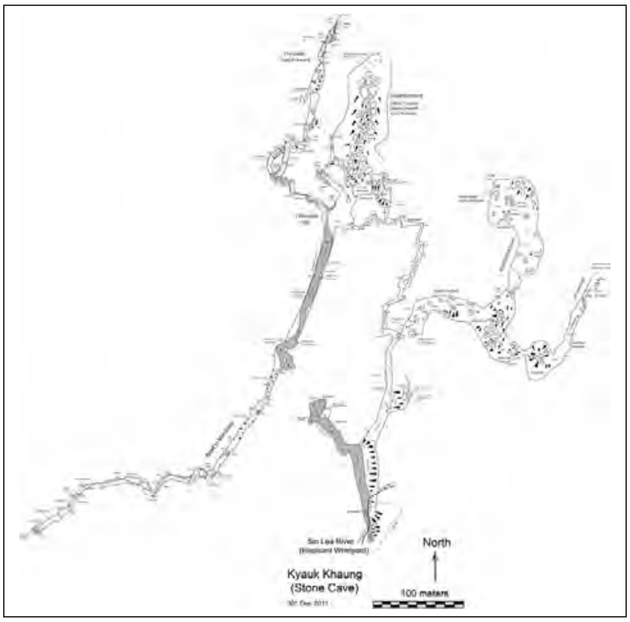

Figure 12. The map of Kyauk Khang cave.

3.6. Lashio

The area around Lashio was briefly visited in 2011 and 2012. It takes considerably time to reach it and is one long day travel from Mandalay. In 2011 a significant resurgence cave called Htam Nam Lay was identified near the village of E-nai, approximately 15 km north and west of Lashio. Study of satellite photography suggests this river cave could be a through trip across one of the significant N-S trending limestone ridges. However, it was soon determined that access to Htam Nam Lay was practical only by motorbike, which given the limited time meant the cave could not be explored. The intention was to complete these tasks the following year. However, regional instability prevented a return in January 2012.

The 2012 team instead mapped a few caves immediately to the south of Lashio, some only 5 km from the city centre.Three caves near the village of Khaung Ka are located in an isolated limestone hill and comprise complex interconnected passageways giving a high overall passage density. The maximum length of these three caves is 207 m. Less than 1km to the north a small river cave, Lim Nho was also mapped to 589 m length. However, there does not appear to be significant carbonate deposits in the areas immediately around the city. All the caves visited to the south of Lashio are of spiritual significance.

3.7. Kutkai

In 2011 a reconnaissance was made in the area around the town of Kutkai. The small town is an important staging post on the trade route to the border with China at Muse. Access to the area is restricted and it was not possible to visit all the target areas around the town. The presence of carbonate rocks both to the north and southeast of the area was confirmed.

Approximately 2 km to the north of Kutcai is an area of closed depressions within low relief. Here Naung See 2 cave was mapped to 859 m in length. The cave is a complex mix of dry fossil galleries and small active streamways. The cave clearly contains a substantial volume of flood water in the monsoon period. Several kilometres further north a number of draughting entrances were located, however time and access restrictions prevented their exploration.

10 km to the south of Kutcai the limestone bedrock is of considerable depth, but appears to be formed into major river gorges rather than into caves.

4. Conclusions and Outlook

The findings of the 2010–2012 expedition teams confirm further the potential of the limestone plateau of the Shan States for large cave systems. Two new areas were systematically investigated resulting in the discovery of Khaug Kuang with a length of 2,355 m in Ywangan and an interesting cave cluster near Hopon with river caves and the pilgrim cave Tham Sam. Other areas like Pinlaung and Kalaw were revisited and work from previous expeditions continued. Most significant discovery was Mai Lone Kho as deepest cave of Myanmar (-160 m). In total 44 caves were surveyed with a overall length of 16.9 km.

These findings should not mislead to the impression that the Shan plateau is slowly understood for its presence of karst and caves. In contrary only a tiny area has been investigated. Access is the key for further exploration as areas are restricted, the road network limited and accommodation scare.

The most comprehensive summary of caves in Myanmar is found in the BHB Vol. 39 after an intense literature research done by Laumanns (2010). A Shan edition is in preparation for release in 2013.

The project is open for cooperation in order to provide a knowledge base for further interdisciplinary research.

Team overview

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Ywangan/Lashio 2012: C Densham, T Guilford, L Hong, F Loveridge, L Maurice, P Talling (co-ordinator)

Kalaw/Pinlaung 2012: J Dreybrodt (co-ordinator), U Etter, M Olliphant, N Pistole, A Romeo, H Steiner

Acknowledgments

We appreciate the valuable logistic support of Phyoe Wai Yar Zar and the tireless efforts of our guide and translator Yan Niang. Special thanks to Ven. Ko Yin Lay (Hopon) for his hospitality and help.

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Photos: C Densham, J. Dreybrodt, T. Guilford, A. Romeo, M. Olliphant, U. Etter.

TEN YEARS OF EXPLORATION AND OVER 100 KM OF CAVES SURVEYED IN NORTHERN LAOS

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The karst areas of northern Laos have been systematically investigated by the "Northern Lao-European Cave Project" since 2002. Annual cave expeditions were conducted in eight regions of five different provinces. These regions host a variety of karst landscapes ranging from highly karstified areas to tower karst and high altitude limestone plateaus. Major river caves of several km lengths were found including the Tham Chom Ong System in Oudomxay province. With a length of 17,150 m it is currently the 3rd longest cave of Laos and 10th longest in Southeast Asia. The total length of surveyed passage reached in 2012 was over 103 km with a total of 254 caves. The cooperation with authorities, villages and international development projects proved to be very useful and is one of the main reasons for a variety of research results in cave documentation, ecotourism development, paleoclimate studies and biospeleology.

1. Introduction

The Northern Lao-European Cave Project is an international group of speleologists with the mission of sustainable exploration and documentation of the major caving areas of northern Laos. This is achieved by:

- inviting interested cavers to participate
- fruitful cooperation with the local authorities and international development projects
- including local villagers as scouts and guides
- maintaining good contacts with other active caving groups in Laos
- strictly publishing all results

Apart from the famous tower karst of Vang Vieng, which is a domain of French colleagues and therefore not covered by this article, northern Laos for many years was a blank spot on the caving world map as most speleological activities focused on the Khammouane karst in central Laos. However, in 2000 a Dutch expedition achieved some good discoveries in the Luang Prabang province with 7.4 km of passages surveyed in 16 caves (Eskes et al. 2004).

In February 2002 the German speleologist Joerg Dreybrodt travelled to Laos and visited Luang Prabang as well as the karst regions further north along the Nam Ou river. He visited some caves at the shores of the Nam Ou upstream of Muang Ngoy village. Having established contact with David Eskes, the initiator of the Dutch expedition of 2000, he prepared for a lightweight expedition in 2002, accompanied by Michael Laumanns. Twelve easily accessible caves were surveyed. A follow-up expedition was conducted in 2003/04 reinforced by Helmut Steiner and Wolfgang Zillig. This was the start of annual caving expeditions to northern Laos with participants from various countries and a team continuously increasing in size. A major breakthrough was the 2005 expedition to Phou Khoun (Luang Prabang province) and Vieng Phouka (Luang Nam Tha province) where three long horizontal caves of 2.6, 3.1 and 3.5 km respectively were surveyed within only ten days. After that the average length of surveyed cave passage was typically about 11 km during 15 expedition days. Table 1 shows the ten longest caves in northern Laos. A clear trend showing the discovery of a significant cave each year is apparent. The longest cave found so far is the Tham Chom Ong System (Oudomxay province) with a total length of 17,150 m. It is currently the 10th longest cave in Southeast Asia and the 3rd longest in Laos.

Table 1. The longest caves of northern Laos.

No.	Cave name	Location	Length (m)	Explored
1	Tham Chom Ong	Oudomxay	17,150	2009–2011
2	Tham Na Thong	Oudomxay	5,010	2010
3	Tham Nam Long	Vieng Xai	4,981	2007–2008
4	Tham Nam Lot	Sayabouli	3,560	2011
5	Tham Nam Eng (resurgence)	Vieng Poukha	3,460	2005
6	Tham Nam Eng (fossile)	Vieng Poukha	3,120	2005
7	Tham Nam	Vieng Xai	3,064	2007–2008
8	Tham Seua / Tham Nam Lot	Phou Khoun	2,650	2005
9	Tham Pasat System	Vieng Poukha	2,332	2005–2006
10	Tham Doun Mai	Nong Khiaw	2,090	2012

This article provides an overview of the geo-settings, the visited areas, major caves and exploration results from northern Laos as well as biospeleological studies. Furthermore the attitude of the Lao people to their caves is presented. A conclusion and an outlook on the future activities of the Project conclude this article.

2. Geo-settings

According to Kiernan (2009) little reliable broad-scale geological information is published, the most detailed work being commercially-confidential mapping by overseas mining companies. In northern Laos much of the limestone is of Permian-Carboniferous age but Jurassic limestones occur locally around Luang Prabang. The total carbonate sequence may reach 5,000 m thick but noncarbonate interbeds are common in some areas. The regional situation is complex and the exact extensions of the limestone areas are barely understood. The systematic search for karst features on topographical maps scaled 1:100,000, available from the National Geographical Institute in Vientiane, has proven its usefulness with regard to the location of caves (Steiner, in print). Also literature studies were invaluable. Laumanns (2010) provides the most comprehensive overview on the karst-related geo-settings of Laos.

3. Karst areas

- Four major karst areas are distinguished (see Fig. 1):
- The northwest with Vieng Phouka (Luang Nam Tha province) and Oudomxay province;
- Three distinctive areas in Luang Prabang province, stretching from Nong Khiaw to Phoukhoun;
- Vieng Xai and Vieng Thong in Houaphan province;
- Sayabouli in the extreme west.

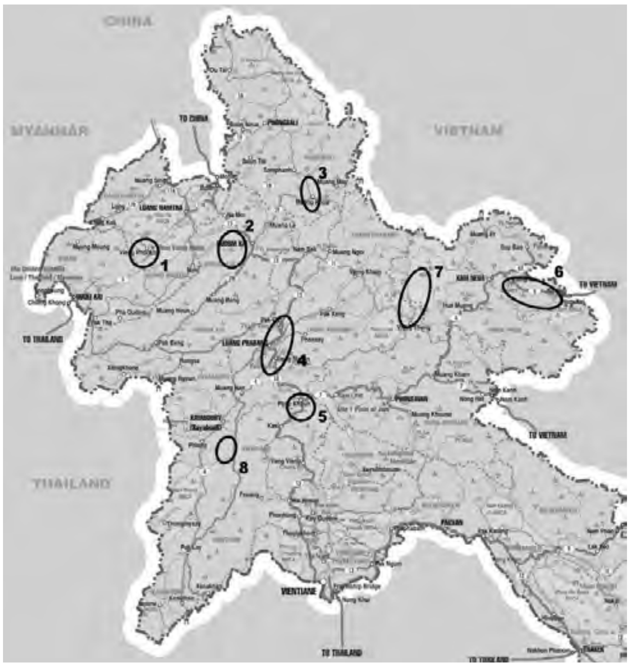

Figure 1. Karst areas of northern Laos covered by this article: 1. Vieng Phouka, 2. Oudomxay, 3.Nong Khiaw, 4. Luang Prabang, 5. Phoukhoun, 6. Vieng Xai, 7. Vieng Thong, 8. Sayabouli.

3.1. Vieng Phouka and Oudomxay

Vieng Phouka and Oudomxay are located in the northeast of Laos on major roads connecting to the important China-Lao border town Boten. The northwest region is highly karstified with the rivers incised into the limestone forming a landscape of valleys with small rivers and low mountains covered by a monsoon forest (Fig. 2).

Figure 2. Typical karst hill between rice fields near Vieng Phouka.

The Project became aware of caves by development projects that promoted rural based ecotourism along the main tourist trail from the Thai border town of Houaysay

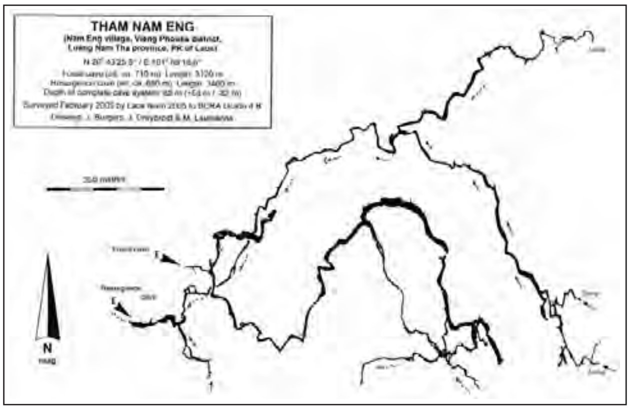

Figure 3. Map of the Nam Eng Caves. The active river cave and fossil cave are overlaying, but not connected.

to the ancient capital of Luang Prabang. Before that the area was not expected to have a significant potential for caves, but now it hosts 5 out of the 10 longest caves of northern Laos. The caves near Vieng Phouka were mainly surveyed in 2005. Most important is Tham Nam Eng with two overlying systems of an active and a fossil level, 3,460 m and 3,120 m in length (Fig. 3). Both cave levels remained unconnected. The 3rd longest system of the area is Tham Pasat 2,332 m in length. It consists of a through cave with a scenic sinkhole entrance and three upper fossil levels with separate entrances connecting via shafts to the active cave level. Three expeditions in 2005, 2006 and 2012 extended Tham Pasat to its current length and discovered several other river caves several hundreds of metres in length blocked by boulders or mud.

Figure 4. Sinkhole entrance of Tham Pasat during the dry season.

The highlight since the Project started in 2002 was the exploration of the Tham Chom Ong System. The provincial tourism office in Oudomxay reported on its website a large cave developed for ecotourism. No end of the cave had been reached by the local villagers. A contact was made and the project was invited to survey the cave in 2009. It was found to stretch along a 4 km long mountain ridge with an underground river and fossil passages with dimensions

20 m wide and 25 m high (Fig. 5 and 6). The cave is a through trip and the whole traverse takes 3.5 hours with an additional 1.5 hours to return from the northern entrance to Chom Ong village. The cave river and the fossil level are connected by steep passages and shafts in places. A large tectonic fault resulted in two huge overlaying chambers measuring 100 m by 30 m in length/width and a height of up to 50 m each. In only 5 days the system was surveyed to a length of 11.3 km. At the last day a connection between the six known entrances was achieved. The cave system was extended until 2011 to its final length of 17,150 m (Fig. 7). Its southern section is now operated as a show cave with LED spotlights and an information display. Visits with overnight stays can be arranged through the tourism office in Oudomxay.

Figure 5. Michael pointing at the inconspicuous limestone ridge hosting the Tham Chom Ong System.

The speleogenesis of Tham Chom Ong appears to be similar to many other caves in northern Laos, especially to those in the Vieng Phouka area, where a strongly developed karst was buried and subsequently uplifted showing many remnants of sediment infillings (breccia) and calcite floors. The latter also occurs in Tham Na Thong, which is located a few kilometres further north. Tham Na Thong is a river cave with a straight passage (10–15 m wide and 25–35 m high) 5 km in length.

Figure 6. Fossil passage of the Tham Chom Ong System close to the southern entrances.

3.2. Vieng Xai and Vieng Thong

The tower karst area of Vieng Xai in Houaphan province is well known for its historical significance as former headquarters of the ruling communist party (Pathet Lao) during the American Vietnam war (Fig. 8). Consequently, it was the subject of intense air bombing from 1964–1973, forcing about 23,000 people to leave their villages and use the surrounding natural caves as shelters. The caves were enlarged, tunnels were dug, concrete ceilings inserted and caves were used as bank, bakery, hospital, garage, and even as a theatre (Kiernan 2012) (Fig. 9). Its remoteness in the extreme northeast of Laos and its secrecy made the area off limits to foreigners for a long time until the government decided to develop the site as national monument (memorial caves). We succeeded in 2007 to be the first permitted to survey the caves. Beside the historical caves, underground river courses with huge and well-decorated cave passages were found. Many of them are through caves where a river enters a karst hill, resurges and enters the next karst ridge. Within three expeditions in 2007, 2008 and 2012 seventy-four caves were surveyed with over 28.7 km of mapped passages. The region now holds the third and seventh longest cave of northern Laos (Tham Nam Long at 5 km, and Tham Nam at 3.1 km [Fig. 10]). The caves also attracted the media and a film documentary was produced for the French/German TV channel ARTE during the 2008 expedition highlighting a fascinating combination of karst landscape, cave exploration and war time history.

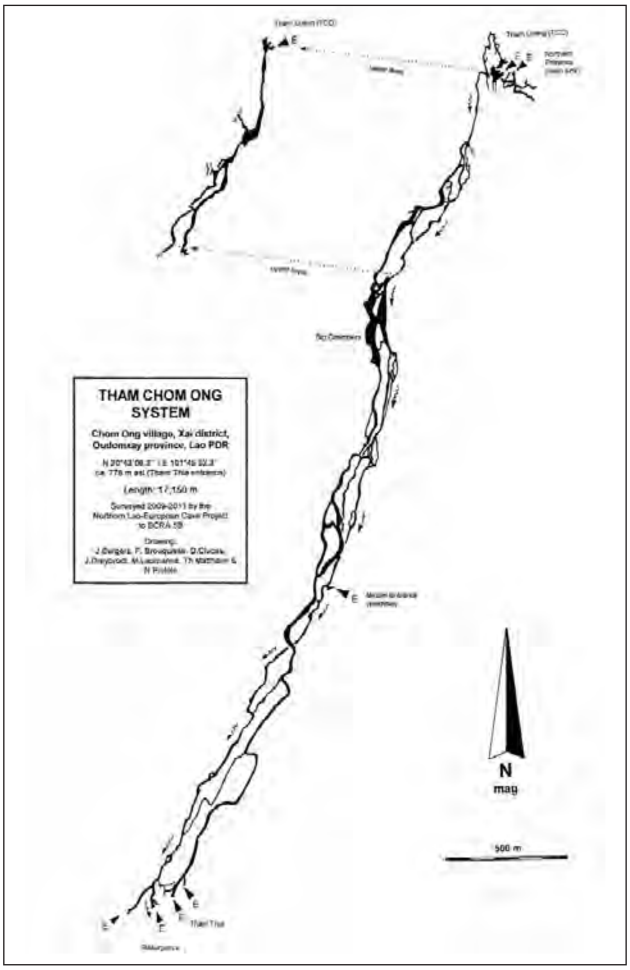

Figure 7. Map of Tham Chom Ong System showing its final length of 17,150 m.

Further west in Houaphan province, the caving area north of Vieng Thong was visited three times, mainly during stop-overs. This region belongs to the Nam Et Phou Louey National Park famous for its tiger preservation project with caves mentioned in a World Wildlife Society report. The area is also known from archeological excavations during colonial times in 1923 (Tham Hang) and more recent times. The road heading north to the Vietnam border was systematically checked and many caves were surveyed, the longest of which is Tham Thia Thong 1,360 m in length and well decorated. Vasile Ersek from Oxford University collected stalagmites for speleothem dating from this cave in order to reconstruct the Quaternary history of the Southeast Asian monsoon (Ersek 2011). Another surprising discovery was Tham Kokai (1,125 m long), featuring a main passage with its floor covered for hundreds of meters by dry rim stone basins filled with calcite pearls.

Figure 8. Scenic tower karst near Vieng Xai.

Figure 9. Theatre in Memorial Cave Tham Khamtay

Figure 10. Main passage in Tham Nam Long.

3.3. Luang Prabang

Luang Prabang province of northern Laos resembles a classical karst region. Early travellers reported on their findings from this area, mainly on Pak Ou cave near Luang Prabang city, famous for its thousands of ancient Buddha statues. The first full scale Dutch expedition confirmed good cave potential by mapping 7.4 km of cave passages in the Nong Khiaw area along the Nam Ou river (e.g., Tham Pageo at 1.5 km). The impressive landscape has steep limestone cliffs covered by primary rain forest (Fig. 11). The depth potential is considerable with the elevation of the valley at about 360 m whereas the mountains summit at 1,700 m. The same applies for the table mountains around Luang Prabang where karst ridges stretch over tens of kilometers in a NNE to SSE direction with sparsely populated plateaus. A three week expedition investigated the valleys and the mountains by long walks and overnight stays in villages. One cave of significant length was found on the plateau (Tham Loum, 1.6 km). Most of the other caves are a few hundred meters long, with a depth not exceeding 60 m and they are of various forms including single chambers, short fossil hill-top passages and maze-like systems near river level. The absence of any deep caves still lacks explanation.

The longest currently known cave is Tham Doun Mai (Muang Ngoy, 2,090 m, Fig.12), which is the upstream section of 679 m long Tham Doun from which it is only separated by a ~60 m long undived sump. The 2nd longest is the Tham Seua/Tham Nam Lot System (2.6 km long) near Phoukhoun, a village at the road junction of the highway 13 to Xieng Khouang province. Two other caves 1.2 and 1.3 km in length (Tham Dout and Tham Deu) are located not far towards the east. At the time of exploration in 2007, the area was a stronghold of rebels and was only accessible with a police escort.

Although Luang Prabang province seems to have limited potential for caves it is of great archeological interest. Since 2005 the Middle Mekong Archeological Project (MMAP) from Penn University (USA) has investigated cave entrances based on the published expedition book from 2005.

Figure 11. Karst scenery along the Nam Ou river upstream from Nong Khiaw.

3.4. Sayabouli

This area was only briefly visited in 2011. Like in Oudomxay the project co-operated with the provincial tourism department and a development aid project. The investigations took place around the villages of Ban Keo and Ban Nathang, about 40 km south of Sayabouli town. Within only 5 days about 9.5 km of new passages were mapped, including the 3,650 m long Tham Nam Lot – a through cave with an underground stream and a long semi-fossil extension. The cave potential remains high and also concerns other districts like Khop and Paklai. Interestingly, the deepest cave of Thailand (Tham Pha Pueng, -367 m) borders the Khop district, which indicates depth potential. Regrettably, permission for a return visit to this province has not yet been granted.

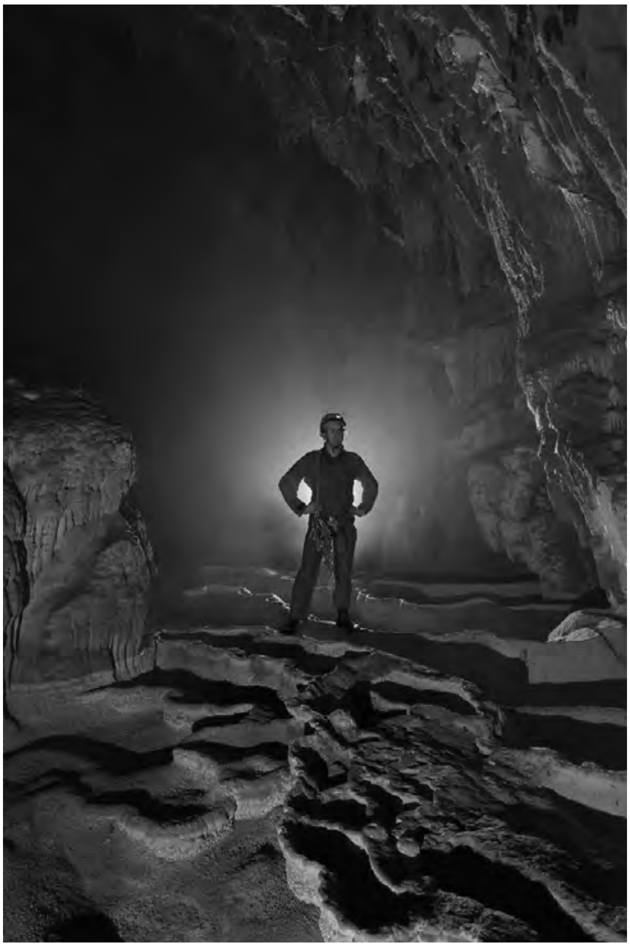

Figure 12. Fossil passage of Tham Doun Mai featuring rimstone basins.

4. Biospeleogy

Surveys of the cave fauna have been an integral part of expeditions from the beginning, because nothing on this topic was previously known. The principal elements are similar for all Laos caves. Cave crickets (*Diestrammena* or closely related genera) of all sizes are found in almost any cave. They most probably feed on fungus growing on guano and other decaying organic material and constitute the main prey of various predators. Other common consumers of organic material and/or its fungi are millipedes and woodlice. Cockroaches occur mainly in caves with substantial guano buildup. A multitude of spiders, opiliones and various insects prey on these. Top predators are the longlegged centipede (*Thereuopoda longicornis*) and the large huntsman spiders (*Heteropoda* spp and *Sinopoda* spp.). Heteropoda show a distinct geographic pattern, the species found in the Northern Laos caves being *H. simplex*, while Vang Vieng and Khammouan caves harbour different species. The more cave adapted *Sinopoda* species are restricted to a single or a few caves. In Northern Laos six different species are found, all only recently described. They include *Sinopoda tham* from the Tham Chom Ong system and *Sinopoda peet* from the recently found Tham Doun Mai.

To date, eleven new species have been described from specimens (see table 2 for Northern Laos).

Much of the collected material is still awaiting classification, thus offering the prospect of more exciting discoveries. Our inventory has to be regarded as being still superficial, and every future collection will greatly add to our understanding of the Lao cave fauna.

Figure 13. Sinopoda tham, a new species of huntsman spider discovered in Tham Chom Ong.

Table 2. New species from caves of Northern Laos.

Species and Tax.	Province and Caves
Spiders:	
Fam. Psechridae	
Psechrus ancoralis Bayer and Jäger, 2010	Luang Namtha: Tham Nam Eng, Tham Pasat Thia 1&2; Luang Prabang: Tham Seua-Tham Nam Lot; Huaphan: Tham Mue; Oudomxai: Tham Na Thong
Fam. Pholcidae	
Pholcus steineri Huber, 2011	Oudomxai: Tham Chom Ong, Tham Na Thong, Tham Mokfek
Pholcus namou Huber, 2011	Luang Prabang: Tham Muay; Luang Namtha: Tham Roj Ru
Pholcus namkhan Huber, 2011	Luang Prabang: Tham Pha Man
Fam. Sparassidae	
Sinopoda steineri Jäger, 2012	Luang Namtha: Tham Nam Eng
Sinopoda tham Jäger, 2012	Oudomxai: Tham Chom Ong, Tham Na Thong, Tham Mokfek; Luang Namtha: Oung Pra Ngiene; Luang Prabang: Tham Luang
Sinopoda sitkao Jäger, 2012	Luang Prabang: Tham Doun Mai
Sinopoda taa Jäger, 2012	Luang Prabang: Tham Nguen
Sinopoda suang Jäger, 2012	Huaphan: Tham Ho Neung
Sinopoda peet Jäger, 2012	Huaphan: Tham Ma Liong
Diplopoda, Fam. Sinocallipodidae	
Sinocallipus steineri Stoev and Enghoff, 2011	Luang Prabang: Tham Gia

5. Caves and Culture

Caving in Laos involves getting in touch with the local villages and experiencing a diversity of hill tribes and rural life. Caves are often known from fishing in the underground streams or catching bats at the cave entrances. The Hmong minority, who lives high up in the mountains, enter the caves and know them very well. The Khmu, who are peasants, usually know the cave entrances but have a limited understanding of cave extensions. The impact of the American war is easily visible in the heavily bombed regions of Houphan, Xieng Khouang and Luang Prabang provinces. Villagers are very reluctant to disclose information since caves were used as shelters and hiding places. The locals believe in ghosts and bad spirits that influence life. Any visit to such a cave without the permission of the nearby village can have serious consequences for an expedition. Also unexploded ordnance (UXO) might be present and the villagers are the only ones who are aware of potential danger in the field.

6. Conclusion and Outlook

After ten consecutive annual expeditions the Northern Lao – European Cave Project has succeeded in developing an understanding of the major karst areas and caves of northern Laos. The total length of surveyed cave passage exceeded the 100 km mark in 2012 in over 250 caves surveyed, the longest of which is the Tham Chom Ong System with a length of 17.1 km, currently the 10^{th} longest cave of SE Asia. The karst areas are very diverse with morphologies ranging from highly karstified shallow ridges covered by jungle to steep (almost alpine) limestone cliffs and classical tower karst. The longest caves are river caves in shallow ridges partially resembling through caves. A significant depth potential has not yet been realised despite limestone plateaus with over 1,000 m of relief above the known karst springs.

Co-operation with community-based development projects proved to be very sustainable as the knowledge gained by the extensive field work and publication efforts of the project improved the development of ecotourism, stimulated archeological and paleoclimate studies as well as biodiversity capacity-building by the identification of cave fauna.

Although most karst areas of northern Laos were at least partially investigated, the only major untouched province is Xieng Khouang featuring significant karst in its eastern part.

Future work will aim to understand the detailed extent of the karst areas and presence of caves. This will be achieved by small and flexible expedition teams. We are open to cooperation. If you wish to contribute to the project, please contact the authors.

Acknowledgements

Our fully published results would not have been possible without the support of the Lao people as well as 31 cavers from 14 different nations.

We are also grateful to the provincial Lao tourism offices and international development organizations that assisted with permissions and logistical support: the Dutch SNV, the German GiZ and the European Union Microprojects. We acknowledge furthermore the financial support of the European Speleological Federation (FSE) as well as the US National Speleological Society (NSS). Special thanks to Siegfried Moser and our reliable guides Cheav Moua, Juu Moua and Hong Tong.

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CZECH DISCOVERIES IN THE MAGANIK MTS., MONTENEGRO

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Caving Club Suchý žleb Brno (Czech Speleological Society) operates in Montenegro since 1983. Earlier, we mainly explored in the Krivosinska area around Velji Hill near Boka Kotorska (Orjen Mts.). All discoveries and achievements were published in several articles in Speleoforum Memorial Volumes. The most important papers dealed with the Pema cave, Maglena jama and especially Goat's hole (-662 m/1,700 m long), which is also our biggest discovery in this area. The prospect of deep mountain systems attracted us so much that we decided to explore further inland in the High Karst Zone, between the steep cliffs of Maganik Mts. near the town of Niksic, in the vicinity of canyon Mrtvice. This canyon cuts through the surrounding massif of Cretaceous limestones into the depth of more than 1 km and creates the potential of 1,000–1,800 m deep cave systems. Together with convenient structural pattern (more details in paper of Otava – Baldík in this Proceedings) there were ideal conditions to start explorations in the untouched territory.

1. Maganik Explorations

The first time that we visited the Katun (settlement) Maganik travelling on a bumpy mountain tarmac full of bends and twists was in 2009. Since then we organized there three-week long expeditions, undertaken in "alpine style" in small groups, during which we managed to discover several interesting places and objects. Even the transport of material to the base camp at 2,000 m a.s.l. was an interesting sport event.

2. Nyx Abyss

In the case of this cave we have hit the jackpot. Nyx was the first entrance, which we decided to explore on Maganik during our first, very strenuous expedition and at the same time it was a unique find thanks to the discovery of 429 m deep vertical, which the cave hid (today approx 12th deepest in the world). Its location is also exceptional in its own way because it is situated in the central area of Tresteni Hill in a maze of tens of meters deep karren, among which winds the only viable access path.

Nyx was also surveyed in 2010 when we discovered its furthest ends. The entrance is the example of "Light Hole Abyss" 50 m deep and approximately as wide, which opens up between two limestone ridges running parallel to each other, whose bottom is covered with snow all year around. From the bottom continues 60 meters deep shaft in the shape of a star where descend must be done by means of a narrow projection which bypasses several collapses of mountain blocks and rocks, caught in the main gullet. After this follows another snow covered area, this time a gentle slope, leading the descend route away from the reach of the daylight. In the dark a window opens up into a parallel shaft, falling from the onset to the depth of 429 m and rising up to a place under one of the cracks in the vicinity of the input crater. The abyss is free of any breaks, ledges and significant changes of direction. The opening of the crack measuring 10× 1–2 m slowly rounds off into a fissure, in the narrowest point 5 m wide but after 100 m slowly expanding up to 30 × 7 m. However pure fosiliferous light limestones change here into dark limestone with shale intrcalations. They appear tens of meters above the bottom, which causes repeated narrowing of the shaft and at the depth of 540 m closes up completely. Dark, less permeable limestone indicates one of local thrust zones which are visible at more places in deeper parts of cave systems of the area. Quite powerful meander drains an abundant shower of melted snow all the way to the next level, this time it is about 60 m deep Black abyss, wonderful, bell-shaped expanding well, which is unfortunately the last reflection of monumental space that is lost in time. Asset flows through very narrow cracks without drafts and older small meanders are descending only few meters. In these places we encountered for the very first time on Maganik another typical feature. It was fairly unusual decoration represented mainly by stalagmites, coatings and helictites in the shades ranging from orange, red, dark brown to black color, a décor reminiscent of the old ore mines.

The parallel branch into which we got by traversing several meters above the opening of Black abyss ended in a blind end and same thing happened with the "Behind the window" branch, turning at the shaft 429. The depth of the cave reached 622 m, the length of the polygon exceeds 1 km.

3. Aither Abyss

The Aither abyss is one of the largest underground chambers in Montenegro. Although the entrance on the surface is only few meters wide, already 150 meters below the gullet the gap expands to 35 × 30 m. It is basically one cave descending directly from the entrance into the depth of 351 m in subhorizontal thick bedded pure limestone. The main shaft is followedby short sequel, created by one horizon and two parallel, approximately 30 m deep, shafts. Their bottoms are clogged with fine debris and draft, which is here fairly strong, disappears up the chimneys.

4. Propast pod Medvedici Abyss

The abyss called "Propast pod Medvedici" is the second entrance, hiding on top of the mountain plateau called "Tresteni vrch" that is worth mentioning. Its discovery was preceded by an extended survey of deep labyrinth of fissures that this unusually developed karren fields offer. The gap is located in the vicinity of a doline that is surrounded on three sides by rocks. On the bottom of the doline can be found the second entrance nearly covered by rubble, merging more than 100 m bellow with the well known part of “Propast pod Medvedici”. The entrance was discovered in 2010 but we did not manage to organize the expedition until one year later. The abyss represents classical form known for this area based on subvertical joints cutting through subhorizontal thick bedded limestone. First tens of meters it respects the tectonics and does not reach larger width, but gradually expends and after connecting to the parallel gullet it becomes regular rim. In the depth of 200 m from the entrance it narrows to very narrow fissure without hopeful perspective.

5. Iron deep Abyss

One of the many monotonous descends into an infinite number of sinks, cracks and pits eventually led us to the coveted target. When it seemed that the cone of snow will fill the entire bottom of the p 40, we found an opening the size of a door in the bend of the shaft, partially hidden by stump of a tree which was holding back a substantial part of the snow, piled at the bottom. It is hard to say whether the warm weather of the past winters caused that the other 40 m could be descended through caverns between the glacier and the rock wall to a short horizon, leading the path away from places that can be anytime covered by snow and ice. The second half of the expedition of the year 2011 was here. This year we were able to surpass the 500 m mark below surface and one year later the cave brought us to just over the magic kilometer depth.

Pure, well permeable light grey limestone subhorizontally bedded and subvertically jointed is typical for the upper part of the system. It is followed by dark varieties of pelitic limestone in the lower parts and it determines the character of the cave, which transforms from wild vertical sequences into long horizons with almost no slope. Initially everything is taking place according to the well know scenario. The leading part falls swiftly, mainly thanks to the 200 meters deep stair-step shaft, all the way to the depth -350 m. It is already deep in the black-gray rock, through which squeezes a narrow meander. The black limestone suddenly widens out up to 80 m deep cascade, the enlargement is caused by an old tributary in the form of monumental chimney, which walls disappear in the dark. Next, there is again meander, adhering strictly to the flat bedding, only this time a little taller and in the upper storey easier to traverse. Upstream there were also found several horizontal sequels, intersecting younger vertical branches and surprising by richly decorated corridors in the length of several hundred meters (Fig. 3). In the depth of 500 m the cave again begins to gain momentum, the tectonics and composition of limestone changes and meanders interrupted here and there by small precipices start quickly gaining depth. In the depth of seven hundred meters below the surface the subvertical jointing can be seen again when the cave suddenly breaks into one hundred meter deep shaft. Thus we come to the end of the known area that encompasses steep cascades, with approximately 5 m wide and 37 m deep conduit at the end of which several inflows converge. Behind that the cave continues by inclined crevice, probably parallel with a fault. On the surface approximately one kilometer far from this point there is the canyon of Mrtvice River.

Figure 1. Vertical of the Nyx system is cutting subhorizontal Cretaceous limestone beds.

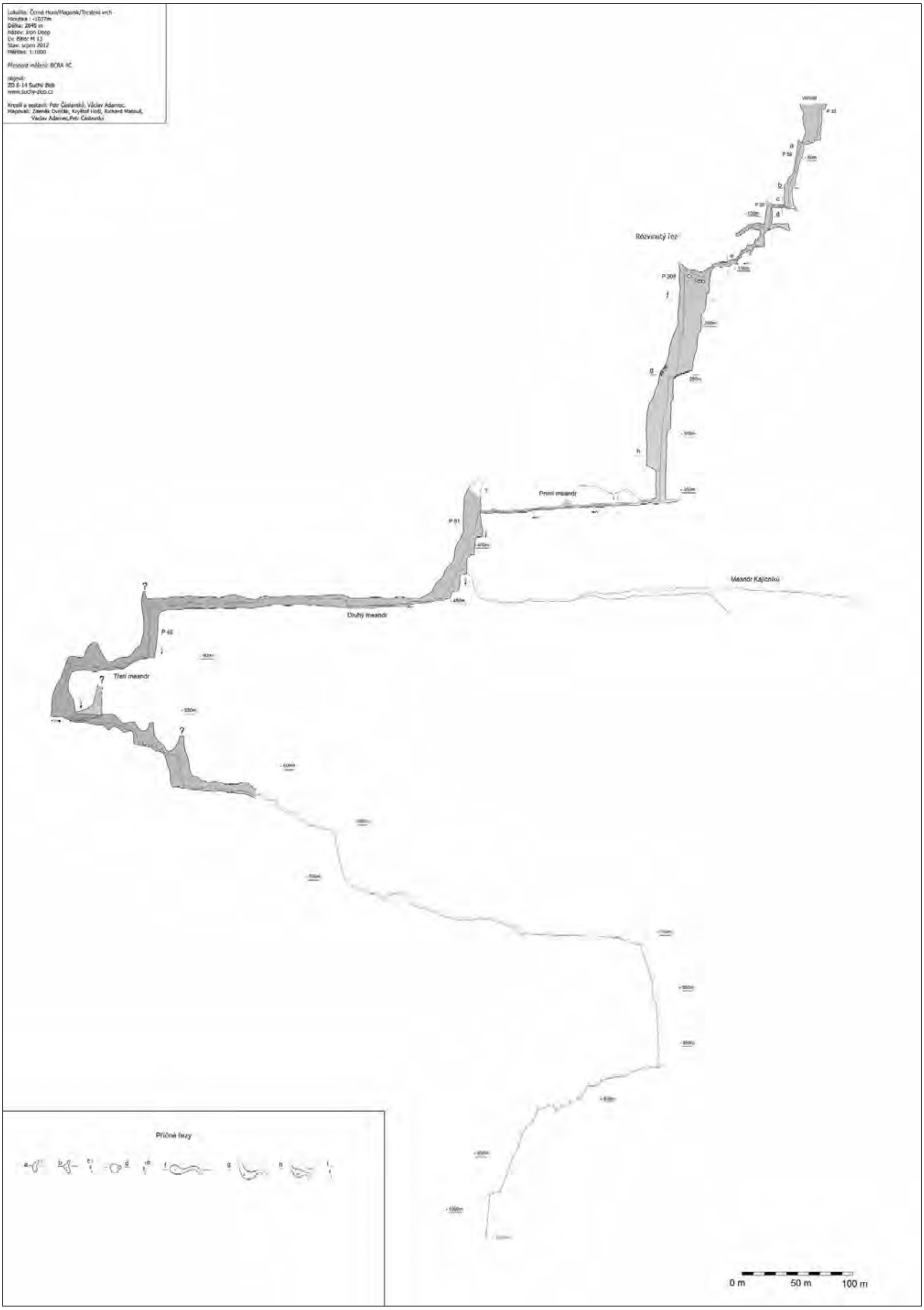

Figure 2. Section of the Iron Deep System, Maganik, Montenegro. Accuracy of measures BCRA 4C.

Figure 3. Unusual color dripstone decoration in the Meander Kajícníků (see the section) 450 m below surface.

6. Discussion and Conclusions

Nowadays it is unclear whether the system is drained directly into the canyon of the Mrtvica River. Other possibility is the connection with the main resurgence of Jama, located several km downstream. For now the length of the Iron Deep system is three kilometers, and the depth 1,027 meters.

EXPLORATION OF THE CHESTNUT RIDGE CAVE SYSTEM BATH AND HIGHLAND COUNTIES, VIRGINIA

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Chestnut Ridge, a small ridge straddling two synclinal valleys in Bath and Highland Counties, Virginia, has been the focus of concentrated cave exploration activities for more than 50 years. The geology and topography of the ridge combine to create body-size vadose canyon passages which typically follow the dip of the carbonate bedrock down to a large network of trunk passages. Bobcat Cave was the first of three major caves to be explored on Chestnut Ridge. Exploration of Bobcat spanned multiple decades, involving extensive digging before breaking into large trunk passage deep under the ridge. Eventually, Bobcat was connected to the more recently discovered Blarneystone Cave, thereby creating the 21 km Chestnut Ridge Cave System, then the deepest cave in Virginia. A third cave on the ridge, Burns Chestnut Ridge was also the site of a multi-decade digging effort of monumental intensity and duration, ultimately resulting in a breakthrough into several kilometers of large stream trunk, and surpassing the Chestnut Ridge system as Virginia's deepest. Persistent digging in Blarneystone's Ghost Hall resulted in the 2003 discovery of an additional 8 km. of new passage and the connection to Burns Chestnut Ridge, expanding the system to 33.6 km in length and 240 meters in depth.

1. Introduction

Hidden away amongst the ridges and valleys of the Southeastern United States is a karst area known as the Burnsville Cove. Situated near the boundary of Bath and Highland Counties in the State of Virginia, the Burnsville Cove has been the locus of systematic cave exploration and scientific study for more than half a century.

Beginning with the exploration and survey of Breathing Cave in 1954 followed shortly thereafter by the discovery of Butler Cave in 1958 (Nicholson and Wefer 1982), cavers quickly realized that a vast cave system was likely to exist under the pastures and hardwood forest of the "Cove". By the 1970s, more than 29 km of cave passage had been mapped, the majority of that being found in Breathing and Butler Caves (approx. 7 km and 18 km respectively) making them two of the longest known caves in Virginia. However approximately 3.5 km separated Butler's sumps (siphons) and the suspected resurgence along the Bull Pasture River Gorge to the Northeast, and attempts to find additional entrances to tap into the potential downstream portions of the system were largely unsuccessful.

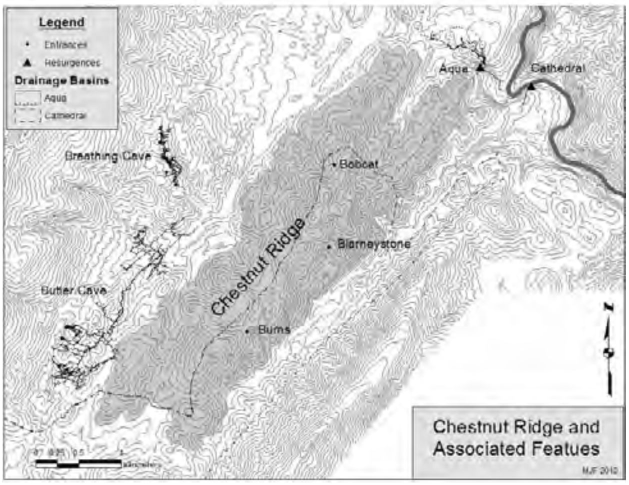

Figure 1. Location of Chestnut Ridge and Related Features.

As it turns out, one of the elusive "keys to the system" was an obscure blowing entrance first reported in 1957, and located on the side of Chestnut Ridge; the exploration of the cave passages under and astride that ridge would consume the lives of three generations of cavers, and push the physical and psychological limits of all of those involved.

2. Geographic and Geologic Setting

Chestnut Ridge is a small anticlinal ridge flanked by two synclinal valleys, oriented in a northeast-southwest direction and plunging slightly towards the northeast. Cumulatively, these features comprise the Burnsville Cove.

The caves of Burnsville Cove are developed within Silurian and Devonian Age carbonate rocks with a total thickness of approximately 230 m (Hess and White 1982). This carbonate stratigraphy as found in the Burnsville Cove, typically includes multiple resistant beds of sandstone which appear to influence passage development, resulting in multi-layered passage profiles with passages sometimes "perching" on top of the resistant beds.

Both surface and sub-surface drainage is predominantly towards the northeast, with the majority of flow ultimately discharging to the Bull Pasture River, primarily via several karst springs distributed along a 700 m reach of the River. The most significant of these springs are the Emory, Aqua and Cathedral springs. Dye tracing studies have demonstrated that discharge from Aqua spring primarily represents drainage from the syncline along the northwest side of Chestnut Ridge, while Cathedral Spring drains the southeastern syncline. The role that Emory spring plays within the context of Burnsville Cove hydrogeology is likely minimal due to the location of its catchment area, and the degree and character of karst development associated with Emory Spring is not well understood.

3. Exploration

3.1. Discovery of the Bobcat Entrance and Initial Exploration

In 1957 Dave Nicholson discovered air blowing out of a small cleft in a rock outcrop near the top of the northwest side of Chestnut Ridge (Rosenfeld and Shifflett 1995). This opening was subsequently enlarged with a crowbar and approximately 300 m of passage was explored, most of it consisting of torturous muddy canyon "ending" in an impenetrable squeeze. The cave, then named Chestnut Ridge Blowing Cave, was mostly forgotten for the next 22 years until a group of young cavers from the Shenandoah Valley Grotto of the National Speleological Society (NSS) visited the cave and were intrigued by the strong air flow and the potential for a big cave under the ridge. This resurgence of interest in what was renamed "Bobcat Cave" thus kicked off the second wave of cave exploration in the Burnsville Cove, introducing cavers to the struggles of pushing Chestnut Ridge's impossibly tight, muddy, entrance series which have become the stuff of legend.

Using what was to become an integral tool in the exploration under Chestnut Ridge, the Shenandoah Valley Grotto (SVG) cavers blasted through the restriction that had stymied previous exploration and discovered a continuing sinuous canyon trending down-dip with a small trickle stream. The canyon, barely large enough to accommodate a wetsuit-clad caver lying on their side, was pushed through multiple restrictions, and soon became known as Cyanide Canyon due to its "poisonous" character. The down-dip passage was interrupted with many short (1–3 meter) climbable pitches and plunge pools as it headed down into the heart of the ridge.

The wind blowing through Cyanide Canyon was one of the few things responsible for the sustained efforts in pushing the cave during the period of 1982 through 1983. That canyon, continuing ever deeper into the ridge, with so much air flow, had to be going somewhere exciting. Then, in July of 1983, it did! After approximately 500 m horizontally and 100 m in depth, the torturous entrance canyon intersected a major trunk passage.

With renewed enthusiasm, a flurry of subsequent trips discovered a largely dry paleo level trunk passage developed along the strike (northeast-southwest trend). Passage dimensions were an order of magnitude larger than in cyanide canyon, and the drool of mud and water of Cyanide Canyon was replaced by dry clay, sand and gypsum crusts. In the southwestern direction, the cave became dissected with multiple pits and downward-trending passages ultimately leading to a sump at a depth of 220 m, thereby replacing Butler Cave (189 m) as the deepest in Virginia. Several small leads and digs remained in the southern end of the cave, but the real action was found going north, where the main trunk continued with numerous side leads and a steady draft of air.

Around this time several additional cavers joined what to this point had been a very small group of SVG members exploring Bobcat. These newcomers were largely associated with the Butler Cave Conservation Society (BCCS) which had been mapping the caves in the Burnsville Cove for two decades. The prospects of exploring an exciting new discovery right in their backyard was more than enough incentive for them to endure Bobcat's misery.

With the cave breaking out in numerous directions and trip durations of 19+ hours becoming the norm, it was decided to establish an underground camp and push the cave via three- to five-day camp trips. While hauling camping equipment through the entrance series was brutal, once established, only food and other consumables had to be replenished. Between March 1984 and August 1990, approximately 14 kilometers of passage was mapped via 27 separate cave camps.

Figure 2. Bobcat Cave, Sixth of July Room. Photo by Ron Simmons.

Discoveries to the north included highly decorated passages adorned with anthodites and various forms of gypsum, which up to that point had been largely absent from other Burnsville Cove caves. There was plenty of large rambling trunk passage being found, but an equal amount of less friendly breakdown, pits, and climbs were encountered as well. Perhaps the most exciting single discovery in Bobcat was the Burnsville Turnpike, an impressively large (44 m wide, 30 m tall) passage that stretched for more than 600 m before becoming choked in breakdown. The Turnpike was also notable in that it is developed within the Aqua drainage, while the majority of Bobcat is in the Cathedral drainage. The crossing of this drainage divide opened up the possibilities for Bobcat to connect with Butler Cave and other caves in the aqua drainage. Such a connection would create a monster of a system.

By 1990, the rate of new discoveries in Bobcat had slackened, and caver motivation also ebbed to the point that exploration in the cave was unofficially suspended. However this did not represent an end to the interest in Chestnut Ridge's underground secrets, just a shift of attention.

3.2. Blarneystone: Attention Shifted

Bobcat had demonstrated that significant cave development existed under Chestnut Ridge, and that the small entrances and sinks that dot the Ridge could be the key to finding more. The Bobcat crew was motivated by that realization, and had begun searching for and digging open potential entrances. One of these candidates was a small shallow depression on the southeastern side of the ridge, approximately 1 km. southwest of the Bobcat entrance (and 15 m lower). On March 16, 1991, after just two hours of digging the bottom fell out of the hole being dug in that inconspicuous sink, thus opening the next chapter in the exploration of Chestnut Ridge's subsurface.

The new entrance, named Blarneystone because it was opened on St. Patrick's Day, consisted of a narrow 10m vertical rift whose sloping floor led to a series of short rope pitches separated by a narrow muddy canyon. A strong breeze blew through the passage and a small stream flowed along the floor. The seasoned veterans of Bobcat exploration were unsurprised when at the bottom of the entrance pitches, the passage morphed into a torturous, slimy canyon cutting diagonally down and across the dip towards the northeast. The character of this canyon mirrored that of Cyanide Canyon, and thus soon became known as Strychnine Canyon for its similarly poisonous nature.

Several trips during the spring and summer of 1991 pushed Strychnine Canyon, with its plethora of short awkward downclimbs and tight squeezes, for a distance of approx. 300 m and to a depth of 120 m. Then in July of 1991, a bolt traverse over a 10 m pitch, subsequently dubbed Artz's Attic, dropped the explorers into a 30 m wide trunk passage; Ghost Hall.

Figure 3. Mike Kistler and the Ghost in Ghost Hall. Photo by Nevin Davis.

Ghost Hall, so named because of a ghostly solitary stalagmite perched in middle of the passage, stretched out along strike for almost 200 m, mostly as 30 m × 20 m borehole. Survey data indicated that Ghost Hall was aligned with the southern end of Bobcat's paleo trunk (called The South Lead) and the two passages were developed at the same elevation. Surely the passages were related, but would they connect? Pushing the northeast end of Ghost Hall led to spectacularly decorated passages festooned with gypsum/aragonite chandeliers, anthodites and stal., and a continuation of large trunk passage (Over Forty Passage). However this continued for only 300 m before the trunk degenerated into a complex area of sediment filled passages, infeeding stream canyons, and vertical shafts. While more than a kilometer of cave was mapped in this area, with the airflow disappearing into this maze of passages, it became obvious that a connection to Bobcat was not going to be easy.

The southern end of Ghost Hall became truncated by a large flowstone-infused breakdown collapse. However an inconspicuous streamway (the Black Diamond Crawl) was intersected in this collapse area, leading to approximately 2 km of interconnected passages. These discoveries included Moon River to the west, and Beyond the Pearly Gates and Slop Hollow to the east. These latter two passages continued down-dip to the deepest point in the cave at 181 m below the entrance.

By the summer of 1994, Blarneystone had expanded to more than 5.5 km in length. While many leads remained, including an intriguing air-blowing dig above the breakdown collapse at the south end of Ghost Hall, the Burnsville cavers turned their attention back to the north where their old friend Bobcat lurked just 53 m away.

Over the course of several trips in July and August of 1994, the southern end of Bobcat and the northern end of Blarneystone were pushed hard. Teams working simultaneously from both caves first established an "air" connection through the use of smoke bombs, followed by a voice connection though the sediment-choked passages. Then on August 20, 1994 a frenzy of digging, spurred on by increasingly clear voices from each side, led to one of those rare events that all cavers relish. Bobcat and Blarneystone had become one; the 21 km long Chestnut Ridge Cave System was born!

3.3. Burns

Marion Smith, a well known caver from the American Southeast, has referred to a number of Chestnut Ridge cavers as "ultra horror specialists", a reference to the severe conditions endured while pushing the caves under Chestnut Ridge. There is one cave in particular that provides a litmus test for separating the "ultra horror specialists" from the more common hardcore exploration cavers. That cave is called Burns Chestnut Ridge, more affectionately known simply as "Burns".

Situated near the crest of Chestnut Ridge, approximately 2.4 km southwest and 15 m above the Bobcat entrance, Burns is yet another obscure entrance that happens to blow a steady gale of wind on cold winter days. The cave was first discovered by Ike Nicholson in the 1950s (Shifflett 2003). Exploration at that time found approximately 60 m of narrow canyon passage, and several short rope pitches, ending at a point where the small stream flowed into passage too small to follow.

The 1960's saw a renewed interest in the cave as a group of Duke University cavers pushed the cave for another 100 m through the liberal use of explosives (Shifflett 2003). The sinuous narrow canyon passage they were following continued down and across the limestone's dip towards the southeast. However by the early 1970s, the Duke group, worn down by the cave's unrelenting obstacles, lost motivation and abandoned their efforts. About that time Nevin Davis, one of the founding members of the BCCS, continued the pushing of Burns as his pet project. He discovered a bypass to the pinch that had stopped the Duke team, and over the next three years methodically blasted through successive restrictions in the wet, contorted stream canyon. Finding companions for these trips was difficult, as most refused to return for a second round of the beatings that the cave doled out to those brazen enough to enter. Travel time from the pushing front to the entrance, a mere 250 m distance, was typically between two and three hours; much of that being spent thrutching along while lying prone in a muddy stream.

There was a hiatus in Burns activity during the latter half of the 1970s, brought on by a dishearteningly narrow bedrock slot through which the cave's stream (and air) flowed. However several SVG cavers, who would later be instrumental in the exploration of Bobcat, provided an infusion of energy to the project. Enlargement of the narrow bedrock slot, subsequently named the Bone Crusher, proceeded over the course of multiple trips; ultimately breaking out into a small mud-filled room. Unfortunately, celebration was premature as the cave continued to present serious obstacles. Subsequent trips during the early 1980s successfully dug and blasted through the Mud Room and the Second Mud Crawl, stopping at yet another narrow bedrock slot. By 1984 the exploration of Bobcat was in full swing, therefore Burns and its funhouse of horrors received little attention for the rest of the decade.

Figure 4. Ben Schwartz in the Burns Entrance Series. Photo by Mike Ficco.

By the time 1990 rolled around, the wounds inflicted by Burns had healed, and another surge of pushing activity was launched. The vertical bedrock slot at the end of the Second Mud Crawl was widened, and the passage ahead enlarged to walking dimensions and dropped down a 10 m pitch. Below, a narrow canyon continued, larger than before, but the obstacles kept coming. Additional pinches were encountered and passed, and with each one, the passage ahead seemed to let up just a bit, suggesting that the cave was finally going to break open. Then in June of 1995 it did. A blast opened up the top of a 10 m pitch (Dead Cousin's Pit) into decidedly larger, flowstone covered passage. More than 30 years of digging, hammering and groveling had finally paid off!

Beyond Dead Cousin's Pit, the cave steadily lost elevation as it trended down dip to the southeast, and dropped down several short pitches. After approximately 200 m the cave turned northeast along strike and the character changed to a multi-level trunk with an active stream canyon developed below an upper level paleo-trunk. Additional water was picked up as infeeders came in from the sides. The downstream streamway roared on for another 600 m of exciting streamway, to a sump at a depth of 225 m below the entrance. However a daring freeclimb accessed an upper level sump bypass leading to more than 1 km of continuing paleo-level trunk with multiple side leads. By the end of 1995, Burns had replaced Bobcat as the deepest cave in Virginia.

Another exciting discovery was made in June 1996. A side passage, a large hydraulic lift tube near the northeastern end of the paleo-trunk, was pushed down a slope of sand and gravel towards the southeast. After a few tens of meters the lift tube intersected a large stream, the Cathedral River, which drains the entire valley on the southeastern side of Chestnut Ridge. This was the first time cavers had encountered the main flow of the underground Cathedral River and the excitement was palpable; this discovery could be the key to tens of kilometers of passage in the up-stream portions of the Cathedral Drainage. Alas, despite all of the positive thoughts and wishes, an up-stream sump of the river was encountered immediately around the corner. Downstream, approximately 400 m of nice 6 m wide canyon was mapped to a low-airspace near sump, extending the depth of the cave to 240 m. Pushing beyond the near sump would be risky, and with no detectable airflow, the potential for continuing was low. The cave was shutting down and the remaining leads did not look great, particularly when considering the brutal 5–6 hour travel time to get to the leads.

Several additional trips followed in an attempt to make something go, with little success. The last of these occurred during the summer of 1998, which involved a tricky aid climb into a side passage off of the paleo-level trunk. The climb, referred to as the "Pot Metal Piton Climb" led to a drippy intersection of narrow canyons and a low stream crawl. A hint of air flow was detected, but further exploration was halted by exhaustion and the late hour.

That was 15 years ago, and it seemed unlikely that Burns, then 3.8 km in length, would connect to the Chestnut Ridge System. A large empty space on the map and considerable lateral offset separated the two caves, and promising leads were scarce. The fact that no one has been back to visit Burns' defining landmarks such as the Bone Crusher, the Mud Crawls and Dead Cousin's Pit, might suggest that the story of Burns exploration is over. Not quite.

3.4. Upper Ghost Hall and the Airblower

During the exploration of Blarneystone's Ghost Hall, an obscure drain was found atop the flowstone-covered breakdown at the southern end of Ghost Hall. The fist-sized hole was unremarkable except for the strong draft that blew from it. Intermittent efforts to enlarge and follow this drain, dubbed The Airblower, occurred throughout the 1990s with limited success. The flowstone-cemented breakdown resisted the effects of blasting, and diggers were forced to work in wet, difficult conditions.

Then in 2001, a more sustained campaign of digging was launched. The use of improved technologies such as lithium battery-powered drills enabled more efficient, precision excavation of rock. Following the Airblower's namesake

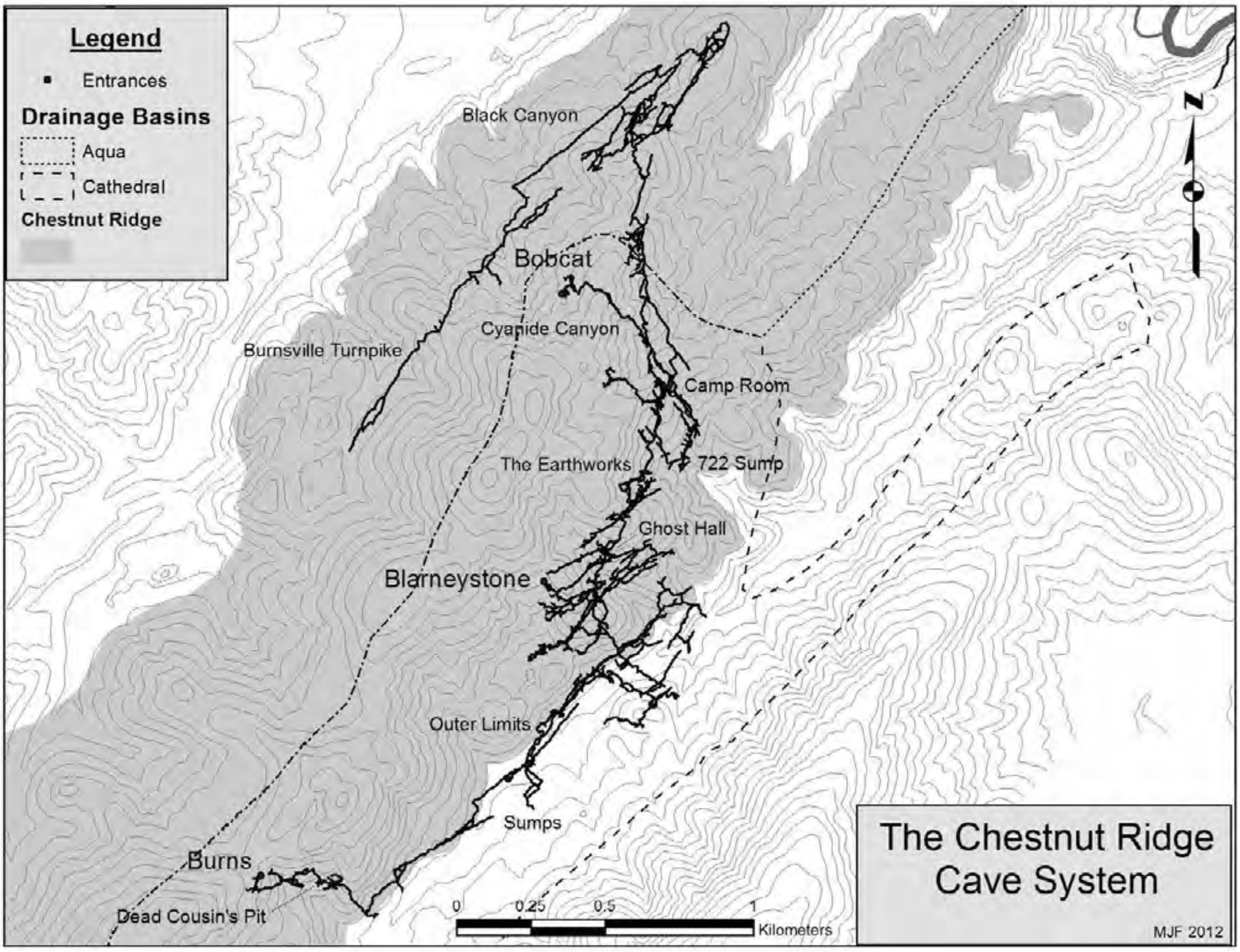

Figure 5. Map of the Chestnut Ridge Cave System.

draft, a passage was mined down through the cemented breakdown in a corkscrew fashion. In October 2003 after excavating nearly 23 vertical meters, the breakdown choke yielded and the blackness of virgin borehole stretched out into the distance.

A flurry of exploration followed. A paleo-level trunk, likely a continuation of Ghost Hall, headed off to the southeast for 200 m before branching off in multiple directions. Anthodites adorned the walls and ceiling of the 15 m wide passage, and pits opened in the floor. One of these pits led the way down to a massive lower level trunk running northeast-southwest, 50 m below Anthodite Alley. This breakdown-floored passage, called Boulder Dash, continued southwest for close to 400 m to a muddy sump, located tantalizingly close to the downstream terminus of Burns.

To the northeast, Boulder Dash morphed into a network of large phreatic tubes with steeply sloping, gravel-floored lift tubes and multiple sumps. It was later determined that Boulder Dash, and its northern extension "The Butler Quarters", function as a flood overflow route for the Cathedral River, with floodwaters rising nearly 25 vertical meters before flowing to the sumps in The Butler Quarters.

Additional breakouts of new exploration occurred in other areas beyond the Airblower, including an area southeast of Boulder Dash where a significant streamway (the Pigeon Tooth River) and a tall dome complex were found.

However perhaps the most significant discovery of this most recent period of Chestnut Ridge exploration was a small muddy dig found along a shelf near ceiling level near the southern end of Boulder Dash. Named Opportunity Knocks, this blowing lead was excavated over the course of several trips before taking off on a meandering route towards the southwest. Consisting of a mix of low crawling and vertical thrutching, all while thoroughly saturated in mud, the route called the Outer Limits, was unpleasantly reminiscent of a certain deep cave less than a km to the southwest (i.e. Burns). For a good reason too, because on December 3, 2005, after 748 m, a muddy low-airspace pool was pushed at the end of Outer Limits, and a connection was made to the top of Burns' Pot Metal Piton Climb. Burns was now part of the Chestnut Ridge Cave System!

All told, more than 8 km of passage has been mapped beyond the Airblower dig, and the System's length stands at 33.6 km. Leads remain in several areas, including one near the Burns connection that has potential to bypass the Burns upstream sump thereby accessing the many kilometers of theorized cave passage of the upper Cathedral drainage. However the remoteness of some of these leads presents a daunting challenge; travel time from the end of Outer Limits to the Blarneystone entrance is more than 8 hours.

3.5. Continued Exploration and Future Potential

Exploration continues under and around Chestnut Ridge. Recent discoveries in Bobcat such as the Stomping Borehole have inspired a renewed interest in the cave. New caves have been found such as By the Road Cave (BTR) which is strategically located in the Cathedral drainage presenting the exciting potential for a bypass to the upstream sump in Burns. If such a bypass is found, it is reasonable to predict that 20–30 additional kilometers of cave passage could be found. Recent efforts to reopen a cave known as Robin's Rift could also lead to breakthroughs into the Cathedral drainage. Other new and ongoing projects are too numerous to describe, however based on past history, the system will continue to grow.

Diving of the Aqua and Cathedral springs has revealed that these resurgences are fed by conduits at significant depth, making underwater exploration impractical using current technologies.

4. Summary

The exploration of the Chestnut Ridge System has spanned a period of 60 years, resulting in the third longest and second deepest cave in Virginia (33.6 km and 240 m respectively). The success that the tightly-knit Burnsville Cove cavers have had in pushing the system is a testament to persistence, a systematic approach, and a high pain tolerance.

Attempts to connect the Chestnut Ridge System to Butler Cave and to extend the System into the upper Cathedral drainage have so far been unsuccessful. However through the use of continuously evolving digging and prospecting techniques, it's not unreasonable to predict that a 60+ kilometer system may one day be found under the Burnsville Cove.

Acknowledgments

The author wishes to thank the members of the Butler Cave Conservation Society, particularly Nevin Davis, Gregg Clemmer, and Tommy Shifflett, for providing data, historical references, and stories around the campfire. I would also like to thank Dr. William B White for providing access to portions of an unpublished manuscript for a book on the Burnsville Cove, which is currently being prepared for publication by the BCCS.

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CAVES OF TONGZI, TUDI, JIELONG, WULONG COUNTY, CHONGQING, CHINA – SIX YEARS AND COUNTING

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Between 2007 and 2012 expeditions of the Hong Meigui Cave Exploration Society have explored the karst and caves near the towns of Tongzi, Tudi, and Jielong, in Wulong County, Chongqing, China. As of Spring 2012, 57 km of cave passage has been documented and numerous additional caves, karst features, and springs have been identified. The caves are located in the watersheds just west of the UNESCO South China Karst World Heritage sites that contains the Houping Cave System which has over 125 km of related caves in addition to five classic tiankengs.

Most effort has been focused on the Quankou Dong (Spring Mouth Cave) System. Of particular note is Cloud Ladder Hall which is believed to be the sixth largest room in the world by floor area and third by volume. Cloud Ladder Hall likely represents a proto-tiankeng, that is, in near geologic time it will join the ranks of the giant open air tiankengs. The Tongzi System has seen less work but has significant development.

The watershed consists of four elongated north south trending dolines, the longest of which is 11 km long and over 500 meters deep. These flow into a mountainous plateau which itself contains some very large sinkholes. The resurgence entrance is 116 meters tall, 25 meters wide, and the resurgence flows about 3.5 cubic meters in the dry season. After the 2012 expedition the length of unconnected caves in the lower system totaled 35.0 km and the deepest vertical extent is greater than 450 m.

The Tongzi group in an adjacent watershed contains the un-connected Shanghetaowan (Walnut Bend) and Lao Chang Dong (Old Factory Cave). Shanghetaowan is 8,489 m long and 471 m deep and has potential for much more.

The uniqueness and scale of the watersheds imply much more cave exists than has been found to date.

1. Introduction

The project was first envisioned in 2004 while searching the then newish Shuttle Radar Topography Mission (SRTM) terrain models for an interesting area to make a cave project. These public domain models were subsequently incorporated by the virtual worlds of the internet like Google Earth and others. The Tongzi area was adopted by the Hong Meigui group as a perfect extension of the regional projects near one of the UNESCO South China Karst World Heritage sites.

Yearly expeditions were begun in 2007 and run during the relatively dry season of March when the snow has mostly stopped falling and the spring rains have not yet arrived. Parts of the system are very susceptible to flash flooding and it is believed that many of the caves are only approachable during the driest times of the year.

2. Geographic Setting

The study area is dominated by steep terrain ranging from 500 to 1,500 m a.s.l. developed in thickly bedded Cambrian and Ordovician limestones. Surface drainage is dominated by four large parallel blind valleys with sinking streams contributing to the underground hydrologic network. The area is quite rural with roads only recently reaching some of the villages. Expedition life has been characterized by the warm hospitality of remote villagers.

The area thus far investigated can be viewed as three groups: the Quankou System, the Headwater Dolines, and in a separate watershed the Tongzi area caves.

3. Quankou Dong Hydrologic System

Most of the known Quankou Dong System lies under the Ranjaigou elevated valley that extends east-west along the bottom of four large dolines. The resurgence flows about 3.5 cumecs in the dry season and may represent most of the water sinking in the dolines. There are currently 4 unconnected parts of the greater system that contain the main streamway. These are: Quankou (4 entrances), Wudi (3 entrances), Shengkongba (1 entrance), and Yingjaiwan (3 entrances). Adding in a few smaller caves there are 35 km of passage known in the immediate area of the Quankou System.

3.1. Quankou Dong

Quankou Dong (Spring Mouth Cave) is the main resurgence entrance. It was first visited in 2007 after the analysis of SRTM terrain models implied this should be our top target area. The 116m tall entrance passage quickly forks. To the west is a very large canyon that carries most of the water. To the north large up-trending passage continues through to Gaiping Doline. Both sides have tremendous airflow.

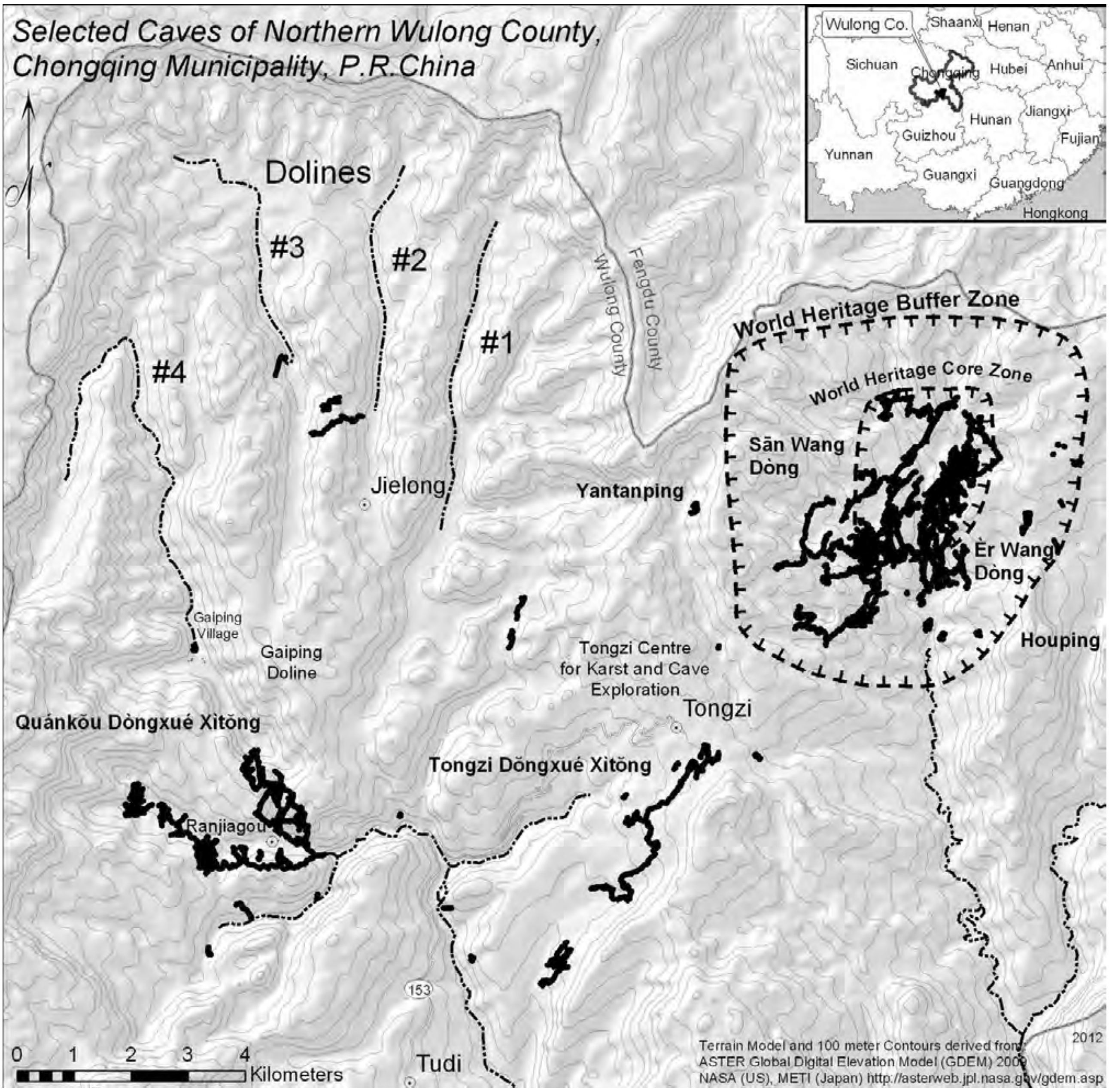

Figure 1. Regional Overview.

The western "Wet Side" or "Ron Simmons Streamway" is characterized by deep rapid water, sporting waterfall climbs, and beautiful large passage that continues for 1.4 km to a sump. To the north the "Dry Side" passage requires 6 short rigged climbs that are the floor of a huge paleo trunk. The airflow is so strong the team filmed a video of flying a kite in the main trunk. A set of side passages lead to a higher paleo segment know as "Ultrabore". Farther up the main passage is very flashy infeeder and Cloud Ladder Hall, one of the largest rooms in the world. Beyond the main passage continues to the 80 m high Er Long Dong (Two Dragon Cave) entrance at the bottom of Gaiping Doline. Half way along this last segment a series of side passages develop westward and ultimately reach a grouping of smaller paleo entrances also in the bottom of Gaiping Doline. The primary route under the ridge between the two main entrances is just over 3 km.

In the east end of Ranjaigou valley are the other two entrances to Quankou. On the south side is Xiniu Dong which almost immediately drops a 170m pitch to a large trunk that soon drops pitches of 10 m and 30 m to drop into the high stream passage of the wet side. Directly across the valley to the north is Zhaishi Dong. Here a sizable up-trending trunk narrows into a climbing canyon that is best done with several traverse lines. A series of short climbs, one rigged, opens onto a balcony high in the wall of Cloud Ladder Hall. After a rebelay at -22 m a free hang rappel is made into the middle of the room for a total pitch of 244 m. This astounding triple connection was made in 2010, and Xiniu was joined in 2012. This group is 16.0 km long and 430+ vertical. Of additional interest is a tight muddy shaft series dubbed "Jet Stream Cave" on the ridge directly above Cloud Ladder Hall. Despite tremendous airflow the cave ends in tight rifts and drains. The bottom at a depth of 111 m must be close to breaking into the unseen ceiling of Cloud Ladder Hall. A connection would increase the cave depth to about 550 m.

3.2. Wudi Dong, Tianshengyan, and Liuqianwujian

Wudi Dong, Tianshengyan, and Liuqianwujian form the next cave group. Wudi is almost a karst window in the bottom of a very large steep sinkhole about 1.5 km long and 100 m deep. A large passage at the bottom quickly intersects the stream. A short way to the east is a sump that is very close to the upstream sump in Quankou. To the west is deep water in very tall canyon. After 2.2 km and several waterfall climbs the upstream sump is encountered. There are several side passages at this lower level. Tianshengyan is up the hill on the south side of the valley, past Wudi. It is dry mazy, and contains old saltpeter workings. Just down the hill is the small entrance of Liuqianwujian where a pit is immediately encountered. Several more pits follow and the cave develops at a mid-level underneath Tianshengyan. A series of pits connect both caves to the lower passage in Wudi. This group is 10.8 km long and 228 m deep.

3.3. Shengkongba

The entrance to Shengkongba (a place name) is a large obvious wet weather insurgence in a long shallow sink near the west end of Ranjaigou valley. The main passage quickly chokes in cobbles and organic debris, but a side passage leads to a maze of crawls and short pitches of 7, 6, 9, 10, 8 m. Then the 6th pitch of 34 m finally intersects base level where a large trunk leads to the active stream way. Unfortunately only 170 m of the stream is traversable as it sumps up and down stream. Shengkongba is 2 km long and 118 m deep and a number of leads remain.

3.4. Yingjiawan

The last cave in the valley is Yingjiawan. An active stream from the non-carbonates to the west flows into a prominent entrance in a shallow sink. The stream immediately spills over a 12 m pit and enters large borehole steeply trending down. Several obscure climbs and incoming passages are passed before the passage levels out in an oval wind tunnel. After several hundred meters the main stream passage is encountered. Unfortunately it sumps up and downstream in short order while the air is lost in a complex of infeeders. Near the entrance are two other entrances, one which drops a very nice 82 m pitch after a short canyon section. This group is 3.9 km long and 169 m vertical. Sitting above Yingjiawan, but not yet connected, is Shizikou Dong. This horizontal complex has four entrances and is 1.6 km long and 60 m of vertical extent.

3.5. Cloud Ladder Hall

Cloud Ladder Hall is the tallest of the world's very large rooms. It sits under the ridge, on the high-water flow path, between the lower end of Gaiping Doline and the Quankou resurgence. This flow accounts for the removal of collapse rock as the ceiling continues to stope upwards. Several waterfalls enter the room from very high indicating active development. Passage in Zhaishi Dong intersect the walls of Cloud Ladder Hall at a point 244 meters above the floor, yet the ceiling can still not be seen at this point. Jet Stream Cave located directly above the room further indicates extensive shaft development between the ceiling and the surface which is estimated to be less than 100 meters. Due to these features Cloud Ladder Hall is considered a proto-tiankeng – a chamber in the final stages of transition into a tiankeng. The floor area is 51,000 square meters, and the volume is estimated to be as much as 5.8 million cubic meters, ranking it sixth and third respectively in the world.

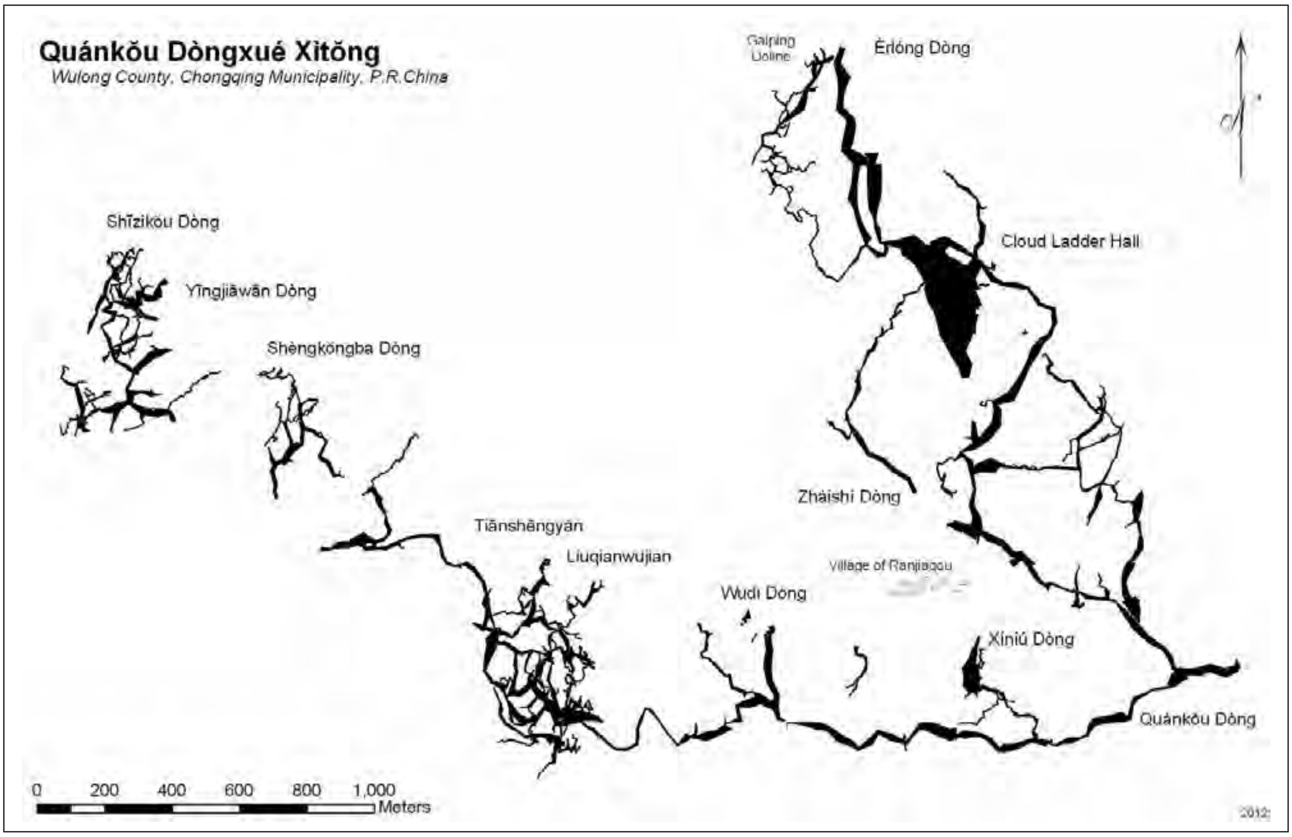

Figure 2. Quankou Cave System and Location of Cloud Ladder Hall.

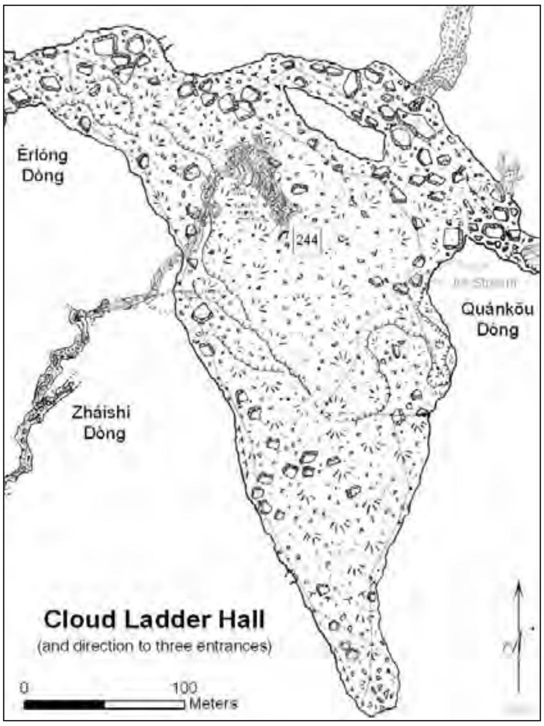

Figure 3. Cloud Ladder Hall.

4. The Dolines

Perhaps the 4 dolines north of Quankou all feed into one big system. Thus far relatively little cave exploration has been conducted despite large sinking streams in each. In the western and largest, the fourth or Gaiping Doline, is the Er Long entrance to Quankou, and a massive insurgence, Erlongkong (length – 177 m, -20 m). Local people tell stories of more caves.

In the third doline from the east, some work was done in 2007. The entrance to Jiugoubashui Dong (553 m, -87 m) is formed where the doline's stream plummets over a 57 m pitch into a large open air shaft. At the bottom a large passage diminishes to a choke rather unexpectedly. On the east hillside two beautifully decorated caves were partially explored, Xiniu Dong (846 m, -56 m), and Sancha Dong, (1,391 m, -74 m). The team has not yet explored the second doline where the town of Jielong is located, nor the first doline. In the hills a little closer to Tongzi, two paleo trunk segments are next to the road, Wantangsui (520 m, -15 m) and Wantangda (421 m, -15 m), as well as numerous other small caves and unexplored entrances.

The team's impression is that a great deal of significant cave will be found in the valleys, ridges, and plateaus along the big dolines.

5. Tongzi Area Caves

5.1. Tongzi System

The system is located down the ridges southwest of the Houping System along similar structural lineaments and begins inside the Town of Tongzi. The most prominent entrance, Shanghetaowan Dong (Upper Walnut Bend Cave), is a classic karst window which serves as the town dump. Upstream of this point several dendritic passages lead to additional pit entrances. Downstream a large passage continues, passing a short breakdown choke, and intersecting the infeeder of Leng Dong after about 1 km. Leng Dong (Cold Cave) is the preferred entrance for the lower cave and accesses a continuation of the stream canyon after a complicated 12 m pitch avoiding a waterfall and plunge pool. After a couple kilometers of winding passage a sump is encountered. Near the sump an infeeder was followed for 1.3 km with many leads left unexplored. The Tongzi System is 8,489 m long and 471 m deep. Unfortunately the cave is horribly fouled with trash which has severely dampened interest in further exploration.

5.2 Lao Chang Dong

Lao Chang Dong is a 3,146 m long and 98 m deep cave complex that is about 1.5 km southwest and downstream of Shanghetaowan, and possibly containing the same stream. Old saltpeter mining vats, trails, and artifacts are in abundance, giving the cave its name. Many leads remain to be explored and more entrances have been seen farther down the mountain.

5.3 Other Caves

Numerous other smaller caves also have been found and documented in the general area. Despite some of them being prominently visible in the mountainsides, they have thus far been found to be relatively small.

6. Conclusions

The cave systems of the Tongzi, Tudi, and Jielong townships are significant in size, extent, hydrology, and geomorphological development. The team believes a great deal more cave exists in this area and the finest discoveries are yet to come.

Acknowledgments

Many thanks go to all the people and organizations that have supported Hong Meigui's efforts and made all this possible: National Speleological Society for their exploration grants; Ghar Parau Foundation; Andy Eavis, Pangjie and the Peoples' Government of Wulong, Chongqing; The numerous local officials and townspeople who have made our visits enjoyable.

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THE HISTORY AND CURRENT STATUS OF EXPLORATION IN YANTANGPING CAVE SYSTEM OF WULONG COUNTY, CHINA

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The Hong Meigui Cave Exploration Society (HMG) is an organization with wide international membership which is devoted to exploring and characterizing China's many caves. Its main area of focus is Wulong County, Chongqing Province. Its permanent base of operation is in the town of Tongzi. HMG's main function is to facilitate the organization of expeditions by providing a presence on the ground in China yearlong. There are many logistical challenges that expeditions must overcome when working in developing countries; Additionally, China poses its own unique legal challenges that classify many forms of cartography as infringing on state secrets.

Yantangping cave (HMG logging code 48H-H12-127-yantangping) is located in the Houping area of Wulong County, China. It lies just outside the buffer zone of the San Wang Dong (SWD)/Er Wang Dong (EWD) UNESCO World Heritage site. It is considered a significant cave by HMG members because of location, depth, difficulty and potential for new discoveries. It has a total vertical extent of 491 m and a surveyed length of 1,210 m. Significant passages have been discovered in SWD and EWD that extend out of the UNESCO protected area and far into the UNESCO buffer zone, thus indicating that both the protected and buffer zones should be expanded; however, the likely interconnectivity of the Yantangping System demonstrates the enormous extent to which these zones need redefining. Until recently Yantangping was never the primary focus of an expedition, but due to the length and difficulty of exploration trips it is inefficient to explore as a tertiary objective; the first full scale expedition focusing on Yantangping is scheduled for Chinese New Year 2014.

1. Introduction

Yantangping Cave System (YTP) is located north of the town of Tongzi in Wulong County, China. Expedition participants typically arrive in Chongqing via domestic flights; from there it is a 2 hour bus ride to Wulong City followed by a three hour "bread" van to the town of Tongzi. Despite the fact that Tongzi has an estimated population of 200,000 people, its infrastructure is similar to that of a town of 500 people in North America. YTP is situated on the east side of Yantangping Valley on a steep hillside at an elevation of approximately 1,340 m above mean sea level. The entrance is accessed via foot path by a 90 minute hike. This path repeatedly crosses a streambed which is dry most of the year. There is a small reservoir farther up the valley than the entrance from which the local community pipes much of its drinking water.

Weather in this region of China is relatively stable with four seasons and a clearly defined wet season. Average monthly temperatures in the town of Tongzi range from -10 °C to 40 °C. Unlike the province capitol, Chongqing City, the air quality in Tongzi can be good.

2. Geology

Yantangping Valley runs from the northwest toward the southeast. It separates the Houping watershed from the Gai Ping Doline and associated Quankou Cave System. It shares a large section of ridge with the San Wang Dong Cave System (SWD) and is formed in Ordovician limey dolomite and other Ordovician carbonates. Although a full characterization of the area has not been finished, scattered field work indicates a 3° dip toward SWD. In-cave observations show large variation in the rock quality and composition; members vary from easy to hand drill to so hard and siliceous that drill bits spark.

Several dye traces have been done in the area using fluorescent dye dumped at the entrance to YTP. However, numerous dye receptors were lost because of high flow at the bugging locations and no dye was indicated. This is potentially due to the high flow at the springs relative to the low volume of water flow in the cave. More dye traces are planned for the future.

The YTP Valley walls are very steep and covered with heavy brush making climbing them extremely difficult. The ridge in which YTP is developed is forested with small conifers as well as heavy deciduous brush; it has not been fully explored and there is no complete catalogue of surface karst features. It is likely that there are additional entrances located on the ridge top as there is rumor in the village of large pits. There is a total possible increase of 250 m of vertical extent by adding an entrance on the ridge top directly above the current entrance. Satellite imagery shows several shadows on the ridge that could possibly be pits; however, their existence has not been confirmed.

3. General Description

The nature of cave passage varies greatly with depth – this is the most intriguing aspect of the system secondary to possible connection to SWD. There is a strong, perennial draft at the entrance and a very slight inflow of water from the surface drainage at that point on the valley wall. The upper most section of the cave has very few side passages

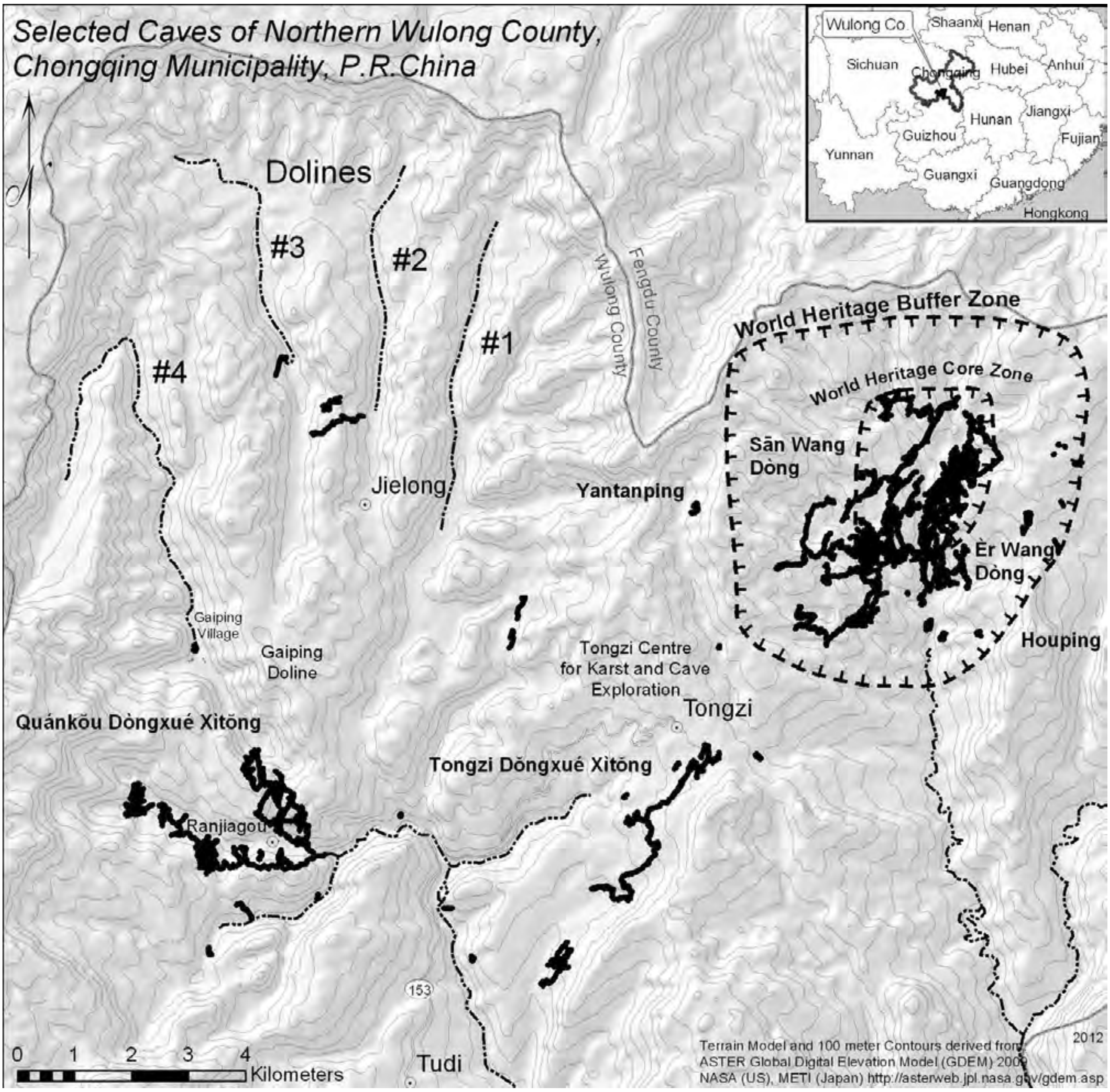

Figure 1. Regional overview of selected caves in northern Wulong County showing the relative location of Yantangping Cave to San Wang Dong and Er Wang Dong. Image courtesy of Mike Futrell.

and is typically joint-controlled: significant pits alternate with narrow rifts down to -194 m. It is in this section of the cave that the most difficult challenges to exploration are encountered. There is one notable non-joint controlled crawlway in the upper section. It is a low volume passage with a flowing stream and grapefruit sized cobbles. This is the one part of the cave discovered to date in which a flooding event could be deadly; however, the current entrance configuration makes it highly unlikely that large amounts of rain water would ingress at that point.

There are several significant obstacles in the upper section of the system: a long, cobbled, wet crawlway; a chest compressing rift; a floorless, wall less traverse to a pitch head, a chest compress on rope; and numerous long pitches sprinkling water. At -261 m a 30 m long section of especially challenging rift is encountered. This passage is the single most difficult to traverse and was dubbed “Riff Raff” during exploration. If not for the valiant efforts of Tommy Shifflet exploration would have gone no further. This section of rift is not quite chest compressing in width and not tall enough in height to travel upright. It is slightly tilted from vertical and the less than vertical wall is perfectly smooth and mudded whereas the overhanging wall is forested with snagging protrusions. Additionally, the cross section narrows toward the bottom so that bags and bodies get wedged; there is no floor to use for support. In the last few meters of this passage it drops down to the floor and requires crawling on one’s side in 15 cm of water to progress.

The second section of the cave consists of voluminous and deep vertical spaces. Beyond Riff Raff the streamway cascades down into a large cross section. The water falls 20 m and lands just to the west of an underground watershed. At this intersection the cave gains volume without a clear explanation for why. Comfortable walking passage goes in both directions, and both directions slope downward. The water flows a short distance westward before falling into a significant vertical space. This space extends upward and downward. It takes a stone over 3 second’s freefalling to make contact with something and then rattles foe an additional few seconds. This estimates the drop to be over 100 m. The vertical space has the look and feel of a massive cross canyon extending in two directions rather than a simple pit or migrating shaft. It has not been explored to date.

To the east there is 90 m of gently descending, dry walking passage which is terminated by another large vertical space. This large pit has several adjacent pits which are connected at a mid-level but do not appear to reconnect below. Enormous alcoves are visible on the far side of the pit and appear to have significant in feeding passages. This pit is approximately 27 m in diameter. Below the initial pit the passage turns a corner and continues downward via another large pit with windows, a canyon, and another pit at which point a sloping ceiling becomes visible. A few short drops and one more pit complete the journey to the only established camp site in the cave at -401 m. The ceiling is an obvious bedding plane tilted at approximately 30°. Camp is situated in the first of 3 adjacent pits.

From here there are numerous passages extending in several directions with mostly horizontal travel. This area is considered the third section of the cave in that the nature of passage is different from the previous two sections. The most notable passage in this area is the Downward Spirals passage which intersects a fault and follows it downward; it doubles back under itself many times as it gains depth. It is in this area that the hardest rock is encountered. Eventually, Downward Spirals reaches the lowest point in the cave to date after 100 m of rope from camp. While most of the passages in YTP are wet, many of the passages after camp are very dry and at least one area has large amounts of gypsum. One exception is the terminal room of Downward Spirals which is 20 m tall and has a cracked mud floor. There is a strong draft coming from a too-tight bedrock squeeze some meters off the floor.

4. History of Exploration

Modern exploration in YTP began with the entrance being logged by HMG in 2007 after a team was led to the entrance by a local villager. It is unlikely that there was significant exploration before this point because, while the entrance is horizontal, ropes are needed immediately for a 30 m pitch. The first survey to penetrate beyond the first pitch was conducted by Duncan Collis and Mike Ficco in April 2007. Survey trips were routinely added on to the beginning or end of other expeditions. As exploration continued and trips became longer it became more and more unfeasible to rerig the cave and proceed to survey on a single trip, even with the practice of leaving derigged ropes in the cave. Soon it became necessary to spend a day rerigging, and then a second day surveying and derigging. The majority of exploration trips were limited by the amount of rope the team could carry. No hammer drills have been taken beyond Riff Raff thus on numerous trips the number of self-driven bolts that could be set were the limiting factor.

All exploration was done on extended, single day push trips until December 2010. By this point travel to the pushing front with equipment required 8 hours. Duncan Collis, Rob Garret and the present author established the only in-cave camp to date. The team hauled a tackle sack of hardware to rerig to the pushing front and 3 tackle sacks of camping gear. They rerigged to the watershed and left the gear. The following day the team returned with 3 additional tackle sacks of camping gear and rope; they pushed onward rigging into the unknown and hoping to encounter a reasonable location to make camp. After several new pitches and exploration of junctions it was late into the night. Camp was set at the first possible location, which proved to be an uncomfortable camp.

The current YTP camp has just enough room for 3 hammocks, two of which suffer scattered drips of water. The floor beneath camp is sticky mud. The water source is a 27 m drip which is collected in a Darren drum and allowed to sit overnight so the sediment can settle. The drip collection is a scant meter away from the toilet.

Due to the infrequent nature of trips it was decided that human waste, both liquid and solid, could be left in the drain of this small pit and would have sufficient time to wash down stream. Only after fully exploring this area and near the conclusion of the camp trip was it realized that the toilet drain does not merely reconnect to another lead below, but is a lead that needs exploration. In addition to the toilet lead one other lead was left coming off of camp. This second lead was drafting at the top of a small pitch where exploration was ended. All passages explored to date in YTP have been surveyed in keeping with the HMG policy of “no scooping”.

All ropes save the first are left in-cave but all hangers and maillons are removed after exploration. Rigging thus far has been done using 8 mm wedge anchors above Riff Raff and 12 mm Spit self-drive drop-in anchors thereafter. Petzl aluminum alloy twist, and bend hangers, as well as amarrage supple hangers are used. Excluding the first rope, the cave is rigged using 9 mm and 8 mm diameter ropes.

5. Connection to San Wang Dong

There is currently a separation of 1,670 m horizontally and 0m vertically between the closest known passages in YTP and SWD. SWD is developed at a lower elevation and to the east of YTP; there are currently going climbing leads in the farthest west passages of SWD. Based on the passage density in neighboring areas it is reasonable to believe that there is a connection to SWD. With the impending connection of SWD and EWD this connection would make a system with total length of at least 128 km and a vertical extent of 1,160 m. The current YTP entrance would be the highest point in the system.

Recent explorations in SWD have discovered several large diameter passages each over 1 km in length; it is not impossible that a single day of survey could result in a connection.

6. Future Expeditions

It is inefficient to further exploration in YTP via single day trips thus necessitating dedicated expeditions. The first of these is planned for Chinese New Year 2014. The primary objective will be to finish exploration of the dry side of the watershed in the first week and then push into the wet branch. Additionally, it may be possible to find a bypass to Riff Raff, which is a tertiary objective. Exploration is planned to be done on 5 day rotating, hot bedded camp trips.

There are already several hundred meters of rope in the dry branch which can be used there and then subsequently in the wet branch. The expedition will take several hundred additional meters of rope as well as a hammer drill to use beyond Riff Raff.

Acknowledgments

Exploration in YTP would not be where it is today without the persistence and drive of Duncan Collis and the continued support of the Hong Meigui Cave Exploration Society's Chair, Erin Lynch. Thanks are due to Mike Futrell for preparation of the North Wulong regional map.

UNDERWATER EXPLORATION OF THE BJURÄLVEN VALLEY CAVE (SWEDEN) UNDER EXTREME WINTER CONDITIONS

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The underwater cave in Bjurälven valley in the Swedish county of Jämtland was discovered in 1979. An attempt to dive into the cave was made in 1997, but the system was deemed undivable due to very high (up to 20 knots) water flow. However, in the early 2000-s, a group of Swedish cave divers determined that favourable conditions in the cave system can occur and proved that it can be dived in early spring when ice covers the entrance and the flow is moderate. The exploration in Bjurälven thus began.

The first Expedition Bjurälven was carried out in 2007, and since then divers have visited the harsh winter landscape every year in March. The documented, explored and mapped cave system now measures more then 700 meters; the deepest part is at around 20 meters. The tight and narrow passages as well as extreme water temperatures (down to 0 ºC and lower) require the use of special diving techniques and equipment, some of which has been developed specifically for this project.

Through cooperation with the local community, Expedition Bjurälven gained a special place in the lives of the local residents and authorities. The expedition was included in a recent European Union regional development project "From Outer Space to the Inner of The Earth" and a documentary about the Bjurälven valley by Kurt Skog was released in the spring of 2012. Through joint efforts of the expedition members and the local community, Bjurälven is now the longest underwater cave in Sweden. Research within hydrology, geology and biology is carried out in cooperation with universities and new results come forward every year.

Figure 1. Bjurälven valley cave is full of hidden beauty; small tight tunnels open up into big vaults further inside.

1. Introduction

Does cave diving in the middle of Swedish winter only steps away from the Polar circle sound crazy to you? With temperatures down to minus 25 °C, a thick layer of ice covers every waterhole. To get to the cave, a lengthy trip on a snowmobile has to be undertaken first. And yet, this year is the seventh year that a group of Swedish cave divers and researchers organize an expedition to the Dolinsjön cave in Bjurälven valley. Overcoming the difficulties, fighting the weather, the expedition continues to add newly explored sections of the cave to the Dolinsjön system. Join the explorers on their quest described in this paper, and you will understand why the cave calls for them again and again every year!

Some caves are big and roomy; you could almost drive a truck though their passages if they were dry. Diving there is pleasant and effortless; you simply glide through the tunnels and enjoy the scenery hovering above the floor. There are plenty of such caves in Mexico, France or Florida. Some caves are exotic and unusual, like the Tank cave in Australia och the Molnar Janos cave in Budapest. Some caves are cold – Plura River cave in Norway or Ordinskaya cave in Russia are good examples. A few caves are tight and nasty, almost trying to catch and trap you everywhere you go. Now imagine the cold and the tight confined spaces combined together; to move somewhere you often have to squeeze through passages that can barely accomodate a diver, the water temperature so low that you stop feeling your fingertips in dry gloves only a couple of minutes into the dive. And what can be more exotic than cave diving in the middle of arctic landscape far away from the entire civilisation? The cave in the Bjurälven Valley is amazingly beautiful though – low passages open up into vertical cracks, everywhere there are evidences of extremly high water flow during the summer months. Passages are eroded into streamlined channels; walls are covers in thousands of ripples and facets. Limestone is hard and loose rocks on the bottom are shaped into sleek purposeful shapes. All small objects and loose rock are washed away by the current which in the summer months can reach up to 20 knots. This is the main reason for the expedition to be orginized during winter, when the water flow is virtually zero and the entrance pool is covered by more than a meter of ice. Another reason is the remote location of the cave. During summer, the only access to the cave is by foot through more than five kilometers of forest and marsh. No terrain vehicles are allowed since the whole area is a nature reserve. During winter, however, the expedition is granted permission to use snowmobiles and the logistics become much simpler. Small vegetation is covered by deep snow and the bare trees are not an obstacle when snowmobile trails are prepared.

Figure 2. The first task each year is to clean the diving site from all the snow, drill a hole in the thick ice and establish a base camp.

2. Materials and methods

2.1. Support from the local community

Diving expeditions to such a remote location would never be possible without the support of the local community. The support for expeditions to Bjurälven has always been amazing! Residents of the nearby Blåsjön village make a large effort each year by preparing the scooter tracks which span approximately 6 kilometers from the nearby road to the cave entrance. The expedition members live in an old village school and have access to warm food and sauna after exhausting days in the field. Everybody, from housewives to the local village business owners, is involved in making expeditions to Bjurälven a success!

2.2. Cooperation with the authorities

Bjurälven valley lies within a nature reserve. This means that special permits are required to be able to for example operate snowmobiles in the area. Due to the many years of fruitful cooperation with the local authorities, the paperwork is seldom a problem and the expedition receives all kind of support from the county of Jämtland. As a payback, a lot of publicity is created around the Bjurälven valley and the unique tourism destination it is. Expedition to Bjurälven has been subject to a lot of attention from the media, from local radio stations and newspapers to large national media houses.

Figure 3. The entrance to the cave is low and treacherous, first hundred meters are basically one long restriction.

2.3. Diving techniques and equipment

Due to the small size of the cave, the technique called “side-mount” diving has to be used. While normally divers carry the tanks on their backs, in side-mount diving they are carried along the sides which gives a very low and stream-lined profile. Equipped like that, the divers are able to enter the cave. Each diver carries three large 12–15 liter tanks (most of the air supply is reserved for emergency). The third cylinder is mounted on the chest and can be removed when passing obstacles. To be able to withstand the freezing cold for several hours at a time, thick undergarments, double hoods, dry gloves and electrical heating are used. Divers must not disturb the fragile environment in the cave and this is why many hours are spent each year practicing diving trim and buoyancy, an art of swimming in the cave without disturbing its walls, floor or ceiling.

2.4. Underwater cave mapping

The goal of many of the dives is to explore the cave system and produce a map of it. The cave is mapped using volumetric measuring techniques – each 2.5 meters the divers measure distances from the guideline to the walls, the ceiling and the floor using a measuring tape. This information is later fed into a computer programme CaveX that generates a three-dimensional image of the mapped cave passages.

2.5. Tracing of the divers in the cave

By putting an electromagnetic tag on a diver, a pulsating magnetic field can be detected on the surface with a radio location device. The radio location and communication device, M-85, is developed, built and described by Bo Lenander, SM5CJW, member of CREG (Lenander 1987). M-85 is a 32768 Hz 1.5W DSB transceiver with a 420 mm circular tuned loop antenna. The tag is a 33 kHz transmitter with a horizontal 300 mm single turn tuned loop antenna. While the tag is under water, its water sensor activates the transmission of short 33 kHz bursts with 2 Hz pulse repetition frequency (PRF). That can be heard as an audio tone signal in the M-85 receiver. The R6/AA battery and electronics are put in a 125 mm long watertight Al-tube. Total tag weight is 100 g. The device can be seen in the figure below.

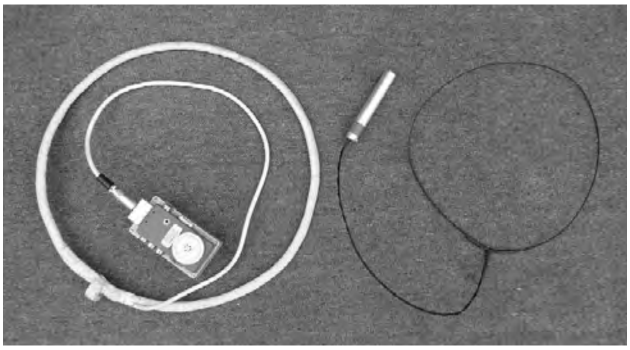

Figure 4. Radio location device on the left and electromagnetic tag on the right.

2.6. Biological research

Biological research in the 2011 expedition focused on carrying out an inventory of the species *tolypella canadensis*, a rare and endangered charophyte. This species was announced in 1973 (Sawa 1973) and has only been observed in relatively few sites in the Arctic-alpine region (Langangen 1999). Research into the question was initiated after initial findings from our expedition in 2010 when the species was informally observed to be growing in the area.

Possible sites where the species was likely to grow (pools with a soft sandy bottom) were investigated under the direction of Markus Nord. A diver wearing a mask and snorkel searched each site carefuly.

3. Results and discussion

There are very few “fun dives” on the Bjurälven expeditions. Although this is not completely true since all dives there are extremely exciting. But there is a mission for each and one of them. Every diver, entering the water, has a task to do, be it digging at a remote stone choke to see if a connection can be made or laying new line and mapping new passages.

Figure 5. Further inside, the cave opens up and sometimes divers swim through big vaults where multiple passages coverge.

Each dive usually starts with a briefing with the surface manager and safety diver on duty. After clearing the dive plan and discussing the mission, it is time to kit up with sidemount tanks and jump into the hole in the ice on top of the Dolinsjön, a small lake at the entrance of the cave system. The visibility there is usually rather poor and a thick blue guideline leads under a ledge to finally disappear in a tight horizontal crevice. The floor is loose gravel and sometimes, an effort of some digging must be made at the beginning of the dive to make it through with the stomach in the gravel and the back against the cave ceiling. Inside, the cave opens up. Suddenly the visibility clears and amazing view comes into sight – sleek tunnels polished by water for thousands of years, disappear into the darkness. There is not much silt since most of it is carried away by summer flow – even small stones are not that common in some cave passages.

Figure 6. Throusands of small facets on the cave walls are formed by the summer flows; using their shape and size it is actually possible to calculate the volume of water passing through the cave.

Up to date, the longest penetration in Dolinsjön cave is some 250–300 meters. This does not sound like a lot, but considering the environment it is a lengthy distance to swim. Several tight restrictions block the way and have to be negotiated, sometimes taking off some of the tanks. Safety bottles, placed every 20 meters, help to reduce the risks but are a big job to place out at the beginning of each expedition. Although each dive is a mission, there is a lot of time to admire the cave. The tasks are usually at the end of the line and thus, there is a lot of time to look around on the way in and out.

3.1. Cave exploration and mapping

Three-dimensional cave map, created by the divers, can give a lot of valuable information. It can be clearly seen which passages come close to each other and the divers then attempt to make a connection between them. So far, over 700 meters of cave have been mapped. The map also allows performing calculations of the cave volume which then, if the flow of water is known, can be used to calculate the amount of water passing through the cave each year. Flowmeters have been placed out in the cave for this purpose. Hydrological and geological research can be performed using the data obtained. For example, the age of the cave can be estimated if facets and ripples on cave passage walls are measured and the amount of water flowing by each year is known. The flow conditions also help to learn more about the melting of the ice in the mountains upstream from Bjurälven.

Figure 7. Total mapped length of the cave by 2011 was approximately 700 meters.

3.2. Tracing of the divers in the cave

The operating range of this equipment is up to 50 m and it is possible to measure how deep under the surface the diver is by use of standard methods. In an urban area, where the electromagnetic noise level is high, the practical operating range will be reduced. The electromagnetic noise in the Bjurälven area is very low. It is important to avoid the use of digital cameras and LED-lights within 1 m from the receiving loop antenna as those devices can give a high noise level.

With the described equipment we were able to follow the divers in the cave below the snowy mountain and that gave the dive master helpful information both for safety reasons and for timing of planned dive operations. The footprints/tracks in the snow, after the divers have been followed, showed the horisontal projection of the cave, a scale 1:1 cave map. In the future it would be useful to have a 2-way communication with the diver. Questions

are given from the surface and the diver can answer yes/no with a single tone burst. The operating range of the electromagnetic equipment is highly dependent on the transmitter power as the operation is within the near field of the loop antenna (inverse cube law). For further use of this tracing method the transmitter power of the tag must be much higher than at the moment.

Figure 8. Winter landscape of the Jämtland county is an impressive sight in itself! It is not a coincedence that the area is a national park.

3.3. Biological research

Three sites were investigated:

From the main resurgence cave (RT90: X7202791, Y1419988) to the bridge over the river. Outside of resurgence is where initial observations of the charophytes were made during the previous year. The bottom structure of the river is stones and coarse gravel with some limestone. However, no traces of the species were found in 2011. No other areas with a sandy bottom were discovered.

Along the course of the river from the resurgence at Semigrottan (RT90: X7202522, Y 1419184) to the main sinkhole are two areas with a soft sandy bottom: Pooled water where the river turns through 180 degrees at RT90: X7202458, Y1419292 and a large pool 25m downstream of Semigrottan at RT90: X7202522, Y1419196. No traces of the species were found.

The third area is around Dolinsjön (RT90: X 7202434, Y 1418696). In the north-east basin (where diving takes place) charophytes were found, but it was determined that they were not the species *tolypella canadensis*. The south west edge of the doline has a soft sand bottom whereas the east has a bottom of mainly rounded gravel.

Thus although charophytes were observed during the 2011 expedition the species *tolypella canadensis* remained elusive and no positive identifications were made.

3.4. Equipment development

Expeditions to Bjurälven are perfect for evaluating the performance of existing diving equipment in extreme environment. Also, new equipment is manufactured and tested specifically for the expedition, most often by the divers themselves. One examples of such equipment is the regulator heating systems. Extreme temperatures in the Dolinsjön cave make regulators malfunction. Normally, a freezing would lead to a freeflow which is fairly simple to handle – the worst thing that can happen is so-called “valve

Figure 9. The temperatures, both topside and in the water, are so extreme that diving regulators need to be submerged at all times to prevent them from freezing.

breathing" when the tank valve is feathered at each breath. While probably a source of a lot of stress for a novice diver, such procedure is fairly easy to use if proper trained. Tank valve with the freeflowing regulator is closed and the diver has to open it a little bit to take each breath; this way very little gas is wasted and the diver can head home in relative safety.

Figure 10. Extreme cold puts pressure on both the equipment and the divers.

The problem, experienced on many occasions in Bjurälven has been that regulators do not freeflow upon freezing – they simply stop giving gas. The flow of gas becomes smaller and smaller and after a minute or so just stops completely. This happens due to build-up of ice inside the regulators and it is a rather frightening experience. There is simply nothing to breathe. Of course, double and triple systems help – but those might freeze just as easily, especially if the breathing is a bit on the heavy side due to some stress. Special heating sleeves were manufactured to attempt dealing with this risk. Fitted on the heat exchangers on the second stages, the plan was that they reduced the risk of freezing simply by heating the regulator in an efficient manner. It is too early to say if this method was a success, but it can be concluded that none of the regulators, fitted with the heating sleeves, froze while there were multiple freezings of regulators without the heating system during the last expedition in 2011. To collect more statistically reliable data, this equipment will be used in future expeditions and hopefully, at the end, help to reduce accidents connected to second-stage freezing.

4. Conclusions and summary

Most of the passages explored and mapped so far end in an intersection where two or three new tunnels reach out into the darkness, around each corner there is most often not a dead end but pleny of new passages to explore. With it`s 700 meters, Dolinsjön cave is today the longest underwater cave system in Sweden. Since there are so many new leads, the system gets significantly longer each year.

Acknowledgments

We would like to thank all our sponsors for making Expedition Bjurälven possible! Especially the main sponsors, technology company GELAB and diving equipment manufacturer SI TECH, are acknowledged. Support from the local population, the Swedish Speleological Federation (SSF) and local authorities has been a prerequisit for successful expeditions through the years. Finally, we would like to express our gratidude to everyone who have perticipated in the expedition since 2007, striving to our common goal of making the Bjurälven Valley known to the world.

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Figure 11. Every expedition is a teamwork and a celebration of team spirit in cave exploration!

GROTTA DEL BUE MARINO – SARDINIA

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In 1986 happened a small miracle. During totality when the travel to the west world has been nearly impossible small group of Czech speleodivers from Speleoaquanaut club found themselves in the small spa town of Bad Urach in West Germany. Jochen Hasenmayer has held a lecture there for the guest of the spa about his recent discoveries in the cave Blautopf. Unfortunately the Czech divers were unable to get permission to dive in the cave but the meeting with Jochen has opened the way to Italian island of Sardinia. The diving in this picturesque place called Hasenmayer during a meeting with the Czech group after a lecture as one of the most beautiful in Europe. It has been 25 years since the exploration vehicle Avia with Czech speleodivers first came to the mountains of Supramonte in the Golfo di Orosei.

1. Bue Marino

You can find here one of the most beautiful cave system of Sardinia. The full name of the entrance of the cave, which is known for several centuries, is the Grotta del Bue Marino. It is derived from the Mediterranean monk seal (Monachus monachus), that is in Sardinia called Bue Marino – sea ox. Seal colonies have appeared in the cave till the early 70-ies of the last century.

Figure 1. Entrance to the cave (Photo Radoslav Husak).

Grand entrance portal of the cave must have been noticed by fishermen that sailed boats along the coast. Forms in the shape of human figures carved on the walls date back to 6–8 thousand years ago. Probably even early man used the cave, that provided protection from the weather, and when the sea level was a few meters lower, fresh running water. Some inscriptions in the upper part of the portal are from the late 19th century. Systematic discovery and mapping Bue Marino started to happen from 50's of the twentieth century. The greatest credit for the survey of the dry parts of the cave system goes to teams of cavers from Sassari and Dorgali.

2. Waiting for aqualung

Rising of the seas ten thousand years ago caused secondary flooding of the monumental corridors. Sumps created an obstacle that was for dry cavers unsolvable problem. The two at the time known branches of Bue Marino cave – Ramo Sud and Nord – were waiting for a time when aqualung will let speleodivers penetrate sumps and the exploration of the caves will progresses further. At the beginning of the 70-ies of the last century came to Sardinia Jochen Hasenmayer. Little guy with tremendous vitality. Discoverer, explorer, innovator. Second of August 1972 he plunged for the first time into a siphon at the end of Terminale Ramo Sud (South branch). September 1, 1977 he surpassed (on the third attempt) 630 meters long and 32 meters deep sump. After that he swam through two short sumps Apnea 1 and 2, and discovered nearly 1.5 kilometers of dry tunnels and sumps Owest, which we later named Hasenmayer's question mark. In the seventies Jochen as well dived in Ramo Nord. During several attempts based on the information by Axel Mahler he came all the way to the sump, which is in the last overall map marked as cave called Siphone Nord Grande. Hasenmayer's memory sketch from 1972 shows that this admirable man has been diving in Ramo di Mezzo. This branch of the Bue Marino cave has been rediscovered only in 2005. Stainless steel wire used instead of guide lines by the Austrian ended a mile from the entrance to the cave. At that time that has been truly remarkable performance.

3. The inscription at the end of the cave

Sumps Bue Marino enticed other speleodivers. Between 1981 and 1982 the French Speleologists Crouquet, Hilaire, Granier and Eric Le Guen went through the sump Terminale. In the turn before sump Apnea 2 they found sump Terminus, interrupted by dry sandy stretches. They got to a distance of 600 meters.

Figure 2. Public parts (Photo Radoslav Husak).

Figure 3. Lakes of Ramo Sud (Photo Karol Kyska).

We discovered their guiding cord in 2010 in a small trap at the very end Ramo Sud. It is called The French 2. Here, according to a memory sketch a diver got 20 meters away, and 8 meters deep. The French group left cave inscriptions at three locations, which marked the reached positions.

Figure 4. 15th siphon of Ramo Nord (Photo Radoslav Husak).

4. The era of Czechoslovakia

The first Czech expedition to Sardinia in 1987 examined the inland caves of mountains Monte Alba and Supramonte, also coastal springs on the west coast. Systematic cavediving exploration of Bue Marino by Czech speleodivers began in 1989. Cavers gradually penetrated new parts of The Ramo Nord and mapped it in detail. They overcome 530 meters long and 30 meters deep sump Nord Grande after which they advanced into three corridors of several kilometers. In 1993 Lubos Benysek, Milan Slezak and David Netusil swam along with their Italian colleagues Leo Fancello and Roberto Loru again through siphon Terminale in Ramo Sud. They got to where they were before Hasenmayer and the French. They were forced to return, just before the end of the southern branch by lack of light sources. After this joint Czech-Italian venture there now were three memory drafts of space behind sump Terminal. It was time to map this part of the cave in detail. It happend in 1998 and it was done by a couple Hutnan – Hota. During the seven hours that they spent behind the sump they made mapped documentation to the end of Ramo Sud. But still there remained some unknown places. The Czech pair was unable to localize the mysterious Hasenmayer's sump Owest and both french sumps.

5. New Millennium

The activity of the Czech speleodivers in Bue Marino increased with the advent of the new millennium. In the years between 2001–2012, 10 expeditions took place under the leadership of Daniel Hutnan. Their goal was to map out the whole cave again and move on to the unexplored parts of the cave system.

Ramo Nord (Northern Branch), also known as Czechoslovakia, was gradually supplemented by new discoveries. In 1993 Slezak and Benysek reached a total length of 8 km in this tree. Eighteen years after their exploration, these two end parts were extended by further discoveries with the prospect to continue. The detailed mapping of Ramo Nord lasted three years.

Figure 5. Map of Bue Marino with the latest discoveries.

In 2005 speleodivers encountered guiding cord stretched by Thorsten Wälde. This cord led into the hallway discovered and surveyed by Hasenmayer in 1972. We gave her name Ramo di Mezzo (Middle branch).

In the years 2006, 2007 and 2011 here Radek Husak and Jan Zilina gradually reached the underwater distance of 4,000 meters. Group of Czech speleodivers also discovered 700 meters of dry passages that begin in turn at 2,650 meters of Ramo di Mezzo.

Figure 6. Penetration through siphon of Ramo Nord (Photo Radoslav Husak).

Cooperation with Italian colleagues Leo Fancello and Roberto Loru led to completion of missing parts of the cave into the central map. Leo provided all the documents from mapping all the dry parts of Ramo Sud as well as Ramo Nord. Also he found in his archive some old memory sketches done by Hasenmayer and French speleodivers from 1981 and 1982. In cooperation with the Italian group and with the help of beacons we were able to pinpoint the exact location of the end of Ramo Sud and in addition to discover one of the passages that is closest to the valley Codula di Luna. The distance to the surface at this spot is 22 meters.

Daniel Hutnan overcame with his colleagues sump Terminale six time in total. Here they gradually discovered and mapped 1,500 meters of passages. With his son Martin, Mira Manhart and Martin Hones Daniel discovered mysterious places which were not clear from memory sketches. The French sumps could be then studied and mapped in detail. They also found the entrance into the never explored Hasenmayer's sump Owest (Hasenmayer's question mark).

6. Gigantic system

In view of the position of cave systems in the valley Codula di Luna, it is clear that in the past it was single large system, running the length of tens of kilometers. Deeply cut valley separates the present cave, located in the right part of the valley (Su Palu – Su Spiria, Carcaragone, Su Molente, Cala Luna), from 21 km long Bue Marino. Overcoming the valley below ground was a dream that would open the way to the creation of the longest cave system in Italy.

7. Sump Martin

The desire to swim underneath the valley became a reality in October 2012. Trinity of Daniel and Martin Hutnan together with Martin Hones has found at the very end of Ramo Sud new sump. It was located near so called French 2. Mapping of the final passages of the cave delayed Daniel Hutnan together with Martin Hones. In the meantime Martin Hutnan crawled through all possible cracks cover with fine sediment. In between some rocks he found a passage ending at a little pond. They called it the sump Martin.

After short preparation Daniel Hutnan submerged himself in the sump. Since the end of the cavern is at the edge of the valley, there was little chance of finding passages that were wide enough to get through. The bigger was Dan's surprise when the passage under water continued further south. After about 80 meters the sump ended in a pond 10 × 5 meters. After removing diving bottles Daniel continued further through wide dry corridor covered by decorations. This ended after 330 meters in a narrower sinter corridor with sump. The whole discovery is 400 meters long and in general is directed south – perpendicular to the valley. Entering the measured data into the map after returning proved that this was historically first successful

Figure 7. Dry passages of Ramo Sud (Karol Kyska).

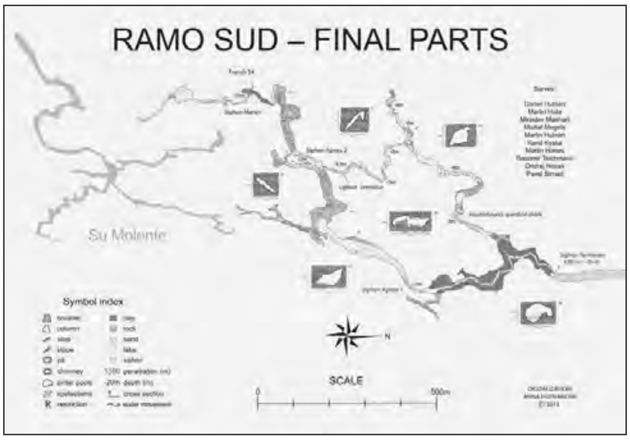

Figure 8. Final parts of Ramo Sud under the valley.

underground pass under the valley Codula di Luna. Thanks to this discovery the door is open for creation of the longest cave system not only in Sardinia but also in the whole Italy. By combining all known caves in the right and left side of the valley the final length can be 70 km.

On discoveries in the cave of Grotta del Bue Marino participated more than 50 cavers from Czech and Sovak Republic. Thanks goes to not only to the local speleological groups from Dorgali and Sassari. We want especially say thank you to those who helped with obtaining permits to work in this beautiful cave and provided historical records and personal assistance: Leo, Maria, Roberto, Mario, Gianpaulo, Fabio.

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Figure 9. Cave systems in the valley Codula di Luna.

History of exploration – Grotta del Bue Marino (Leo Fancello, Daniel Hutňan).

Ramo Sud

Date	Name	Location/Activity	Cave lenght
since 1950	Dorgali	dry parts from entrance	?
1987–2007	Sassari, Dorgali	draving dry parts	2,960 m
2. 8. 1972	J. Hasenmayer	Sifone Terminale – 270 m	3,230 m
23. 7. 1974	J. Hasenmayer	Sifone Terminale – 550 m	3,270 m
1. 9. 1977	J. Hasenmayer	Sifone Terminale – 630 m, Apnea1, Apnea2	4,590 m
5. 9. 1981	Chouquet, P. Penez	Sifone Terminale – 550 m	4,590 m
14. 9. 1981	P. Penez, Chouquet, Hilaire, Granier	Sifone Terminale, Gallerie Sable, Salle Blocs	4,790 m
16. 8. 1982	E. Le Guen, P. Penez	Gros Golets, Sif. Terminus – 640 m, Sif. F2-20 m	5,510 m
30. 10. 1993	Benýšek, Slezak, Netusil, Fancello, Loru	Salle Blocs	5,510 m
30. 11. 1998	D. Hutňan, M. Hota	survey dry parts after Sifone Terminale	5,510 m
5. 12. 2007	D. Hutňan, M. Hutňan, M. Manhart, M. Megela	radar	5,560 m
9. 10. 2010	D. Hutňan, M. Hutňan, M. Manhart, M. Hones	radar, survey	5,590 m
10. 10. 2011	D. Hutňan, M. Hones, K. Kyska, P. Strnad	Sif. Terminus – 800 m, dry parts – 200 m	6,590 m
7. 10. 2012	D. Hutňan, M. Hutňan, K. Kyska, M. Hones, O. Novák, R. Teichmann	Sif. Terminus – 200 m, sif. before Apnoe1 – 60 m	6,800 m
10. 10. 2012	D. Hutňan, M. Hutňan, M. Hones	Sif. Martin – 80 m + dry parts after – 330 m	**7,210 m**

Ramo Nord

Date	Name	Location/Activity	Cave lenght
7. 8. 1972	J. Hasenmayer	Lago Smeraldo-Lago Nero, 520 m	520 m
14. 8. 1972	J. Hasenmayer	Lago Nero-Lago Barbara, 160 m	680 m
10. 8. 1973	J. Hasenmayer	Lago Barbara-Sifone Finale 73,	2,150 m
1. 9. 1977	J. Hasenmayer	Sifone Finale 73-Sifone Nord Grande	3,350 m
1990	Czech – 10 divers	draving parts in front of Sifone Nord Grande	3,350 m
1991	M. Slezak, S. Bilek, L. Fancello	second floor after 700 m, 300 m	3,650 m
1992	Czech – 7 divers	Sifone Nord Grande-520 m, dry parts after-800 m	4,520 m
1993	Czech – 7 divers	parts after Sifone Nord Grande, 2,230 m	6,750 m
2005	Czech – 16 divers	draving parts from entrance to 700 m	6,750 m
2006	Czech – 11 divers chemical analysis, 100 m news	draving parts behind Sifone Nord Grande, 6,850 m	
2007	Czech – 11 divers	draving Sifone Nord Grande, 100 m news	6,950 m
1987–2007	Sassari, Dorgali, CSS	draving dry parts from entrance-1,340 m	8,290 m
2005–2010	CSS	dry parts after 700 m-250 m	**8,540 m**

Ramo di Mezzo

Date	Name	Location/Activity	Cave lenght
1972	J. Hasenmayer	Lago Smeraldo-1,030 m	1,030 m
2005	Thorsten Waelde	Lago Smeraldo-750 m	1,030 m
2005	D. Hutňan, R. Husak, K. Svobodová	survey, mapping	1,500 m
2005	R. Husak, K. Svobodová	survey, mapping	2,400 m
2007	R. Husak, J. Zilina	survey, mapping	4,750 m
9. 10. 2011	R. Husak, J. Zilina	survey, mapping	4,850 m
11. 10. 2011	R. Husak, D. Hutňan, R. Teichmann, P. Strnad	dry parts after 2,600 m, 700 m	**5,550 m**
Total			**21,300 m**

EXPLORATIONS IN THE LOFERER STEINBERGE

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The Loferer Schacht is currently the deepest and longest cave in the Loferer Steinberge. Characterised by a 600 m deep vertical segment that leads into a fossil, mostly horizontal area, this cave develops in the upper Dachstein limestone levels, under which an insoluble dolomite base exists. Given the limestone's inclination and other indicators such as wind and water systems within the cave, it is presumed that the cavity progresses deeper toward the valley. Further exploratory work is required to confirm this hypothesis.

1. Introduction

The Loferer Schacht (Cat.-Nr. 1323/42) was discovered in 1983 by a team of Polish speleologists from the KKTJ Cracow, who had been systematically exploring and mapping the region of the Loferer Steinberge. The KKTJ surveyed the western branch of this cave between 1983 and 1984. The DAV Höhlengruppe Frankfurt/Main undertook a re-surveying of the western branch down to a maximum depth of -665 m between 1990 and 1991, arriving at the same dead-end first reached by the Polish. During de-rigging in 1992 a connection to the eastern branch was discovered at -106 m: the "Frankfurter System". Exploration in this branch continued, leading to the discovery of a fossil, horizontal segment of the cave between 1999 and 2000. The deepest point surveyed, named "Hades" (-796.67 m), was reached in 2004, as was the current exploration lead, "Sekt oder Selters" (-730 m). Here strong wind blows into an area of blocks, still too narrow for passage. Currently, the surveyed length comprises 10,449 m, extending between +9 m and -796 m measured relative to the main entrance (Hartig 2008).

Loferer Schacht's three known entrances are found roughly 200 m to northwest of the saddle of the Kleine Wehrgrube, between the Reifhorn and the Hochsenhorn, at a height of 2,200 m. The entrances are usually blocked with ice until August. An entrance in the SW face of the Reifhorn, especially in the area of the Weittal and Hafenloch, is presumed. Surface explorations in these regions, in 2005 and 2008, provided an approximation up to ±70 m from charted sections of the cave. Nevertheless, an entrance in this region is yet to be found.

The Northern Calcareous Alps, in which the Loferer Steinberge are included, are characterised by the existence of high-altitude karst plateaus and by the presence of large horizontal cave levels, known as "Riesenhöhlen", between the altitudes of 1,600 m and 1,800 m.

The Loferer Steinberge, in which the eponymous Schacht is located, are composed of a ca. 1,000 m thick, soluble Dachstein limestone cap, under which an equally thick layer of dolomite stone is found (Fig. 1). Due to the latter's low dissolution potential, speleogenesis is sparse, and thus the maximum potential depth is indeed around 1,000 m. The interface between these layers can actually be reached at the lowest point of the known extension of the cave (ca. 1,400 m NN). The slope assumed by the layers, directed to north and northeast (Žák 2008), implies the possibility of achieving greater depths should karstification have continued within the Dachstein cap.

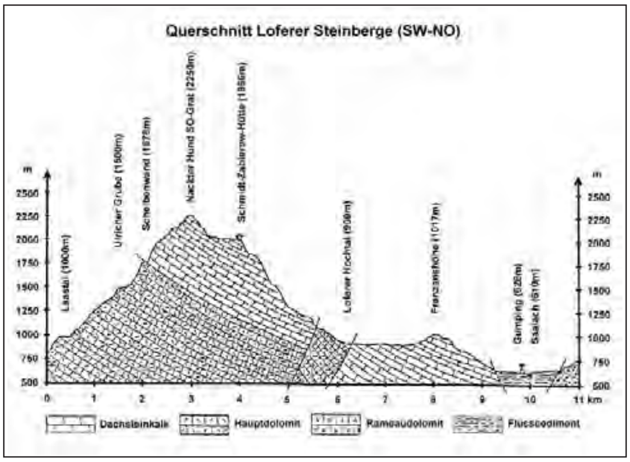

Figure 1. Geological profile SW–NE (Reinl 1993).

The higher-located and vertical segment of the Loferer Schacht comprises a number of active pits, collecting rain and thaw water from the surface, and displays characteristic erosion surfaces. During progression into the cave, it is evident that both dissolution and erosion of the rock, as well as tectonic processes and collapse, were responsible for the character of this cave. The horizontal section, reached at about -600 m, is markedly different from the vertical passages so far, and it is thought to have developed earlier. Of particular interest are the large, horizontal passages, where flowstone can be found at a number of places. While numerous stalactites of up to 30 cm are known, only three stalagmites were observed to date. Cauliflower and other immersion formations, as well as ground coatings, are also observed at specific locations and mark a supposed waterline (Hartig 2012).

Development of the passages along layer interfaces and faults can be easily discerned in the lower, horizontal part described above. As an example, the large corridor called "Minas Tirith" follows accurately the inclination of the limestone layers (Fig. 2). This passage is still characterised by large, finely polished slickenside surfaces, which are also found frequently throughout the carve.

Conglomerate structures have been observed at a single site, corresponding with the lowest point in the cave.

Figure 2. Loferer Schacht in profile (SW-NE).

2. Hydrology

With a poorly developed soil and epikarst zone in the recharge area, mostly above the treeline, the surface around Loferer Schacht is characterised by the presence of perennial snowfields and ice plugs in karst depressions. The residence time of water here is in the order of half a year to several decades, and melting during the summer season can contribute greatly to the recharge. Virtually all charted sections of the cave are located in the unsaturated (vadose) zone, in the sub-zone of free-draining percolation. Water transport through the large vertical extent found in the Loferer Schacht is extremely rapid, with effects of heavy rain at the surface reaching a depth of 600 m within 5 minutes.

The roughly horizontal passages in the Frankfurter system are mostly inactive today, and are thought to have developed under a different hydrological regime at an earlier point in time. The morphology of these corridors suggests their formation under at least partly phreatic conditions. Observations in this section of the cave also indicate that the position of the whole mountain block might have changed since the former's formation.

Based on evaluation of the geological structure and water flow direction within the cave system, it can be presumed that the Loferer Schacht system is drained to the east or northeast, into either the Maria-Kirchental or the Loferer-Hochtal. Direct drainage into the Saalach or Haselbach valleys are also likely. Nevertheless, water composition and temperature at these locations indicates that the water being discharged may not be entirely related to the Loferer Schacht system (Žák 2008).

A number of distinct water lines collect in the Frankfurter system to form a creek, which becomes particularly evident at -530 m, in the "Stolichnaja". In the cascades that follow, dangerous conditions can occur during heavy rainfall. The creek then disappears through blocks on the ground at -580 m, after which it cannot be followed. No resurgence at lower sections of the surveyed cave could be found. From this point onwards, water is still available in small volumes at scattered locations, in particular pits conveying water from above. Of interest is the fact that the current exploration head, at "Minas Tirith", is absolutely dry. Water percolating from the region around the Reifhorn's western face is thought to be responsible for the occurrence of a creek in the southwestern segment of the cave, with water flow correlating directly to rainfall at the surface. The creek collected in the still passable Zick-Zack-meander will later join a second creek, to form the "Schweigender Fluß", which can be followed until its disappearance into an unpassable pit. Again, this waterline has not been found at lower levels (Kube 2012).

Rain events at the surface also cause significant amounts of water to flow through the "Nic Moc Diry" region; this water is appears to become dammed in a siphon at -620 m. This creek has not been found at lower levels.

It is assumed that water collected in the main horizontal passages is flowing in an active level much lower than the currently known fossil passages. It is unclear whether, upon reaching the dolomite layers, this water maintains the general orientation of the upper levels, or flows in a different direction. It is further not known whether water flowing in the active vertical pits actually reaches the horizontal level already surveyed (Kube 2012).

3. Temperature and wind systems

Temperature and wind measurements were carried out with automatic means placed inside the cave for the duration of a year (Fig. 3). The automatic measuring instruments were developed specifically for deployment in the Loferer Schacht and are able to record the temperature at 15 minute intervals. Analysis of data recorded with two instruments, resp. at the depths of -60 m and -585 m, as well as of relevant weather stations at the surface, could show that two distinct wind systems persist in the cave, corresponding to the vertical and horizontal sections, respectively. In particular, the temperature variations as recorded by the two separate instruments are distinct and relate, among others, to the existence of snow covers in the openings feeding the system; the degree of blockage was especially apparent in wind measurement data (Hartig 2006).

Figure 3. Anemometer/Datalogger in Loferer Schacht.

4. Fauna

Bats and insects have been sighted inside the cave, though to this date no living specimens of the former could be spotted. The first bat skeleton was observed in 1995 at a depth of ca. -300 m, probably consisting of an exemplar of *Myotis brandti*. A second specimen was discovered in 2002 at a depth of -285 m, and a further deposit of bones was observed at a depth of 630 m. In the horizontal part of the cave bones and dessicated corpses were found in a several stretches both in the southern and northern branches, as were what appear to be guano deposits. These findings could not, nevertheless, provide any further pointer to a lower entrance to the cave, which is supposed to lie to the southwest. Note that the known entrances at 2,200 m are usually closed until august, and lie rather far from the treeline (Kube 2012).

Insects were observed in areas designated for bivouacs and likely carried by the speleologists or in their supplies. Nevertheless, fly maggots and specimens of *Speleolepta leptogaster* collected in the horizontal section of the cave, specifically in the area designated "Frankenloch", are strong indicators of an entrance in the southwest of this section (Hartig 2008).

5. Current state of exploration

With the systematic surveying of the lowest part of the cave, the number of possible continuation points has reduced from year to year. After several tours in the southwest extreme, known to be the closest to the surface, proved unfruitful, work in this end was abandoned to pursue a possible continuation at a site where copious amounts of wind are registered. This current exploration lead, or "Sekt oder Selters", is located in a branch of high geological interest, where several converging diaclases have created large open volumes and the resulting chaos presents considerable challenges to the interpretation of the cave. Blocks currently prevent further exploration.

6. Related cavities

To date there are no cavities known which could be directly related to the Loferer Schacht system. A notable exception could be the Kreuzhöhle, which is located on the opposite side of the Reifhorn and is accessible through an entrance at 2,175 m. According to survey results, both cavities could be separated by 300 m at their closest point (Kube 2012).

7. Further remarks

The Expedition to Loferer Schacht was the recipient of a European Speleological Federation grant in 2012, within the framework of the Eurospeleo Projects.

Acknowledgments

The authors would like to thank:

- the European Speleological Federation for the support granted in the framework of the Eurospeleo Projects;
- the DAV Sektion Frankfurt am Main, for the long and reliable material support;
- the Landesregierung Salzburger Land, Abteilung Naturschutz;
- the ÖBF, Österreichische Bundesforste AG;
- Ms. K. Filzer and her team at the von-Schmidt-Zabierow-Hütte;
- Mr. F. Ziegler, for letting us borrow the extremely useful CaveLink.

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THE LONGEST LIMESTONE CAVES OF ISRAEL

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Despite Israel's small size and relative aridity, the country has thousands of caves in several rock types, spread out from Mt. Hermon in the north to Eilat in the south. The most common ones are hypogenic karst caves in limestone.

Here we update the list of Israel longest limestone caves, originally published in 1983. The main changes since then result from the discovery of new long caves, as well as the development in caving and survey techniques. For example, the 150 m long southern part of the Abud Cave (western Shomron) was discovered by enlarging a tight squeeze. The newly discovered passages and chambers contained important archeological finds dated to the Chalcolithic and Bronze age. A new survey (by Boaz Langford and Mika Ulman in 2010) extended A'rak Na'sane Cave (eastern Shomron) from 310 to 1,150 m. Such developments led the Cave Research Center to re-survey the long limestone caves of Israel. After two years of intensive survey, it is now possible to present the updated list.

Eight of the ten presently listed caves were unknown to us on 1983. The Judean and Samarian Desert continues to be the leading area in the number of caves. On 1983 only one limestone cave was known to be longer than half a kilometre, while today all 10 caves are longer than half a kilometer.

1. General

Despite Israel's small size, it boasts of thousands of caves, in several types of rocks and spread out from the Gulf of Eilat in the south to Mt. Hermon in the north (Frumkin et al., 1998).

Most common caves are karstic, formed mostly in limestone. In addition, over 100 caves are known in the salt rock of Mt. Sedom diapir (Frumkin 1994). Among these is Malham Cave, over 6 kilometers long, making it the longest cave in Israel and one of the longest salt caves in the world. Other caves in Mt. Sedom, such as Sedom, Dorban and Zchuchit cave are hundreds of meters to kms long.

Here we present the longest limestone caves in Israel, without referring to the salt caves that have and will be referred to separately.

2. The longest caves of Israel

In 1983, several years after the establishment of the Cave Research Center, the list of the longest caves in Israel was presented in "Niqrot Zurim", Israel journal for cave research. The list was updated in 1986 (Frumkin 1986a) and was also discussed in international literature (e.g., Frumkin 2001). Since then, there have been many changes in the list. The main changes result from the discovery of new long caves, as well as the development in the caving techniques in Israel. In particular, new techniques have allowed us to reach remote areas within caves. For example, a new branch was discovered in Tzavoa' Cave in the Kidod hills. Three hours of tight crawl were needed to reach the 150 m long new branch. It contains a series of chambers where a human skull as found, apparently brought by striped hyenas.

Improvements in cave survey techniques, such as the recent use of laser "disto" and digital inclinometer promotes better measurement and higher accuracy.

Pushing the remote parts of A'rak Na'sane Cave (eastern Samaria) has "extended" its length from 310 m, measured by the the Cave Research Center in 1980 (Frumkin 1981) to 1,150 m as measured by Boaz Langford and Mika Ulman in 2010. These developments led the Cave Research Center to fully survey the long limestone caves of Israel. Thirty years after the first list was published and after two years of intensive work, the new list is presented here. Note that ine of the ten longest limestone caves are located in the central range of Israel, and only one is in the Galilee (Yana Cave). Most of the long caves are hypogenic mazes in origin (Frumkin and Fischhendler, 2005; Klimchouk 2007). One (Yana Cave) is a collapsed chamber cave. Another one (Ha'Umah Cave) is a vadose river cave.

3. Description of the caves

Below are details regarding the longest limestone caves of Israel.

3.1. Haritun Cave

The Haritun cave was and still is the longest limestone cave in Israel. A small part of the cave was already surveyed by the PEF (Conder and Kitchener 1883) and also by Strobel (1967). A comprehensive compass and a tape polygon of the cave was measured by Gideon Mann and volunteers of the Society for the Protection of Nature between 1969 and 1971. The Cave Research Center began its research of the Nahal Tekoa caves between 1983 and 1985 (Frumkin 1986B) and re-mapped Haritun Cave (directed by Ahikam Amihai and Shmulik Avidan) the between 2006 and 2008. The new map was based on the polygon of Mann, to which the features of the walls were added. Selected profiles were also added. The cave is within the Late Cretaceous Shivta Formation, Judea Group.The cave is a rectilinear network maze of passages, with occasional chambers. The main direction of most passages is north-south (approximately) and the secondary direction is east-west. The passages developed mostly in one level but in some places there are 2–4 levels. The measured length is 3,450 m and the cave area is 4,600 m^2. The cave is constrained within a relatively limited rectangle, with an area of 30,000 m^2. The cave has 3 entrances close to one another on the western cliff of Nahal Tekoa canyon, 540 m above sea level. No morphogenticic connection was found between the entrances and the canyon: it seems that the canyon breached the cave randomly. The morphology of the cave (e.g., feeders, cupolas, maze) indicates a hypogenic origin.

3.2. Ayalon Cave

Ayalon Cave is an isolated hypogenic cave developed in in late Cretaceous limestone (Bi'na Formation, Judea Group). The entrance of the cave was created by quarrying at the Nesher Quarry in Ramle and was found by Israel Na'aman in a cave exploration conducted by the Cave Research Center in 2006. The cave is 2,700 m long, constrained within a rectangle of 100 × 140 m. The cave is a network maze with two main levels, connected through vertical shafts. The upper level is a complex network of passages characterized by narrow passages with rounded or elliptic cross section. The lower level has wider passages with three large chambers. The largest chamber is on the northwestern side of the lower level, at the lowest point in the cave. This hall extends below the regional watertable, forming a fluctuating body of water. In this body of water, as well as in the dry parts of the cave, seven endemic invertebrate troglobite species were found, within a unique ecosystem (Na'aman 2011).

3.3. Sela' Cave

Sela' Cave (Judean Desert) was discovered in 1991. Archeological excavation revealed finds from the Bar Kockba revolt period, including a coin called Sela' after which the cave was named (Amit and Eshel 1991). Following the cave discovery, 600 m of passages and chambers were mapped by the Cave Research Center. In a recent visit to the cave, we managed to reach a high, hardly accessible "window" that had not been explored before. This window led to a new area in the cave that doubled its length.

Sela' Cave origin is hypogenic, and it formed in late Createaceous limestone of Shivta Formation (Frumkin 1999). The cave has three entrances leading to a network of passages developed along fractures mainly in the northwestern direction. At several locations the passages expand forming four central chambers.

3.4. A'rak Na'sane Cave

A'rak Na'sane Cave is in Wadi Ed-Daliyeh, eastern Shomron. On 1962, bedouins from the Ta'amra tribe looked for archeological items in this cave and nearby caves. Following their initial finds, the American School for the Study of the East organized two excavation seasons, in the course of which the Arak A-Na'sane Cave was initially excavated (Lapp P. W. and Lapp N.L. 1974). On 1980 the Cave Research Center sketched an initial map of the cave whose measured length was then 310 m. On 2010 the cave was re-surveyed and its overall length was found to be 1,150 m. The cave has a large entrance located few m above Wadi Ed-Daliyeh streambed. The cave contains complex sub-horizontal passages with a simple network structure. The main guiding fractures and associated passages trend northwest-southeast. The eastern part of the cave is dominated by a large chamber whose length amounts to a third of the overall length of the cave. It is interesting to note that in the cave's passages and its outer parts, there are regionally common insectivore bats of the species *Rhinopoma hardwickei*, while in the large hall and the inner parts of the cave there are rare bats of the species *Asellia tridens*.

3.5. Kanaim Cave

Kanaim Cave (northern Negev) was found on 1960, during the archeological survey of the Judean Desert. Following a report of Giora Ilani, the cave was examined by the Cave Research Center on 1984. After examining the cave, it was surveyed on several occasions and the mapping was completed on 2003. Its overall length is 846 m.

Table 1. The length of the longest limestone cave in Israel as published in the past and according to new discoveries

The longest limestone caves in Israel – 1983			*The longest limestone caves in Israel – 2012*	
	Name	Overall length	Name	Overall length
1	* Haritun	4,000	Haritun	3,450
2	**A'rak Na'sane	500	Ayalon	2,700
3	Hagay (El-Gai)	500	Sela'	1,200
4	A'lma	400	A'rak Na'sane	1,150
5	Ornit	300	Kanaim	846
6	Haeigrot	270	Makuch	832
7	Bereniki	250	Yana	808
8	Hameraglim	250	***Hauma	800
9	Sarah	200	Yogev	788
10	A'tarot	200	Tzavoa'	700

**This number has been estimated based on schematic measurements according to the old map of the cave.*
***This number is an estimate.*
****The work in the hauma cave is currently continuing. The number stated in the table is the length of the cave as known today.*

The cave entrance is via a small vertical shaft, where the cave was breached by an entrenching wadi. The cave contains a complex series of sub-horizontal passages on one level. The cave passages formed mainly along fractures in the north-south direction. In the southwestern area of the cave calcite speleothem developed under previous wet conditions. In the inner area of the cave there are also gypsum deposits developed on the walls and the ceiling of the cave.

3.6. Makuch Cave

Makuch Cave was discovered in the Binyamin Desert on 1984 during a regional cave survey by the Cave Research Center (Frumkin 1988). Following its discovery, it was artly mapped by Anan Zeidner and Yehuda Miron and its measured length was 520 m. The mapping was complex, mainly due to a large amount of cave ticks. In 2006 Ahikam Amihai and Matan Avital returned to the cave, measured additional 300 m and located a second entrance leading to a new northern area. We completed the mapping of the cave on 2011, with an overall length of 832 m.

The cave has two entrances in the Wadi Mackuh canyon escarpment. The cave has a complex network of passages. The passages are usually inclined according to the local bedding dip.

3.7. Yana Cave

Locaed at the edge of Ramat Shtula (Western Galilee), Yana Cave was discovered in the 1960s (?) by a team of the Society for the Protection of Nature, who explored only the entrance hall. In 2006 the cave was surveyed again by the Cave Research Center, led by Vladimir Boslov. The full mapping of the cave showed a length of 808 m and a depth of 62 m. The Yana cave developed by phreatic dissolution and collapse, in late Cenomanian limestone (Sakhnin Formation). The cave has a major phreatic chamber with dditionallower-levels voids. Following regional uplift, vadose processes began, including speleothem deposition, such as stalagmites and stalactites. Stoping of the main chamber formed a dome-like structure. Its distal lower parts lead currently to a complex series of extended rooms and passages, on lower levels.

3.8. Hauma Cave

Hauma Cave is a vadose stream cave in west Jerusalem. The cave was discovered in 2010 during the excavation of a shaft in a project of the Israel railay, 75 m below surface. Since its discovery, 800 m were mapped by the Cave Research Center, of which 627 m are in the central channel, and the rest are domepit-like vertical shafts. The mapping of Hauma Cave is ongoing. Hauma Cave is an actively flowing vadose canyon, following the regional dip to the southeast. The canyon formed in late Cretaceous limestone and chalk (Kefar Shaul Formation). The flow of water fluctuates seasonally. Within the meandering cave one waterfall shaft and several vadose domepit shafts were encountered. The surveyed part ends at a sump.

3.9. Yogev Cave

Yogev Cave (eastern Shomron) was found in Wadi Ed-Daliyeh canyon on 1994 by Yogev Karasenty. Mapped by the Cave Research Center, its overall length is 788 m. The cave is hypogenic, formed in limestone of the late Cretaceous Bina Formation. The small cave entrance is hidden at the southern escarpment of the Wadi Ed-Daliyeh canyon. The cave consists of inclined two dimensional network of passages and halls. The cave developed along fracrures, and the passages are inclined, following the regional dip. Few active speleothems were observed, mainly cave corals and flowstone.

3.10. Tzavoa' Cave

Tzavoa' Cave, at the upper Zohar hills (northern Negev) was discovered on 1977 by Giora Ilani who found an impressive concentration of animal bones in the cave, brought by striped hyenas. The activity of large mammals in the cave attracted cave ticks throughout the cave, even in areas difficult to access. The cave was mapped by the Cave Research Center on 2011 with a length of 700 m.

The cave is hypogenic, formed in limestone of the late Cretaceous Shivra Formation. The cave has two entrances at the bottom of a low cliff, close to a small wadi bed. The cave comprises a maze of chambers and passages developed into a complex structure, mostly along northwest-southeast trending fractures.

In the southern part of the cave is a large concentration of calcite speleothems including stalagmites, stalactites, columns, pool deposits and flowstones. They formed mainly during the wetter climate of last glacial period, indicated by U-Th dates (Vaks et al., 2006).

4. Summary

Nine of the ten caves in the list are isolated caves (*sensu* Frumkin and Fischhendler, 2005). Eight of the ten caves were unknown to us on 1983. These caves replaced caves from the original list that are now ranked lower in length. The Judea and Samaria Desert (including the Miditerranean-desert border zone) remains the area with the most large caves. For hydrogeologic spects of this distribution see Frumkin and Fischhendler (2005), Frumkin (1991). In 1983 only one limestone cave longer than half a kilometer was known in Israel. Today all ten largest caves are longer than half a kilometer. The lised caves define the southernmost long limestone caves close to the edge of the Sahao-Arabian desert belt in the Levant.

Acknowledgments

We thank Vladimir Boslov, Mika Ulman, Nevo Fishbein, Shmulik Avidan, Israel Na'aman, Ahikam Amihai, Dan Shtriech and all volunteers who assisted in surveying the caves. We also thank Yigal Sela', Eitan Alumi, Dan Perry, Yoav Sagi and Mordechai Avrahami for the initial data that led us to the Yana cave. Finally, we thank Michal Kidron and Miri Shmida from the Center for Computational Geography at the Hebrew University in Jerusalem for final drowing of the maps.

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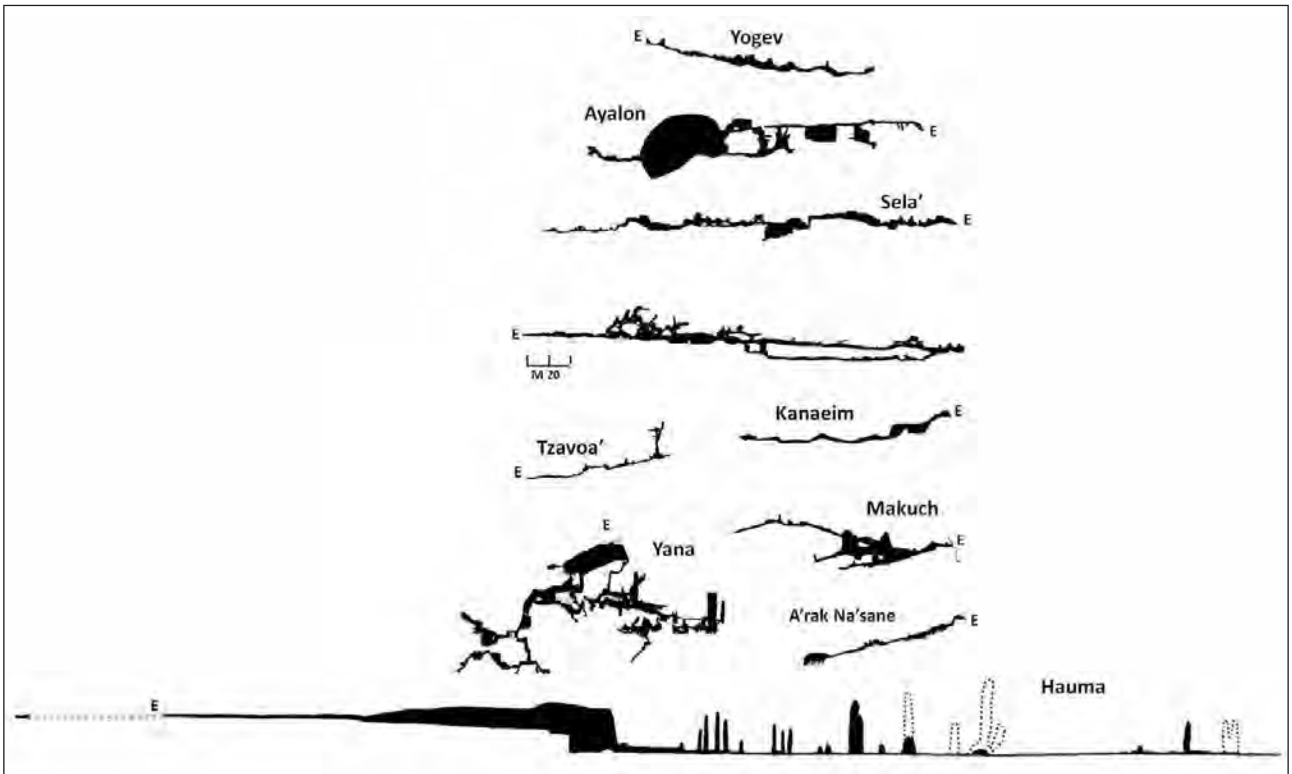

Figure 2. Typical profiles of the largest limestone caves of Israel.

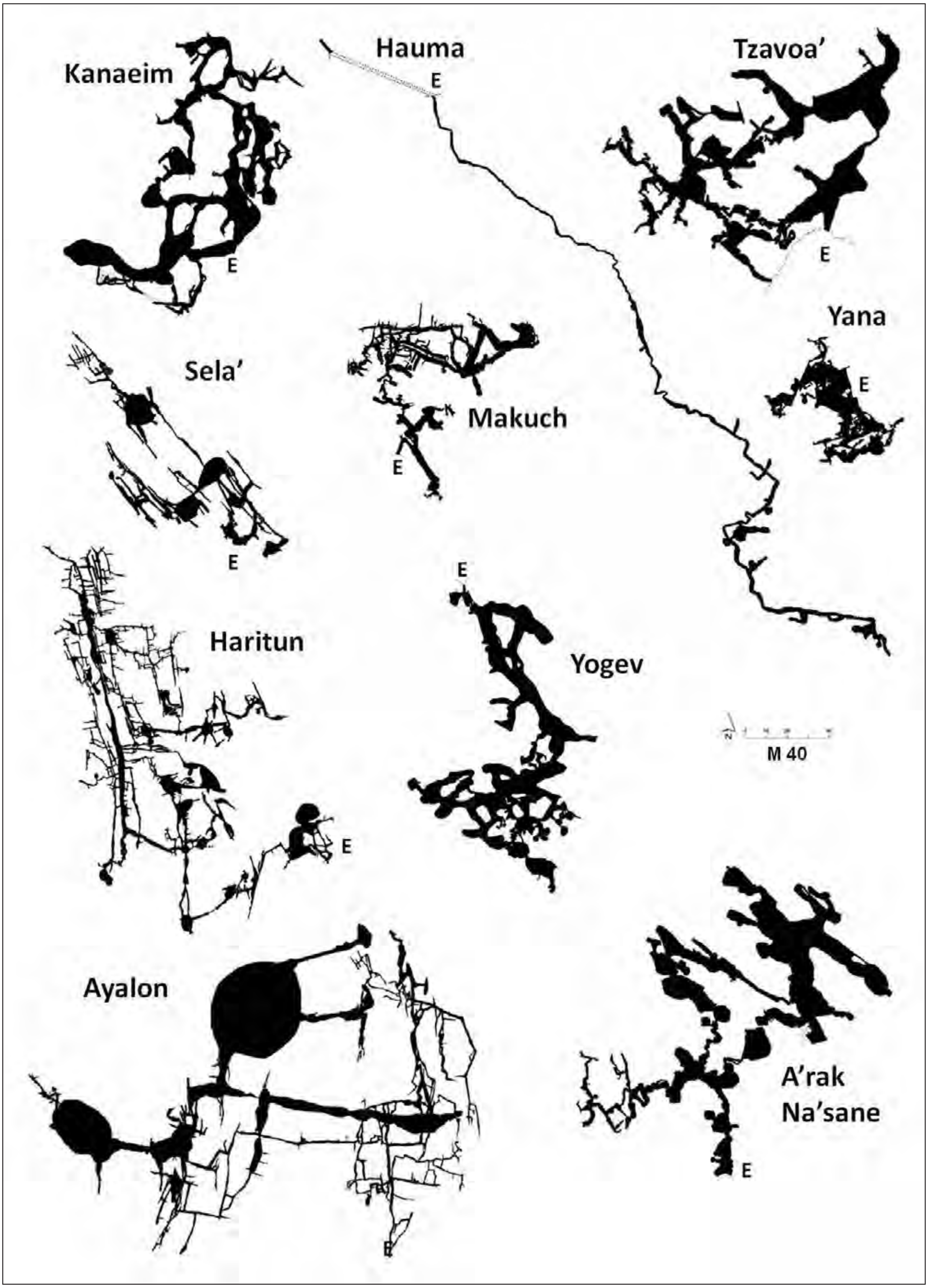

Figure 1. Maps of the largest limestone caves of Israel. Levels are not indicated.

A GENERAL ASSESSMENT OF THE GREAT CAVES AND THE KARST OF SOUTHEAST ASIA

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Karst is a widespread and important phenomenon in Southeast Asia covering about 215,000 km^2 of the mainland part of Southeast Asia and approximately 230,000 km^2 of the surface of the Southeast Asian islands. These karsts belong to the most varied and spectacular on Earth. Information on cave research however is very scattered and often inaccessible. This article is an excerpt of the "Atlas of the Great Caves and the Karst of Southeast Asia" (Laumanns et al. 2010) (www.speleo-berlin.de).

1. Introduction

In 2010 Southeast Asia had the 10th longest cave in the world (*Clearwater System*, Malaysia) at 175,664 m, the largest cave passage on Earth (*Hang Son Doong*, Vietnam) with a 4.5 km long passage of 100 m in diameter, at places even 200 × 150 m, and the largest known underground chamber (Sarawak Chamber in *Lubang Nasib Bagus*, Malaysia, 12,000,000 m^3).

Although our knowledge on the karst and caves of Southeast Asia has witnessed a stunning increase since about 1970, there is still a severe lack of credible speleometric data, which makes it evidently clear that much work remains to be done on further exploration as well as on confirming doubtful data. No attempt has been made so far to compile and assess the complete portfolio of Southeast Asian karst and cave occurrences. Consequently, the authors of this article have compiled speleological information on Southeast Asia during a two-year long exercise, which has resulted in the release of a very detailed "Atlas of the Great Caves and the Karst of Southeast Asia" (Laumanns et al. 2010). If not indicated otherwise all statements presented below were taken from this atlas.

Most limestone deposition on the mainland of Southeast Asia has taken place in the Upper Paleozoic (with the Permian and Carboniferous being the most important). Some Jurassic, Liassic (Thailand, Laos), Ordovician (Thailand, Laos) and even Cambrian (Laos, Vietnam) limestone occurs, too.

The Indosinian orogeny, which has affected most of mainland Southeast Asia, occurred in the Middle Triassic (about 230 mya) resulting in a general uplift and a subsequent erosion episode, including karstification (Indosinian karstification). A second phase of regional uplift began in the Palaeocene about 65 mya, mainly caused by the Himalayan orogeny and the opening of the South China Sea. This period represents the second major phase of karstification as the carbonate deposits all over mainland Southeast Asia became exposed to weathering (Cenozoic karstfication). The long-lasting uplift caused a relative deepening of the base level and has led to extensive planation surfaces, large and deep poljes, tower karst as well as fengcong karst. Due to tectonic subsidence several coastal karst areas have been inundated by the sea, e.g., the islands of the Andaman Sea, the Ang Thong Islands in the Gulf of Thailand, and Ha Long Bay in Vietnam.

The Southeast Asian islands have a complex tectonic setting due to interactions between the Philippines, Pacific, Indian-Australian and Eurasian plates. The area can be distinguished into an older, stable region comprising the Asian mainland, the Proto-Indosinia block and Borneo, which abuts a younger, very unstable region affected by neotectonism, abundant earthquakes and volcanism.

There is no extensive karst known in the small state of Brunei Darussalam as well as in Singapore.

2. Cambodia

Cambodia's karst areas are mainly located in the south around Kampong Trach and Kampot as well as in the northwest around Battambang. A possible and most likely promising third karst area north of Stung Treng has not yet been investigated. In both areas of southern Cambodia and near Battambang, the partly dolomitic limestone of Upper Permian age appears as isolated hills and mountain massifs that overlook the flat alluvial plain. These hills have elevations of up to a few hundred metres and are called "phnom" in Cambodia.

Our knowledge of Cambodian caves is mainly based on a German expedition to Kampot/Kampong Trach in 1995/96 and a German-British project, which was carried out in 2008 in the Battambang area.

The 1995/96 project yielded 37 caves with a total of 11.6 km of passages, including the currently longest cave of Cambodia (*Roung Dei Ho-Roung Thom Ken* at 1,806 m). The 2008 project yielded 65 registered caves, 55 of which were visited and 42 were mapped according to international standards. A total of 4,239 metres of cave passages was surveyed in 2008.

Generally speaking, Cambodia has only small karst areas and thus a limited speleological potential. However, the known caves are comparatively well documented and published.

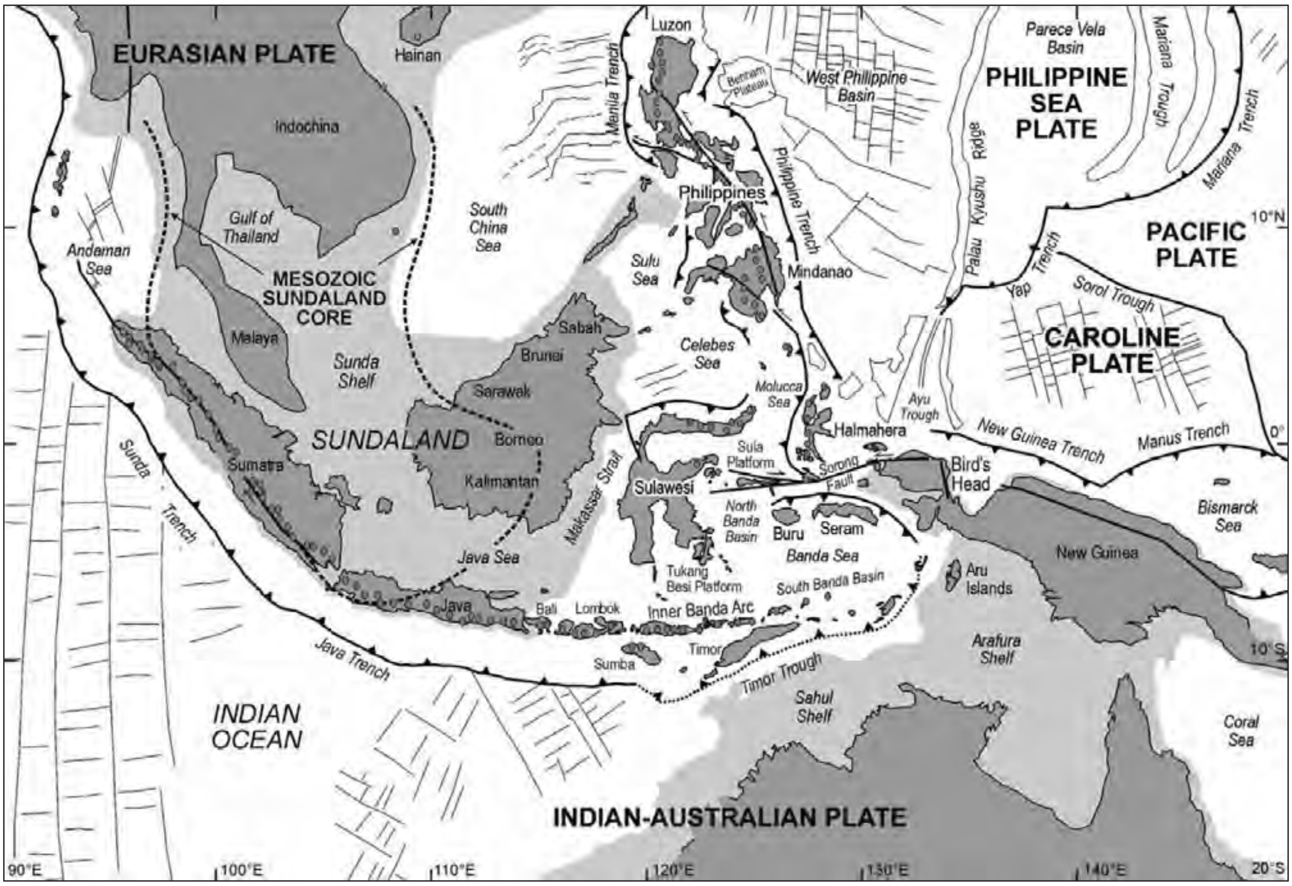

Figure 1. Overview map of Southeast Asia and its geotectonic context (according to Hall 2002, completed).

3. Indonesia

The landscape of Indonesia developed in the Pleistocene during which Indonesia formed a land bridge between the Southeast Asian mainland and Australia. The islands were formed by a rise of the sea level after the last glacial period. This makes the southern Indonesian islands an interesting area to study hominid migration to Australia.

The southern arc of the Indonesian islands was formed by a subduction of the eastern plate of the Indian Ocean and Australian plate under the Sunda shelf, which represents the southeasternmost edge of the Eurasian plate. This subduction zone is associated with a strong Cenozic volcanism. The northeast peninsula of Sulawesi (Celebes) and the Halmahera islands also have strong volcanism caused by a collision zone of the Eurasian Plate with the Philippine Mobile Belt. Only the Borneo block, north-central Sumatra and Timor as well as Irian Jaya, and the Buru and Seram islands have remained stable and expose older rocks. The Sunda and Banda volcanic arcs form the base of a discontinuous karst which consists of Mesozoic and Tertiary carbonates. The stratigraphy of the western part of Indonesia is relatively young, ranging in age from Paleogene to Quarternary. Eastern Indonesia has older stratigraphy compared to the western part. Stratigraphy ranges from Triassic to Tertiary.

Early karst exploration on the Indonesian islands was done by the Dutch. The easily accessible tropical karst of Gunung Sewu (Java) has attracted many scientists since 1910. The same applies to the Maros karst in SW Sulawesi. Many caves on Bali and Sulawesi were described by Kusch between 1979–1982. In 1979 the "Indonesian Speleo Club (Specavina)" was formed by Robby Ko, who established the "Indonesian Federation of Speleology (FINSPAC)" in 1983.

Expedition-style speleological exploration of Indonesia was started on Sumatra in 1977 by a Spanish team (GESM Barcelona). Much knowledge on the karst of Indonesia was gathered by French teams, notably the "Association Pyrenéenne de Spéléologie (APS)", who started exploration in the Maros karst of Sulawesi in 1985 and returned to Indonesia almost on an annual basis until 2002. They released excellent reports with many detailed cave surveys and in-depth biospeleological data. Furthermore, since 1982, many British, Australian, Italian, French, Belgian, Dutch and American teams explored Indonesian karst and caves.

The longest caves known in Indonesia are *Luwang Jaran* (Java, Gunung Sewu) at 18,200 m, *Gua Salukkan Kallang* (Sulawesi Selatan, Maros, Kappang) at 12,263 m, *Gua Tanette* (Sulawesi Selatan, Maros, Kappang) at 9,692 m, and *Gua Barat-Gua Purat* (Java, Karangbolong) at 9,600 m. Ninety-four caves in Indonesia currently have a length equal of or exceeding 1 km. The deepest cave known is *Goa Hatu Saka* (Seram island), which is -388 m deep. Seventy-five Indonesian caves have a depth of 100 m or more.

Speleological documentation of Indonesian caves is comparatively good. Most of the foreign expeditions have produced comprehensive reports. However, publications are numerous and scattered. Important reports are only available through specialised libraries or the explorers. Many reports are out of print.

4. Laos

The topography over much of Laos is very rugged. The tectonic movements have strongly affected the limestone sequences. The main tectonic fractures run from N to S and from NE to SW. The carbonates are heavily deformed, often showing a steep dip, and are partly recrystallised and metamorphized.

Most limestone deposition has taken place in the Upper Paleozoic (with the Permian and Carboniferous being the most important). Some Jurassic, Liassic, Devonian, Ordovician and even Cambrian limestone occurs, too. The carbonates are generally overlain by reddish continental formations from Trias to Cretaceous (sandstone, clay, clayey arenite) which have buried a paleokarst. In some cases the palaeokarst rejuvenated due to new exposure linked to strong Cenozoic erosion. The Permian limestone is discontinuously exposed between the Nam Ou River and the Myanmar border. Near Luang Prabang, the Permian limestone is extensively exposed and extends to Vang Vieng further south. In the Plain of Jars, in the Xien Khouang and the Ban Ban areas limestone of Permian age is exposed. In the Bolikhamsay and Khammouane provinces Permian limestone is widely exposed and forms the well-known Khammouane karst. Some Jurassic limestone layers have been identified in the area between Paklay and Luang Prabang in northern Laos. Ordovician limestone occurs in the Luang Namtha province.

Foreign cave exploration in Laos began as early as 1867 during the French colonial time. Since the retreat of the French Laos was closed to foreigners. Almost immediately after the re-opening in 1990 the country again attracted foreign speleologists. Claude Mouret, was the first to organise an expedition in 1991, which was focused on the Khammouane karst. In 2010 a total of over 170 km of cave passages were explored here, including outstanding caves like *Tham Nam Hin Boun* (over 7.5 km long), *Tham Nam Non*, *Tham Houay Sai-Tham Koun Dôn* (over 27,000 m), and *Tham Thôn-Tham Houey Sam Boun* (13,309 m). Many of these caves are through caves and contain long massive underground river passages.

In 2010, a French-Romanian diving team was able to link *Tham Nam Non* to its sinkhole cave *Tham Song Dang*, creating the longest cave in Laos at over 30 km.

Italian and Canadian/US cavers also occasionally contributed to our knowledge of Laos caves.

The karsts of Vang Vieng and Kasi area half-way between Vientiane and Luang Prabang in the southern part of northern Laos were first visited by British cavers before French speleologists took over in 1998 and conducted a row of successful expeditions. Forty four caves were explored up till 2003 with the longest cave currently known being *Tham Hong Yé* (7,715 m).

In 2000 a Dutch group conducted an expedition to Luang Prabang province, yielding many discoveries. The Dutch were followed by German cavers who founded the “Northern Lao-European Cave Project” and conducted annual international expeditions to northern Laos. Currently, the longest cave in northern Laos is the *Tham Chom Ong System* (Oudomxay) at 17,150 m of length. Over 100 km of passages from 254 caves are currently known from northern Laos.

Only the expeditions that went to northern Laos have fully published all their results according to international standards. A comprehensive publication on the Khammouane karst is lacking. Consequently, the stand of cave documentation in Laos is currently unsatisfactory.

5. Malaysia

Malaysia is divided into the Peninsular or West Malaysia, and East Malaysia on the island of Borneo.

The limestones vary in age throughout the country. In the peninsula, they range from Ordovician through the Carboniferous and Permian to the Upper Triassic. Most occur within the Permian. Whereas in East Malaysia the rocks are much younger, from the Miocene period. In west Sarawak the limestones are of Permian, Jurassic and Cretaceous age, and mainly of Tertiary age in east Sarawak and Sabah.

There are roughly 510 limestone outcrops in Peninsular Malaysia, most of which are not very extensive. *Gua Tempurung* in Perak is the peninsula’s longest cave at 4.8 km. The Gunung Lanno karst was the subject of an Austrian/English/German expedition in 2001 with *Gua Puncak Lanno* (1,584 m) being the longest cave surveyed. Peninsular Malaysia cannot boast of any speleological world records unlike Mulu in Sarawak. Sarawak Chamber in *Lubang Nasib Bagus* is the world’s largest underground chamber. *Clearwater Cave* at 175,665 m is the longest in Southeast Asia, and currently 10th longest in the world. Other long caves from Mulu are the *Benarat-Moon-Cobweb System* (50,669 m), the *Terikan System* (32,573 m) and the *Bridge-Cloud-Cobra System* (15,506 m), which is also the deepest cave of Malaysia with a difference of level of 473 m. All these caves are situated in the Gunung Mulu National Park and were explored since 1977/78 by British expeditions. The current surveyed length of caves in Mulu is 345 km. Gunung Buda adjoins Mulu and has around 50 caves, mostly explored by American expeditions mainly in 1995 and 1997, and 2000. The total cave survey is 83.6 km. Longest caves are the *Green Cathedral Cave System* (26,382 m long), and Snail Shell Cave (11,636 m).

Except of Mulu/Gunung Buda there was no systematic cave exploration so far in northern Borneo, neither in Sabah nor in the Bau area.

Overall, speleological exploration in Malaysia has to be regarded as at the top-end of international standards with regard to the caves of the Mulu and Buda National Parks. This is definitely not the case for the karst areas in Sarawak, Sabah and on Peninsular Malaysia.

6. Myanmar

The main limestone areas are the Shan Plateau in east Myanmar and the southern strip adjoining the Andaman coast. The Shan Plateau is a complex series of mountain chains and plateaus rising abruptly from the central Myanmar plain. The limestone has a thickness of more than

2,000 m in places. It is mostly from the Carboniferous to Lower Triassic period, with some earlier Ordovician elements. In the north it is more brecciated, whereas in the south it is more compact and has cavernous development. Further east, outcrops of Permian limestones are known. The Indosinian orogeny in the Late Triassic and the Cenozoic Himalaya orogeny are responsible for a strong uplift and associated erosion causing strong incision of the rivers. Late right-lateral north-south trending normal faults affect the plateau. The Plateau is dissected by a series of deep gorges such as Gokteik, and those of the Thanlwin (Salween) River and its tributaries towards the east. The most famous cave is *Pindaya Cave*, which contains 8,000 Buddha statues. Further north, there are scattered outcrops of the marbles and limestones of the Mogok Series. In the Kayah State (south of Shan State) are many cave systems, especially around Loikaw and Demawso. In the north of Myanmar, there are outcrops of limestone of Permo-Carboniferous age in the Mytkyina District of Kachin State. Northwest of Yangon is the Nay Bu Taung area of limestone in the Rakhine State. There are some caves. Other small areas of limestone include the Bhamo region in Kachin State, Gangaw region of Magway State. There are Tertiary limestones in Ayeyarwady Division. In the Hpa An (Kayin State) and Mawlamyine (Mon State) areas the strata is Upper Carboniferous and Permian, overlain by reef limestones from the Triassic period. The Moulmein Limestones are highly jointed, sometimes in several directions. The Permian Moulmein Limestone is a continuation of the limestone-dolomite sequence extending from the Shan State south through Kayah and Kayin States into Tanintharyi and is similar to the Phuket Group and the Ratburi limestone of peninsular Thailand. The upper part of this limestone has been considered Permo-Carboniferous in age. Most of the hills are isolated towers, some more than 400 m high, running NW-SE. There is also ridge karst. There is an excess of 40 major caves in 23 groups in the Mawlamyine area. Outcrops of Permian Limestone also occur in the Tenasserim Range but little is known about these deposits. The Andaman coastal area covers the southern part of Mon and Kayin States along with Tanintharyi Division and includes the more than 900 islands of the Mergui Archipelago. There are isolated outcrops of coarsely crystalline thick limestone. These islands have hongs, some are accessible at low tide.

Speleological exploration in Myanmar started as early as 1826 in the areas of Hpa An and Mawlamyine. Since independence in 1948 and the subsequent military rule, Myanmar did not welcome foreigners. Consequently, little speleological work has been done. In 1998 a French group from Société Spéléo de l'Ariège-Pays d'Olmes went to the Shan State. They surveyed some of the longest cave known in Myanmar (*Mondowa Guh*, 1,170 m long, and *Leikte Guh*, 960 m), and published a valuable list of the 32 caves.

The Italian "La Venta" group went twice to the Shan Plateau area in 2004 and 2005. In total the Italians registered 30 caves and mapped 4.2 km of passages.

In 2009 the "Northern Lao-European Cave Project" explored caves in the Hpa An and Mawlamyine areas in the southern Kayin and Mon states. They visited 14 caves and surveyed 12 of them, yielding 3.8 km in 5 days. The longest cave surveyed was *Saddan Gu* (800 m). This expedition prepared the contacts also used by a 2010 British expedition to the Taunggyi/Hopong area (Shan State). The expedition e.g., surveyed *Htam Sam*, a large cave near Hopong. Since then annual exploration projects have been conducted by the "Myanmar Cave Documentation Project" comprising an international team led by J.Dreybrodt and a British group. Publication of these recent results is in progress in the "Berliner höhlenkundliche Berichte", www.speleo-berlin.de).

Everything available on the speleology of Myanmar was compiled in a comprehensive monographic publication (Laumanns 2010). Consequently, the access to speleological data on Myanmar can be regarded as reasonably good.

7. Philippines

About 17 tectonic micro-plates form the so-called Philippine Mobile Belt of the Philippine archipelago, which is a complex and highly active collision zone where the Eurasian Plate is steeply subducting under the Philippine Mobile Belt. Consequently, the archipelago is a tectonically highly active and rapidly deforming region, characterized by strike-slip faulting and multiple volcanic arcs.

Relatively young karst areas, ranging from Cretaceous to Tertiary in age, with the Miocene carbonates predominant, are numerous covering about 10 % of the land surface of the country, but only some karst areas on Samar, Mindanao, Cebu and Bohol exceed 100 km^2. Most of the carbonates are scattered in the central ridges orientated north-south (Mindanao and Luzon) or NE-SW (Calamian islands and Palawan).

Many foreign cavers who have broadened our knowledge of the Philippine caves co-operated with local mountaineers and outdoor clubs. The year 2001 saw the Philippine Caving Society founded.

Exploration of the Philippine karst started with two excursions in 1820 and 1830 when the Frenchman Paul Proust de la Gironière and Hamilton Lindsay from Great Britain visited San Mateo Cave, which is now known as *Montalban Cave*.

Systematic speleological explorations began in 1979–1980 by French cavers in the Sagada karst (Luzon). In 1980–1993 French speleologist Claude Mouret explored caves on Luzon, Mindoro, Leyte, Samar, Bohol and Cebu islands but later focused on Luzon also accommodating Italian cavers on his expeditions. This was followed by Japanese speleologists in 1982 and 1983 (Samar and Cebu). Since then, many other expeditions targeted karst areas on the Philippine islands, e.g., British, Spanish, Dutch/Belgian, Japanese, Slovenian, and German. The Italian "La Venta" group focused on Palawan where they extended the longest cave of the Philippines, *Saint Paul Cave*, also called Puerto Princesa Subterranean River, to its 2012 length of 32,000 m. In the same area "La Venta" also surveyed the currently deepest cave of the Philippines, *Nagbituka 1* (-270 m). Later French expeditions focused on Samar island, where they surveyed *Lungib Can-Yawa* (11,700 m long), the currently 3rd longest cave of the Philippines.

Generally speaking, the speleological literature on the Philippines is incomplete and difficult to access because of the language of the publications. Some important results were not published at all. Thus, the Philippines belong to the SE Asian countries where improvement with regard to cave data is expected.

8. Thailand

Karst covers 18 % of Thailands surface. On the western edge of the Khorat Plateau (northeast Thailand) there is tower karst in Loei and Nong Bua Lamphu and some areas of cockpit karst in Khon Kaen and Chaiyaphum. There is some sandstone pseudokarst, too. Tower karst and isolated limestone hills can be found in Sukhothai, Phetchabun, Uthai Thani, Nakhon Sawan, Lopburi and Saraburi. The longest known cave in Thailand is located at the edge of the plain in Phitsanulok (*Tham Phra Wang Daeng*, 13,844 m long).

Karst is scattered along the length of the Thai peninsula from Phetchaburi in the north to Yala on the Malaysian border. There are areas of mountain karst and some long stream caves in Surat Thani, Phang Nga, Nakhon Si Thammarat and Phatthalung. However, this region is known for its spectacular tower karst, including karst islands (e.g., Phang Nga bay).

The Thai limestones are a wide variety of ages from Ordovician through to Middle Jurassic. The youngest limestones found are of Middle-Lower Jurassic age. They are distributed down the western side of the country and have been found locally in Mae Hong Son and Kanchanaburi while in the Mae Sot and Umphang areas of Tak they are more massive and form large hills. Near Umphang some large stream caves have been found in the Jurassic limestone. Triassic limestone is known in many areas from the peninsula to northern and eastern Thailand. Triassic limestones have been identified from Phattalung, Phetchabun, Uthai Thani and in Nan. The most widespread limestone is Permian. Lower and Middle Permian limetones are widely distributed. Permian limestones have been confirmed from Loei and Khon Kaen, Phetchabun, Lampang, Saraburi and Nakhon Ratchasima, Mae Hong Son and Surat. Carboniferous limestones are less widespread. They have been found in eastern Thailand, central Thailand near Noen Maprang, Phitsanulok and Chon Daen, Phetchabun, in Loei, Mae Hong Son, Chiang Mai, Kanchanaburi and the southern part of Peninsular Thailand. Limestones from the Devonian are less important, but are widespread being found in Loei, in western Thailand from Chiang Mai to Satun, from the Mae Ping National Park, Lamphun and in the Thong Pha Phum National Park, Kanchanaburi. The oldest limestones found in Thailand are Ordovician. These limestones are widespread in the western part of the country from Mae Hong Son down to the Malay border.

Between 1973 and 1978 the Austrian caver Heinrich Kusch published reports with descriptions, some surveys and a list of 94 caves. The first expedition-like speleological project was carried out by Catalan cavers in 1978 who located 34 caves in 12 provinces. At the start of the 1980s only seven caves were known to be over 500 m long, and no known caves were deeper than 100 m. By 1990 there were 22 caves over 1 km in length and 13 deeper than 100 m. This intense phase of foreign expeditions began in 1983 with a series of Australian expeditions as well as French projects carried out by the "Association Pyréenné de Spéléologie (APS)". Many American, Polish, and French groups also visited Thailand. The first British expedition was carried out in 1988 and together with Australian projects most of the long and deep caves we know today from Thailand were explored by Anglophone cavers: *Tham Phra Wang Daeng*, *Tham Mae Lana* (12,720 m), *Tham Yai Nam Nao* (10,442 m), *Tham Nam Lang* (8,550 m), and *Tham Takobi* (7,346 m). The deepest cave in Thailand was only recently explored by a British team to -367 m of depth (*Tham Pha Phueng*). Near Krabi, the Vauclusian spring of *Tham Sra Kaeo* was dived to a depth of -240 m, representing the 2nd deepest cave of Thailand. The presence of Dean Smart in a professional position in Thailand triggered a very productive phase of cave exploration. More recently, Martin Ellis from the UK moved to Thailand and assiduously created an incredible website on Thai caves with all available cave surveys, and also published a stunning cave catalogue in a series of publications including over 3,700 caves. Although Thailand still awaits the foundation of a national speleological organisation the country is definitely the most well-documented in Southeast Asia with regard to its cave-related data.

9. Timor Leste (East Timor)

The oldest limestones in East Timor date to the Permian, which represents the oldest sedimentary rocks known so far from Timor, mainly consisting of shale, siltstone, sandstone and locally, limestone and marl. The Cribas Limestone has a thickness of about 500 metres. Other limestones are from the Triassic through to the Tertiary. The Post-Pliocene Baucau Limestone consists of massive white coral-reef limestone well developed around Baucau town. A continuous outcrop occurs along the north coast. In the southern foothills, the Baucau Limestone also crops out in scattered hills. The limestone occurs as coral-reef, calcarenite and a greywacke-pebbly sandstone facies.

Caves of East Timor have not been well documented, most of the work having been done by archaeologists, e.g., from the Australian National University, e.g., *Lene Hara Cave* near Tutuala and *Jerimalai* rock shelter on the eastern tip of the island.

10. Vietnam

Carbonate rocks cover almost 20 % of the Vietnamese territory. Most carbonates crop out in the mountainous parts of northern Vietnam, where the deepest cave known is situated (*Cong Nuoc*, -600 m), currently also the deepest cave of SE Asia. The largest continuous carbonate zone stretches over 300 km in north-west Vietnam from the Chinese border at Phong to the coastline of Ha Trung including Son La. In the central part of the country the famous karst of Phong Nha-Ke Bang is located. The 1,100 m thick carbonate sequence is mainly middle Carboniferous to lower Permian. Devonian and some

Visean carbonates are also present. The longest caves currently known in Vietnam occur in the Phong Nha karst. Most caves are horizontal and drain huge underground streams.

The spectacular drowned Permian karst plain of Ha Long Bay at the Gulf of Tonkin (Bac Bo Gulf) is probably the most renowned Vietnamese karst area. The Carboniferous and Permian limestones reach from Haiphong to the Chinese border. The ensemble of rocky islands forms one of the most beautiful and famous coastlines on Earth.

A small tower karst area of isolated hills formed by Permian limestone can be found in the area of Ha Tien-Hon Chong in the extreme southwest of Vietnam at the coast and the border with Cambodia. A remnant tower karst consisting of five limestone mountains ("Marble Mountains") also occurs 8 km southeast of Da Nang.

Carbonates were deposited over the widest possible time span, from Archean to recent reefs. Thin-bedded, impure Precambrian and early Paleozoic limestone is less suited for karstification contrary to the very pure Permo-Carboniferous and Triassic limestone, which reach a considerable thickness of 1,000–2,000 m. Neotectonic uplift and subsequent erosion has exposed these limestones over several thousands of metres, allowing rapid development of vertical karst features.

Similar to Laos, early cave exploration took place during the French colonial period. Foreign speleological exploration began in 1990–1993 with two British-Vietnamese expeditions to the Phong Nha, Quang Binh and Ke Bang Massif in central Vietnam. In later years the British explorers extended their working area also to northern Vietnam. The team maintains an excellent website with reports on their expeditions (www.vietnamcaves.com) and a list of the longest/deepest caves of Vietnam. The first Belgian-Vietnamese project to Son La (northern Vietnam) took place in 1993 and also extended in later years to many other karst areas in northern Vietnam. Both projects are still ongoing and the most continuous sources of speleological data from the country. Many other occasional expeditions visited Vietnam, notably Franco-Italian, French, Italian, Polish, Bulgarian, and Australian expeditions, as well recent German-British projects to Ha Tien and Da Nang in south Vietnam.

In 2009 an enormously large 4.5 km long cave passage of 100 m in diameter (at places even 200 × 150 m) was found by the British explorers in *Hang Son Doong*, exceeding the dimensions of the reportedly largest cave passage on Earth known so far from Deer Cave (Mulu, Sarawak, Malaysia). The longest caves of Vietnam are: *Hang Khe Rhy* (Phong Nha-Ke Bang, 18,902 m long), *Hang Vom* (Phong Nha-Ke Bang, 15,310 m), *Hang Phong Nha* (8,821 m), and *Hang Co Ban* (~8,500 m).

Speleological documentation on Vietnam is well developed, although published data are often only available from private expedition reports and the www.

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THE LONGEST CAVE IN HUNGARY

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Within the city boundaries of Budapest, on the Buda side of the Danube, in the side of the 300 m high hills, quarries were opened in the 19th century in order to extract the 40-million-year-old shallow sea limestone. In 1904, several hypogene caves opened during the quarrying works, such as the entrances to the Pál-völgyi, Harcsaszájú and Hideglyuk caves. The last two only led into caves 100–300 m long, but soon the Pál-völgyi was explored to a length of 1 km. In the 1930s, in the quarry across the road, the first couple of hundred metres of the Mátyás-hegyi cave were discovered. In 1948, most of the inner passages of the cave were found, so the Mátyás-hegyi cae became 2.5 km long (today it has reached a length of 5 km). In 1980, continuation of the Pál-völgyi cave was found, and thanks to constant exploratory work, its length has reached 14 km… The exploration of the Hideglyuk and the Harcsaszájú caves was resumed in 2006, with findings in the former in 2009 and new passages in the latter in 2008 – these caves are now 4 km long each. During the year 2010 two connections were made between these two caves, and in 2011, the connection between the Pál-völgyi, the Mátyás-hegyi and the Hideglyuk-Harcsaszájú caves was found, making this c. 30 km long cave system Hungary's longest. The previous longest cave was the Baradla-Domica system of Aggtelek with 26 km, which is an active cave and a UNESCO World Heritage site.

1. Introduction

We've known for nearly a hundred years, since the time of Ottokár Kadic, that Budapest is the capital of caves, even though in Kadic's time, there were far less caves underneath the city were known than today. Back then only a couple of caves had been explored, totalling a few kilometres in length. Today we can enter eight caves, each of which are longer than 2 km, all underneath the city, and we have records of about 200 additional shorter caves. And, since December 2011, the longest cave in Hungary can be found underneath Budapest.

How did we get here? If I had to summarise the answer in one sentence: through hard work spanning several centuries. The best example for this is the Pál-völgyi (Pál-valley) system, which reached a length of 29 km last year. In contrast, our second-longest cave, the Baradla-system near Aggtelek-Jósvafő, which is a UNESCO World Heritage site, is only c. 26 km long including a section underneath Slovakia.

2. The beginnings of exploring: the Pál-völgyi cave

The first sections of the Pál-völgyi system were explored in the first years of the 20th century. Back then, protection of natural heritage was nearly non-existent, and no one worried about extracting parts of a cave system together with the limestone in the quarry in the upper Pál-valley… As the quarry works dug deeper, more and more caverns were found. These were the ends of passages of a connected system. Some of these passages weren't small either: the Harcsaszájú-cave (whose entrance is the highest up) was soon discovered to be at least 320 metres long, and the Hideglyuk-cave was explored to the 170 metres mark. A further smaller caves were also registered.

In 1904, the entrance of the Pál-völgyi cave was discovered here, in the Holzspach-quarry. The Pál-völgyi is the longest section of the system even today. The first entry into the cave was achieved through widening the crack between two layers of rock and was done by János Bagyura (the teenage son of the quarry guard) and Kornél Pál Scholtz, mountaineer and cave explorer. Soon they were joined by Károly Jordán and Imre Gábor Bekey, and together this team made important discoveries in 1906 and 1910. Thanks to their efforts, by the end of WW1, the length of the cave had reached 1 km. In 1927, the first 400 metres of the cave were fitted with electric lighting for the first German-Hungarian Cave Conference, and by the '30s, the cave was open to the public on weekdays as well.

In the meantime, due to development of the city and the high demand for limestone, quarrying started just opposite the Holzspach-quarry on the other side of the Szépvölgyi road at the bottom of the Mátyás-hegy (Mátyás-hill). On the lower levels – again – multiple caves were found. The Upper-cave and Tűzoltó-branch were often visited by cavers in the '30s, and during WW2, the cave length grew to nearly 400 metres due to capping. During the capping, other caves were found, such as the Futura-cave with its length of 80 metres.

3. Finding the Mátyás-hegyi cave

This small cave proved to be vital for today's giant cave system: in March 1948, Béla Mohos crawled into virgin cave from the end of the Futura by clearing out a 2 m long, 1m wide tunnel. He found what we know today as the Mátyáshegyi-cave: in remembrance of the Hungarian revolution of 1848, they named the newly found section Centenáris-passage. Óriások útja (Giants' Way), Névtelen-folyosó (No Name Passage), and Színház-terem (Theatre Chamber) were found shortly afterwards, and explorers reached the karst water level, with a permanent lake 92 metres below the entrance. (In 1959, cavers swam across this lake but found only a couple of metres of passage on the other side). Soon enough, the Mátyáshegyi-cave became

2.5 km long. The members of the Red Meteor Caving Club (known today as Meteor Caving Club) were constantly exploring the ends of the cave and after smaller findings, they found a larger passage (Meteor-branch) in 1962. Later, in 1965, the students of the Toldy Secondary School found a passage that they named after their school. Members of Meteor found the Természetbarát-szakasz (Nature-Lovers' passage), so the length of the cave was extended step-by-step.

Of course these passages existed previously, but they were not known. This is due to a peculiar feature of the caves of Buda (which are thermal-karst caves): large chambers and wide passages are often connected by tiny squeezes, and these small passages are often filled with rubble due to rockfalls. Water draining into the cave brings some marl from the levels above the system, and as a result, the scree is hardened so much that even the most experienced cave explorer has difficulty noticing that this solid wall used to be open cave passage! Finding these passages can be aided by tectonics measurements, and also by watching out for cave draft: air can flow through such tiny cracks that one can't even see through with head-torches. Cavers sweaty from digging will appreciate the draft, but it is also indicated by the light of a candle, or – God forbid – cigarette smoke… The reason this wind exists is the difference between the temperature on the surface and the constant temperature of the caves (which is equal to the yearly average temperature of the area), and as a result, the difference in the density of the air. The direction of the air flow is the opposite in winter and summer.

4. Connecting the Pál-völgyi and Mátyás-hegyi caves

These examinations were done in the Pál-völgyi cave by members of the Kinizsi Cave Exploration Group, who were working in the cave after WW2. They were led by János Palánkai, but found only smaller passages: by the end of the '70s, the total length of the Pál-völgyi was "only" 1,200 metres… At the same time, the length of the Harcsaszájú-cave and the Hideglyuk-cave remained the same, although in 1964 Csaba Laufer and his team did manage to connect the Harcsaszájú and Bagyura-cave, which was directly below the Harcsa.

The long awaited breakthrough happened in 1980, when Attila Kiss and József Kurucz found the 400 metre-long December-passage behind the Pál-völgyi's Színház-chamber. Their team, called the Imre Bekey Cave Exploration Group, was formed within the Hungarian Karst and Cave Research Society (Magyar Karszt-és Barlangkutató Társulat, MKBT). With Attila Kiss and Katalin Takácsné Bolner as leaders, they found new passages year by year — a good habit that they still have to this day (though since 2011, the leader of explorations is Attila Tóth). In 1981 they found the Térképész-passage (Cartographer-passage), in 1982 they found the Negyedik Negyed (Fourth Quarter), 1987 the Déli-passage (Southern passage), 1989 marked the year the Szépvölgyi-passage was found (which ended very close to the Mátyáshegyi-cave). In 1992 the boulder choke of K2 was explored and in 1994, after widening a long and torturous squeeze (the Goffri [Waffle], where the caver is the "filling"), they reached the 3 km long Jubileum-passage, which even today remains the cave's most well-decorated and pretty section. In the following year, smaller successes followed (the side passage of the Delfin-passage and the Fodros-passage), so by the year 2000, the length of the Pál-völgyi cave reached 13.5 km. This meant that the biggest dream of Buda's cave explorers had now become a possibility: to find a connection between the Pál-völgyi and the Mátyáshegyi caves.

But this connection could not be made without parallel exploratory work being carried out in the Mátyáshegyi cave. For example, members of the Acheron Caving Club found the Trón-termi passage (Throne Room passage) and Mikulás-branch (Santa Claus branch). After several smaller findings, in 2001, explorers finally made the connection from the Pál-völgyi cave to the Természetbarát-branch of the Mátyáshegyi, making the total length of the system over 19 km!

5. Resuming work in the Hideglyuk and Harcsaszájú caves

In the new millennium, findings became rare in the Pál-völgyi cave, despite the constant work. However, in 2005, the exploration of the tighter passages of the Hideglyuk cave began, but remained unsuccessful for four years, despite the labours of the József Szabó Caving Club and their lead explorer, András Nagy, who spent most of their weekends working in the cave. In 2007, intense exploration of the Harcsaszájú-cave began, with Attila Nyerges leading the members of the Barit Caving Club. In 2008, after nearly twenty days of digging, a team of cavers led by Domokos Gergely Nagy and Lénárd Szabó reached the rear passages of the cave which were well-decorated with promising muddy chokes. Heading in a northwesterly direction, along the main fault lines, the cavers soon found over 3 km of passage!

During autumn next year, explorers reached a breakthrough in the Hideglyuk-cave as well: squeezing through the tight Guillotine-choke, they found a well-decorated passage with boulder chokes and huge chambers. Soon the length of this cave exceeded 3.5 km as well. The caving community was informed of the findings in these two caves week-by-week, and on the 6th of March 2010, the connection between the Harcsaszájú and Hideglyuk caves was finally made! From this point onwards, all the Buda cave explorers dreamt of connecting the two big systems: the Pálvölgyi-Mátyáshegyi system with the Hideglyuk-Harcsaszájú.

Surveys of the caves were compared and it seemed that there were at least 25–30 metres between the closest points of the two systems, and no sign of a through passage…

6. The connection is made

It was around this time that members of the Bekey Club thought about trying work in the narrow Nyomdász-prés (Printer's Press) section, which points towards the 100 metres long Kis-Hideglyuk (Small-Hideglyuk) cave, which had already been connected with the Harcsaszájú-Bagyura system.

In the autumn of 2011, members of the Barit Club organised a big exploration camp in the Pálvölgyi quarry for a long weekend, with 100+ participants. Multiple shifts of cavers worked in the Nyomdász-prés (and at endpoints of other caves), but progress was slow: towards the end, over 20 people were passing buckets of mud that had filled up the passages. Success didn't seem close at hand…

However, at the end of November, starting from a spherical niche on the surface, cavers found a new smaller cave between the Kis-Hideglyuk and the Nyomdász-prés. This cave was named Meta-cave, and from the open ends of its passages, it was easy to reach the Kis-Hideglyuk, the Pálvölgyi cave, and into one of the side passages by the Nyomdász-prés. This way, the connection was made on the 11th of December and the Pál-völgyi cave system was created! (Cavers often call the system Szépvölgyi-system as well). Even since the connection was made, some new passages have been found in the Mátyás-hegyi cave (in a previously unsurveyed section): so the total length of the system is now 29 km!

Those who have never participated in expeditions can't even imagine the tension and expectations involved in this kind of work, and what unbelievable joy it is to find wonders never before seen by the human eye! It's worth it to work for these moments, often for years and years. But for great findings, we also need luck: not all diligent cave explorers get to experience the euphoria of finding virgin passage – in the same way that not all athletes who train for years will get to win an Olympic gold.

7. Formations of the Pál-völgyi cave system

The Pál-völgyi cave contains many interesting and beautiful formations. The prettiest ones are the sheets of calcite hidden away in the Jubileum passage, these were formed on the surface of the warm water of an underground lake. These sheets formed cones (the highest of which can reach 2 metres) and the cave pearls that cover the whole formation. This cave contains the highest amount of calcite sheets among all the Buda caves! There are deposits of this material above each other, with a difference of 3–4 metres, which has a scientific significance: examining these can help determine the age of the cave and the movement of the karstic water. Only in this cave can we find folias, which is the line of calcite on the side walls, marking the water levels. Also, many baryte chrystals can be found in the cave. These calcite veins were deposited here from the liquids flowing in the cracks before the cave itself was formed. In some places (like the Gipszes [Gypsum] branch), we can marvel at little developing gypsum chrystals. The solution forms and spherical niches are also very pretty (for example in the Hosszú-folyosó [Long passage]). In the ceiling of many a passage we can see a 0.5–2 m wide zone of flint which mark the presence of warm water solutions passing through the cave and transforming the original rock. Many stunning dripstone formations can be found in the cave in the following passages: II-es vágány, Schönvinszky-terem, Ezüst utca.

The Mátyás-hegyi cave is poorer in formations, but as there are less mineral aggregates on the walls, the solution forms can be studied better (for example: Földtani Intézet chamber). We can see fossils in many a passage (Nagy-terem, Névtelen-folyosó): the shell of seashells and sea-urchins is more pure calcium-carbonate than the slightly clayey rock, so these petrified shells are more resistant to solvents, so the stand out from the wall. We can see flint zones here as well, and the passages actually reach the level of karstic water. A while ago in there were beautiful gypsum formations in the passages (like the Színház-chamber), and while unfortunately these have been destroyed, in the newly found passages we can still marvel at these beautiful formations.

The Harcsaszájú and Hideglyuk caves are very rich in formations, but the detailed mineralogical examination of these caves has not yet happened.

8. Summary

To summarise: the Pál-völgyi system is Hungary's longest, most scientifically interesting and most beautiful cave system. Its speciality is that it is right underneath the streets and houses of the capital city, which could possibly threaten the integrity of the cave and the buildings above.

Acknowledgments

I am grateful to all the explorers of the Pál-völgyi cave system in the past 100 years, but in particular to the members of the Bekey Cave Exploration group and its leaders, Attila Kiss, Katalin Takácsné Bolner and Attila Tóth. I would also like to thank the József Szabó Cave Exploration group, led by András Nagy, who worked in the Hideglyuk cave, and to Domonkos Gergely Nagy, Attila Nyerges, and Lénárd Szabó, who are the leaders of the Baryte Caving Club and have done valuable work in the Harcsaszájú cave. I am also grateful to Eszter Kalóczkai for her help with translating this article.

EU PROTEUS – EU PROJECT FOR RAISING AWARENESS AND IMPROVING EFFECTIVENESS OF CAVE RESCUING

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Almost half of the territory of Slovenia and more than half of that of Croatia is karst. Owing to the work of active and well-organised speleologists there are almost 20,000 known and registered caves in both Slovenia and Croatia. These numerous and impressive cave systems result in a high frequency of touristic visits and spurs on further speleological research. In the event of an accident rescue operations are performed in Slovenia by the Slovenian Cave Rescue Service (SCRS) while in Croatia by the Croatian Mountain Rescue Service – Cave Rescue Commission (CMRS-CRC), both are now also active in international cave rescue. An important milestone in this field is the setting up of an international mechanism for the education of cave rescuers i.e. the "Cave Rescue Training (CRT)" programme and the implementation of the European "EU Proteus" project that brings together Slovenian and Croatian cave rescuers. This paper describes the project and its main activities concerning reviewing the existing legislation on cave exploration, accident prevention, and cave rescue training. The EU Proteus project presents a model study of two cave rescue organisations (the SCRS and the CMRS-CRC) both of which are run and implemented by volunteers. The project contributes to an overall improvement in standards, greater capacity and efficiency of rescue operations, and the international integration of cave rescue services.

1. Introduction

Limestone and dolomite bedrock, covering 43 % of the land surface of Slovenia and 52 % of Croatia (over 70 % if submarine areas are included), enables the formation of the karst phenomena where amongst its natural features caves stand out for their exceptionality. Of the 20,000 registered Slovenian and Croatian karst caves only 0.1 % are designated and equipped as touristic caves and even these to a limited degree. For example in the world-famous Postojna Cave, only 3.2 km of the explored 20.5 km of passages are made accessible to tourists. It is a fact that a considerable part of the underground world is represented by more or less vertical pits that are especially notable in the Alpine karst. These areas that are interesting for tourism and are frequently visited can "hide" potentially dangerous caves. In the Slovenian Kanin massif with a surface area of 8 km^2, more than 300 caves are known; while in an area of similar size in Northern Velebit, Croatia, there are 348 caves. It is worth mentioning that worldwide, there are 96 known caves deeper than 1,000 meters (Gulden 2012) located in 17 countries and of these, 9 are located in Slovenia and Croatia. An important characteristic of the Slovenian and Croatian caves is their verticality. In this area, the largest verticals in the world can be found: Vrtiglavica (-643 m), Patkov gušt (-553 m), and Velebita (-513 m), which implies the use of special rescue techniques. In addition, the problem of rescue from natural springs has to be mentioned e.g., Crveno jezero lake (-281 m), Una spring (-205 m), Divje jezero lake (-160 m), Sinjac lake (-155 m), and the Kolpa/Kupa spring (-154 m).

Therefore, the subterranean world is only accessible to qualified speleologists (skilled cavers knowledgeable and practiced in vertical caving) as well as professional visitors to the karst terrain (researchers, foresters) who are able to explore its secrets safely and successfully due to their knowledge, special technical equipment and physical preparedness. While performing such activities, they face potentially serious or even fatal injuries due to numerous objective hazards and possible subjective errors. However, in most danger are those who find themselves in caves unintentionally, due to either a slide or a fall from the surface. These typically include mountaineers, skiers, hunters, hikers and excursionists, both native and foreign. Records show that there have been a considerable number of such accidents in the past.

2. Dangers in caves and cave rescue

As a rule, a high percentage of "caving" accidents involve non-cavers, with a remark that rescuing cavers stands out in terms of duration and difficulty of rescue. So far, the longest and most difficult rescue operation in Slovenia occurred in 1990 when cave rescuers from Slovenia and Italy rescued an injured caver from the Črnelsko brezno pit. The rescue started at a depth of 1,200 meters and lasted for 10 days. In Croatia, the longest and most difficult cave rescue operation occurred in 2012 in Kita Gaćešina at a depth of 483 m. The operation involved 114 rescuers from 16 CMRS stations. The time required, from reporting the accident to the extraction of the caver, took more than 26 hours. All together, when the last rescuer exited, it amounted to 36:23 hours. Members of Slovenian CRS were also on standby to join this rescue operation in case of a prolonged period of rescue. The Corpo Nazionale Soccorso Alpino e Speleologico (CNSAS) from Italy and the Alliance of speleological organizations in Serbia also offered their help.

Karst terrain in Europe covers large areas (approximately 30 %) which are not equally explored. A high percentage of karst is typical of Greece, Spain and countries of South East

Europe including Slovenia and Croatia. According to the World Declaration on Cave Rescue Organisation, individual countries have to elaborate their rescue plans and provide for the organisation of cave rescue.

This project was initiated because of the desire to explore the largely undiscovered, unexplored, and unpredictable underground environment. Karst caves are exceptionally dynamic and diverse, the exploration of which requires a significant amount of knowledge and expertise from potential visitors. Currently, there are many caves in Slovenia and Croatia that are dangerous to visitors and consequentially to rescuers because they are either unknown or unexplored and hence have not been assessed in terms of risk. In general it is impossible to prevent the public from searching, researching and visiting caves; but unfortunately, such visits can results in accidents. The so-called urban underground should also be mentioned here (industrial shafts, sewage system, abandoned underground mining, industrial and military systems) with the exception of active mines. However these require confined space permit entries and differ with respect to rescue and extraction procedures from those of cave rescue.

In general, cave rescue is difficult and due to the environment (enclosed, limited, dark, cold, humid cavities) specific to the cave in question and will require specialized skills. A rescue in a horizontal cave is not the same as a rescue in a stair-step shaft, a rescue in the high mountains is different from a rescue in the lowlands and rescue operations in water caves with rivers are still different, not to mention the obstacles imposed by waterfalls, siphons, ice caves, labyrinths, narrow passages, and areas full of mud. The air in caves is cold and humid. Air temperature typically varies between 0 and to over 14 °C, while in ice caves it is below freezing. Humidity is close to 100 %. In case of an injury where the injured person is left unable to move, the body cools rapidly and soon enters the vicious circle of hypothermia. Among the many risk factors, hypothermia of an injured person is often the more critical than their injuries. When rescuing an injured person from a cave, the required amount of time is usually several times longer than the time needed for an individual descent. In the case of a major accident, rescue can take several days.

Cave rescue in Slovenia is performed by the Slovenian Cave Rescue Service (SCRS) with the Speleological Association of Slovenia as the responsible body. It operates directly under the auspices of the Administration of the Republic of Slovenia for Civil Protection and Disaster Relief (hereinafter referred to as ACPDR). In Croatia, cave rescue service is organised under the Croatian Mountain Rescue Service as a Cave-Rescue Commission (CMRS-CRC).

Within Europe, there is a lack of organised networking and cooperation between speleological organisations which is necessary for the exchange of knowledge and expertise. A possible solution would be to establish an expert rescue unit at the EU level.

3. Methods

The qualification of cave rescuers is an important factor in any cave rescue service and decidedly affects the success of rescuing injured persons from caves. The Cave Rescue Service of Slovenia, together with ACPDR and partners from South-eastern Europe (Croatia, Serbia, Bulgaria and Romania), have developed the Cave Rescue Training (CRT) Programme to provide rescuers with a basic knowledge of cave rescue (Merela 2010; Stražar and Ilič 2010). The programme was performed for the fifth year under the Disaster Preparedness and Prevention Initiative for South-Eastern Europe (DPPI) organization and focuses on specific procedures and the organization of rescue teams involved in accidents or drills. Cave rescuers are trained to deal with cave conditions (abysses, meanders, rivers, etc.) and special rescue techniques. The aim of the programme is to achieve, in a rational way, a satisfactory level of qualification of speleologists in different countries, providing them with the ability to react rationally and uniformly and to provide effective assistance in the case of accidents or other extraordinary events. This programme provides the basic skills for cave rescue, but is insufficient for advanced training and the training of cave rescue instructors.

An upgrade of the successfully implemented CRT Programme is the European project – EU Proteus (Figure 1). EU Proteus with its full title "Raising Awareness and Improving Effectiveness of Cave Rescuing within Community Civil Protection Mechanism" is a 24 month long project (2012 and 2013) and is the first large European cave rescue project (http://www.eu-proteus.eu). The project is supported directly by the European Commission – Directorate General for Humanitarian Aid and Civil Protection – Civil Protection Prevention, Preparedness and Disaster Risk Reduction Unit Office.

Figure 1. The Logo for the EU Proteus project is shown above.

EU Proteus aims towards the better organisation of cave rescue in Slovenia and Croatia by analysing the current situation, preparation of common standards and studying the conditions that exist in other organisations from Participating States. This goal is to enhance the awareness and preparedness of cavers and to improve the preparedness and effectiveness of cave rescuers (emergency response).

4. Results and discussion

4.1. Main project Tasks

Several tasks were defined and proposed in order to achieve a safer caving and a significant improvement of the cave rescue service in Slovenia and Croatia. The main goal was to improve cross-border cooperation between rescuers as well as raising the level of preparedness for cave related emergencies.

A series of joint thematic workshops helped in drafting and establishing general rules, standards and rescue techniques and the criteria for setting-up and equipping preventive bivouacs in caves to assist in a rescue. All of these were verified by organising practical exercises.

An expert team was put together to prepare and draft a training programme for instructors and the general and specialised parts of the programme including the curriculum and a catalogue of the necessary skills. The next step involved establishing a joint commission for technical issues such as checking and comparing the various caving equipment used by Slovenian and Croatian cavers. Based on these findings, the commission will prepare standards obligatory for cave rescue and recommendations for other cavers. An important outcome of this initial preparation was the translation of the Cave Rescue Manual from French into the Slovene language.

A priority was the implementation of joint rescue exercises to improve the knowledge of cave rescuers. In the first year of the project's duration, Slovenian and Croatian cave rescuers were involved in five joint rescue training events (http://www.eu-proteus.eu; www.hgss-kshgss.com).

4.2. International cave rescue training for instructors (CRT) 2012

The International Cave Rescue Training 2012 (CRT 2012) event was the EU Proteus project's most important action in 2012. CRT 2012 took place between the 16th to 23rd September in Sežana, Slovenia. Forty participants from 10 countries including Albania, Bosnia and Herzegovina, Bulgaria, Croatia, France, Macedonia, Montenegro, Romania, Slovenia and Turkey attended the exercise. The participants were made up of 28 trainees and 12 Cave Rescue Instructors (two from the French SSF- Spéléo-Secours Français). The trainees were made up of skilled cave rescuers, cavers and non cavers, including firemen and mountain rescuers. Based on past experiences of organising this kind of event, we divided the trainees in two groups: basic level and advanced level cave rescue training (Figure 2).

Figure 2. Participants are shown performing a climbing skills test.

The training exercise began with a step-by-step instruction of the key elements of cave rescue manoeuvres. Initially, the instructors kept to the principle of working in small groups and organised several workshops near the crag wall. Later, the exercise involved combined rescue manoeuvres (Figure 3).

Figure 3. Participants perform the complex combination of various rescue manoeuvres.

A demonstration was also given on the proper use of the Petzl "Nest" cave rescue stretcher (Figure 4). This represents the state-of-the art in stretchers for use in cave rescue. For the rescuers it is important that they are acquainted on how to position the casualty correctly on the stretcher. It must be noted, that this procedure should be performed under medical supervision. By the end of the exercise and after several rescue manoeuvres the transport of the casualty on the stretcher was accomplished.

Figure 4. Cave rescuers demonstrate how to work with the specially designed "Nest" cave rescue stretcher.

Demonstrating how to systematically review and evaluate the physical condition of casualty was also emphasised (Figure 5). An uncomfortable and inhospitable cave environment requires special procedures for a systematic assessment of the casualty. Another important issue is how to deal with hypothermia and frostbite in the case of a very cold cave environment.

After successfully completing the outdoor training sessions, several rescue exercises were performed underground. Prior to the final exercise the organisers had visited and selected

Figure 5. A medical doctor demonstrates how to evaluate the state of an injured person.

several caves with different polygon configurations (i.e. vertical and horizontal caves). The rescuers were divided into groups working in different parts of the cave. Vertical pits were equipped for vertical transport using counterweight systems (Figure 6) while hard passable areas were rigged for transport via Tyrolean lines. For communication purposes a cave telephone (VOX system) was installed.

Figure 6. The rescuers are shown transporting the casualty in the cave.

At the end of the training, the trainees performed a final rescue exercise in the Najdena Cave. The Najdena cave is a complex cave with vertical pits, long difficult passages, mud and a water siphon. The exercise was designed to bring together international cave rescuers: members of the Slovenian Cave Rescue Service, Slovenian Cave Rescue divers and members of the Croatian Mountain Rescue Service (Cave-Rescue Commission). The number of participants was 63. A telephone line had been installed during previous training exercises (1.4 km) and the 30 m long and 6 m deep siphon had been secured with a safety line. The telephone had also extended to the far side of the siphon.

Because of the importance of this international rescue exercise, the event was strictly controlled by the members of the Slovenian Administration for Civil Protection and Disaster Relief, the President of Speleological Association of Slovenia, the Head of Slovenian Cave Rescue Service and by the main inspector of the Inspectorate for Protection against Natural and Other Disasters.

Cave rescue is a difficult activity and any rescue attempt from behind a siphon is extremely hazardous. Furthermore, any rescue exercise must be precisely planned in advance. This was the first cave rescue exercise where the team worked with actual cave rescue divers whose role it was to dive to the far side of the siphon, place the casualty in the stretcher and then transport them safely back. The international team of trained rescuers received the casualty from the siphon (water temperature: 8 °C) and immediately installed a special body heating device to prevent hypothermia (Figure 7). The whole operation lasted for approximately 10 hours.

Figure 7. The casualty is shown being transported from the 30 m long siphon.

The cave rescue training exercise managed to attract up to 40 participants from 10 European countries. Cave rescue training was acknowledged to have been a success on the grounds of the knowledge received by the participants. Of course the main purpose of CRT (2012) was that the participants would then disseminate this knowledge within their own organisations. During the eight day training event we fulfilled our plan of 80 hours of intensive lectures, short demonstrations, and practical work in smaller caves in readiness for the final full-scale rescue exercise.

An important result of all our efforts was the great publicity for the EU Proteus project and for EU visibility. Ultimately, we performed a successful final rescue practice for which we received the highest rating by a team of independent evaluators.

4.3. European Cave Rescue Association (ECRA)

Both the SCRS and the CMRS-CRC support the organization of the new European Cave Rescue Association (ECRA). On May 12th in Castelnuovo Carfagnana, Italy, seven national cave rescue organizations from Great Britain, Germany, Italy, Austria, Slovenia, Croatia and Serbia came together to establish the European Cave Rescue Association.

The goals of the ECRA are the following:

- promote the exchange knowledge and expertise in the field of cave rescue,
- facilitate cooperation and support between members,
- advance and improve cave rescue knowledge and the capabilities of member organizations,
- provide information and statistics on cave rescue incidents,
- exchange knowledge and experience concerning the best practice in cave rescue between cave rescue organizations, caving organizations, manufacturers of caving equipment and other interested bodies,
- conduct research with a view to improving the efficiency and effectiveness of cave rescue and
- conduct such ancillary activity as the ECRA shall think appropriate to better achieve these goals.

5. Conclusions

Cave rescue in Slovenia and Croatia is run by volunteers whose goal is to design and develop a cave rescue module and to start a procedure for the registration of a multinational cave rescue module for rescue operations in cave related emergencies. The expected outcomes of this project was that, by using the cave rescue organisations of both Slovenia and Croatia as a case study, we would perform a risk assessment on cave related issues followed by a unique "train the trainers" programme and to set standards for visiting caves, researching caves and cave rescue together with medical issues.

The overall findings of this project will be used as the basis for modifying existing regulations concerning speleological research with the added intention of adopting them into a Community Mechanism for Participating States.

The beneficiaries will not just be Slovenian and Croatian cavers but also those from others countries since many (several hundred per year) come to explore our magnificent cave systems. Finally, it is important to emphasize that both countries and the public in general benefit from a well-regulated system that allows for an effective response in the case of emergency.

Acknowledgments

EU Proteus project is co-financed by the European Union under European Commission – Directorate General for Humanitarian Aid and Civil Protection – Civil Protection Prevention, Preparedness and Disaster Risk Reduction Unit Office. We would also like to thank the Administration of the Republic of Slovenia for Civil Protection and Disaster Relief for their universal support.

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ON THE SEARCH FOR KING BARBAROSSA IN UNTERSBERG

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In recent years important discoveries in Untersberg mountain near Salzburg were made. The length of long known *Kolowrathöhle* (AT) was extended to 38 km and the karst water table was reached in four different passages at a total depth of more than 1,100 m. Many leads with strong wind hold the promise of further discoveries. On the German side of the high plateau a new cave called *Riesending* was found in 2002, to date explored to a length of 18 km, through which a huge collector could be reached at a depth of 900 m. After a long detour the trunk passage turns into the direction of Fürstenbrunn, where the main resurgence of the mountain is located, still nearly 3 km away but only 200 m below the horizontal passages in *Riesending*. *Riesending* also gets close to the lower reaches of *Klingertalschacht*, which is part of the 12 km long, complex maze of *Windlöcher* (AT), and lately a new wave of exploration was triggered in this cave. A connection of the three major caves of Untersberg would result in a huge system of at least 70 km length.

1. Introduction

Untersberg mountain is located in the Northern Limestone Alps, close to Berchtesgaden and Salzburg (Fig. 1). The border between Austria and Germany runs over its' high plateau, which culminates in Berchtesgadener Hochthron (1,973 m). For more than 100 years cavers frequent its' steep slopes and barren limestone pavement. Most of the plateau and parts of the slopes, all together close to 15 km², are drained by *Fürstenbrunner Quellhöhle*, where the water emerges from a deep sump. Beneath Salzburger Hochthron (1,853 m) extents the massive labyrinth of *Kolowrathöhle*, at more than 38 km total length the main cave of the mountain. The distance from the lower reaches of *Kolowrathöhle* to *Fürstenbrunner Quellhöhle* is little more than 1 km, a connection of the water tables in the two caves is proven, but a way through is unlikely to be found due to the long and deep sumps separating the two caves.

The second well known cave complex on the northern flanks of the mountain is Windlöcher. With 12 km length and accessible by 12 different entrances it connects the three cirques Schosstal, Klingertal and Wasserfalltal. Via Klingertalschacht it drains in the direction of the central plateau, but the distance to the resurgence at Fürstenbrunn is still about 3 km. The stream sinks into large boulders at the floor of the final chamber and to date all attempts to find a continuation at this low level failed. New discoveries at a fossil level have raised new hopes and exploration is just gaining momentum again.

The entrance to the third big cave of the mountain is located on the high plateau, close to Berchtesgadener Hochthron. *Riesending* is a rather recent discovery, being explored for only 11 years. In this short time it has grown to over 18 km in length and more than 1,000 m in depth and the potential for further discoveries is still great. The distance from the entrance to the resurgence is, at nearly 5 km, the greatest of all three portrayed caves. Nevertheless, *Riesending* provides the key for the understanding of the speleogenesis and hydrology of Untersberg mountain.

The trunk passage found at 900 m depth seems to be the old collector of most of the plateau. Now fossil it cuts through the mountain with huge dimensions and at a constant elevation of 870 m above sea level. Several sumps are reached in fissures and shafts 100 m to 150 m below the old stream way. Observations with pressure gauges indicate, that these belong to hanging water tables. New discoveries in *Riesending* and *Kolowrathöhle* raise the hope to one day connect both caves. Each year a number of week long expeditions take place, organized by small, but dedicated teams from the Verein für Höhlenkunde in Salzburg (AT) and the ARGE Bad Cannstatt (D). Due to the massive difficulties in the exploration of the caves, the great depth, long distances and technically very challenging terrain it will not be a fast success. Legend knows, that in the heart of the mountain old king Barbarossa sits in his throne room, bored to death, and waits for some unwary cavers. We are up to meet him.

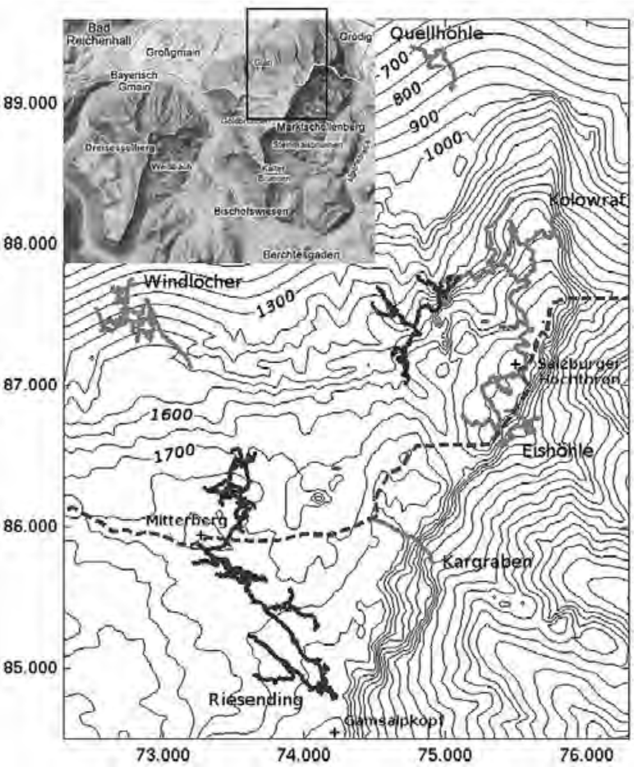

Figure 1. Caves of Untersberg presented in this article, recent discoveries in black lines (map inlay ©2012 Google, map data ©2012 GeoBasis-DE/BKG).

2. Windlöcher (1339/31)

The main entrance to *Windlöcher* is located at an elevation of 1,300 m in the steep northern slopes of the mountain below the alp Klingeralm. The cave was first visited by Fugger in 1875 and explored to a length of 400 m by Urbanek and Abel in 1934. The following year Czoernig discovered *Klingertalschacht*, which was surveyed by Abel to a depth of 60 m in 1947. It was quiet around the caves until in 1975 in a big breakthrough in *Windlöcher* a fossil trunk passage was found and the length rapidly grow to 2.5 km. In 1982 a restriction was opened, giving way to *Palästinahalle*, from where a connection to *Klingertalschacht* was found, which meanwhile had been explored to a length of 2 km and a depth of 322 m by cavers from Belgium. The total length of the cave system thereby rose to 6 km.

In 1989 Holvan started a complete resurvey of the cave, in the course of which another 3.5 km of passages were added. In 1995 the Belgians struck again, connecting the deep shaft *Supernova* to the final chamber in *Klingertalschacht* (Klappacher 1996). A way around the breakdown blockage in the final chamber could not be found. The last achievement of that period was the connection to *Stützinger Schacht* in 1996, bringing the total length of the system to 11.3 km. With the end of the resurvey campaign and the Belgians shifting their focus to another cave farther away in Sulzenkar, it became quiet around *Windlöcher*, despite a number of strongly drafting leads. Only when *Riesending* was getting close to the final chamber of *Klingertalschacht* (700 m as the bat flies), a new team from Salzburg revisited the cave and found upper levels that show great promise to circumvent the blockage in the final chamber.

The passages in *Windlöcher* may be separated into three different levels. The trunk passage *Hauptgang* close to the main entrance and the surrounding labyrinths lay at an elevation of 1,300 m. They are characterized by breakdown. A lower level is found in *Palästinahalle* and its continuation *Palästinagang*, another trunk passage at 1,200 m elevation that runs parallel to the upper one. The end of this massive, 20 m wide tunnel is actually marked by a deep shaft that has not yet been descended. The lowest level of the cave is reached *Klingertalschacht* at an elevation of 1,000 m. It contains a stream and ends in a massive chamber, where several big shafts enter the system, more or less directly from the surface 400 m above.

Hauptgang and *Palästinagang* both follow south trending joints and slowly rise, following the dip of the bedding planes, at an angle of about 15°. The labyrinths mainly follow southwest-northeast and southeast-nordwest trending fissures. *Klingertalschacht* is also developed in a southeast trending joint. The stream at its bottom, whose head waters are not yet fully explored, may be followed through a number of deep lakes to the final chamber, where it sinks into boulders. The final chamber is reached more easily by fossil upper level passages, or directly by the *Supernova* entrance through a number of deep shafts and narrow meanders. All known entrances to *Windlöcher* exhale during summer, the uppermost entrances to the cave system are not yet found.

3. Kolowrathöhle (1339/1)

Kolowrathöhle is a mazy cave of massive proportions, that developed under phreatic conditions. Two main levels can be distinguished, the upper one at elevations between 1,400 m and 1,600 m, the lower one between 1,000 m and 1,200 m. Both levels are connected by vadose canyons, some of which are still active. They continue below the lower level until at an elevation of 700 m they submerge into the karst water table.

The cave is situated in the northeastern part of the plateau, below the summits of Salzburger Hochthron and Geiereck. The main entrance at an elevation of 1,370 m at the foot of the east face of Untersberg has been know for centuries. It became a tourist attraction in the 19th century and people used its massive entrance chamber for summer ice skating. Fugger based his theories on ice caves on observations in *Kolowrathöhle* and nearby *Schellenberger Eishöhle*. But the ice started to melt after enlarging the entrance for ease of access and nowadays only small relics remain.

The breakthrough into the main cave was not achieved through this entrance, but when the nearby *Gamslöcher* were connected to *Kolowrathöhle*. The entrance to *Gamslöcher* high in the cliff of Dopplerwand became accessible after the Dopplersteig was built in 1876, but only in 1979 a shaft at the end of the known cave was descended and the large passage *Rundstollen* discovered. Via *Rundstollen* the *Broadway* was found and finally a high aven in *Kolowrathöhle* was reached and the explorers abseiled into the large ice chamber and left via the main entrance. After this connection the length totaled 2.5 km.

Figure 2. The maze like passages at the lower level of Kolowrathöhle are bone dry (Dirk Peinelt).

Following *Rundstollen* and its continuation *Prachtstollen* further into the mountain, a breakdown stopped the explorers. It was opened in 1982 and gave way into the dark aven *Zwentendorf*. Descending the following shafts the trunk passage of the upper level was found and baptised *Mainstream*. To the south it led to the high aven *Walkerpfeiler*, that was climbed in the same year. Its continuation, the 20 m wide *Champs Elysees*, ends in the *Louvre* in a massive breakdown. With this impressive discoveries the total length of *Kolowrathöhle* made a big jump to 5.6 km.

From *Zwentendorf* a passage leading to the north led to the deep shaft *Kalkar*, where a traverse gave access to *Erpelcanyon* and its little stream. Through this canyon the upper level of the cave is left and in 1984 the breakdown chamber *Hot Spot* was discovered. The length meanwhile reached 10.2 km. From Hot Spot two ways led on. Down the shafts *Karato Prak* the lower level of the cave was entered and the mazes of *Dackel mit Hut* and *Tonplattenlabyrinth* explored. Not far from the base of the shaft *Onan der Barbar* exploration was halted in 1986 by the lack of rope at another small drop and not continued until more than 20 years later. The last trip of this very successful phase of big discoveries took place in 1989 to *Hungerkluft*, a passage forking from *Hot Spot* to the north and ending (to this day) at a deep shaft. This is the closest point to the resurgence *Fürstenbrunner Quellhöhle*, the distance is still more than 1 km. The length of *Kolowrathöhle* remained stable at 16 km for the coming 15 years (Klappacher and Mais 1975, Klappacher 1996).

Not far from Salzburger Hochthron the strongly drafting entrance to *Salzburger Schacht* is located at an elevation of 1,800 m on the high plateau. It was discovered in 1923 and explored to a depth of 170 m by Abel and companions in 1935, making it the deepest cave of the region at that time. In the 1970s a continuation was discovered and with the new single rope technique explored down to a depth of 400 m. There large galleries and a stream were discovered. To the north the gallery ends in a huge breakdown in *Allendehalle*, close to the *Louvre* in *Kolowrathöhle*. Downstream the *Via Belgica* was followed to a muddy sump at a depth of 600 m. An inlet to *Via Belgica*, which rises from a constricted sump, drains the lower reaches of *Schellenberger Eishöhle*. A connection of the two caves could not yet been forced, in spite of a strongly drafting but very narrow side passage close to the sump. In 1982 Brunntalschacht, a shorter and much easier entrance to the main passages of Salzburger Schacht, was discovered, but nevertheless exploration came to a stand still at a total length of 6 km (Klappacher and Mais 1975; Klappacher 1996).

It was quiet around both caves, until in 2002 Georg Zagler entered the scene and together with some indestructible companions and a lot of chiseling forced a connection from the *Champs Elysees* in *Kolowrathöhle* to *Salzburger Schacht*. Further passages were found climbing *Walkerpfeiler* to heights not yet heard of. By the end of 2005 the length of the combined system reached 25 km (Zehentner et al. 2006). Not yet satisfied they pushed on into the depths of the cave. To safely explore the lowest reaches, a new and avalanche proof entrance to the cave in winter was needed. This goal was achieved in 2007 after a long and arduous dig in one of the dolines close to Zeppezauer Haus. In the following winter season exploration continued from a new bivouac near the base of *Onan der Barbar*. The first great success was the exploration of the canyon *Alien 1* and its continuation *Kugelcanyon* to a big sump at a depth of 1,119 m below the entrance to *Salzburger Schacht*, high point of the system.

In the summer of 2008 mazy passages close to the new bivouac were explored, culminating in the discovery of *Krabbelsprint-Labyrinth*, where a powerful draft chilled the exhausted cavers to the bone. The wind gets lost in *Phantom der Oper*, the surface of Brunntal only about 100 m away, but no new entrance to these remote parts of the cave could be found to date. Beyond the labyrinth a large passage *Wadi* continues in southerly direction. The whole region of the cave is very dry and later was baptized *Wüste* (Fig. 2). A variety of gypsum crystals is abundant. In the winter season 2009/10 a big shaft *Elefantenschacht* was reached, already at a distance of 4 h from the bivouac (Zehentner 2010). To keep exploration efficient a shortcut through the labyrinth was searched and eventually found in the fabulous canyon *Auf dünnem Eis*, where a thin layer of flowstone separates the passage into an upper and a lower level that were only connected artificially after careful survey of a very long deviation.

Now the way was open to erect a new bivouac *Baumhaus* on a balcony of *Elefantenschacht*, near the only pool of water for miles. In winter 2011 a steeply descending passage below *Elefantenschacht* was explored down to several sumps at the level of the karst water table, where a powerful stream was met at the contact to the underlying dolomite in the huge and chaotic chamber *Kartoffelkeller*. But the origin of the wind was found in another passage, quasi the backdoor of *Baumhaus*. A beautiful phreatic passage *Idhrin Eden* gives access to the enormous shaft *Mordor*, filled with the spray of an impressive waterfall, most probably the headwaters of the stream found in *Kartoffelkeller*. Below *Mordor* the steeply descending passage sumps in *Orktränke*, again at the level of the karst water table.

Figure 3. Phreatic passage and sump close to the actual end of Kolowrathöhle (Wolfgang Zillig).

The stream rises from a beautiful sump (Fig. 3) that can be avoided by climbing up and down 100 m in a rift. Beyond the rift the stream is met again, but exploration was halted in a high aven with a waterfall. The level of the horizontal passages beyond Baumhaus corresponds to the level of the trunk passage in Riesending, but the distance between the two caves is still about 1.2 km. The latest news from Kolowrathöhle report of a new but horrible bivouac at the very end of the cave, to aid the artificial climb up the aven. Exploration continues at full speed, but with an effort of nearly two days necessary to reach the final dome the rate of success has slowed down somewhat.

4. Riesending (1339/336)

The entrance to *Riesending* is situated in the southern part of the high plateau, close to Berchtesgadener Hochthron, at an elevation of 1,840 m. It was found in 1996 by members of the ARGE Bad Cannstatt, and is extensively explored since 2002. A series of massive shafts drop down to a first horizontal level at -400 m, narrow canyons and further shafts lead on to a lower level at -870 m, that was reached in 2005. The main stream of the cave sinks into a narrow sump at a depth of -987 m, nearly 5 km away from the resurgence in Fürstenbrunn, but only 170 m above the karst water table found in *Fürstenbrunner Quellhöhle* and *Kolowrathöhle*.

In the following years exploration was focused on a huge fossil trunk passage at -870 m, that follows a dominant joint and in a straight line led 1.5 km to the northwest below the central plateau, without gaining further depth. Finally the joint is left and the passage turns to the northeast in direction of the resurgence, still 4 km away. Along the way only one major inlet, *Schöner Canyon*, now also fossil, is met, but more inlets are assumed to enter the trunk passage high up at ceiling level, which mostly is out of sight. Before the passage starts trending towards the resurgence, a number of shafts *Sechs Schächte* have to be traversed. One of these shafts breaks through into a lower level of the cave, also with huge dimensions and a strong draft, that is completely blocked by silt at a depth of 1,058 m (Meyer and Matthalm 2009).

Figure 4. A deep lake in the main passage of Riesending is crossed on a small rubber dinghy (Wolfgang Zillig).

Beyond the shafts the deep lake *Reitertränke* (Fig. 4) blocks the main passage, which has to be crossed on a rubber dinghy. Shortly after the lake a side passage connects to the massive shaft *Monsterschacht*, which most time of the year is impassable due to a powerful waterfall. The waterfall may be avoided by *Nebelschacht*, which joins *Monsterschacht* further down and finally leads to a little sump at -1,059 m. At this depth a hanging water table seems to exist under this part of the mountain. *Monsterschacht* surely is a much younger cave than the trunk passage of *Riesending* and only intersects *Riesending* by chance. It is probably connected to another deep shaft *Eisbläser* (today sealed by an ice plug) in the middle of the plateau near Mitterberg. The distance to the low point of *Eisbläser* is about 400 m.

After the turn towards the resurgence the main passage changes its character. The bleak area of the *Maulwurfstunnel*, a now dry sump, is passed. At one point the gravel fill had to be dug out for close to 10 m to enable human passage. Shortly after the dig the main passage forks. An upper level *Wundergang* contains a nicely bedded sediment fill (gravel and silt), but after a short distance is plugged. It can be avoided by a lower passage that joins the far end of *Wundergang* again in a big chamber full of wet mud. In this chamber another passage forks of, the steeply ascending and strongly drafting *Fratzengang* (not yet fully explored). The main continuation drops down to an old sump area *Auenland*, where dark sediments attest frequent flooding, and a powerful stream *Auenbach* is met. It rises from a sump and after a short distance tumbles down into a narrow canyon, that has been explored to -990 m and still continues. It offers a nice prospect for reaching a new deep point but is only accessible in very dry conditions.

Auenland is left via *Wachturm*, a 80 m high aven that had to be climbed with the help of a power drill. The logical continuation of the main passage forks off halfway up the climb and immediately drops down to a sump. Luckily at the far side of *Wachturm* another big passage *Westzubringer* could be reached, which leads to a canyon inlet and to an huge trunk passage. Their origins are not yet explored, but may be connected in one way or another with the complex of *Windlöcher*. The trunk passage also has a continuation in the general direction of the resurgence that was baptized *Kristallgang* due to large quantities of beautiful frostwork. It ascends another 100 m, before passing a now dry sump, a side passage to a shaft and finally continuing with much smaller dimensions (Fig. 6) for 300 m to some small shafts, through which *Wassergang* is reached.

Wassergang contains a stream and enters the cave from the west, so when first found in 2011 it was assumed to be the continuation of *Klingertalschacht* beyond the final chamber (700 m away and only 50 m higher than *Wassergang*). But exploration in 2012 revealed that the origin of the stream is found in several small inlets and the huge passage continues dry for a short while, until it drops down to a sump. Since it corresponds in height very well with the sumping passage near *Wachturm*, it may as well be the continuation of the main passage of *Riesending* (after a detour to the west). However, after a short way the downward continuation of

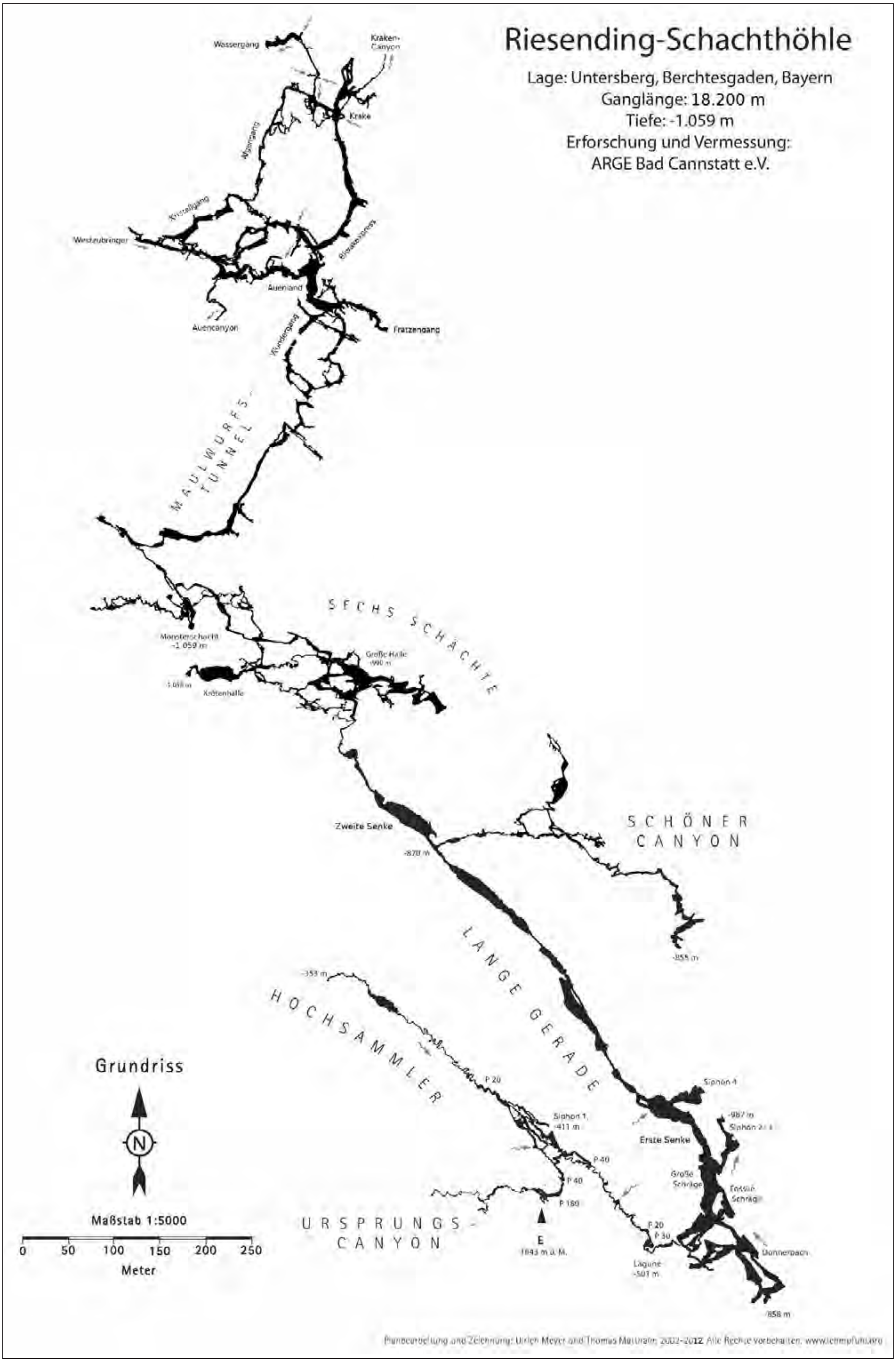

Figure 6. Close to Wassergang the size of the passage shrinks to a low ellipse, which was formed by corrosion of a fossilized layer of algae (Wolfgang Zillig).

Wassergang drops down into a wet and sporting canyon which obviously leaves the level of fossil trunk passages, that had lead the explorers through half of Untersberg.

But *Riesending* did surprise its explorers one more time, when in 2012 a little shaft forking off *Kristallgang* was dropped and a barely passable hole was forced to another huge tunnel, which in essence runs in parallel to *Kristallgang*. Descending the tunnel in the general direction of *Auenland*, the upper end of *Wachturm* was reached and hence a long loop closed. In the opposite direction a low crawl with more delicate frostwork had to be passed, until the passage started descending and finally opened out into a huge space with a very complicated shape, after the first shock called *Krake*.

A number of inlets enter through high avens and the floor is perforated by large and black abysses. Dropping the least intimidating of the holes, the canyon continuing from *Wassergang* was reached and another big loop closed. The canyon was explored to a depth of 990 m and still continues, but like the canyon in *Auenland* requires dry conditions for further exploration. It was also tried to follow upper level passages above the canyon, but in many places the lack of a floor renders this undertaking rather difficult. The distance to the high aven at the farthest end of *Kolowrathöhle* is about 1.2 km, the level of the passages corresponds very well and at both places a strong draft lures the explorers onward. But at close to two days approach to *Krake* the effort for further exploration is not a whit smaller than in Kolowrathöhle and success will neither be won fast nor easily.

Figure 6. Close to Wassergang the size of the passage shrinks to a low ellipse, which was formed by corrosion of a fossilized layer of algae (Wolfgang Zillig).

5. Fürstenbrunner Quellhöhle (1339/10)

The main resurgence of Untersberg and thereby of all the caves presented so far is found at an elevation of 600 m at the northern flanks of the mountain close to Fürstenbrunn. The mean flow of the resurgence is 750 l/s, during snow melt or after heavy rain a max. discharge of about 15 m²/s may be reached. The way into the mountain is blocked by a 40 m long sump and by a strong gate (since 1875 the resurgence supplies Salzburg with drinking water). In 1976 a second entrance was found (now also gated) and the cave explored to its' present length. The main passage is a big tunnel with a small canyon at its floor, cut by the stream. Close to the main exit of the resurgence the stream sinks into the sump, and only a short distance into the cave it rises from another sump (once dived by Hasenmayer to a short stream passage and more sumps). These sumps may be circumvented by arduous crawls to a higher level of the cave, where at an elevation of 700 m an abundantly decorated passage leads to a final sump. Water level in this sump is known to vary by more than 40 m but the sump was never found dry (Klappacher 1996). Recent observations confirmed, that at normal flow the water level corresponds to the one of the sumps in Kolowrathöhle, nearly 2 km away. This fact and the depth reached in Riesending and even further away at the far end of the plateau in Fledermauscanyon prove the thesis of a nearly homogeneous water table through most of Untersberg. A connection of Fürstenbrunner Qeullhöhle to Kolowrathöhle seems unlikely due to the long and probably quite deep dive necessary.

5. Summary and Outlook

Looking at the recent discoveries in *Riesending* and *Kolowrathöhle* and lately also in *Windlöcher*, a connection of all three caves to a system at least 70 km long and more than 1,150 m deep seems possible. The horizontal distance between *Riesending* and *Windlöcher* is 700 m, between *Riesending* and *Kolowrathöhle* still 1.2 km, but the elevation of the corresponding end points matches well. A hydrological connection is very likely and is proven between *Kolowrathöhle* and the resurgence *Fürstenbrunner Quellhöhle*, but the connecting sumps will probably never be conquered. All hopes lay in the continuation of the fossil passages overlaying the active canyons at the known endpoints of all three major caves. The way to reach these points consists of more than 5 km of strenuous and often very technical passage at depths of 900 m in Riesending and Kolowrathöhle, limiting exploration to week long expeditions. But cooperation is very good and the teams are still highly motivated to scale all difficulties and one day shake hands in the throne room of King Barbarossa, deep down the very heart of Untersberg.

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K´OOX BAAL – 4TH LONGEST UNDERWATER CAVE SYSTEM IN THE WORLD

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In February 2006, members of the Czech Speleological Society started with the exploration of K'oox Baal, 3,5 km long underwater cave system in the Chemuyil area on the Riviera Maya – part of the eastern coast of Yucatan Peninsula, Mexico. These expeditions discovered, explored and surveyed 17 km of new passages until the end of 2008. (Proceedings of 15th ICS, Kerville, USA). Since 2009 they have discovered another 40 km of new passages and connected this cave system with Tux Kupaxa underwater cave system, so the total length of K'oox Baal is now 75,140 m! It is the 4th longest underwater cave system in the world, but thanks to the fact that all discovered parts were immediately mapped, it is the longest completely surveyed and mapped underwater cave system in the world!

1. Resurvey of Tux Kupaxa

The main goal of the expedition in 2009 was detailed exploration and remapping of the Tux Kupaxa cave system, which is located near the south end of the K´oox Baal. Cenote Tux Kupaxa was discovered in 1998 by Gunnar Wagner and Robbie Schmittner, but unfortunately from this expedition there isn´t any preserved information with regards to the length of the cave nor a map. Another cenote located near, was the Sac Xiquin, which was soon connected to the Tux Kupaxa and fully mapped. In the space of one month, 12,828 meters of corridor was mapped and 2017 meters of new space was discovered. The cave of Tux Kupaxa with the length of 15,138 meters became the eighth longest underwater cave system in the Yucatan (Fig. 1).

Figure 1. Main passage of Tux Kupaxa Cave. Foto by Radoslav Husak.

2. Huge tunnels in Balam Ts'al

In 2010 two more expeditions took place. First from January 26th until February 16th, 2010 and the second from November 16th until November 30th, 2010. The first expedition, thanks to a forest fire which the previous year destroyed a large part of the jungle, was discovered ten new cenotes in the area located south of the well known K'oox Baal cave. Our attention was at first directed to an easily accessible cenote, located approximately 200 meters from the road, which begins as an expansive dry cave, where we have found the remains of charred palm leaves from the first visitors. Due to the similarity to the banana leaves we named the cave Ha'a Kak (Banana candle). The first two groups are gradually discovering 2 km of corridors and diving in another of the new cenotes – Muk Wakal. The third group is initially trying their luck in a beautiful, large cenote, but when they failed to find the continuation of the input dome, they carry their equipment to a further positioned smaller cenote located directly next to the path. They named it Kot Be (Under the path) and here they gradually discovered 1,5 km of passages. In the following week we were able to connect the two above mentioned caves to the known cave system K'oox Baal. In the meantime together with our colleague and friend Robert Schmittner, (respected researcher of the world's second longest cave system Sac Actun), we have discovered additional 1,5 km of space in the cenote located the furthest away from all the new ones – Sac Xib (White man) and this we are again able to connect with K'oox Baal. Since the biggest one of the 10 new found cenotes containing a big lake did not lead to the desired continuation, we are also turning our attention to the remote but beautiful complex of three cenotes with several lakes and long stretches of dry parts. Thanks to the number of jaguar's paw prints left in the dust we have decided to call it the Balam Tsa'l – (Jaguar's paw). Already the first dives brought discoveries of unexpectedly large halls with beautiful dripstone sceneries and connection of new cave to canote Kot Be, thus Balam Tsa'l also became part of the K'oox Baal. We have spent the entire final week of the expedition gradually discovering and surveying additional kilometers of

Figure 2. Large tunnel under the cenote of Balam Tsa'l, K'oox Baal Cave System. Foto by Radoslav Husak.

corridors and giant domes. It is not unusual for the width extending in places to 20 meters or more, and the height reaching up to 8 meters. In Balam Tsa'l we discovered the total of 3,6 km, bringing the total length of K'oox Baal system to 28,6 km (Fig. 2).

The second expedition that happened in fall was undertaken as a miniexpedition of two members and their main goal was to find connection between the K'oox Baal cave system and the Tux Kupaxa cenote located nearby. The pair began with a detailed survey of the parts discovered during the spring between Kot Be and Muk Wakal and they were able to penetrate through a set of low crawl spaces to the west, into a larger continuation. In a course of 13 dives, lasting approximately 3 hours each, they discovered and mapped 2,3 km of new space, bringing the total length of the K'oox Baal to more than 30 km and reached the total of 30,933 m. Although the new discovered passages are pointing towards the Tux Kupaxa cave system the connection between the cave systems was not yet found.

Figure 3. Richly decorated passage in K'oox Baal. Foto by Radoslav Husak.

3. Connection

In 2011 two expeditions took place. First from February 1st until February 23rd and second from November 28th until December 10th.They brought extensive discoveries of new spaces and the coveted connection of the two neighboring cave systems.

The first pair turned their attention to the parts that have been discovered in fall 2010 with a clear objective – to find the connection between K'oox Baal and Tux Kupaxa, because according to the map they are located within 20 meters of each other! Alternately they are trying their luck from both sides, finding over 1 km of new passages, but the connection to link them in the maze of narrow channels and manholes cannot be found. The second group started their exploration in Cenote Kot Be, where in the northwest direction can be found many undiscovered branches and gradually they discover this year's first hundred meters of new passages. The third pair headed to cenote Balam Tsa'l, where last year was discovered massive corridor of nearly 4 kilometers and where many questions were unanswered and continuations opened. During the first three dives they find more than 500 m of corridors on the western side. However the character of the corridors is becoming that of tumbled domes that are necessary to swim over or around and unfortunately it is not always successful. The same character is known from virtually all tunnels that are heading west, which suggests the possibility of extensive fracture zone that lays in the direction of NW-SE along large part of the cave. For that reason further exploration in this direction has a little value.

In the course of the second week the first pair continues with extreme dives on the edge of human abilities in order to achieve the connection between K'oox Baal and Tux Kupaxa. Alternately they dive from cenote Muk Wakal, Tres Estrelas and Side Mount and stretch through many other straits, unfortunately without success. The second group completed survey of the northwestern part under cenote Kot Be and moved to join the third group at cenote Balam Tsa'l. Together they explore and map all unexplored branches from the main corridor. In total they add to the length of the cave additional 2 km of passages, mainly flat channels, which is in general the shape of local caves, but in places with rich sinter decoration.

The last week of the expedition, the first pair resigned on finding the link and focused all their efforts on the southernmost part of the K'oox Baal cave system, where we left off a year ago on the doorstep of new unknown tunnels and domes (Fig. 3).

Considerable distance from the entrance now requires the use of underwater scooters and additional tanks. From the last point reached in 2010 massive corridors continue in almost an identical profile for another 500 m, here we were forced to stop the exploration due to the time restrain. The same length was also reached by a significant left branch, where we also did not reach its end. The most interesting thing about these newly discovered passages is their general direction, leading SW to SSW, which is very unusual. Additional half kilometer of passages was discovered in various branches and parallel corridors. Several dives were also devoted to the exploration of a significant corridor that extended out towards the well known corridors of Tux Kupaxa cave and where nearly 300 meters of passages were discovered. The exploration ended in a narrow but high meandering corridor that eventually went into a crack. Due to the complicated access we did not continue in the exploration of this corridor. As it later turned out this passage was significant for further exploration. During the three week expedition we discovered and mapped 7 km of new space and the length of the K'oox Baal reached 36,634 m!

Also the second expedition tried to find the connection between the systems of K'oox Bal and Tux Kupaxa. In three

Figure 4. Passing through narrow passage in Tux Kupaxa Cave System. Foto by Radoslav Husak.

new cenotes – Tan Ich (Glasses), Numya (Passion) a Sac Ktu Cha they gradually discovered and mapped 1,460 m, in some places large and beautifully decorated corridors, but mostly again small narrow channels and manholes, in which they tried to find the connection during the 12 days (Fig. 4).

On December 9th we connected 19,850 meters long Tux Kupaxa cave and 36,741 meters long K'oox Baal cave into one cave system! So the 4th longest underwater cave system in the world was created with the total length of 52,591 meters!

4. Discovery in Chun Che Chen

In 2012 were traditionally organized two expeditions. First from February 8th until March 3rd and second from November 24th until December 9th.

East of the cave system K'oox Baal was 1,300 m long cave located in cenote Chun Che Chen. As in the case of Tux Kupaxa, the Chun Che Cen was first discovered by team of explorers Gunnar Wagner and Robbie Schmittner in 1998. Due to the lack of maps of the cave we decided to measure again the entire polygon and draw a map of the area. Another reason for mapping of the entire area of the polygon again was that its premises were located less than 100 meters from the end of K'oox Baal.

During mapping we found extensive sequences in several different parts of the cave. Three large tunnels in the newly discovered section lead north and within we gradually discover 5 km of new, very rugged and diverse space! Great halls alternate with narrow restrictions, austere rock tunnels with chambers richly adorned by sinter decorations. During the following week after several dives in extreme straits we finally managed to connect the Chen Chun Che to K'oox Baal, thanks to which the length of K'oox Baal exceeded 60 km! The remaining time of the expedition was devoted to continuation of exploration in the southern and southwestern parts, first discovered in 2010, where still are great passages undiscovered even after the discoveries in 2011. The only complication is the great distance from the entrance and therefore limited time for survey due to the transportation of large quantities of bottles. In spite of that during five dives we discover additional 2 km of new huge tunnels and the length of K'oox Baal reaches 64,600 m! At the end of the expedition we organize several trips into the jungle with the goal of finding new entrance, which would facilitate an easier access to the southernmost part. After few days we find a great cenote with several lakes and after the first dive in one of them, we reach without a problem K'oox Baal. We decided to call this cenote Shaman EK, according to the sign on the corner of the property.

The second expedition started the survey in the cenote Shaman Ek, from where it is closest to the southeast part of the cave. This cenote is accessible using only very badly maintained road that is more than 3 km long, which greatly prolonged the transport of diving materials. Initially, it was possible to continue the exploration through large tunnels, which meant first kilometers of discoveries. Unfortunately the tunnels abruptly ended and we had to continue systematic survey of all branches. The idea of easy continuation south was quickly reduced to slow crawl through narrow passages. The same way ended the attempts on the north side. The only direction, in which the corridors were free to continue, was west to a distance of one and a half kilometer from cenote Shaman Ek. In the end, during the two weeks we were able to discover another 9 kilometers and two new cenotes. The total length of all the underwater parts of the cave is 73,600 m. Together with some dry parts the total length of the K'oox Baal system is 75,140 m! (Fig. 5).

5. Summary

K´oox Baal is the longest completely mapped and drawn up underwater cave system in the world. The other three longer underwater cave systems are polygon measured but only partially mapped. Between 2009 and 2012 Czech Speleological Society organized seven expeditions to the K´oox Baal and follow people participated: Miroslav Dvořáček, Petr Chmel, Martin Honeš, Radek Husák, Daniel Hutňan, Martin Hutňan, Radek Jančar, Michal Megela, Zdeněk Motyčka, Jan Sirotek, Kamila Svobodová, and Karol Kyška.

Acknowledgments

Special thanks to QRSS – Bil Philips and Jim Coke for their support and Robbie Schmittner, Nadia Berni, David Sieff for their friendship and help.

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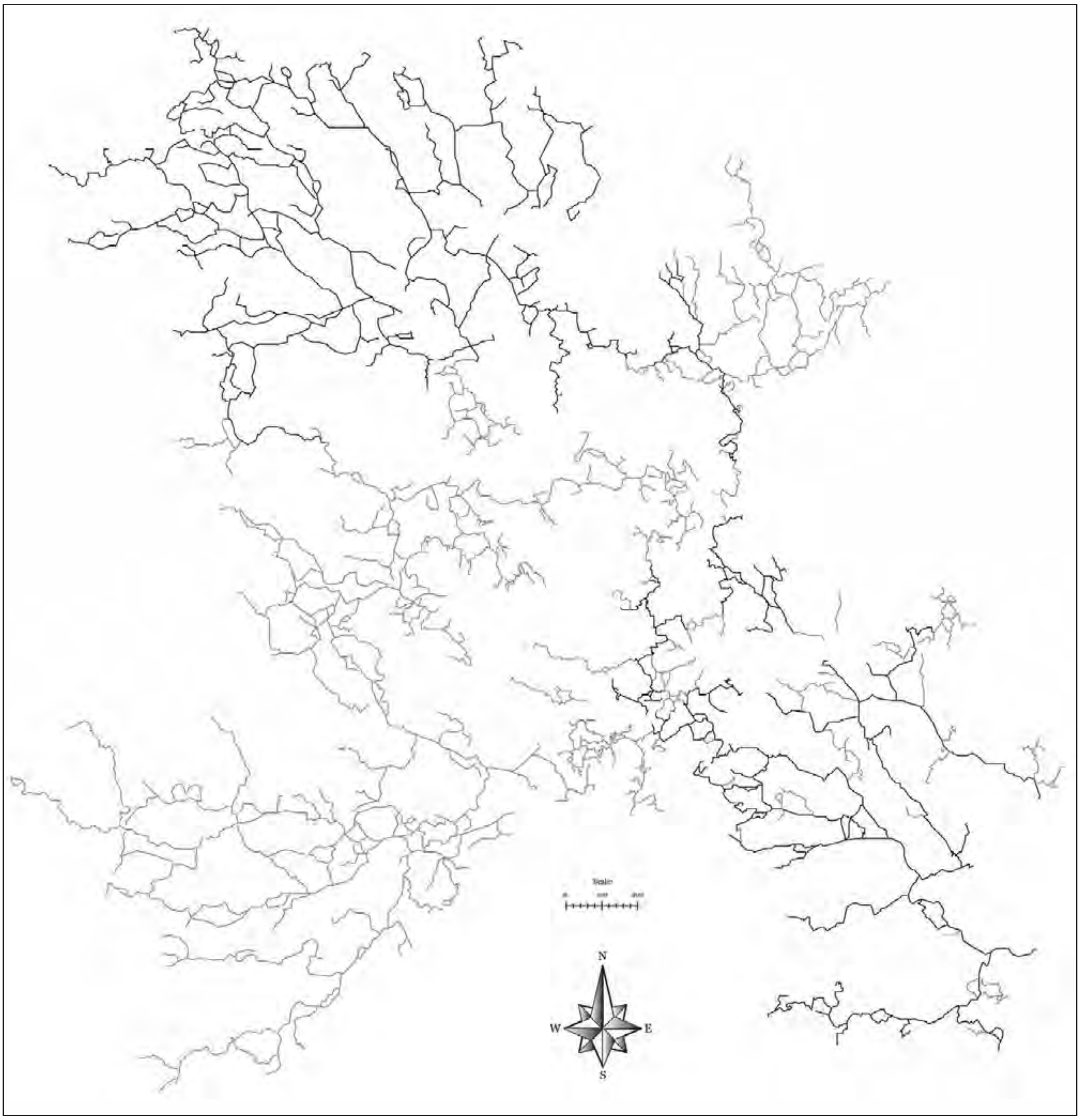

Figure 5. Complete map of K'oox Baal as of December 9, 2012. Explored and surveyed by members of Czech Speleological Society, Slovak Speleological Society and Quintana Roo Speleological Survey. Darker lines represent passages known until 2008. The lighter lines present new discoveries since 2009.

GEOLOGY AND DEEP VERTICALS: CASE STUDY FROM MAGANIK MTS., MONTENEGRO

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The formation of deepest karst vertical shafts in the world has been probably controlled by similar geological factors. Universal factors include convenient lithology and hydrological or precipitation potential. The study from Maganik Mts. shows substantial difference between the “density” of deep vertical shafts at the area of flat, subhorizontal beds and the area of duplexes, folds and faults. The first area displays dense network of deep vertical shafts the depth of which is controlled by thickness of flat bedded limestones and by subvertical joint sets. When the vertical shafts bottomed at calciturbidites with shale rhythmic interbeds, the shape of cave quickly changed to meanders and lower vertical steps.

1. Introduction

The topic of the paper is as we hope universal for karst areas all around the world. The area of study seems to be favourable for understanding the processes and circumstances especially because of excellent visibility and absence of confusing younger sedimentary cover. The surface and underground observations and documentations continue at the area for several years and every season brings new pieces of knowledge and discoveries.

2. Geography and geology

Maganik Mountains at Montenegro belongs to one of most famous karst areas of Dinarides, the High Karst. It is situated less than 100 km NE from Boka Kotorska, Adriatic Sea in close eastern vicinity of Nikšič town (Fig. 1).

The terrain of the High Karst Zone is built up of Triassic, Jurassic and Cretaceous carbonates several km thick. Reverse faults and thrusting cause even higher thickness.

Figure 1. Location map (width 30 km) of the explored area.

High Karst is characterised by all surface occurrences and all processes characteristic for holokarst.

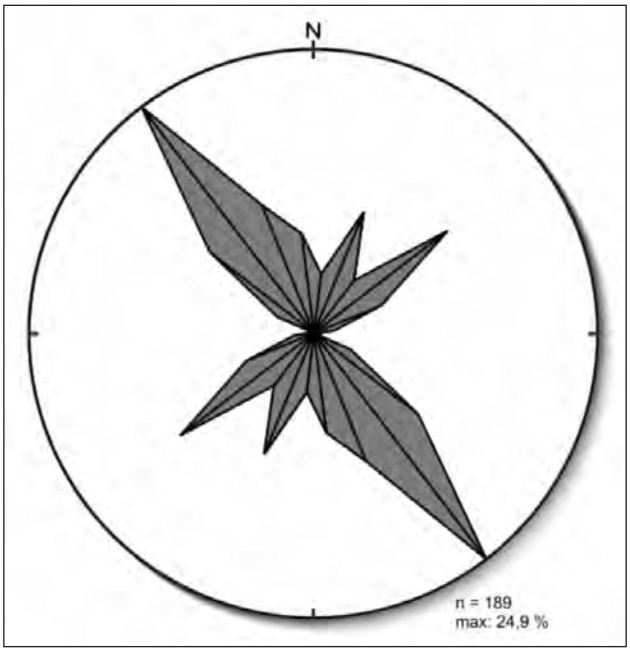
Maganik itself is about 20 km long and 10 km wide mountain range situated in the central part of Montenegro. It is surrounded and drained by rivers Zeta in the south and Mrtvica and Moraca in the north. The Maganik massiv streches generally in the NNW-ESE direction and orographically it is separated form Moracka Planina in the north and Prekornica mountain in the south.

The eastern part of Maganik Mts. is built of shallow water platform Upper Cretaceous carbonates (Pajović 1999). It is an area of great potential for vertical systems. The precipitation mostly exceeds 3,000 mm per year, the highest parts of the limestone massif is rising over 2,000 m a.s.l. and the resurgences are situated around altitudes of 300 m a.s.l.

3. Tectonic overview

The area of interest is just several square kilometers, nevertheless there is substantial difference between its NE and SW parts (see Fig. 2 and Fig. 4). The NE part represents a slightly dipping table mountain of Trešteni vrh, which is considered from the structural viewpoint as a parautochonous part of the area. On the other side the SW part of the section, the massif of Mededi vrh, is in its upper part undoubtedly allochtonous block divided from Trešteni vrh by a duplex (thrust) fault (Fig. 2).

Figure 2. A view to SW from Trešteni Vrh to Mededi Vrh: Flat bedded limestones in the front (A) and folded and faulted duplex of Mededi Vrh at the horizon (B) – contrast between conditions for vertical shafts evolution.



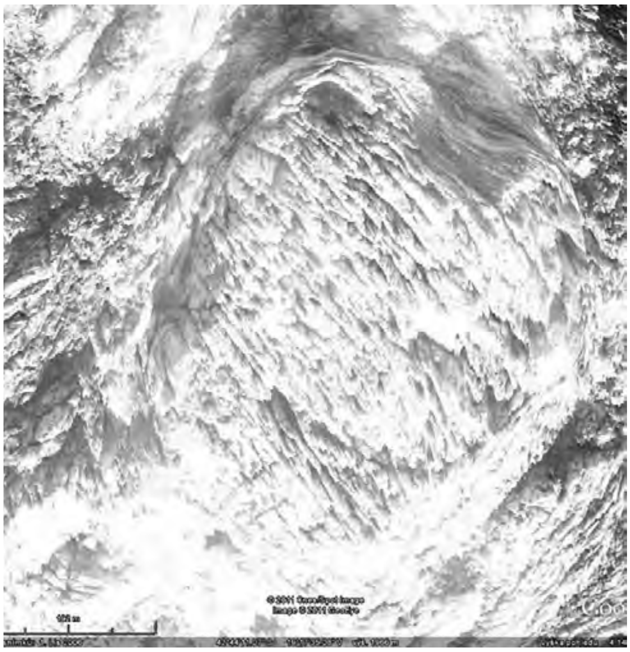


Figure 3. Left: Rose diagramm of subvertical joint system at the terrritory of Trešteni vrh parautochtonous subhorizontal limestones. Data plotted on Lambert lower hemisphere, SW Statect version 2012, courtesy of Jiří Rez; right: Aerial Google view of Trešteni vrh joint pattern. The width of lower side is 1,500 m.

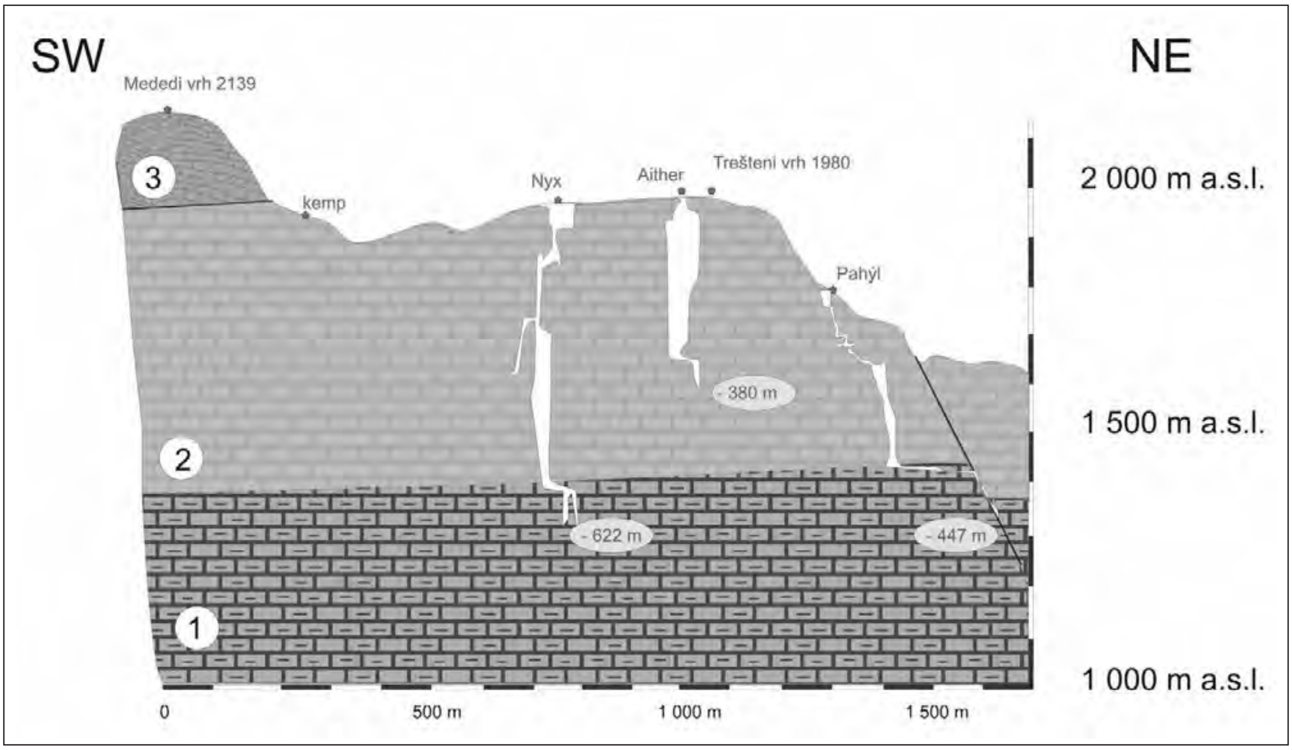


Figure 4. Geological sketch cross section with position of vertical shafts (courtesy of Z. Dvořák and P. Čáslavský).Explanation: 1 – para-autochtonous Cretaceous calciturbidites (interbedding of limestone and shale); 2 – para-autochtonous Upper Cretaceous thick bedded limestone; 3 – allochtonous limestone of the Mededi vrh Thrust.

There is a more detailed contribution on the speleological exloration activities during the season 2012 inside the Proceedings. The most interesting of it is the prolongation of the Pahýl Abyss (see NE part of the Fig. 4) over 1,000 m – contemporary name "Iron Deep", total depth 1,027 m.

4. Discussion and Conclusions

Comparison of density of deep vertical shafts between the thrust of Mededi vrh and the table mountain of Trešteni vrh, Maganik Mt. Montenegro, resulted strongly in favour of flat-bedded para-autochtonous limestones of Trešteni vrh. It is explained by favourable lithology and by favourable structural conditions. Similar lithotectonic pattern was described earlier e.g., in Palmer (2007). System of subvertical joints (see Fig. 3) controlled the origin of many vertical one step shafts. The 429 m step in the Abyss of Nyx and 351 m deep step in the Abyss of Aither belong to the deepest shafts in Europe (Dvořák 2011).

The conclusion for explorative speleology is thus quite clear:

Generally good conditions for the origin of deep caves include high precipitations, pure limestone, high difference of altitudes between ponors and resurgences. The structural circumstances are often complicated and changing within the system.

The finds of deep vertical steps are most hopeful in subhorizontal thick bedded pure limestones with subvertical system of jointing (Fig. 3). Shafts in limestones of such tectonic pattern are prone to cut the whole thickness in one step. There are many examples among well known shafts, e.g., Provatina, Vrtiglavica, etc. On the other side the change of favourable lithology downwards, e.g., presence of thin bedded marly limestones, calciturbidites, shale intercalations, thrust zones and planes results in substantial change. The cave morphology characterized by meanders, subhorizontal passages, narrows and lower steps are controlled by different mechanical properties and rate of dissolution of the bedrock.

Acknowledgments

Our thanks belong to members of Suchý žleb Caving club, Czech Speleological Society, and all participants of Maganik expeditions and to friendly local farmers in Maganik. Preparation of this paper was supported by the project No. 321100 of the Czech Geological Survey.

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KAČNA JAMA (THE SNAKE CAVE) – DIVAČA, SLOVENIA

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Systematic research of water cave system Reka (SLO) – Timavo (IT) in the Classic Karst of Southern Europe.

Figure 1. Entrance hall, photo by Borut Lozej.

1. Kačna Jama research 2004–2012

We came to the region of Classic Karst in 2004, when our speleoclub Plánivy initiated a co-operation with the local speleoclub Gregor Žiberna from Divača. Our interest aimed to Kačna Jama, which was a 12.75 km long cave system flowed through by the Reka River. This river sinks in a UNESCO's World Natural Heritage cave Škocjanske Jame, which is famous for its 2 km long, gigantic underground canyon. The Reka River disappears here in a terminal siphon and after 0.75 km reappears again in Kačna Jama where it forms a complex labyrinth of corridors and galleries. Kačna Jama is the last cave of the system, where long galleries formed by the river are known. Other abysses leading from the surface to the active river level are located 6 km far away, but they reach only short parts of the active Reka River delimited by complicated siphons.

After the first easy visits to Kačna Jama, we decided to organize an expedition with help of other clubs from the Czech Speleological Society (CSS) aimed at the outflow section of the cave – flood draining corridor. In summer **2005**, during a one week event we passed almost through the whole section, but we stopped above a 12 m deep pit, 350 m from the terminal siphon in Cimermanov Rov. We turned back because of a difficult progress and a lack of rigging material. As a conclusion, we found this part of the cave very interesting for research, but also very dangerous because of risk of fast flooding. In **2006** we tried to find upper entrance to these outflow parts from surface localities, but with no interesting results.

In **2007** we came back to Kačna Jama into the Zahodni Rov (Western Corridor) branch, which was approximately 450 m long, and had been known from the end of the 19th century. In the opposite direction to Zahodni Rov, there is Vzhodni Rov (Eastern Corriodor), which leads to main continuation of the cave with the Reka River active flow. The length disproportion between the two corridors was the reason, why we attacked a roof formed by fallen boulders in the remote parts of Zahodni Rov. We went through a place with periodic draught, and this place brought us to an unexpected discovery of two big domes with very high ceiling. Their length is about 100 m. Above the second dome, we climbed up a 45 m high canyon-like chimney, where we discovered a great horizontal level full of wonderful decoration, called Clean Area, which ends up in the distance of 100 m by a sinter and mud plug. At the right wall of this corridor a deep shaft was located. We descended there to the depth of 75 m. The bottom with many draining clefts was marked by frequent floods. A corridor in the lowest point leads to a small dome with a siphon. In summer 2008 it was dived through by **Ivo Záruba**. Behind the short siphon we passed through a draining corridor that led approximately 200 m from the P75 shaft. On this occasion we discovered other inflows from an unknown part of the cave system but of a small cross-section. This place is located about 20 m above the active river level but it is very complicated to reach this terminal point. The research of this area has been stopped in 2009. We named this place **Plánivský Rov.**

The most remarkable result of year **2008** is a discovery of a 200 m long **Plzeňský Rov** (Pilsner Corridor), because it brought in new knowledge about a hydrological situation in Kačna Jama. This corridor is situated almost under the entrance abyss and it ends up by cave-in. At the end of Plzeňský Rov we got to the 400 m straight line distance from the terminal siphon where the active flow of the Reka River is vanishing in a gigantic underground cave-in.

Figure 2. Plánivský rov – Clean Area, photo by Petr Polák.

Perhaps there is the most hopeful chance of discovery of further continuation of the active Reka River here. From 2008 on, we started to cooperate with other members of CSS and hungarian cavers from Papp Ferenc caving club and FTSK from Budapest in our research of Kačna jama. Also other foreign cavers have been joining our summer expeditions.

1.1. International expedition Kačna jama – Reka exploration 2009

concluded with a great success. Czech, Moravian and Hungarian speleologists succeeded to discover a prolongation of the flood draining corridor. Two experienced cavedivers, **Jan Enčev** and **Pavel Říha,** managed to achieve this discovery behind the terminal siphon of Cimermanov Rov (Cimerman's Corridor), the remotest and the worst accessible part of the cave system. On July 6, 2009 the divers set off from this point for the historically first exploration of the final siphon, despite these places had been known since 1972. Each diver was equipped with 4 independent air containers with 24 litres/ 300 bar of total volume. They returned after three and a half hour. Behind the siphon they discovered a gigantic corridor with average width of 15 m and height of about 30 m. They advanced almost 700 m. The divers turned round in the point where the bottom of the corridor was covered by rocky blocks (approximately size of a bus). They turned in a 20 m wide and 30 m high corridor. We named the discovery **Rov za Zrcalom** (Corridor behind the mirror). The second week of the expedition the team spent time with retransporting of all the stuff. There were little summer storms which increased the underground Reka River flow rate from 2 to 14 cubic meter per second and the water level rose by approximately 3 m. We used our safety fixed ropes for a retreat.

1.2. International Expedition Kačna Jama Reka Exploration 2010

successfully tested some few world innovations in caving equipment. Among them it was a DistoX digital survey set which can greatly speed up the surveying process. Two devices for wireless communication between underground and surface stations (Heyphone and Cavelink) made the key part in achieving a significantly higher safety standard during the Kačna Jama exploration. Finally the most effective was Cavelink that is a special sophisticated device aimed at short message communication even in very difficult surface and underground conditions. It can use multiple frequencies for its operation, and this was the best solution for us in an environment, where a lot of high voltage overhead lines is present on the surface.

The main aim of the expedition was to continue in the exploration of the recently discovered Rov za Zrcalom, where we found another 330 m of passages that led to a siphon. Over 1,000 m of gigantic underground space was surveyed and photographic documentation of dominant features was made as well.

In Rov Človeških Ribic (Corridor of Protei) located near the entrance abyss, diver **Jan Enčev** documented the second inflow siphon was documented by means of diving technique to the distance of 370 m from the entry point of the dive. This amazing distance exceeded the previous achievements by 200 m. Maximum depth of 20 m was reached in the terminal section.

Figure 3. Rov za zrcalom, photo by Petr Polák.

1.3. International Expedition Kačna Jama Reka Exploration 2011

with over fifty participants carried out diving through the second siphon, at that time the known end of Rov za Zrcalom.

On Thursday, August 4, the principal diver, **Jan Enčev** plunged into the so far unexplored water. Two hours later he was back with 340 m of line unreeled but without contact with free surface. Maximum dive depth was about 22 m and the most distant point showed signs of decreasing depth.

On Sunday, August 7, he dived again with full dive bottles and after 415 m of underwater passage with bad visibility he emerged in a spacious dome. This cavity is 150 m long, 30 m wide and 12 m high with corrosive ceiling and with a pool along almost whole right wall. After a plot of survey polygon was made, it was evident that because of bad visibility the diver made some unnecessary turns and the real length of the second siphon is about 325 m.

Figure 4. Rov za zrcalom – 2. siphon, photo by Petr Polák.

The discovered corridor passes to the third siphon. Jan dived again and the siphon turned out to be 90 m long and 10 m deep. Next free cavity is 115 m long, 13 m wide, 22 m high and its flat bottom is formed from gravel. It ends up in a 25 m long lake with the fourth siphon. With respect to remoteness of this point, Jan didn't proceed to any further and returned back to the rest of the company.

Overall length of the newly discovered passages is 768 m and its general direction leads to the vicinity of Povir village. In addition to the main effort, a documentary was filmed and some side branches of the cave system were surveyed with digital set and Pocket Topo software. Also a chimney above Lojzov Podor that was climbed up +120 m during the two previous expeditions was de-rigged, because it didn't lead to a prospective terrain.

Figure 5. Diver Jan Enčev, photo by Petr Polák.

During winter expedition of the beginning of 2012, our diver Jan Enčev made an incredible diving attempt was taken in the middle parts of Kačna jama, called Okretnica. Here a small brook disappears to an unknown siphon. The diver found there another free continuation after the first 15 m long siphon with a final 2 m deep jump into the next lake with water level of second siphon. Here he also made an exploration. He turned back in small flooded corridor filed by a cave-in and trees. Completely he discovered about 70 m.

1.4. International expedition Kačna Jama Reka Exploration 2012

wasn't interested in seriously oriented diving in the end parts of Kačna Jama, but the main aim was to climb up a chimney above Slabeto lake (close to Cimermanov Rov). There we felt a possibility of finding some upper level and then continuation to the surface. Unfortunately we got just to the height of 90 m above water level and here we were stopped by a sinter formation which closed further continuation. Another window and a few interesting chimneys above Slabeto lake were left for the next time. Our international team mapped the active outflow corridor Ozki Rov, which terminates by a cave-in. For the first time, we visited parts around Saturn abyss and did a digital mapping of Hojkerjeva Dvorana.

On the surface, we dug a promisingly looking breathing spot called Vitkuv Dihalnik. At the end of 2012 we were here in the depth of around 10 m. Luckily, we were present at the place just while the Kačna Jama system was being flooded up, and we observed very strong draught here that continued for 2 hours. This filled us with a hope that this digging would lead to the lowest level of the system and could be eventually used as a short cut for a transport of the diving stuff. We will see how lucky we will be there!

For 2013 we plan a detailed research of Hojkerjeva Dvorana and, if a dry weather permits, also the Ozki Rov outflow corridor.

2. Kačna Jama official length:

1889 1,900 m
(first descent, Zahodni Rov and Vzhodni Rov)
1972 8,600 m
(Reka River, outflow section up to Cimermanov Rov)
1997 12,750 m
(section from behind Ogabno Jezero siphon – Novi Deli to the intake siphon)
2007 13,250 m
Plánivský Rov +500 m
2008 13,750 m
Plánivský Rov +300 m, Plzeňský Rov +200 m
2009 14,450 m
Rov za Zrcalom +700 m
2010 15,100 m
Rov za Zrcalom +330 m, 2nd siphon Človeških Ribic +200 m, chimney in Lojzov Podor +120 m
2011 16,068 m
Povirski Rov +768 m, intake siphon and continuation + min. 200 m (Slovenian team)

Total length of Kačna Jama is over 16 km (2012).

Figure 6. Rov desetih jezer, photo by Jindřich Dvořáček.

3. Credits also:

To all participants from the Czech Speleological Society for their contribution to the expedition. It wouldn't be feasible without that.

Thanks to our Hungary and Slovenian caver friends for cooperation!

Many thanks to the Gregor Žiberna local club for offering a refuge, lending a material, for a help with the realization and for an opportunity to carry out a research in their home territory.

If you would like to make an earnest expedition to Kačna Jama, please contact the local club at: http://www.divaska-jama.info/kontakt_os.htm

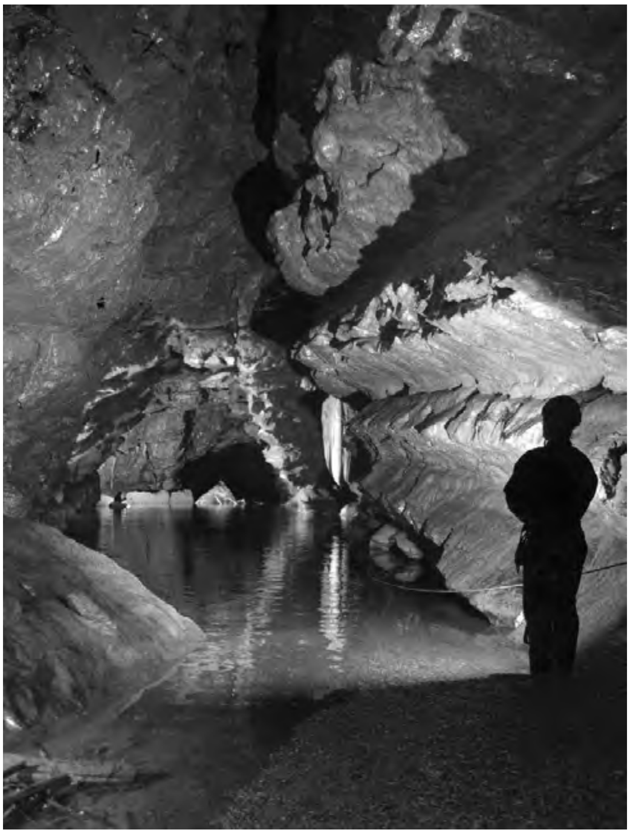

Figure 7. Active Reka River, photo by Jindřich Dvořáček.

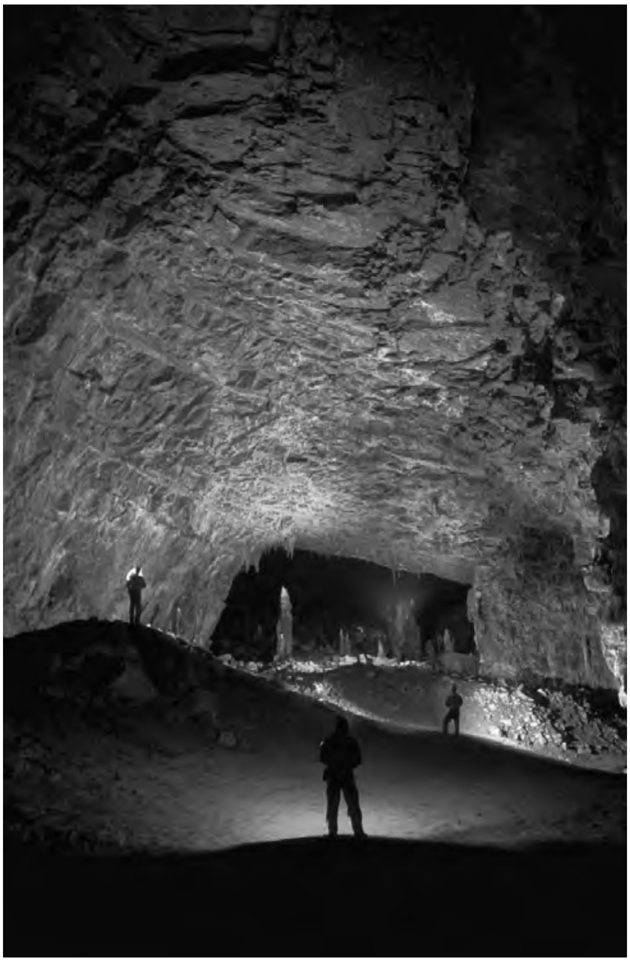

Figure 8. Vzhodni rov, photo by Csaba Egri.

4. Glossary

Rov = Corridor

Podor = Cave-in

Dvorana = Dome

Dihalnik = Breathing spot

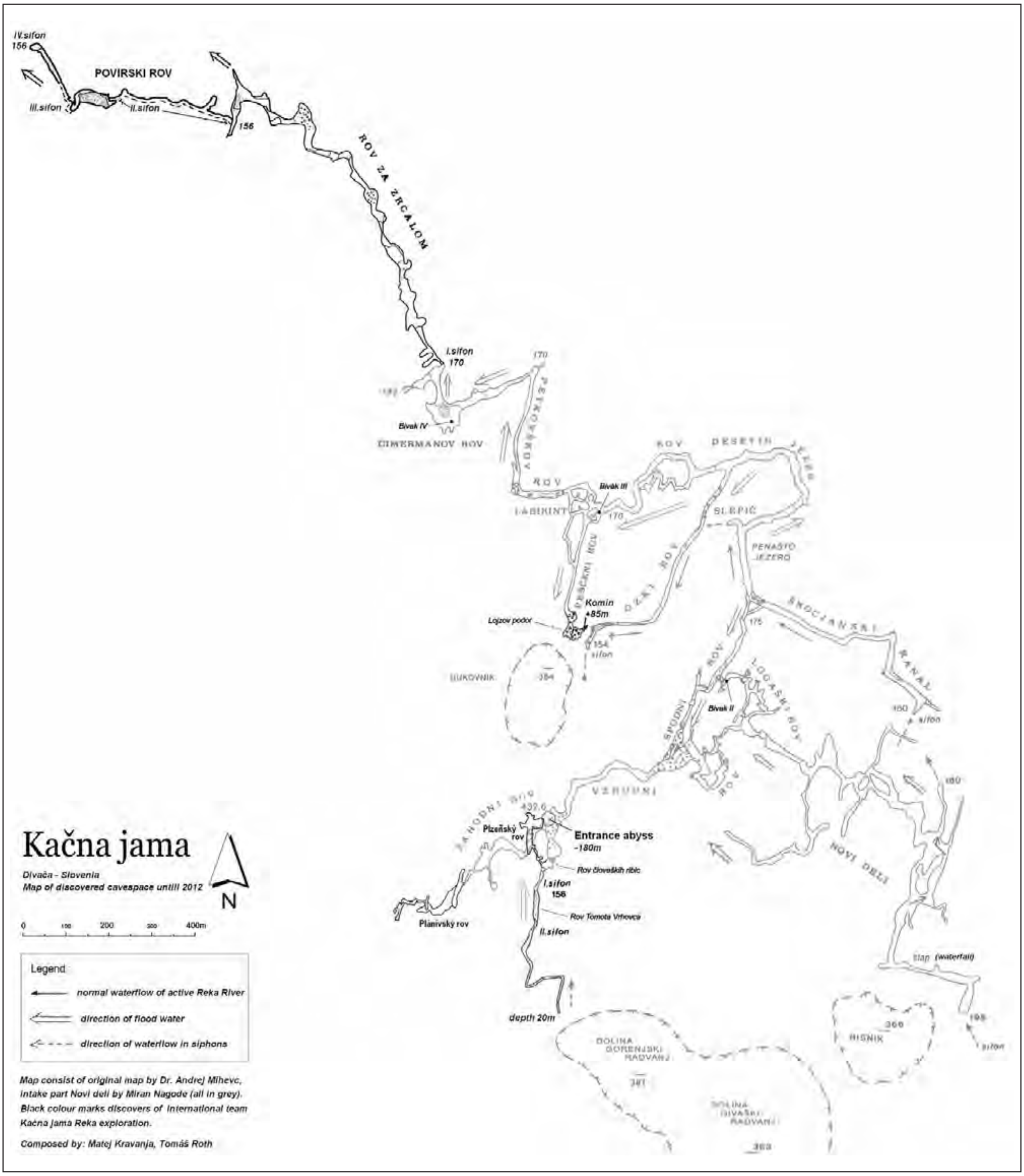

Figure 9. Map of actual known cavespace of Kačna jama system.

IMAWARÌ YEUTA: A NEW GIANT CAVE SYSTEM IN THE QUARTZ SANDSTONES OF THE AUYAN TEPUI, BOLIVAR STATE, VENEZUELA

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In February 2013 a new huge cave system in quartz-sandstones has been discovered in the eastern sector of the Auyan Tepui, Venezuela by an Italian-Venezuelan team (La Venta Esplorazioni Geografiche and Teraphosa Exploring Team). In twelve days of exploration over 15 km of passages were surveyed and other 4 km were explored. The system has nine entrances and hosts three rivers giving rise to three resurgences. The cave passages belong to two levels, an active one in which the rivers flow with a general and gradual WNW trend, and a inactive level located from 4 to 20 metres higher with a N-S direction. The active levels are lithologically controlled whith typical pillars, potholes and wide and rounded bedrock channels with very scarce sediment fill. The inactive level instead hosts large quantities of secondary minerals, mainly sulphates-phosphates, and very nice and rare opal and silica speleothems. Flowing, drip and standing waters have been analysed in situ for their Si content and many morphological observations have been carried out in order to try and understand the speleogenesis of such large quartzite caves. Further geological, mineralogical, geomicrobiological and biological studies are required in this exceptionally interesting quartzite cave.

1. Introduction

About twenty years ago cavers and karst scientists believed that speleogenesis of caves in the quartz-sandstones of the tepui mountains (Bolivar State, Venezuela) was related to exceptional conditions and only of local importance. In the 80s and 90s the exploration of deep and wide shafts called “simas” was explained as the result of arenisation processes along open fractures close to the high cliffs surrounding the plateaus. In these decades the researches didn’t investigate the inner sectors of the plateus believed to be less promising for the discovery of caves.

Since 2000, instead, several horizontal cave systems have been explored and obviously this required to rediscuss the speleogenesis of quartzite caves (Aubrecht et al. 2011; Aubrecht et al. 2013; Sauro et al. 2013). After the exploration of kilometre long caves in the Roraima and Chimantha massifs (Galán et al. 2004; Sauro 2009; Brewer Carìas and Audy 2011), in April 2013 a new giant cave, named Imawarì Yeuta (the Cave where the Gods live in Pemon Kamarakoto indian language) was discovered by an Italian-Venezuelan expedition on the Auyan Tepui in the Canaima National Park. This exploration suggests that well developed and extensive underground drainage systems probably occur below the surface of most of the tepuis in the Gran Sabana area. Speleological investigations in the quartz-sandstone mountains of Venezuela and Brazil seems to be only at the beginning.

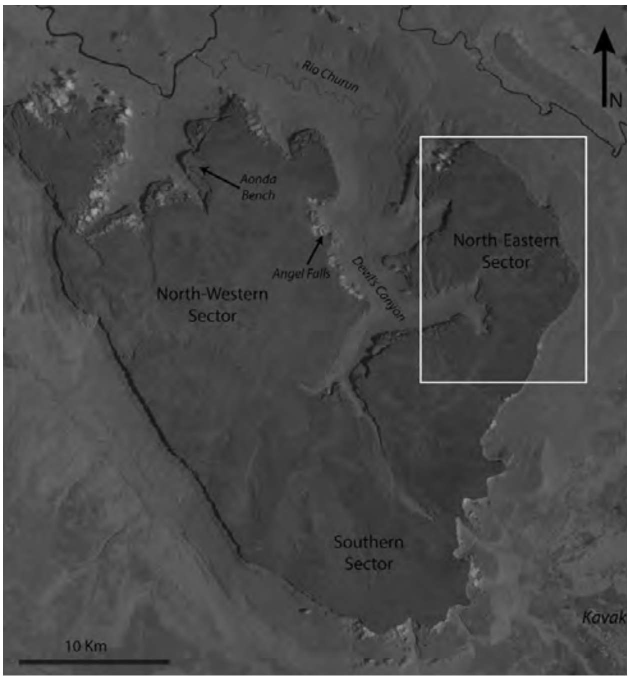

Figure 1. The Auyan Tepuy from a Landsate image. The bounding box represent the North-Eastern sector of the tepui.

This article shows the main results of the expedition “Auyan Tepui 2013” and the scientific researches planned for the future.

2. Geographical and geological settings

The Auyan Tepui is one of the largest table mountains of the Gran Sabana area (700 km^2, Fig. 1), well known for the presence of the Angel Falls, considered the highest waterfall in the world (975 m).

The Gran Sabana is a vaste geographical region located in northern South America, between Venezuela and Brazil, crossed by several tributaries of Rio Caroní, which in turn flows into the Orinoco River. The Auyan Tepui has the shape of a large table mountain delimited by vertical to overhanging walls, often more than 1,000 m high. In plan view it looks like a triangle pointing to the south. In the inner part the Canyon del Diablo separates the north-western sector from the north-eastern one, while the southern part is a continuous plateau reaching its highest elevation at 2,450 m asl.

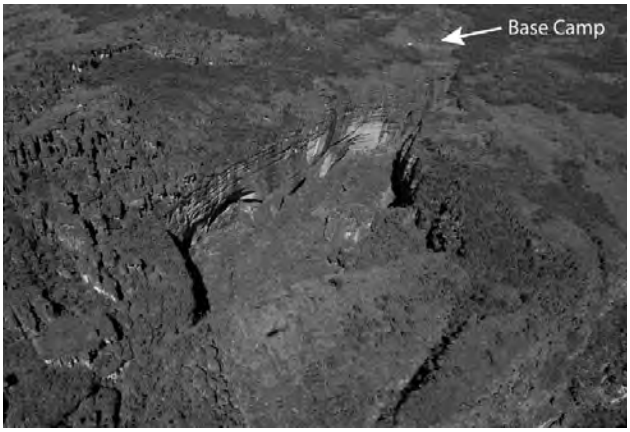

Figure 2. The large collapse of Sima del Viento represent the main entrance of the Imawarì Yeuta Cave. Photo by F. Sauro.

From a geological point of view the Gran Sabana is part of the Guyana Shield. The igneous and ultra-metamorphic rocks in the northern portion of the shield (Imataca-Bolivar Province, after González de Juana et al. 1980) have an age of 3.5 Ga. The silico-clastic rocks (Roraima Group) belong to the continental-to-pericontinental environment of the Roraima-Canaima Province (Reid 1974). The age of this arenaceous group can be inferred only on the basis of the absolute dating of the granitic basement (2.3–1.8 Ga) and of the basaltic dykes and sills that cross the upper formation of the Roraima Group (1.4–1.8 Ga) (Briceño and Schubert 1990; Santos et al. 2003). The Roraima Group was also intruded by Mesozoic diabases (Hawkes 1966; Teggin et al. 1985). These form thin NE-trending dykes with ages around 200 Ma.

A slight metamorphism, with quartz-pyrophyllite paragenesis in the more pelitic beds, is the result of the lithostatic load of almost 3-km-thick sediments now eroded (Urbani et al. 1977).

3. Brief history of speleological explorations in the Auyan Tepui

The presence of caves in the Auyan Tepui is reported already during one of the first ascensions of the mountain, the expedition of Felix Cardona Puig and the italian geologist Alfonso Vinci in December of 1946 (Vinci, 1957). The cave explored and described by Vinci was never found again (Merlak, 2010).

The first speleological expedition, with helicopter support, was realized in 1983 by the Sociedad Venezolana de Espeleología, with the main aim to explore the Sima Aonda (Fig. 1), previously known thanks to aerial surveys in the NW sector of the massif. With its 362 m of depth this collapse was considered the world deepest quartzite cave until 1993, even if it consists of an elongated depression and not a true shaft.

Most of the expeditions carried out in the years after were basically concentrated in this area where the SVE explored several other deep “simas”, such as the Sima Auyantepuy Norte and the Sima Aonda Este 2.

In 1992 an Italian expedition organized by four caving clubs (CAI SEM Milano, Castellanza, Laveno and Cividale del Friuli) works on the upper Aonda platform and explores several caves summing up to 1,700 m of development. The same year La Venta carries out a first aerial recognition in the Aonda area in order to organize a future expedition. The year after a big expedition organized by La Venta works in three different areas of the same western sector: in Camp Aonda, the team descends Sima Aonda and explores the active horizontal system at its bottom (Ali Primera Cave) and other deep shafts of the platform; in Camp 1, slightly NE, Sima Churun (Sima Auyantepuy Norte 2) is explored, and in Camp 2, moved further W, Sima Auyantepuy Noroeste is discovered, becoming the deepest and longest quartzite cave in the world at that time (3 km, -370).

In 1996 La Venta organizes another expedition in the Aonda area, exploring several other simas and connecting Sima del Bloque to Ali Primera, realizing a cave system 352 m deep and about 2 km long. In 2010 a short prospection to the south-western plateau allowed to find and explore the Cueva Guacamaya (1.1 km), the first horizontal cave found in the Auyan Tepui, presenting peculiar morphologies similar to those described in the cave systems of the Chimantha massif.

Before the expedition of April 2013 a total of about 10 km of cave passages were explored on Auyan Tepui, but exclusively in the western part of the massif. The southern and eastern sectors were completely unknown from a speleological point of view.

4. The expedition Auyan Tepui 2013

The joint Italian-Venezuelan expedition on Auyan Tepui took place in March 2013. The expedition was organized by La Venta Esplorazioni Geografiche together with the Teraphosa Exploring Team from Puerto Ordaz city. Ten cavers (7 from Italy and 3 from Venezuela) and two park rangers from InParques took part to the expedition. The main aim was to explore the southern and eastern sector of the mountain, with several unknown entrances located during previous flights by the helicopter pilot Raul Arias.

The expedition was based in Kavak and a helicopter supported the installation of the exploration camps on the plateau. A total of 12 days of exploration activity was carried out on the mountain. A first group reached an entrance which opens on the eastern wall of the mountain, suspended nearly a thousand metres above the surrounding plain. Unfortunately the impressive opening revealed only a short gallery about sixty meters length. The same day another group descended a big collapse, named Sima del Viento (Fig. 2), apparently close to the bottom. After several hours of research, finally a narrow passage in between big boulders led to an impressive active gallery. In the days after a new camp was installed on the border of the collapse, allowing a continuous work of exploration, survey, documentation and scientific researches. After only four days about 5 km were surveyed, following two main rivers (Fig. 3). The exploration led quickly to two further entrances, named Mundo Perdido and Grieta de Los Guacharos. In the meantime the structure of the cave suggested the presence of another river to the north-west, in direction of a giant collapse doline. The supposed river was finally reached from inside the system through a labyrinthic network of fossil galleries. An underground

Figure 3. Gallery along the "Rio de los Venezuelanos". Photo V. Crobu.

camp of three days permitted to survey about 10.5 km of new galleries, with huge rooms (the biggest 270 metres long and 150 metres wide), complex labyrinths and other three new entrances. Finally the total surveyed length reaches 15,450 metres, thanks to the use of the Polish CaveSniper instrument (www.caveexplorer.eu). About other 4 kilometres were explored but not surveyed because of lack of time. Imawarì Yeuta represents one of the world's longest quartzite caves explored until now, consisting in a unique cave not divided by valleys, collapses or "grietas". The structure of the cave is quite complex but the main hydrological routes draining the plateau are already well clear (Fig. 4). Only the network of no more active branches needs to be better explored and documented.

The expedition recovered all the wastes produced and also all the faeces from the cave and the surface of the tepui to avoid microbial contamination. The exploration was carried out using always the same trail to limit our impact on the vegetation going to the cave and on the fragile cave floor, in particular in the fossil branches.

5. The cave Imawarì Yeuta

The new cave consists of three hydrologically independent collectors (Fig. 5), two of which coming from the big sinkhole of Sima del Viento, while the other one derives from the catchment area of a large collapse doline to the north, about five hundred metres wide, and of a nearby smaller sinkhole. Here a stream falls into the cave with a waterfall about 90 metres high. During our explorations, carried out during a particularly dry period, the first two streams had a minimum discharge of about 20 l/s, while the main river reaches a minimum of 100 l/s. From the signs left by water on the walls it is clear that this last river can probably reach several cubic metres per second during floods. The direction of drainage is in general from ESE to WNW following the dip of the sandstone beds. A labyrinth network of inactive galleries, developed along an evident bed, interconnects the different rivers. This "open" bed can reach impressive width (more than 300 metres in some sectors) creating huge environments where the ceiling is supported only by random pillars. This situation causes large collapse zones with chaos of fallen boulders. In some cases the fossil galleries show palaeo-phreatic rounded morphologies and are in general almost perpendicular to the actual vadose drainage.

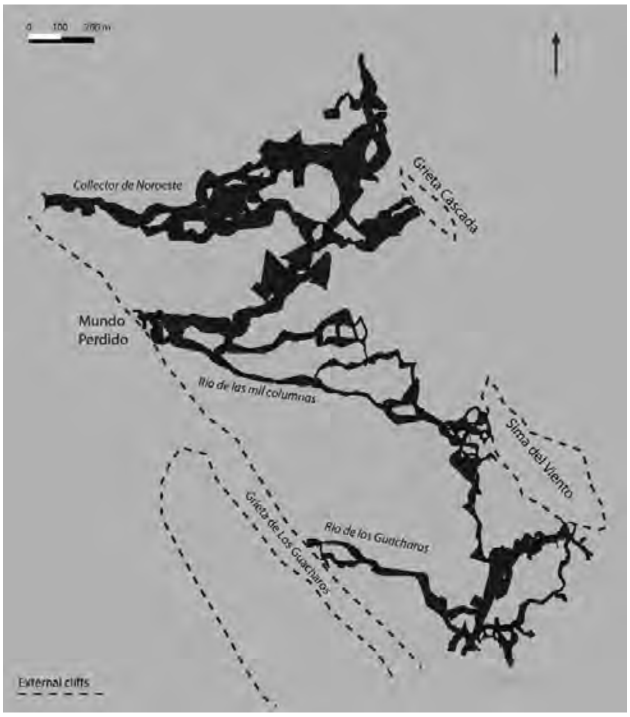

Figure 4. Preliminary sketch of the cave plan obtained using the Cave Sniper instrument.

One of the most impressive peculiarities of the cave is the presence of widespread crystallizations of gypsum, opal, and other secondary minerals (probably alunite, sanjuanite and rossiantonite). The gypsum occurs in form of acicular crystals, flower-like forms, crusts and desert roses covering thousands of square metres of the cave floor. Also deposits of iron hydroxides are present, in form of stalagmites up to 5 metres high, flowstones, rimstone dams, and coralloids. Anemolites, helictites and stalactites and other speleothems of opal and amorphous silica are present (Figs 6–7).

These formations are extremely fragile and the exploration-documentation of the cave must be carried out with double flagged trails in order to avoid unnecessary damages.

6. Researches and scientific interests

One of the main objectives of the 2013 expedition to Auyan Tepui was scientific research, especially concerning speleogenesis on quartzite caves, in the framework of a PhD thesis by one of the authors (FS). InParques granted us the autorisation to carry out chemical analyses on waters, and to make geomorphological observations at the surface and inside the discovered caves. Water samples have been taken in underground streams, of drip waters, in still-standing pools and lakes, and of surface waters. The very low contents of Si and SiO_2 in the sampled waters required quick in situ measurements (UNESCO-WHO 1978; Mecchia and Piccini, 1999; Piccini and Mecchia, 2009) with an Aquaquant © 114410 Silicon by Merck, able to analyse in a concentration range of 0.01–0.25 mg/l, with an error lower than 20 %. Analyses were carried out within 24 hours from sampling. Samples with a higher concentration of Si were analysed by dilution with distilled water. Temperature, pH, and electric conductivity (EC) were measured by a HI 991300 Hannah Instruments © field portable instrument.

Figure 5. Sixty meter wide gallery along the "Collector de Noroeste". Photo V. Crobu.

Figure 6. Coralloids of amorphous silica growing on the cave floor. Photo V. Crobu.

Running waters have a pH ranging between 3.1 and 5.9. Still standing waters in cave pools and lakes can reach neutrality and high SiO_2 values 7–8 mg L^{-1}. The highest SiO_2 content was documented for an about one hundred cubic metres pool of standing water with a value of 8.6 mg/l. This confirms that running waters (streams) are always undersaturated with respect to Si because of their fast passage through the system while percolation waters are generally much higher in content confirming that a dissolution process in fractures and cave walls is effective. These results support the arenisation model of speleogenesis in quartz-sandstone (Martini 2000; Sauro et al. 2013), even though also processes of hydrolysis and laterisation are possible where sandstones also contain silicates as suggested by Aubrecht et al. (2011). For morphological and speleogenetic studies we measured size and bearings of over 100 pillars in the cave, together with fractures and bedding planes in order to check the theory of "pillar flow" proposed by Aubrecht et al. (2011). The results of these studies will be presented soon.

Further researches are planned for the near future also regarding the secondary minerals deposits present in the cave.

7. Conclusions

Imawarì Yeuta represents one of the largest cave systems in quartz sandstone in the world. The discovery of this cave demonstrates that speleogenesis is widespread in the tepuis of the Gran Sabana region suggesting that many other cave systems are waiting to be discovered and documented.

Figure 7. Rounded silica speleothems in the ceiling of the inactive network. Photo V. Crobu.

The scientific interest of these caves is very high, ranging from the processes of weathering that lead to the cave formation, to the exceptional secondary minerals, speleothems, cave fauna and geomicrobiological interactions. In particular this last topic will certainly need more attention in the future in order to better understand all the processes interacting in the weathering and secondary mineral deposition processes. For this reason La Venta is going to organize a new expedition to this cave, hoping to achieve all the permissions from the Venezuelan Ministery of Environment for geological, biological and geomicrobiological sampling, involving Venezuelan cavers and scientists interested in this project.

The fragility of this cave will require a protocol of protection similar to those applied in many other caves in the world (for example Lechuguilla Cave), where the visits must be carried out only for documentation and scientific purposes, following restricted trails and recovering all artificial and human waste in order to minimize the impact.

Acknowledgements

The following persons took part in the expedition: Virgilio Abreu, Raul Arias, Alfredo Brunetti, Carla Corongiu, Vittorio Crobu, Antonio De Vivo, Jo De Waele, Fulvio Iorio, David Izquierdo, Jesus Lira, Francesco Sauro, Freddy Vergara, Jesus Vergara, and the helicopter pilot Julio Testaferro.

The expedition was possible thanks to the permission for speleological explorations granted by the Director General Sectorial of InParques Ing. Carlos Cova and by the sponsors Geotec SPA, Raul Helicopteros and by the following technical partners, Dolomite, Intermatica, Ferrino, Amphibious, De Walt, Allemano Metrology, Chelab, Scurion, GTLine, New Foods, Bialetti, MountainHouse.

A big thanks to Ortensia Berti and to the community of Kavak, to Felipe Campisi and his Robinson, to Karina Ratzevicius of Raul Helicopteros, to the Hotel Gran Sabana and to Elements Adventure for the logistic support.

The following institutions gave their patronage: Ambassador of the Republic Bolivarian of Venezuela in Italy Julian Isaias Rodriguez Diaz, Foundation Dolomiti Unesco, Italian Speleological Society, Central Commission for Speleology of CAI, CONI Veneto, Italian Institute of Speleology.

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EXPLORATION OF HIGH ALTITUDE CAVES IN THE BAISUN-TAU MOUNTAIN RANGE, UZBEKISTAN

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In the late Eighties some Russian, Italian and British expeditions started the detailed exploration of the Baysun-Tau region, a series of parallel limestone ranges showing karst features in an high altitude desert environment, with cave entrances between 3,000 and 3,900 m a.s.l. The exploration came to a halt soon because of the breaking up of the Soviet Union and related border contentions between Uzbekistan and Tagikistan. Over the past five years, the improvement of the political situation in Uzbekistan and the possibility to get permits for exploration in this remote area has lead the Ekaterinburg Speleological Club, with the support of La Venta Geographic Explorations, to inaugurate a new season of expeditions. In two years, 2011–2012, new and extensive branches were explored in the cave systems Festivalnaya (-625 m, 16 km; entrance at 3,500 m a.s.l.), Dark Star (-610 m, 7 km; entrance at 3,640 a.s.l.), with more than 11 km of new passages surveyed. Dark Star, renamed as Central Karst System of Hodja Gur Gur Ata, in particular shows a great potential to become one of the deepest caves of Central Asia, reaching now over 600 metres of depth but with a potential of 2,400 metres between the entrance and the resurgence of Machai. In 2011 also Ulugh Begh Cave was reached again, twenty years after its first and unique exploration, discovering a new entrance at almost 3,800 m a.s.l. Additional to explorational works, Chinese, Russian, and Swiss scientists harvested the first samples for climatic studies in 2012.

The Baysun Tau limestone ranges show exceptional potential not only for exploration and connection of the caves, but also for future scientific research on paleo-climate and the paleo-geographic evolution of the area.

1. Introduction

The great central Asian limestone ranges are among the most exciting frontiers of speleological exploration in high altitude environment. After a long and successful period of expeditions in the 80s, the complex political changes in this area related to the breaking up of the Soviet Union in 1991 hindered the speleological investigation for more than fifteen years. After a prospective return expedition in the Hodja Gur Gur Ata in 2010, the Ekaterinburg Speleological Club, in cooperation with La Venta Geographical Explorations, has organized two new expeditions in 2011 and 2012, focused mainly on Festivalnaya Cave (-625 m, 16 km; entrance at 3,500 m a.s.l.), Dark Star Cave (-610 m, 7 km; entrance at 3,640 a.s.l.), and Ulugh Begh Cave (-240 m, 2 km; entrance at 3,750 m a.s.l.). These last exploration campaigns have demonstrated the impressive potential of the area, with entrances at more than 3,700 m a.s.l, and the karst base level inferred to be at 1,400 m a.s.l. (Machai Springs).

2. Geographical and geological description of Baisun-Tau

The region is located within the boundary of Baisun-Tau and Surkhan-Tau, the southwestern spurs of Gissar Range, in the Surkhandar'inskii region, Uzbekistan (Fig. 1). The Baisun-Tau mountain range stretches 50 km from south-west to north-east. Absolute altitudes of its sub-ridges are 3,500–3,900 m. Baisun-Tau consists of two main mountain chains, Ketmen' Chapty and Hodja Gur Gur Ata. Surkhan-Tau mountain range is parallel to Baisun-Tau, is situated

Figure 1. Central Asia and location of Baisun Tau mountain range.

15 km to the south-east, and reaches its highest summit at Chul'bair (3,812 m).

Both Ketmen' Chapty and Hodja Gur Gur Ata are formed by Mesozoic deposits with two different types of karstifiable strata. The upper one consists of a Cretaceous sulphate rock with sandstone and clay bands, while the lower strata are represented by upper Jurassic limestones.

Both Ketmen' Chapty and Hodja Gur Gur Ata are monoclines dipping 10–25 ºC to the NW (Fig. 2). Hence, north-west slopes are gently descending and plateau-like, while south-east slopes are steep with walls up to 400 metres high at the top (Fig. 3).

In Hodja Gur Gur Ata, cave entrances are located on the wall at different heights and represent paleo-phreatic and vadose cavities cut by tectonic and erosion processes. Cave

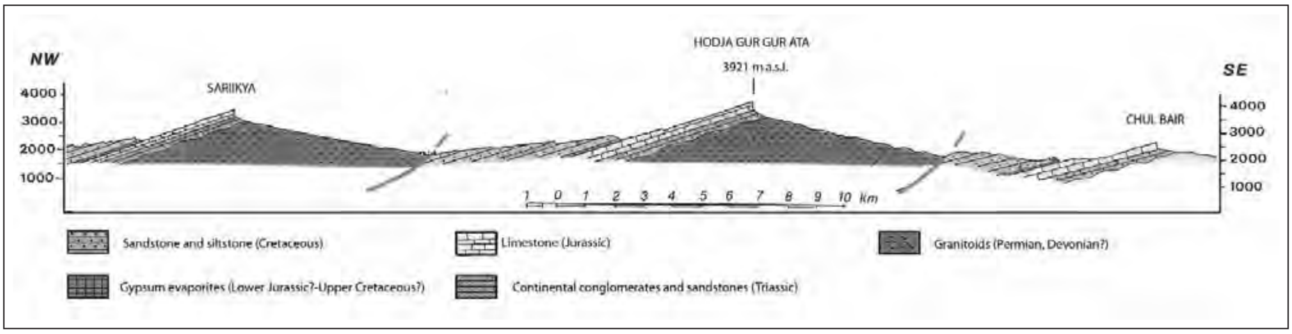

Figure 2. Geologic section of Sariikya, Hodja Gur Gur Ata and Chul Bair monoclines.

entrances are situated in an altitude range between 3,200 and 3,800 m a.s.l..

A hypothesis of origin of these cave systems is described here. Initially, rocks of Hodja Gur Gur Ata formed an anticline with faulting sub-parallel to its axis (Baisun thrust). Water was able to reach significant depths and formed paleo-phreatic galleries at the bottom of the limestone through zones of tectonic weakness and interstrata pathways. At the same time, active formation of sinkholes and shafts took place at the upper ridge of the anticline. These shafts continue downwards as inclined passages and canyons controlled by bedding planes. An increase of total groundwater discharge and glacial erosion processes lead to the opening of parallel fold axis valleys and finally to the wall formation which started to degrade as a result of physical weathering. Increasing weathering of the wall exposed sinkholes and cave passages as entrances.

Groundwater discharge from Baisun-Tau occurs through the springs along the Machai Valley, where the river Machai crosses Jurassic limestones. The biggest spring, with a flow rate of 1 m^3/s, is located at the altitude of 1,400 m a.s.l.. The altitude difference between the highest cave entrances and the springs is more than 2.4 km.

3. History of exploration

Exploration of the southwestern chains of Gissar Range by Sverdlovsk Speleological Club (SSC) started in the 80s of past century. During many different expeditions at Ketmen' Chapty, Ural'skaya cave named after Zenkov was explored. A series of shafts (300 m depth) and a horizontal passage ending in a first sump were explored in this cave in 1981. Following expeditions until 1984 passed 2 sumps and reached a depth of 565 m.

Exploration of Hodja Gur Gur Ata started in 1984 when an expedition led by Victor Dianov attempted the excavation of some sinkholes on the plateau of Ketmen' Chapty. During this expedition two speleologists from Sverdlovsk – Sergei Matrenin and Igor Lavrov – made a prospective trip to Hodja Gur Gur Ata (Fig. 3) in search of new caves. This first scouting was a great success as several large caves (Berloga, Yubileinaya, Sifonnaya) were found along the wall nearby the Katta-Tash summit.

Festivalnaya cave, the largest cave on Baisun-Tau, was found during the following expedition led by Aleksandr Babanin in 1985. Exploration of Festivalnaya cave, which later became Festivalnaya-Ledopadnaya Cave System, continued until 1990 with 12.5 km of explored passages up to a depth of 625 m (Fig. 4). Exploration of that cave system was a result of joint efforts of speleologists from many cities of the Urals (Ekaterinburg, Chelyabinsk, Orenburg, Magnitogorsk, Perm, Berezniki, Kizel, Gubakxa ets.) as well as from Moscow and St. Petersburg (Sapozhnikov and Matrenin 1989; Vishnevskii et al. 1989). Speleologists from Italy and England also visited the cave and gave an important contribution in scientific researches and explorations (Bernabei et al. 1990).

Many other cave entrances on the main wall (35 km long) were clearly visible from the distance, but it was impossible to reach them without climbing equipment. In 1986, a small group led by Aleksandr Babanin walked along the base of the wall until the Babagui summit (3,921 m) and tied the new cave entrances to survey points R-10, R-19 and R-21. In 1988, a team from Izhevsk reached these entrances and surveyed 1,600 m of passages in Isetskaya cave (R-10), 450 m in R-19 and 100 m in R-21. Unfortunately, the plans of these last two caves were lost.

The main entrance of Dark Star cave was reached in 1990 by the English expedition Aspex '90, with a 3 day long climb on the wall (Vale 1991; Vale and Wallis 1991). The cave entrance, 60 m high and 7 m long, is located at the height of 160 m from the bottom of the wall. Cave temperature varied between 0 to -5 ºC. Cave walls were covered with large ice crystals and many frozen lakes were found. More than 2 km of passages were surveyed to a depth of 100 m. The cave ended at a T-junction (T Chamber) with several ascending passages and a large shaft, unexplored due to lack of equipment.

In 1991 the English expedition Aspex '91 attempted to continue the exploration of Dark Star but was stopped by a large amount of water from melting ice (Gregory 1992). At the same time, nearby Ulug-Begh Cave was explored by an Italian team (Badino et al. 1992). This is one of the highest entrances in the wall at 3,750 m a.s.l. with a depth of 240 m and length of 1,700 m.

In 1985, speleologists from the Ural started the exploration of Boy-Bulok Cave on the nearby Surkhan-Tau mountain range. Fourteen expeditions to Boy-Bulok were organized, also in cooperation with Italian cavers. Finally the cave reached 1,415 m of total depth, which made it the deepest in Central Asia (Bernabei and De Vivo 1992).

From the early 90s to 2006, Baisun-Tau and Surkhan-Tau were inaccessible for explorers due to the complex political situation in the region. In 2007, a new expedition to Boy-Bulok cave showed the possibility to re-start the explorations in this region.

Figure 3. The 450 meters high Hodja Gur Gur Ata wall, rope line to Dark Star Entrance. (photo A. Romeo/La Venta).

In 2010 a new prospective expedition to Hodja Gur Gur Ata was made with the following results: 1) new easier routes to the wall and plateau were found; 2) new sources of fresh water for the base camp were identified; 3) new equipment and technology were tested and 4) promising directions for future work in Festivalnaya cave were established. This prospecting expedition was the premise of the two main expeditions of 2011 and 2012.

4. The expedition Baisun-Tau 2011

The joint Russian-Italian expedition on Baisun-Tau mountain range took place in August 2011. The expedition was organized by the Ekaterinburg Speleological Club (former Sverdlovsk Speleological Club) with the assistance of the Ural Speleological Association and the technical consultancy of La Venta Esplorazioni Geografiche. Twenty-two members from Russia and Italy participated to the expedition.

The following issues have to be taken into account for the organization of an expedition in this area:

1) The caves are situated in a border area between Uzbekistan and Tagikistan, where special and frequently changed rules for registration of foreign visitors are applied;
2) The logistics are really complex because cave entrances are located on the wall at an altitude of more than 3,600 m above sea level and it is not possible to use helicopter to reach the cave area, therefore the transport of all the equipment has to be done with donkeys and on foot.
3) The expedition was made possible thanks to the assistance of several old friends from Tashkent, Baisun and Kishlak (village) Dyuibolo.

Exploration and documentation works in the expedition were carried out by 3 different groups. The first group, called “Bottom” and second group called “Big Grot” were based in two different underground camps in Festivalnaya System. A third group, called “Plateau”, was based near the Ulug-Begh and Dark Star caves and carried out researches for new entrances and attempted to reach Dark Star cave.

The “Bottom” group, during an underground camp of ten days, reached the bottom of the cave and searched for possible unexplored passages. In addition they explored the higher part of “Down with the CPSU” Branch, from passage “Baiba” to the bottom of the cave and some south-eastern branches near the “Clay City”.

The deepest point of the cave was explored in 1990, but very few works were carried out there, as the expeditions in 1998 and 2010 were unable to reach that part of the cave because of technical problems.

Primary tasks of “Big Grot” group were climbing to reach some windows in the “Big Grot” Hall, and search for new passages in the upper branch “Salavatskii kosmos”. This part of the cave (more than 2 km of passages) was discovered by Ural cavers in pre-expedition of 2010 after a climb in the “Big Grot” Hall. The hope was to find new passages leading deep down into the massif, as all searches at the cave bottom were fruitless.

The “Plateau” group had the task to reach Dark Star and Ulug-Begh caves and search for further continuations, but also explore and survey new cave entrances on the plateau near Festinal’naya-Ledopadnaya cave system and carry out a topographic survey and exploration of caves discovered, but not yet explored, by Krasnoyarsk speleologists in 1996 due to lack of equipment.

This team was supposed to camp on the high plateau between Ulug-Begh and Dark Star and to carry on simultaneous works in both caves. The Asian climate forced this team to change plans. A hot spring and an early summer in 2011 led to a complete lack of snow and therefore water on the plateau. For this reason it was impossible to camp there. While groups in the Festivalnaya were working according to plans, the “Plateau” group was forced to camp under the Dark Star entrance near the only source of fresh water nearby. As a result, “Plateau” group changed plans and focused exclusively on explorations in Dark Star. Here the explorations pushed further than the last room explored by the British cavers in 1989 and led to the connection with R-21 cave and with a new entrance on the wall, Red Wine. But the most important result was the exploration of a new series of giant galleries descending to a sump at 300 metres of depth. The 2011 expedition ended confirming the great potential of Dark Star and Festivalnaya System, while Ulugh Begh wasn’t reached because of the very dry conditions of the high plateau.

5. The expedition Baisun-Tau 2012

Thanks to the promising results obtained the previous year, in 2012 the Ekaterinburg Speleological Club, again with the support of the Ural’s Speleological Association, launched the most prominent expedition on the Hodja Gur Gur Ata mountain range over the last decade. Twenty-nine cavers from many Russian cities took part in the expedition, together with Italian, Spanish, British and Chinese cavers sponsored by La Venta Geographical Explorations.

The expedition had a long list of tasks most of which were fulfilled. The Hodja Gur Gur Ata wall was reached very fast due to a new convenient ascending route and a large number of donkeys for the transportation of the equipment. Such fast ascension led to some troubles with acclimatization among the members of the expedition. The place of Oasis base camp (3,200 m a.s.l.) was covered by a major spring mudslide, but this inconvenience was soon forgotten in the

Figure 4. Plan view of the Western Karst System of Hodja Gur Gur Ata (Festivalnaja-Ledopadnaja).

light of a new problem: half of the ropes hidden in the Festivalnaya cave at the end of last year expedition had been stolen. Therefore, an unscheduled trip was made in the Caucasian Gallery of Festivalnaya cave to recover some old ropes from the shafts. Two people descended also to Baisun to bring 200 metres of spare rope, a courtesy of Sebastian Breitenbach.

There were 3 main directions of work in 2012: to continue the exploration in the new sector of Dark Star in order to by-pass the siphon; to reach Ulugh Begh cave and re-open its exploration; to continue the exploration in the upper part of Festivalnaya System.

In addition to the exploration works, samples and data for paleoclimate researches were collected by scientists from Switzerland (Sebastian Breitenbach) and China (Yan Bin). Samples of water, snow and ice were taken from underground and surface sites, while temperature and humidity data loggers were set in Tonnel'naya cave.

In Dark Star System the survey has reached -610 m with the exploration over -650 m and the cave continues downward with a series of shafts. In Festivalnaya many new branches were explored with a great potential for future explorations. The entrance of Ulugh Begh, 350 metres up on the wall, was reached again after twenty one years of break. A new easier entrance to this cave was found leading to a new sector of narrow meander. In the last days all the ropes were used in the different caves and the exploration stopped only because of lack of equipment. Almost all cavers were involved in surveying, with up to 5 teams working at the same time. Finally the 2012 expedition surveyed more than 6 km of passages, most of them in very challenging conditions (ice and cold wind). Most of the surveys were carried out by girls. Ten girls participated in the expedition in 2012, more than a third of the group.

6. The new explorations

6.1. Dark Star-Central Karst System of Hodja Gur Gur Ata

Dark Star was first explored in 1990 by the English expedition ASPEX '90 for more than two kilometres of huge galleries to an unexplored shaft. In 1991 the english cavers tried to carry on the exploration but they were forced to halt due to changing climatic conditions and melting of ice floors forming impassable lakes. Then the cave was abandoned for twenty-one years.

In 2011, more than 400 metres of ropes and three days of works were necessary to reach from above the main entrance of Dark Star. Fortunately the first scouting inside the cave revealed that the lakes that had stopped the English team in 1991 were frozen allowing a fast walk to the last known room ("T" Room). After the new shaft of about 25 metres, a 10 metre wall was climbed leading to a new big gallery characterized by strong wind. Finally the cave turns to the south connecting with the big entrance of R-21 (Izhevskaya), a cave on the wall explored in 1988 by the Izhevsky Team whose survey was lost. This new entrance, situated only one hundred metres high on the wall allows a faster and easier way to the deepest part of the cave than from the main entrance of Dark Star. One other new entrance to the system, the Red Wine cave, was found exploring a 700 m long meander named Passakalosky. But the most important discovery was achieved through a fifteen metres climb above the "T" Chamber leading to 1.5 km of new giant galleries explored to a sump located at

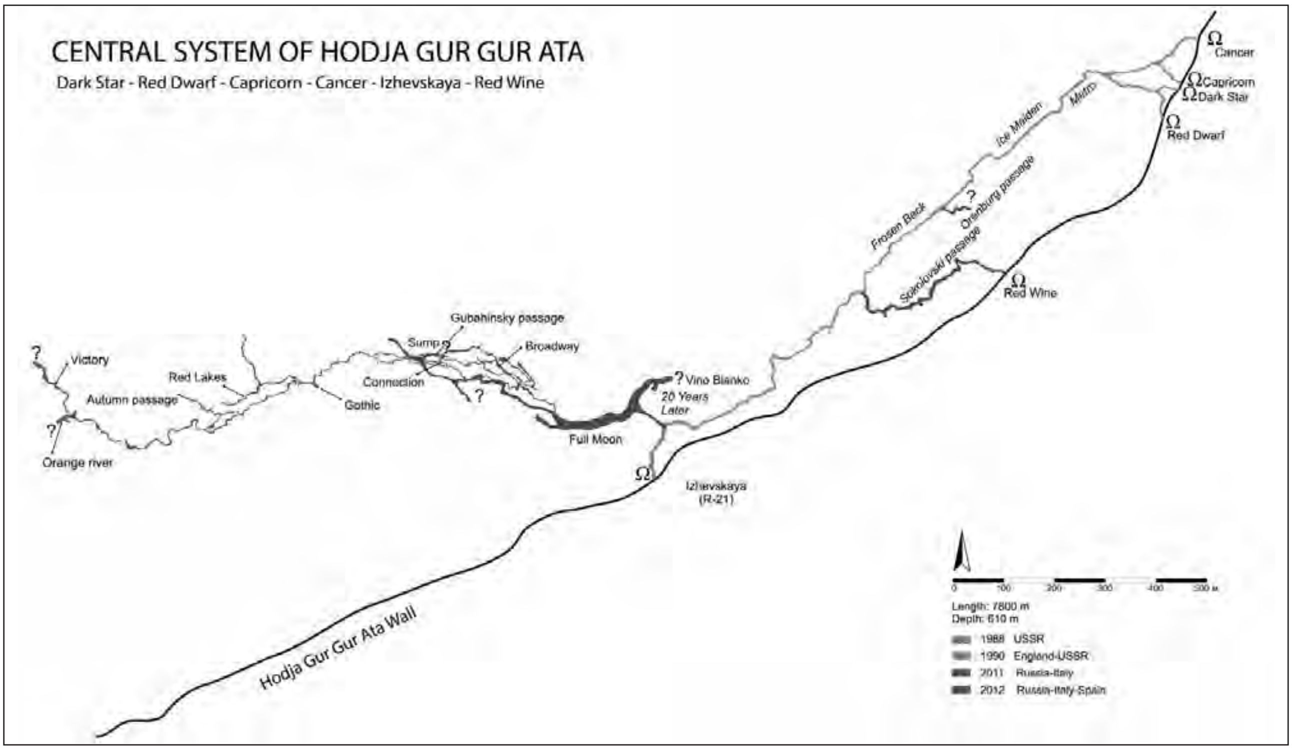

Figure 5. Plan view of the Central Karst System of Hodja Gur Gur Ata (Dark Star).

a total depth of 300 metres. A very impressive big room, the "Polnolunie" Hall, characterized by peculiar formations and giant crystals of ice, was found (Fig. 6). The 2011 expedition ended with many other unexplored branches in this sector of the cave.

The winter 2011–12 was characterised by the largest amount of snow over the last 50 years, and therefore the cave climate was strongly influenced. During the 2012 expedition the first trips to the cave discovered a large amount of snow at the entrance and all the frozen lakes were turned into pools of mushy ice. All works in the old part of Dark Star were impossible. Luckily, the new entrance (R-21) discovered in 2011 enabled to access the deepest sector of the cave.

In this expedition the work in the cave was focused on one of the lateral branches discovered in 2011 at -240 m. An underground camp was set not far from the new part of the cave and accommodated 3–6 cavers working in shifts. A series of small shafts was explored leading to a big chamber with two passages. One of them was called Corallite meander and represents an alternation of narrow passages, small shafts and squeezes with the walls thickly covered with calcitic coralloides. Corallite passage leads into a big gallery crossed by a stream (2–3 L/s). The downstream ends in an unpassable squeeze only 10 cm high swallowing the main stream at the depth of 540 m. Also other parallel passages and galleries were explored and surveyed, and in particular a new easier route, bypassing Corallite meander, was found.

In the last days of the expedition, an exploration of the upper part of the meander near Gothic chamber at -450 m, led to a new huge paleo-phreatic sector of the cave. The last descent of the 2012 expedition reached the depth of 610 m and stopped above a deep shaft lacking ropes and time.

The connection with new entrances and the presence of a huge network of fossil and active branches suggest to consider Dark Star as part of a more complex system: the Central Karst System of Hodja Gur Gur Ata. Until now 7128 m of passages were surveyed, with 6 entrances (Dark Star, Capricorn One, Red Dwarf, Cancro, Red Wine, R21-Izhevskaya) but much more is expected along the unexplored branches of the cave.

6.2. Festivalnaya-Ledopadnaya – Western Karst System of Hodja Gur Gur Ata

In 2011 the bottom of Festivalnaya Cave, at -625 m of depth, was again reached twenty years after its first exploration and confirmed to be impassable. Nevertheless new discoveries were carried out, most of which in the upper paleo-phreatic levels of this system. The exploration of the "Clay City" branches led to a new meander with a huge chamber at the end where one other passage continues upwards. Other new branches were discovered in the upper part of Salavatskii Kosmos Branch. One of the passages ended in a huge chamber named Everest. Another passage goes over Yubileinaya Cave. During the 2011 expedition more than 2 km of new passages were explored, 1.3 km of which were surveyed.

The exploration in Salavatskii Kosmos continued in 2012 and, in particular, in the meander Enigma discovered the year before. The underground base camp was relocated from the Room of Ural's Cavers to the lake nearby Enigma in order to save time and energy. Several shafts from 10 to 45 metres were explored but most of these were dead ends. However, one of them led to an impressive chamber of more than 6,000 square metres. The most promising branch was found not far from Enigma at the end of the expedition and was not completely explored. During this expedition the work in the cave was complicated by the large amount of water. As a result, in 2012, a group of 8 cavers explored and surveyed more than 2 km of new passages (Fig. 4).

Now Festivalnaya-Ledopadnaya reaches 16 km and -625 m.

Figure 6. Walls covered by ice crystals in the "Full Moon" Room in Dark Star (photo A. Romeo/La Venta).

6.3. Ulugh Begh

Ulugh Begh is one of the highest complex caves in the world, at 3,750 m a.s.l.

The entrance was reached in 1991 by Italian cavers thanks to helicopter transport on the top of the wall of

Hodja Gur Gur Ata. It was hard to believe in 2010 that it would be possible to live and work on the top of the plateau without using helicopter. Unexpectedly, this goal was achieved in 2012. Thanks to the logistic support of all the cavers of the expedition, a camp for 8 people was set up on the plateau. Ulugh Begh cave was reached after more than 20-years break. The progress into the cave was hampered by cold weather and wind at the surface camp and an ice plug at the cave entrance which took three days to break through. The main branch of the cave didn't yield anything new, but one of the lateral passages led to a new entrance on the wall. This new entrance was more easily accessible than the main one. From here some new narrow meanders have been explored and the cave continues with an unexplored passage characterised by strong air flow.

7. Conclusions

The most remote part of the system Dark Star is only 1 km apart from Isetskaya cave and only 1.5 km apart from Ledopadnaya cave which is a part of Festivalnaya system. Connection of the two cave systems seems to be only a matter of time.

Furthermore Festivalnaya-Ledopadnaya has a real chance to be connected in the future with Yubileinaya, Berloga and Uchitelskaya caves as they overlap on the plan.

In two expeditions (2011–2012), a total of 11.5 km of new surveys were achieved, confirming the great potential of the area.

Hodja Gur Gur Ata and, in general, the mountain chains of Central Asia could become among the most promising frontiers of cave exploration in high mountain environment in the next years. This region is situated in a really "hot" political zone, between Uzbekistan, Tagikistan, Turkmenistan and Afganistan. If this situation will remain stable and favorable for caving expeditions it is probable that really deep (more than 2 thousand) and extended caves (tens of kilometres) will be explored here in the near future.

Exploration of the region will continue in summer 2013.

Central Asia is waiting…

Acknowledgements

Special thanks to Alexandr Plastinin for financial support and our friends from Salavat Cave Club for equipment. Intermatica for the satellite phone communication. Ural Airlines for discount of luggage fees and Asia Adventures for organization. But most of all Sadyk and our friends from Djibala for their support in Uzbekistan.

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KES MOUNTAIN SINKHOLE (KAHRAMANMARAS – SOUTHEASTERN TURKEY)

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As OBRUK Cave Research Group, we've been exploring Kes Mountain Sinkhole since four years. The sinkhole is 65 km north of Kahramanmaraş in southeastern Turkey, high on the mountains at the east of Tekir Village. It is believed that the waters that enter the underground aquifer from that cave, which is at 1,900 meters of altitude, pass through the Yesilgoz Doline, at 900 meters altitude. Total distance between the doline and sinkhole is roughly 4,000 meters. During the first expedition in 2009, our team dived in Yesilgoz and found the underwater entrance of the cave. In addition, we explored Kes Mountain Sinkhole for the first time. By 2010, it was understood that the pit which begins at -175 meters continues as a single drop of 170 m. Moreover, at that point the cave's structural formation has an immense alteration; suddenly the huge galleries of the cave changed to a very narrow and endlessly long and deep fault fissure. By July 2011, after OBRUK's third exploration at Keş Mountain Sinkhole, the total depth of the cave reached to -650 meters, being fifth deepest cave of Turkey. Finally, by July 2012 we had reached a siphon at -728 meters. Unfortunately, connection with Yesilgoz resurge couldn't be proved. So, a dye test, not only at Kes Sinkhole, but also in 3 different sinkholes in the same area is planned for next year.

1. Introduction

Kes Mountain Sinkhole is located at an altitude of about 1,800 meters on Keş Mountain, near Tekir Village, 65 km north of Kahramanmaraş city, southeastern Turkey.

As OBRUK Cave Research Group, we had been informed about the sinkhole by the Middle East Technical University Cave Diving Group (MADAG). During their reconnaissance dives to Yesilgoz Doline in the same area at 2008, villagers informed them that the water which springs from the bottom of that doline comes from a sinkhole on the top of the mountain.

Cave divers found two separate entrances at the bottom of that resurgence, roughly at 40 meters deep. But, unfortunately they were not able to penetrate due to the tightness of vertical passage.

Our exploration began at Kes Mountain Sinkhole the next year. In July 2009, with a small team of 6 cavers we found the entrance of the sinkhole, descended and surveyed down to -175 meters. After the first and second descents, Kes Mountain Sinkhole continues with an extraordinarily wide main gallery and high ceilings.

In certain parts, the width of the gallery reaches 20 meters and the height is more than 30 meters. Although Kes Mountain Sinkhole is an underground aquifer of not one, but two small rivers, this main entrance is almost dry during the summer season and those dimensions are extremely large even for the largest and deepest sinkholes of Turkey. A very limited amount of water was trickling into the main gallery from small branches at a depth of -125 meters, beyond which point, there was a small but constant stream.

At -175 meters, the geological formation of the cave suddenly changed. At that point the width of the main gallery narrowed down to 5 meters, with a seemingly infinite drop. In addition to the depth, it was impossible to see the ceiling and forward of the gallery. The water bed was apparently dropping straight into a huge fault plane.

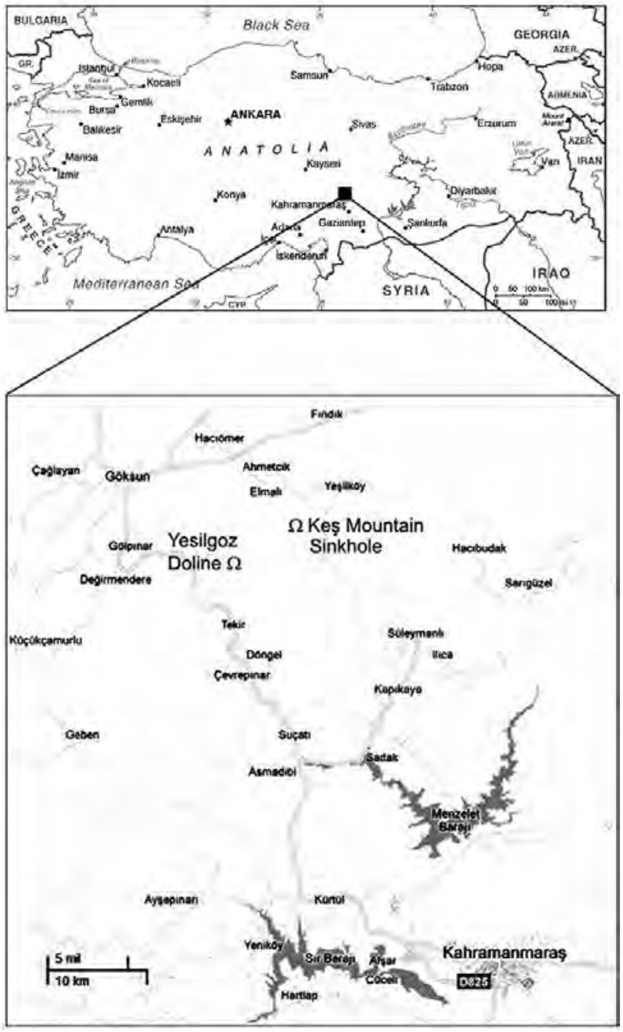

Figure 1. Kes Mountain Sinkhole, Yesilgoz Doline and the area in general.

During the second year's trip, after descending to -300 meters we still hadn't reached the bottom of that pit.

July 2011 marked the exploration's third year. Spending 15 days with a stronger team of 20 cavers, we first reached the bottom of that large pit and set up an underground camp at -345 meters. A two-wire phone connection from that point to the surface camp was also established.

At Day 10 of the exploration, members of OBRUK Cave Research Group reached -650 meters. Cave was still continuing with a cascade of small descents. As we had done previously, nearly 1,000 meters of rope and telephone lines were packed and left in suitable places of the cave for next years' exploration.

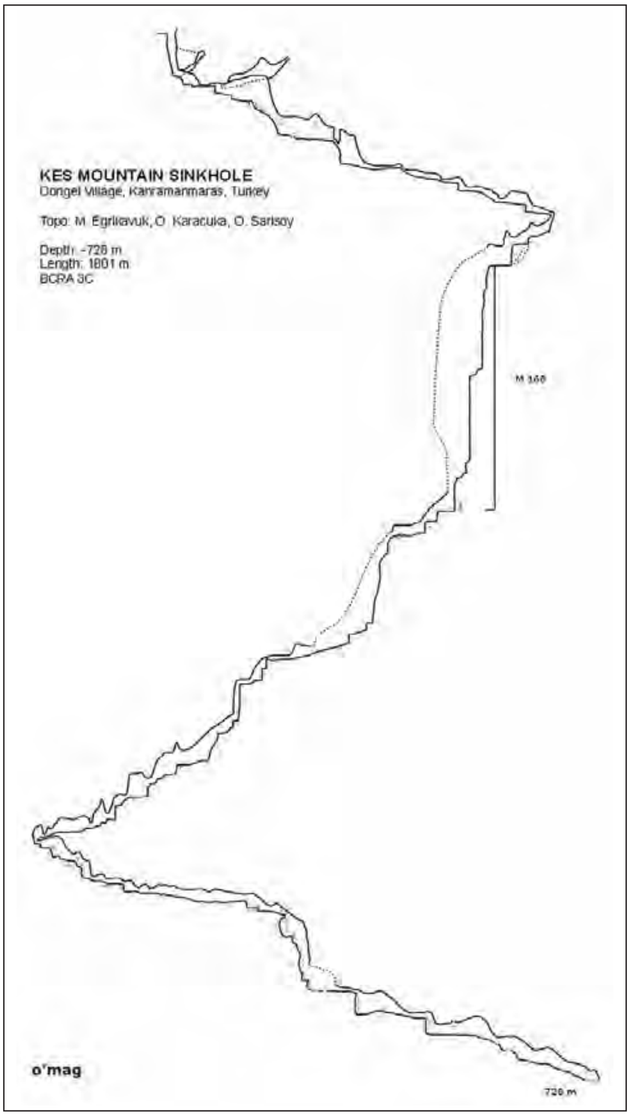

Figure 2. Kes Mountain Sinkhole.

By July 2012, our fourth year began in Kes Mountain Sinkhole. 18 members of OBRUK, in addition to 8 Lebanese and 2 Iranian cavers, explored the cave for 15 days. Around -650 meters depth, geological formation of the cave changed again and it became obvious that Kes Sinkhole will not join with Yesilgoz resurge. Sinkhole; which began with large passages, slowly changed to small, narrow maeanders and descending as spiral passages, rather than covering the distance towards Yesilgoz Doline. Though, for the first time till this depth, we had contacted with a continuous water flow, compared to the doline it still has little water. And, after few more small descends, the sinkhole ended with a small lake and a siphon at -728 meters.

2. Geology

At least five different geological formations can be observed around Tekir Village. These are mostly deep sea sediments and they were in a continuous action within the tectonic movements and overthrust foldings of surrounding area. The area, which lies completely in an orogenic phase, has two main structural differences from east to west. Although all are mostly limestones, there are huge age differences between those formations.

East and southeast part of Tekir village is mostly a single formation. This geological unity, which also includes Yeşilgoz Doline and Dongel caves, is mostly light colored, reefal limestone with corals and foraminifera. There are two different opinions about the period of that formation; either Middle or Upper Miocene.

Within the north east of that unity lies Kes Mountain Formation. It covers the whole area from Kes Mountain towards Kaman Mountain, to the north; with mostly dark gray or gray, re-crystallized and sometimes dolomitizated limestones dated as Permian.

3. Comments on Exploration

Limestones of Taurus Mountains at southern Turkey has some very deep caves and it is obvious that, in the future, many deeper caves will also be explored in those mountain ranges.

The five deepest caves of Turkey for the time being are:

Peynirlikonu Sinkhole (Içel)	-1,429 m
Kuzgun Sinkhole (Nigde)	-1,400 m
Cukurpinar Sinkhole (Içel)	-1,196 m
Kuyukule Sinkhole (Isparta)	-832 m
Kes Mountain Sinkhole (K. Maras)	-728 m

But, apart from being the fifth deepest, Kes Mountain Sinkhole has some different aspects among others. First of all, it is the easternmost cave on that list. Even if we do not consider the first five, but the first ten deepest caves of Turkey, it is still the easternmost of them all.

Secondly, it is the first "deep cave" of Kahramanmaras, which has a limestone area of more than 5,000 km^2, mostly within the altitudes of 1,800–2,500 meters. Apart from its natural beauty, we strongly believe that this area has an enormous cave potential.

4. Kes Mountain Sinkhole – Yesilgoz Doline Connection

The rumor that the water which sinks at Kes Mountain Sinkhole resurges from Yesilgoz Doline was the main reason of our exploration in that sinkhole. All the villagers told us that 24 hours after it begins raining at Kes Mountain, the water of the doline becomes muddy, even though its not raining in the lower parts. Also, it is said that during May and April one can hear the sound of running water under the ground at the farmed fields above Yesilgoz Doline.

But, after four years of exploration, we are still far from proving that connection. Entrance of Keş Mountain Sinkhole is at 1,900 meters altitude and Yeşilgoz Doline is at 900 meters. Apart from that 1,000 meters of depth difference, horizontal distance between the two caves is around 4 km. But after descending nearly 70 % of that total estimated depth at Kes Mountain Sinkhole, its horizontal extension is still not more than 300 meters.

Also, the amount of water resurgence from Yesilgoz Doline and the amount of water flow at the deepest parts of sinkhole are incomparably different. When water output is 6–8 m^3 at the doline, the water flow in the sinkhole is not more than 0.5 m^3.

But, numerous other sinkholes and karstic aquifers around the vicinity of Kes Mountain Sinkhole and Yesilgoz Doline are the evidences of a huge underground water system. So, the water which springs from that doline can be sinking to underground elsewhere. Next year a comprehensive dye test will be carried not only at Kes Sinkhole but, within the 3 additional sinkholes of the same area.

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PREMIER EXPLORATION OF THE CAVES OF HOLY MT. ATHOS, GREECE

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The article presents the results of the exploration under the project "Exploration of the caves of Mount Athos as integral part of the world natural, cultural and historical heritage" under the patronage of Euro Speleo Projects – European Federation of Speleology. During two expeditions carried out in 2011 and 2012, the international team of cavers form Bulgaria, Greece, Romania, Russia, Serbia and Turkey explored 90 caves with total length 792 m. The caves can be divided into three main categories – caves associated with the lives of Saints, cave chapels, caves-cells, usual and sea caves and artificial caves (water catchments and reservoirs.

1. Introduction

The Mount Athos (Greece, Halkidiki Peninsula) occupies an area of 2,886 sq. km in the Northern Greece. The area presents a terrain of different forms. There is a mildly wavy row of hills in the central part of the peninsula with gradually increasing altitude (between 450 and 990 m, before climbing to an altitude of 2,033 m – the summit of Mount Athos) to the southeast. The relief consists of deep, steep traverse gullies alternating with steeper folds. The area belongs to the Serbo-Macedonian Massif, a large basement massif within the Internal Hellenides. The south-east part of the Mount Athos peninsula is built by fine-grained banded biotite gneisses and magmatites. The southern tip of the peninsula, which also comprises Mount Athos itself, is built by limestone, marble and low-grade metamorphic rocks with thickness of 2,000 m. The northern part and most of the western shore of the Mount Athos peninsula are composed of highly deformed rocks, belonging to a tectonic me´lange, named the Athos-Volvi-Suture Zone. The rock-types in this me´lange range from metasediments, marbles and gneisses to amphibolites, eclogites and peridotites. In the north part of peninsula there is an area 11 km long and average 2 km wide covered by Triassic recrystallized limestones-marbles (Kockel and Mollat 1978; Himmerkus et al. 2011) (Fig. 1).

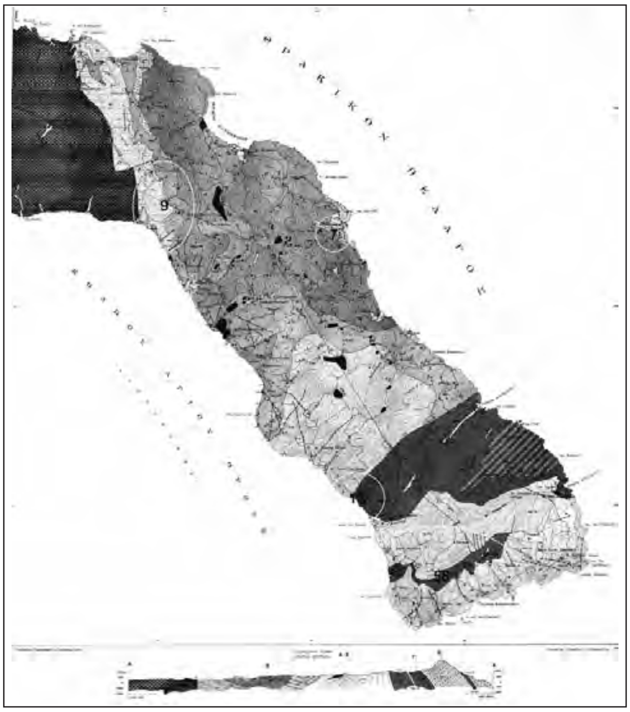

Figure 1. Geological map of Athos Peninsula (after Kockeland Mollat 1978) with the explored areas and number of caves in it.

Mount Athos or Agion Oros ("The Holly Mountain") is a place dedicated to monasticism, to austere asketism and deep contemplation. Among the greenery and the impassable gorges, perched in the most unexpected positions, are situated the monumental walls of 20 monasteries and numerous huts, where hermits spend theirs days in solitude and contemplation.

2. Study of the information for the karst and cave in Athos

The review of the assessable information for the caves in Athos Peninsula and the state of their exploration made in 2010, shows that some of them are described as places, related with religious practices (hermits and cells) and information for karst and cave explorations (including maps) did not exist. In 1988 Mt. Athos was recognised by the World Heritage Convention as a mixed site for both culture and nature. In addition, on the basis of the criteria of the Habitats Directive, the entire Athos peninsula has been incorporated into the EU Natura 2000 Network. Because of inexplicable reasons the caves of Athos did not exist in the documents as a factor of the environment, cultural and historical sites. They are not declared as natural habitats!

That is why the international team of cave explorers decided to organise a long term project under the patronage of ESP of European Speleological Federation for complex speleological and karstological exploration of Mount Athos, named "Exploration of the caves of Mount Athos as an integral part of the world natural, cultural and historical heritage".

The General Aims of the project are:

- Location and survey of all known caves;
- Discovering and exploration and surveying of new caves;
- Carrying out of geological, geomorphological and climatological cave studies;

3. General data for project studies up to date

The first stage of the project was held from 15–22 July 2011. The project team consisted of Zhalov A. – Head, V. Gyorev (Bulgaria), L. Makrostergios, J. Lazaridis, I. Agapov, S. Kaminski (Russia), D. Tomic (Serbia), T. Tuluchan (Romania). During the expedition were surveyed the areas of the monasteries Zograf, Kostamonit, Dohiyar, St.Xenophont, Dionysius, St.Pavlou, St. Grigoriou and Pantocrator and skete communities “ Kafrsokalivion,” Little St.Anna, St. Anna and New Skete.

During the event were identified and mapped 42 underground sites (Table 1) with a total length of 356.20 m. Among them is the longest sea cave near the harbor of the monastery Kostamonit (56.40 m; Fig. 2) (Agapov et al. 2011; Zhalov et al 2011; Zhalov et al. 2012).

The second stage of the international project took place from 1 to 12 September 2012. The team was composed by Zhalov A. – Head, V. Gyorev, Zh.Vlaykov (Bulgaria), L. Makrostergios, J. Oykonomidis, T. Komaditis and M.Karidas (Greece), I. Agapov, S. Kaminski (Russia), A.Yamac (Turkey). There were surveyed the areas of the monasteries, Dohiyar, Xenophontos. The explorations in the vicinity of sketes “Kafrsokalivion,” “Little St.Anna”, “St. Anna”, St. Nilos and “Nea Skite” were continued in more detailed manner.

During the expedition were identified and mapped about 48 underground sites with a total length 435.84 m. (Table 2) Parallel was collected oral and photo information to other cave objects, which will be the subject of future studies. Other 9 objects were only visited and sketched among which is probably the longest cave in Athos for the moment. There were localized, but not explored 2 more caves, one of which probably is so called “The Big Cave of Athos”. According to the existing data, the cave is over 150 m long. Its entrance is 50 m wide and around 80 m in high.

The explored caves can be divided into three main categories – caves associated with the lives of Saints (St. Kozma, St. Pimen Zografski; St. Maksim; St. Gerasim, St. Nile), cave chapels (St. Dionysius and Mitrofan), caves-cells, usual and sea caves and artificial caves (water catchments and reservoirs). The total number of the explored underground cavites under the project up to date is around 90 with total length of 792.04 m.

4. Brief characteristic of the explored caves

Most of the explored karst caves had tectonic-corrosive origin. Their study shows that they are initially tectonic caves enlarged by the corrosion of infiltrate atmospheric waters. They have not big morphometric indexes (length, depth) and some of them could be recognized as niches.

Some of the caves had tectonic origin. Most of them are developed in non-karst rocks as amphibolites alternating with plagioclase gneiss or green schists (Caves close Monastery Pantocrator, St. Pavlou, Skete St. Anna [Danilos’Cave, St. Maxim]). They are characterized by narrow fissure, enlarged by the tectonic movements as a consequence of endogenic processes.

Collapsing or boulder caves are formed in the limestone by natural processes such as collapsing and dilatation movement of slope modeling. The typical collapsing caves are these close to Skete Kavsokalivya.

As sea caves we can determinate the cavities which are located in the contemporary erosion network of the seashore on the sea level, or in the slope at a different altitude (~ 0.5 to ~ 10 m a.s.l.). All caves are formed in karstificated rocks (Fig. 3). The caves in surroundings of Nea Skete are developed in greyish-white and bluish-grey Triassic recrystallized limestones-marbles, but those who are located on the sea level are formed in compact limestones and the rest are in conglomerates.

Coastal caves between the ports of Xenophont and Dohiyar monastery are developed in marbles.

The sea caves can be classify under genetic point as corrosion – abrasive (Seal Cave, Great Sea Cave (Kostamonit), Cristal Cave, The Cave with 4 entrances, The Cave Lokum), due to the rest which are more complex polygenetic origin (probably suffusion – corrosion).

If necessary to analyze the sea caves from morphometric point of view, we can conclude that these ones, located at the sea level and developed in compact rocks, are the longest among all explored caves, but the caves in conglomerates have bigger volume.

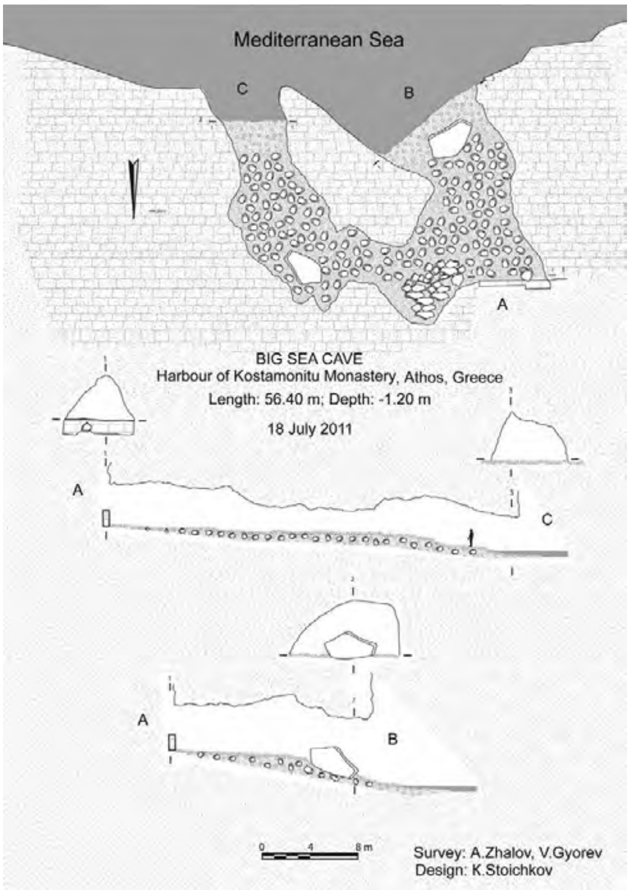

Figure 2. The Sea Cave Kostamonit harbour.

Many of the explored caves are used by monks as storage places or for religious purposes. We can divide them by the kind of use as follows:

1. Natural caves in which there were no traces of permanent human use.

2. Drainage galleries and underground conduits. Caves, carved in the rock (possibly in the course of natural caves small fissure type) for water collection or delivery to a monastery or hermitage. The length of such cavities varies from few meters to 21.6 m.

3. Rock cut storage tanks (cisterns).

4. Small natural caves, grottoes and niches used for the practice of prayer (as a rule, these caves can accommodate only single person.) Have small artificial transformation: planning and opening the cavity masonry (from cleared volume) without a solution for weather protection, equipped with a sitting place, shelf icons, etc. These caves are located near the surface of cells.

5. Hermit's cell, which occupy caves, niches or grottos with volume bigger than caves considered in § 4. The entrance of the caves is barred by stone or wooden wall with windows and doorways. The length of such caves can reach 5–10 m or more. Such cells may be composed of several rooms (ground and surface), which can be used for the practice of prayer, housing, for economic purposes. In some cases, in combination with cells, they can be equipped with a water storage tank (Fig. 4).

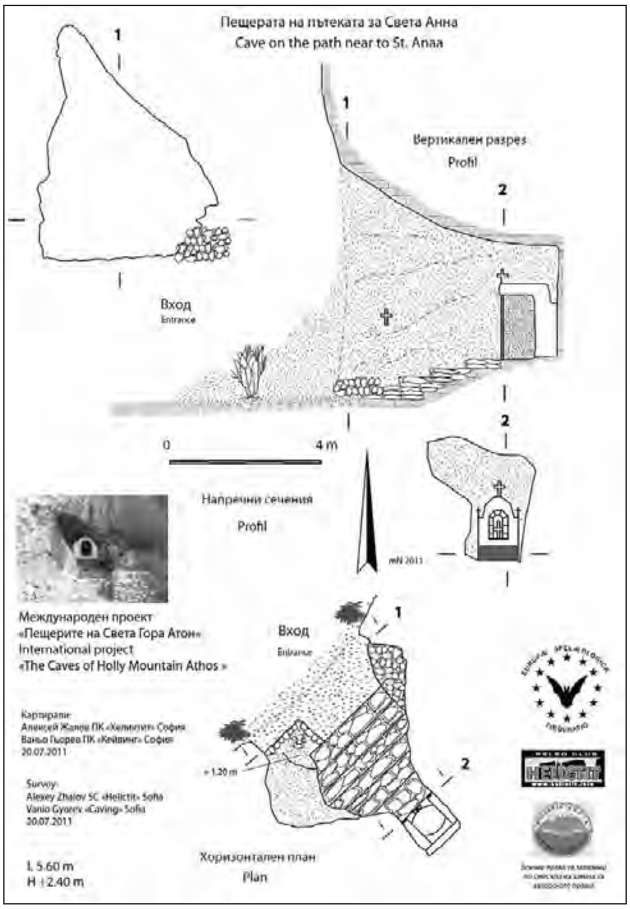

Figure 3. The St. Ana Cave – St. Ana Skete.

6. Cave chapels, dedicated to the memory of the saint, who lived in it. As a rule, in some cases, they are equipped of natural caves used in solitary practice (see section 4) or cells (see section 5). Such cavities in some cases may have a wall of masonry with a doorway (St. Kozma; St. Pimen Zografski; St. Maksim; St. Gerasim; St. Grigoriou; St. Pavlos). The decoration inside the chapel looks like a small temple. The length of such caves is from 3 to 20 m.

7. Chapel, equipped with a cave or grotto (usually along the path between the monasteries; Fig. 3). The length of such cavities may be up to 5 m.

It should be pointed, that the present study of caves in the Athos Peninsula still covers a much lesser area from the whole region, covered with karst rocks. More detailed study of this area could positively lead to discovery of many new different karst and non karst objects. That is why the further exploration will continued while as the explorers discover and study all caves in that sacred and unknown place.

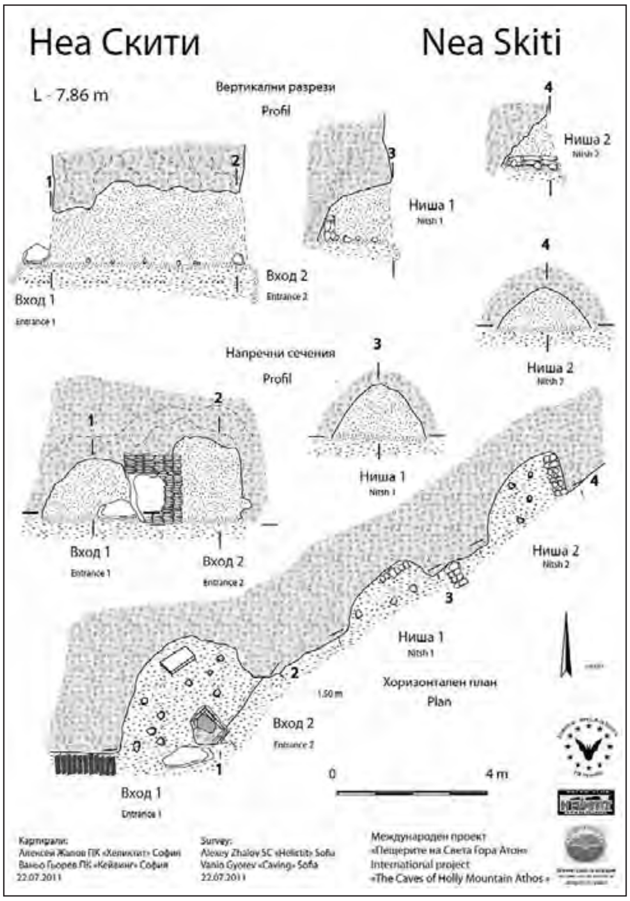

Figure 4. Complex of cave and 2 nishes-Nea Skete.

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Table 1. List of the caves explored during the 1st stage.

No	Name	Locality/ Monastery/Skete	Length (m)	Depth
1	Cave	Pantokratoros	4.00	
2	Cave	St. Ilia	15.00	
3	Cave – (water conduit) Source of the Mother of God	St. Ilia	20.40	***+1.0***
4	Cave of St. Maksimu and Kafrsokalivion	Kafrsokalivion	6.00	
5	Cave	Katounakion	4.00	
6	Cave (cell)	Danailo	6.50	***-2.0***
7	Cave	Danailo	3.00	
8	Cave (water conduit)	St. Anna	4.20	
9	Cave Complex (2 caves) – cell	Nea Skete	5.00, 3.50	
10	Cave (cell)	Nea Skete	4.00	
11	Nishe (cell)	Nea Skete	2.85	
12	Grotto (cell)	Nea Skete	2.30	
13	Cave (cell of Sacred Trinity)	Pavlos	7.55	***+0.8***
14	Cave (cell)	Pavlos	1.50	
15	Cave (sea cave)	Pavlos	20.00	***+4.0***
16	Cave (water conduit) – Complex 2 caves	Pavlos	21.60, 5.00	***-0.85, +1.5***
17	Cave of St. Pavlos (one complex with cave № 16)	Pavlos	3.00	
18	Cave (sea cave) – complex 2 caves	Pavlos	41.40, 2.36	
19	Cave (water conduit)	Dionysius	14.00	
20	Cave (cell)	Dionysius	3.80	
21	Cave (sea cave)	Dionysius	2.50	
22	Cave (sea cave) and 2 sea grotto	Dionysius	6.60, 10.00, 8.00	
23	Cave of St. Grigoriou	Grigoriou	5.7	
24	Cave (water conduit)	Grigoriou	11.15	***+1.2***
25	Cave (water conduit)	Grigoriou	5.50	
26	*Sea cave*	Neo Roda	*7.00*	
27	Cave of St. Kousma	Zograf	*20.23*	
28	Cave of St. Naum	Zograf	*2.80*	
29	Cave 12 Apostles	Zograf	*9.60*	
30	Cave of St. Gerrasim	St.Anna	*3.90* -1.20	
31	Cave of	St.Anna	*5.17* +2.40	
32	Cave	Kostamonitou	*56.40* -1.20	
33	Cave	Kostamonitou	*7.40*	
34	Cave	Kostamonitou	*19.48* +1.80	
35	Cave	Nea Skete	*13.00* +1.40	
36	Complex (cave and 2 nishes)	Nea Skete	*7.86, 1.90, 3.05*	
37	Quanat	Pantokratoras	*20*	
38	Artificial well	Pantokratoras		***15.5***
39	Group of three littoral caves	Pantokratoros	*6.5* *5.5* *1.5*	
40	Shelter Cave (boulder cave)	Pantokratoros	*1*	
41	Cave Georgios (cell)	Pantokratoros	*3*	
42	Cave (spring)	Pantokratoros	*3* **356.20**	

Table 2. List of the caves explored during the 2nd stage.

No	Name	Locality/Monastery/Skete	Length (m)	Depth
1	Water	Catchment St.Anna	2.6	
2	Cave	St.Anna	6.2	**+2**
3	Cistern	St.Anna	3.2 × 1.7	**-1**
4	Cave	St.Anna	3	–
5	Niche	Little St.Anna	2	–
6	Niche	Little St.Anna	7	
7	Cave Church St.Dionysius	Little St.Anna	18.5	
8	Cave Illarion the Georgian	Ipatievskie Cells	11	**+1.5**
9	Cave Arhondrik	Ipatievskie Cells	4.7	
10	Niche	Danailo	3	–
11	Cave	Karaulya	3	–
12	Cave chapel	Karaulya	46	**6**
13	Niche	Karaulya	3	–
14	Cave &Cistern	Karaulya	6.2	–
15	Grotto Temple Christmas	Karaulya		–
16	Cave	Karaulya		
17	Sea Cave 1	Nea Skete	3.9	
18	Sea Cave 2	Nea Skete	3.5	
19	Cave with the well	Little St.Anna	17.1	
20	Cave behind the house	Little St.Anna – Danailo	9.85	
21	Davids' Cave	Little St.Anna	9.36	
22	Cave	St.Anna	8.22	
23	Cave 26 monks	Stavros	1.2	
24	Cave close to skete	Stavros	6.7	
25	Niche	Stavros	1.0	
26	Tectonik Cave	Stavros	6.70	**-6.0**
27	The big Sea Cave	Nea Skete	34	
28	The Seal Cave	Nea Skete	7.40	
29	The Big Sea Cave	Nea Skete	11.56	
30	Cristal Cave	Dohiyar	18.50	
31	The Cave with 4 entrances	Dohiyar	25.26	
32	Cave	Nea Skete	20.12	
33	Cave "Lukum"	Dohyar – Kostamonit	10.57	
34	Tunell	St.Anna	10	
35	Niche	St.Anna	3	
36	Niche	St.Anna	2	
37	Skete Josef Hisiahast	St.Anna	15	
38	Niche Josef Hisiahast	St.Anna	3,2	
39	Niche	St.Anna	1,85	
40	Niche + well – Agiasma	St.Anna	2,80	
41	Niche	St.Anna	2,5	
42	Cave	St.Anna	8	**4**
43	Tectonik Cave	Kavsokalivya	12,35	
44	Tectonik Cave	Kavsokalivya	15	**-8**
45	Tectonik Cave	Kavsokalivya	14	**-4**
46	Niche	Kavsokalivya	12	
47	The Cave of St.Nillus	St.Nilus	12	
48	Cave	St.Nilus	11	
		Total length:	**435.82**	

EXPLORATION OF THE JASANKA CAVE IN BANAT, ROMANIA

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From 2008 to 2012 the members of Czech and Slovak Speleological Society discovered and explored new cave called "Jasanka". This cave is more than 2 kilometres long and thanks to several expeditions it became the longest cave in Muntii Locvei Mountains, Romania. The exploration isn´t finished, because in this location there are still places with possibility of additional progress.

1. Introduction

Our first expedition into Romanian Banat happened in 2006. Since the first expedition we were focused on the speleological research in the surrounding area of the Czech villages especially Svatá Helena in Muntii Locvei mountains. Our fellow countrymen lived in this region since 1823 because of the job opportunities found in the woodworking industry. The total number of the Czech villages was 8 – Sv. Alžběta, Sv. Helena, Bígr, Rovensko, Šumice, Eibenthal, Gernik and Frauvízn, but the first and last mentioned ceased to exist because of the short supply of water. This region is situated close to river Donau which creates natural borderline with Serbia.

2. The geology of the region

The region of interest belongs to the west part of the South-Carpathian "horseshoe". In general, this region is considered part of Alpine-Carpathian belt which creasing began in Cretaceous period as result of subduction of the African plate under European tectonic plate and subsequent collision of the continental crust. The karst plateau itself, on which the village of Svatá Helena is located, is created by Cretaceous limestone.

3. Our first speleological activities in Banat

The main goal of the first expedition was a survey and discovery of the water source in the karst region near Svatá Helena because during the summer months there is short supply of water. Later we turned our attention to regions located further from the above mentioned village into the catchment area of Bazinul Liuborajdea, Bazinul Dunareii and Bazinul Bosneag. Interesting places and caves with potential of the unknown underground were localized by GPS coordinates and became part of a list of the most promising localities, which could yield an access into the draining system of local karst plateau. High on this list figured an outflow with travertine cascade above the Kavčí valley. Local inhabitants called this place "Jasanovka" – it means in dialect "soft stone". We found this place very interesting, because the large mass of travertine had to be created by calcareous water.

4. Jasanka Cave

We started to remove the debris covering the beginning of the travertine cascade in fall of 2008. We were rewarded two days later by discovering a winding corridor that was on average 2 meters high, 0.8 meters wide and 80 meters long and ended at a sump. In places this corridor had standing water up to 1 m deep. We believed that there was continuation of the cave behind the sump. Sediments on the bottom of the cave that were at first muddy changed at the sump to gravel. We decided to call this cave "Jasanka" according to the popular name of the place by local inhabitants (Fig. 1).

Figure 1. Passing through the first sump in the Jasanka Cave. Photo by Zdeněk Motyčka.

We continued our research in fall 2009. This time of the year is the most suitable for a survey of the area due to the low water levels. The sump was very short and easy to overcome. This was followed by a dry corridor with a vertical passage 5 meters high with a waterfall. This passage was also conquered. The following elongation was finished at the next sump but the diving attempt here was not successful.

Other diving attempts were done in 2010 with tube in order to reduce the water level but due to the high levels of water we decided not to continue that year.

In the fall of 2011 the water levels were favourable. The second sump was overcome thanks to a pump. On the other side of the sump we discovered 40 m of new interesting corridor and were again stopped by third sump. The third sump was conquered in the fall of the following year with the help of second sump. The new passages after the sump were evidently greater and longer and they often lacked sediments (Fig. 2).

Figure 2. Main corridor in Jasanka Cave. Photo by Zdeněk Motyčka.

During the three expeditions in 2011 new corridors with character of meanders in length of 1,200 m were explored. The result of the follow-up expeditions in 2012 was the discovery of 600 m long corridor with nice decoration (Figs. 3, 4, and 5).

Thanks to the information from expeditions in 2011 and 2012 we know that Jasanka cave is the draining system of the Dealu Coroneanti plateau. In the cave itself three levels with rising altitude were explored. These levels signalized gradual descent of the water flow. The oldest level has very nice decoration and character of an old meander. Lower meandering corridor is the longest with rare decorations, probably with often active water flow. The lowest part creates small passages with erratic character. Really interesting point is the geological structure of the cave. The corridors are created in the compact benched limestone with subhorizontal bedding. Subhorizontal character is respected by pieces of black silicate. There are three possible variants of genesis of this rock closed in limestone of cretaceous age. Silicate can be product of acid volcanism (in surroundings of the region there are known positions of calcareous dacites and rhyolites), product of hydrotermal activity on the seabed or chemical dissolve of cases containing SiO_2 (sponges, radiloarites).

5. Conclusions

These expeditions were result of cooperation between the caving clubs of the Czech Speleological Society (Pustý žleb, Jihomoraský kras, Tišnovský kras, Devon) and the Slovak Speleological Society (Čachtice).

Figure 3. Richly decorated upper part of Jasanka Cave. Photo by Zdeněk Motyčka.

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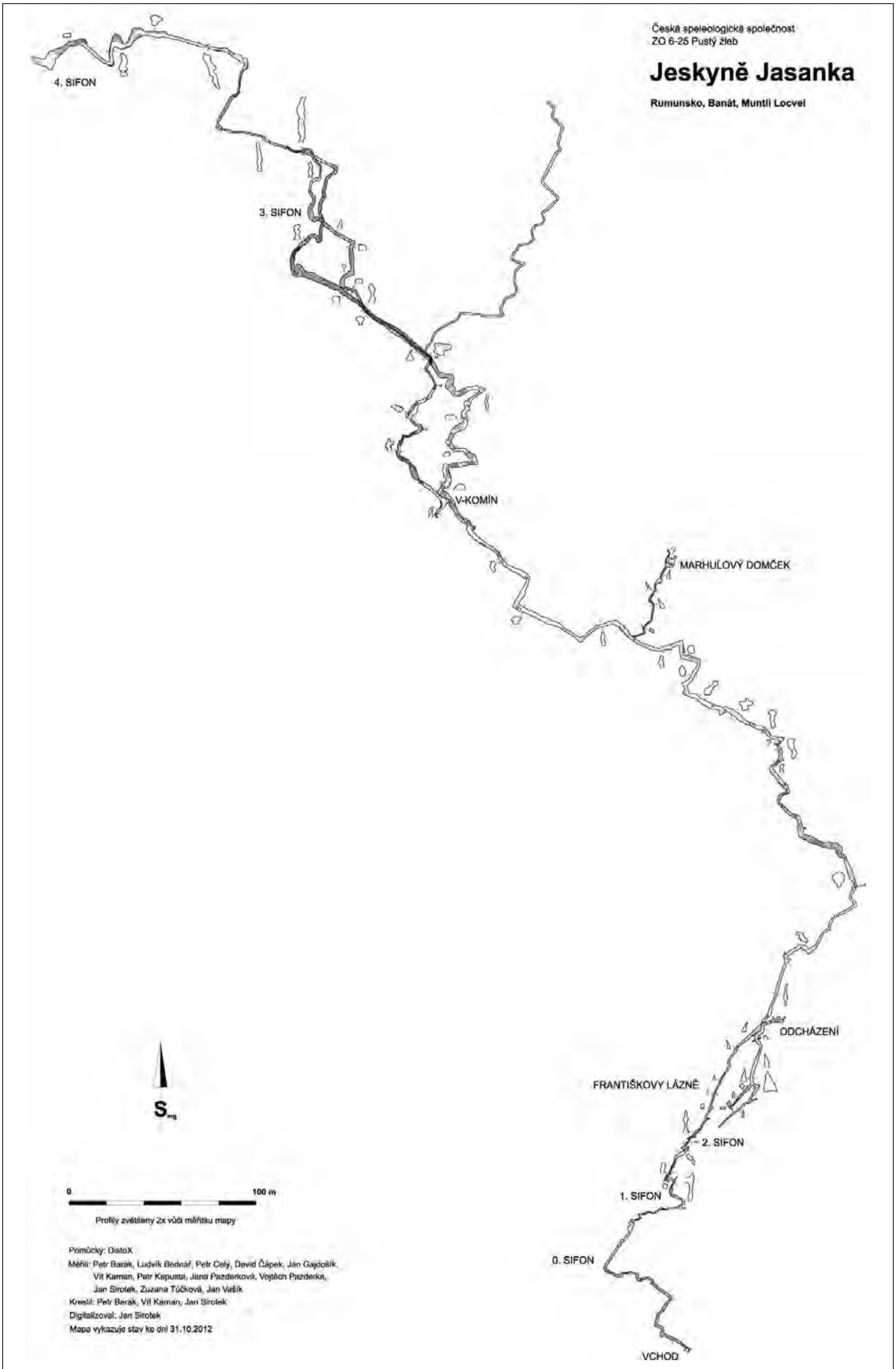

Figure 4. Map of the Jasanka Cave.

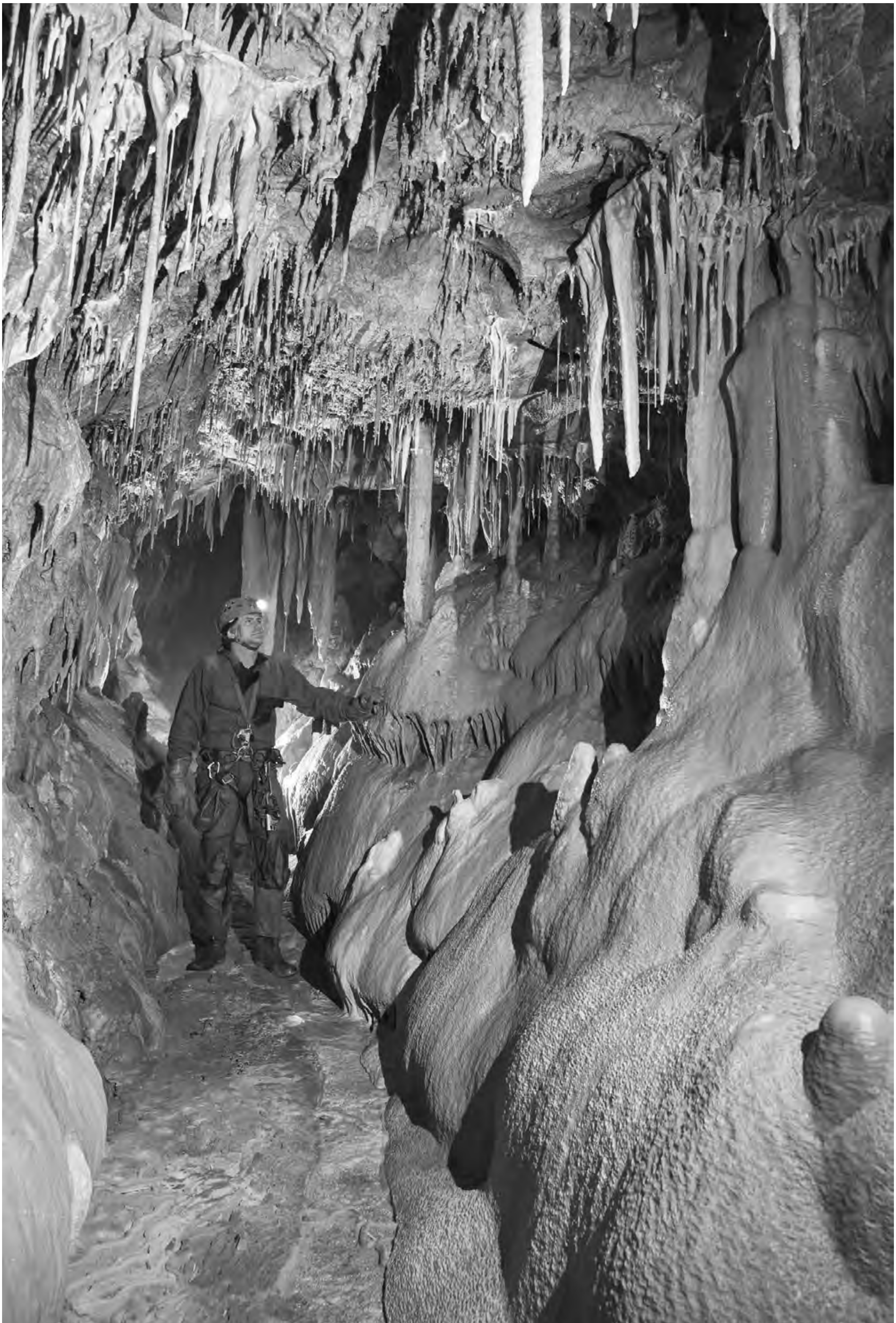

Figure 5. The most beautiful part of the Jasanka Cave. Photo by Zdeněk Motyčka.

CAVE EXPLORATION OF THE BELIĆ MASSIF IN THE PROKLETIJE MOUNTAINS (MONTENEGRO)

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The Prokletije Mountains are located in the southern part of the Montenegro. These are the highest peaks in the Dinarides, where denivelation between them and the bottom of valleys reaches 1,000 m. The selected carbonate massifs have been explored regularly by Polish and Serbian speleologists since 2006. The expeditions have discovered 50 caves, among these the Górnicza Cave was explored to -515 m.

The Prokletije Mountains (also known as the Albanian Alps or Bjeskët e Namuna) are the southernmost part of the Dinarides (Fig. 1). The highest peak of the Prokletije Mts., and also of the Dinarides, is Jezerski Vrh/Maja Jezerce Mount (2,694 m a.s.l.) situated in Albania (Mulić 2009). Geologically, this region belongs to the High Karst unit. It is composed of Mesozoic limestones and dolomites (Kardaś 1978). Glacial and karst forms predominate in the morphology of this area. Cvijič (1913) was first who described glaciations of the Prokletije Mts.: U-shaped and hanging valleys, moraines and cirques occur here in a great number.

The exploration has been conducted near Gusinje, a little town situated in the Ljuča Valley. Two mouths of big glacial

Figure 1. The Belič Massif (Photo: Mariusz Woźniak).

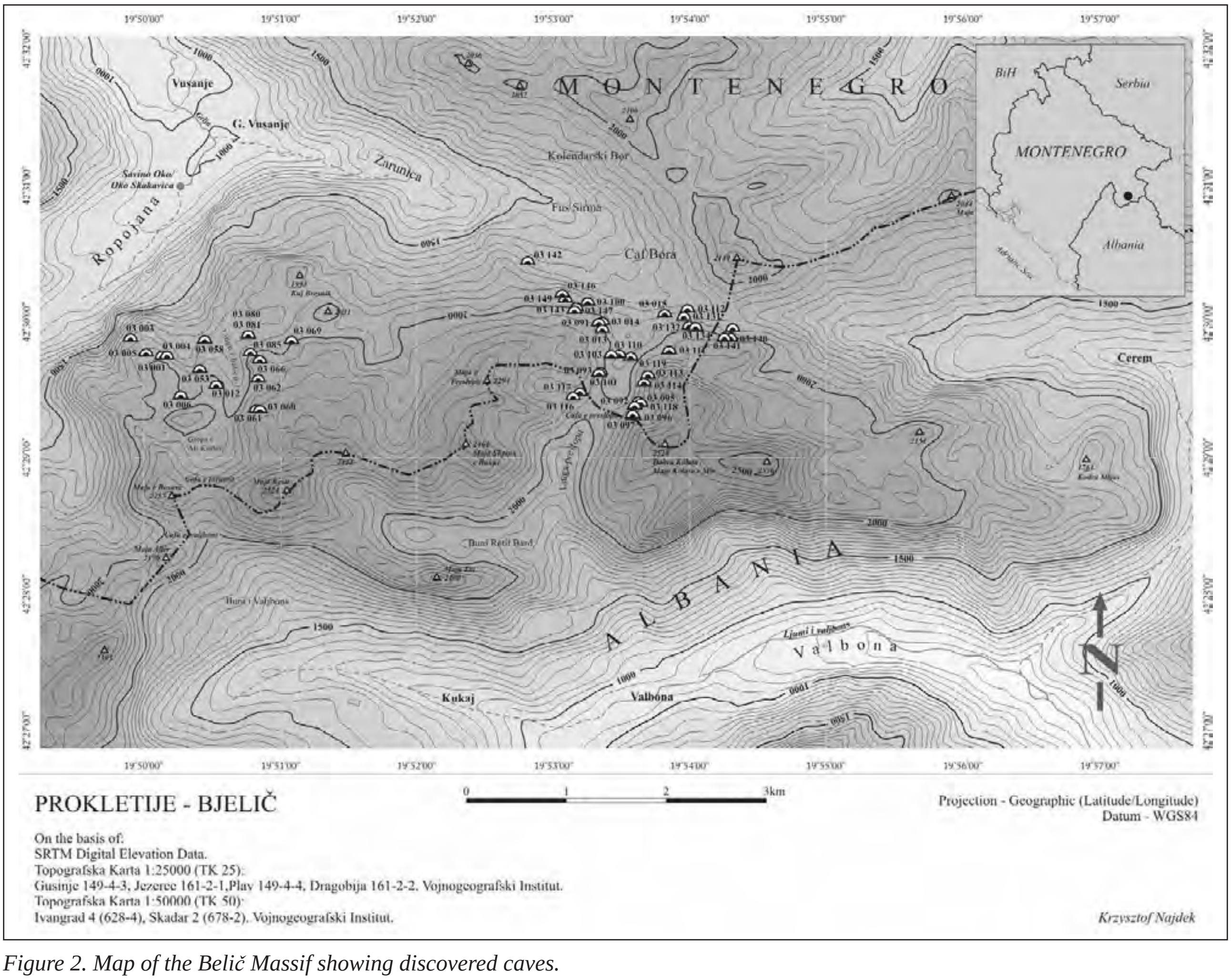

Figure 2. Map of the Belič Massif showing discovered caves.

valleys: Ropojana (Fig. 2) and Grbaja occur in this area. Carbonate massifs surrounding these valleys are drained by two big springs: Alipašni Izvori and Savino Oko (Fig. 3). The Savino Oko spring is discharging the Belič Massif. Two groups from Poland dived in this spring and descended to 96 m deep (Kur 2008).

Figure 3. Savino Oko Spring (Photo: Ditta Kicińska).

The Belić Massif is located at the boundary between Montenegro and Albania. The highest peak of this massif (and of the Montenegro too) is Maja Kolata (2,534 m a.s.l.). The Belič Massif is surrounding by U-shape valleys: Ropojana in Montenegro (Fig. 4) and Valbona in Albania.

During the period of 2006 to 2012 took place 8 exploratory expeditions, organized by Polish and Serbian speleologist (Wielkopolski Klub Taternictwa Jaskiniowego and Speleoklub Świętokrzyski from Poland, and Akademski Speleosko-Alpinisticki Klub from Serbia) in the Prokletije Mts. The exploration was performed in Ploče, Volušnica and Zastan Grbajski (in the Grbaja Valley) and the Belič Massif (in the Ropojana and Zarunica valleys).

Figure 4. The Ropojana Valley (Photo: Krzysztof Najdek).

Among discovered caves the longest and the deepest are:

- Jaskinia Górnicza 03 013 (depth of -516 m, length of 1,218 m) (Fig. 5)
- Jaskinia Lodowa 03 110 (depth of -451 m, length of 1,956 m) (Fig. 6)
- Jaskinia Nibyczarna-Jaskinia Babina Sisa 03 015-03 131 (depth of -236 m, length of 1,611 m)
- Jaskinia Gigant 03 113 (depth of -296 m, length of 1,635 m)
- Jaskinia w Trzech Kopcach 03 142 (depth of 141 m, length of 456 m)
- Jaskinia Entuzjastyczna 03 147 (depth of -107 m, length of 543 m)
- Jaskinia do Savino Oko 03 006 (depth of -256 m, length of 588)
- Jaskinia Łezka-Jaskinia Kolektor 03 311 (depth of -236 m, length of 1,011 m)

The expeditions have already surveyed ca. 50 caves. Every year speleologists check several dozen entrances on surface, but most of them are terminated with blocks, snowy plugs or narrow places. During exploration some caves were connected into bigger systems as the Nibyczarna and Babina Sisa caves or the Łezka and the Kolektor (Kicińska and Najdek 2007; Najdek 2007, 2008; Najdek and Kasza 2008; Biegała et al. 2009; Kasza et al. 2010a, b; Kicińska et al. 2011).

Figure 5. Jaskinia Górnicza (Photo: Zbigniew Tabaczyński).

The caves of Prokletije Mts. developed on tectonic discontinuities or along bedding planes. Vertical invasion vadose passages (Górnicza, Lodowa, W Trzech Kopcach caves) predominate in most caves. In some caves, short horizontal passages (Gigant, Nibyczarna-Babina Sisa) occur as well, except of Čardak in the Greben Massif which wwas known before. Generally, the Prokletije caves are poor in speleothems; more frequent was found in the horizontal part of the Gigant and Čardak caves (stalagmites, stalactites, moonmilk and other).

The exploration and scientific activities is conducted in agreement with the Speleological Society of Montenegro and the National Parks of the Montenegro. All result of exploration are on the website: www.prokletije.pl.

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Figure 6. Jaskinia Lodowa (Photo: Mariusz Woźniak).

VOLCANIC CAVES AND PETROGLYPHS OF BORLUK VALLEY – KARS (EASTERN TURKEY)

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Borluk Valley which continues 6 kilometers towards the east of Magaracik Village of Kars had long been known by its petroglyphs, rather than its caves. However, in 1942 in some caves of that valley, an archaeological survey had been carried out by Prof. Kılıç Kökten and some prehistoric findings had been documented. According to microliths and scrapers that he had found in the caves around Azat and Magaracik villages, Mr. Kokten claims in his article that those caves were all Paleolithic settlements. In this poster presentation, Borluk Valley of Kars, which has an archaeological and cultural importance, will be explained in details, in addition to the caves that were explored. Magaracik Cave, which Prof. Kokten searched 70 years ago and wrote about the importance of findings in detail but had not indicated the exact location, was also found, measured and mapped.

In this poster presentation, those caves and their volcanic formations will be explained. Also, the need for preservation of that area will be emphasized with some interesting examples of petroglyphs.

1. Introduction

Borluk Valley was formed as the result of thousands of years of Borluk Stream erosion which starts 18 km southeast of Kars traverses Magaracik and Azat villages. The stream mingles into Kars Stream at a point a little more north-west, close to Karacaoren Village.

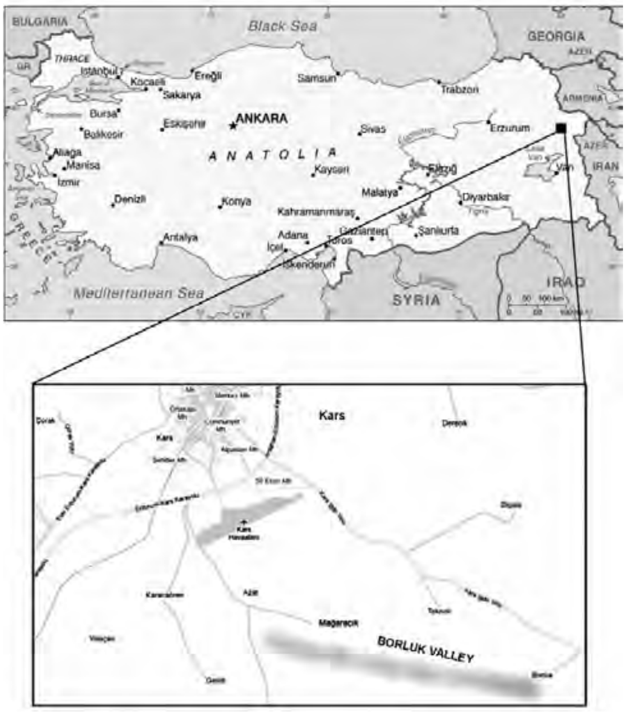

Figure 1. Location map of Borluk Valley, Kars.

Prof. Kilic Kokten made the first scientific research in Borluk Valley in 1942. He published an article where he drew attention to the caves of the region and gave information about the prehistoric materials found in the area. When he went to the region two years after his first research, he made an excavation of a drilling at the entrance of Magaracik Cave and by looking at the finds he wrote that this cave was most probably a Palaeolithic settlement. Nobody had ever went to the mentioned Magaracik Cave nor had anybody known of its exact location. Another research study made in this valley is by Prof. Oktay Belli. About 200 rock pictures were found out during his recent visits to the area.

We found five caves and one church carved into rocks during our exploration at the valley. None of them were ever researched nor published before, other than Magaracik Cave. Today we know that there are very few caves that are composed of andesite and ignimbrite in Turkey. So, these five volcanic caves are of great importance.

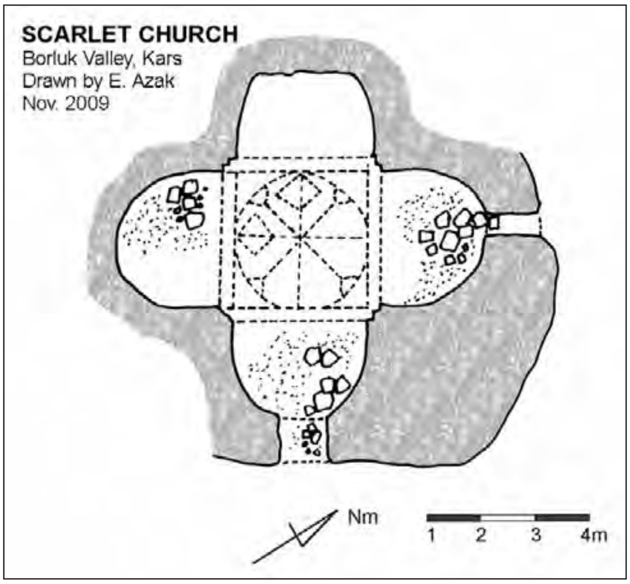

Figure 2. Plan of Scarlet Church.

About 3 kilometers to the southeast of Borluk Valley there is a church carved into the rocks which was named Scarlet Church by the villagers. It is far from all the settlements in the midst of a deserted place. In spite of the long time elapsed and the damage that men have given, some embroidery can still be seen in the dome and on the walls. During the same exploration, a detailed measured drawing of this structure, which was never investigated nor published, is made.

2. Geology of the Area

It is estimated that the most forceful stage of volcanic activity lived in this region is about 6–7 million years ago. This stage is charactarized by widespread rhyolitic - dacitic pyroclastic products and interval lava additives on the surface. It is thought that this material has been driven to the surface from different volcanoes by Sub-Plinia and Plinia high-energy explosions rather than by flow. It is observed that there is ignimbrite and obsidian besides pumice/ash rubble spread over large areas on the surface. Domes and massive lava sequences were formed in southern Kars by ascending of andesitic lava to the surface again 5–6 million years ago. Volcanic activity has been active, especially in western Kars, and has caused the formation of plateaus in the region mostly in this period. Volcanics of Khorasan, which are widely located in northern Khorasan, were formed 4.1 million years ago. Where as, Aladag volcano was formed 3.5 million years ago, which is more to the eastern region. However, the basaltic and andesitic lava flows observed in a large area from north to south of Kars Kagizman continued, until the last eruptions occurred 3 million years ago.

3. Petroglyphs of Borluk Valley

Some of the human and animal figures drawn on rock surface, which were done with scraping and pounding techniques, have been erased by natural circumstances or mostly were damaged by people. A large part of the animal figures are mountain goats, deer and the wild boar. In addition, the figures of a small number of wild cattles are also available.

The most drawing congested part of the valley is Azatkoy vicinity. On the other hand, some of the rock paintings here were too pale and ravaged that they could not be seen if not shown to us by our guide. From the village to the south, in the Tasocagi region, there are many rock drawings. Prof. Oktay Belli has determined the presence of a total of 186 petroglyphs in the valley.

Figure 3. A group of petroglyphs in Borluk Valley.

In the andesite under rock shelter pictures of non-existing varieties of deer, wild cattle, wild boar, mountain goat, mountain sheep along with a variety of kinds of animals that cannot be percieved precisely and figures of the Mother Goddess, hunter shooting an arrow to animals, drawn using scraping the rock surface and line-pounding emphasis techniques, can be seen. More than two thirds of these hunting animals are wild sheeps and goats.

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TRAPIÁ CAVE: EXPLORATION, SURVEY, BIOLOGY AND GEOSPELEOLOGY OF THE BIGGEST CAVE OF RIO GRANDE DO NORTE STATE

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Abstract. Rio Grande do Norte is a state in northeastern Brazil that has a very peculiar karst, characterized by karst pavements (lapiás) and small caves. This karstic area is located on west side of Rio Grande do Norte, near to Ceara state. In September of 2003, a team from the National Center for Research and Conservation of Caves (CECAV-RN) located the entry of a new cave in the valley of the River Apodi, one of the main drainages in the region, near to Felipe Guerra. Since then, several technical and scientific expeditions were organized for the study of this cave called Gruta do Trapiá, the most important cave occurrence in the region. This article describes some of these studies carried out in the cave, the historical aspects of the first cave surveys and the scientific results obtained so far. The cave is mostly consisted by a single meandering conduit that is a tributary of the Apodi river. The main difficulties encountered during first expeditions were a syphon in a norrow passage during the rainy season and the anomalously hot temperatures of 34 ºC (93.2 ºF) on average with week air vertilation, since there is no other entrance. In the biological aspect, collections were made in an area that is approximately ¼ of the cave, resulting in a list of 47 morpho-species. In the geological aspect, some active stalagmites has been collected, and should provide data of unprecedented record of climate changes in the region over the past three thousand years.The Trapiá Cave development reached 2,300 m, becoming the longest cave in Rio Grande do Norte.

Résumé. Rio Grande do Norte est un état du nord-est du Brésil qui possède un karst très particulier, caractérisé par de grands champs de lapiés et des petites grottes. Cette région karstique est située à l'ouest de Rio Grande do Norte, près de l'état Ceará. En Septembre 2003, une équipe du Centre National pour la Recherche et la Conservation des Grottes (CECAV-RN) a trouvé l'entrée d'une nouvelle grotte dans la vallée de la rivière Apodi, l'un des principaux bassin à drainage de la région proche de Felipe Guerra. Depuis lors, plusieurs expéditions scientifiques et techniques ont été organisées pour l'étude de cette grotte appelée Gruta do Trapiá, la plus importante cavité de toute la région. Cet article décrit quelques études réalisées dans la grotte, les aspects historiques des premières explorations et les résultats scientifiques obtenus jusqu'à présent. La grotte se développe pratiquement dans un seul conduit en méandre qui est un affluent de la rivière Apodi. Les principales difficultés rencontrées dans les premières expétitions sont un passage bas qui siphonne pendant la saison des pluies, et la chaleur étouffante, en moyenne 34 ºC (93,2 ºF) sans courants d'air, car il n'y a pas d'autres entrées. Par rapport aux études biologiques, des collections ont été recueuillies dans une zone qui est d'environ ¼ de la grotte, aboutissant à une liste de 47 morpho-espèces. Au niveau de la géologie, des stalagmites actives ont été prélevées et doivent fournir de nouvelles données sur les changements climatiques dans la région au cours des trois derniers millénaires. La grotte Trapia a atteint un développement de 2,300 m, devenant ainsi la plus longue grotte de Rio Grande do Norte.

1. Introduction

The Advanced Base from the National Center for Research and Conservation of Caves of Rio Grande do Norte CECAV-RN operates throughout the Northeast region of Brazil, with the exception of Bahia State. In this region, the caves did not stand out for its development and, so far, only one had surpassed 2 km: the Ubajara cave, in Ceará state.

Since 2002 the CECAV-RN has been conducting surveys over the exposed karst pavements areas where the potential speleological findings is higher in the Rio Grande do Norte State within a area larger than 100 km^2, where 462 new caves were discovered. Trapiá cave has been located with help of local people guidance in September 2003. However, the exploration only began almost three years later, in mid-2006, because its cave entrance, a vertical gallerie of 18 metres was occupied by a huge hive of aggressive types of bees. During this expedition, the CECAV-RN team preliminarily explored 620 meters of the cave, limited to the passages that reached by the floods.

The team returned to the cave in January 2007, together with Vladir Quintiliano (RN Caving Club) and the Professor Francisco Cruz from University of São Paulo, to support new exploration and geological research activities. During this last operation ran up the conduit over the Northern Cave, until a moment in which they feel that the CO_2 concentration was too high, forcing the return of the team.

Despite the difficulties such as beehives, flooded conduits, breathing problems, the possibilitity for potential new discoveries in cave Trapiá fascinated everyone on the team and motivated further missions.

2. History of mapping

In january 2009, during a caving meeting in Brasilia, Jocy Cruz, head of CECAV, invited Leda Zogbi and the team Meandros Speleo Club to explore and survey a newly discovered cave in Rio Grande do Norte.

On February 14, 2009, the Meandros team, composed by Leda Zogbi, Daniel Menin, and the bio-speleologists Renata Andrade and Marcelo Kramer went to Mossoró to join the CECAV-RN staff people, composed by Jocy Cruz, the bio-speleologist Diego Bento, Iatagan Mendes de Freitas and Darcy dos Santos.

Figure 1. Lapias Fields of Felipe Guerra region.

To reach the cave, the path is not easy: after leaving the main road, you take an unpaved road crossing the "lagedos" (flagstones fields). The region is quite arid, with a predominance of lapiás endless fields, shrub and thorny.

The entrance of the cave is located 30 meters from where the car is parked. It is a sinkhole with a pit in the center. At the entrance, we saw the bees signaled by CECAV team. We anchor the rope and descend into the abyss which is 18 m deep.

After a tight passage at the entrance of the gulf, the descent is beautiful, accomplished between large runoff. Then reached the riverbed underground-dry this season – the main conduit of the cave.

The cave is developed by conduits that move in curves, the floor is sand. We passed a low ceiling and arrive in a large room with many speleothems, rare for this region, as gypsum flowers. After two days of hard work, the topography reached 1,225 m line tape, and the cave could already be considered the largest cave of Rio Grande do Norte, passing Furna Feia cave (766 m). After plotting the the mapped galleries on regional map we found that the cave was clearly heading to Rio Apodi, and there was still a significant distance between the end of the topography and the river, indicating a possible continuity of cave.

Our desire was to return soon to finish the exploration, but we had to wait the demise of rainy season in order to avoid eventual cave floods. Still, there was another attempt in March 2009, with the participation of Daniel Menin and Francisco Cruz, who was very interested in using speleothems for paleoclimate studies. He knew from pictures taken by the mapping team, that the cave is densily ornamented with speleothems.

We had to wait until 19 September 2009 to return to the cave. Meanwhile, the team CECAV has been there several times to check the water level, but it still high. In one of the attempts they not even entered the shafted entrance, because the bees were nervous and they retreated before being attacked.

This time we had monitored the temperature that changed dramatically from 29 degrees celcius by the entrance to 34 degrees after passing throught the sifon Thus, these high temperatures and saturated relative humidity made the climate during exploration very unconfortable.

We advanced slowly to the point where we had ended up surveying the last time: we really needed time to adapt ourselves to this unbearable heat.

Once again, the team worked well despite of internal climate. The main passage was mostly a long, meandering gallery with minor straight passages of 5 m wide and 3 m high in avarage. We found an active stalagmite with more than 1.2 m high and decided to call this snippet "Chico's Paradise," in tribute to our friend Francisco Cruz, who certainly would be very happy with this new discovery. We also found an "avenue" beautiful, straight, with a flat profile and several yellow round runoff on the roof, which we call the "The Suns Avenue" because the runoff seemed true suns ceiling. We found many megafauna bones, some quite large fixed in the rock, in a room we call "Hall of Bones."

Figure 2. Large fossile fixed in the rock.

At the end of this stage, the cave reached 2,100 m. By our calculations there were still some 500 m to reach the Apodi river therefore a new assault would be needed before the rainy season.

On November 7, 2009, the same team got together again for a new assault.

It took about an hour and a half to reach from the entrance to the point where we had stopped the topography. We began to map the cave, but the task was not easy: huge fallen blocks covered by a layer of slippery mud hindered progress in the cave. The uncomfortable feelings given by the humidity increased after every step forward. We were evolving at the limit of risk, and luckily we had brought a rope we use to help each other in the most exposed, since there was no possibility of tying the rope anywhere.

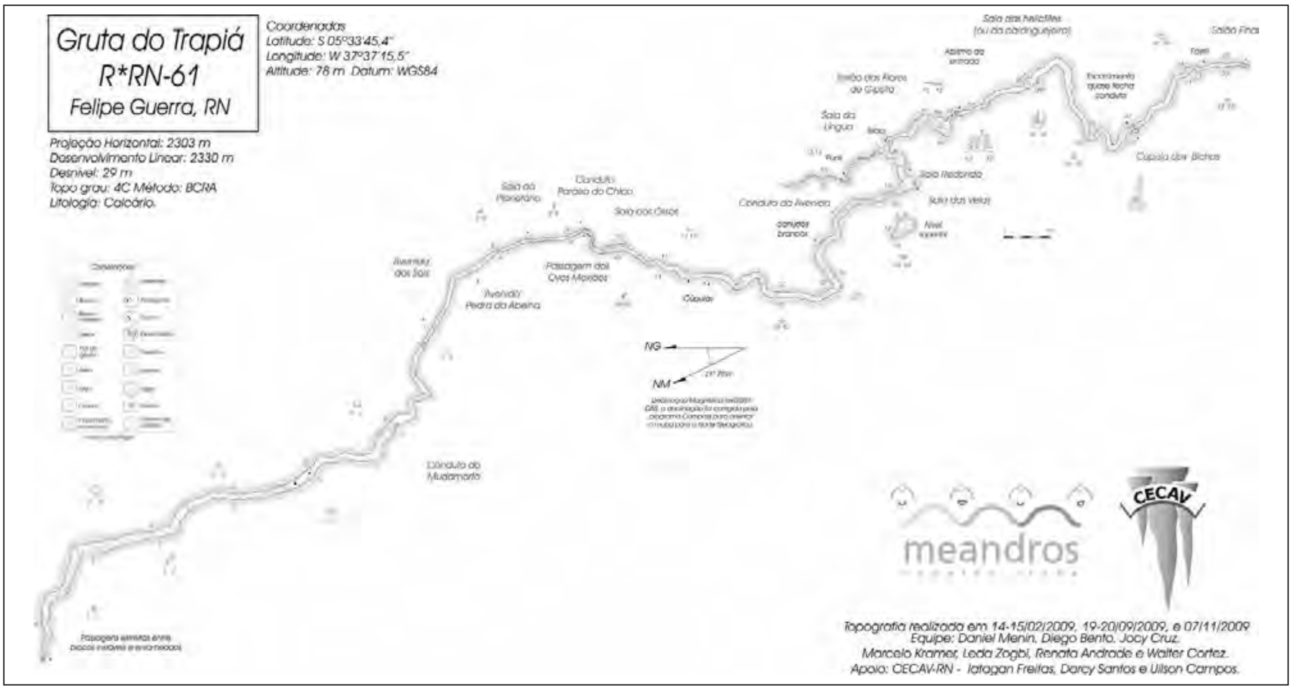

Figure 3. Trapiá Cave map.

After many efforts, we apparently reached the end of the cave, which is an accumulation of large fallen blocks covered with mud and many organic wastes, like a great natural drain. We let a fixed base on a rock at the bottom,

so that if someday someone could overcome the collapse, they could connect the topography. The cave reached 2,300 m and became the largest cave in the Rio Grande do Norte State.

The final map was impressive. The cave is developed almost by a single conduit, meandering off toward the river Apodi. There is only one bifurcation that develops into a much narrower conduit, shortly after the siphon.

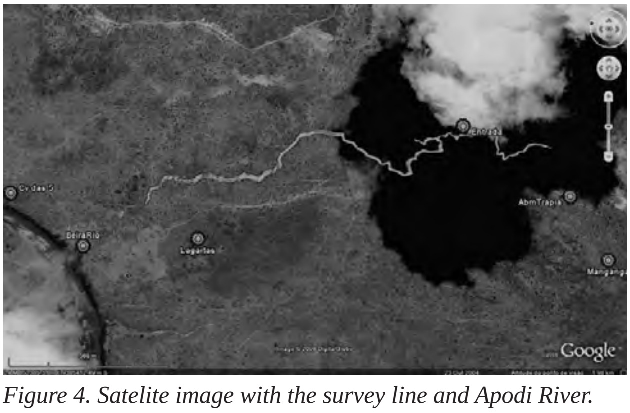

Figure 4. Satelite image with the survey line and Apodi River.

On the map, you can see that the cave is still relatively distant river Apodi. We suggest to friends CECAV-RN they seek from the opposite side, near Rio Apodi, the resurgence of this cave. By the dimensions of the conduits and the volume of water that must pass through the cave during the rainy season, it is likely that upwelling is great, and we can go the other way, rising from the river to the collapse.

Despite the difficulties mainly related to the heat and humidity of the cave leading cavers to their physical and psychological limits, exploring the Cave Trapiá was an extraordinary adventure.

3. Biospeleology

The biological characterization of Trapiá Cave was part of a larger project that included collections of invertebrates (in two campaigns, one at the end of the dry season and another at the end of the rainy season) in 24 wells of the western RN (municipalities Baraúna, Mossoro, Governor Dix-Sept Rosado, Felipe Guerra and Apodi), and data collected in 23 other caves in the same area, coordinated by Professor. Dr. Rodrigo Lopes Ferreira (Drops), UFLA (Universidade Federal de Lavras, Minas Gerais State). This project resulted in the dissertation of Diego Bento. The two sampling campaigns performed on 06/01/2010 (end of dry season) and 08/04/2010 (end of rainy season), were limited to those portions before the siphon (about 25 % of the cave).

Collected in the area, the available trophic resources were: leaves, wood waste, animal carcasses accidental regurgitation pellets of owls (mostly near the entrance, however leaf litter and wood are oftenly delivered by rain water coming into the cave), organic matter carried by colonies of social insects (ants and termites), feces of other vertebrates (frogs and "gias") and patches of guano bats (*Diphylla ecaudata*), the latter being the only resource widely distributed in the observed area. As might be expected, the spatial distribution of population did not occur at random, but strongly dependent on the availability of resources on site. Other species such as *Endecou*s sp. (Ensifera: Phalangopsidae) *Heterophrynus* sp. (Amblypygi: Phrinidae) and *Loxosceles* sp. (Araneae: Sicariidae) were widely distributed throughout the length of the sampled area.

Although it was not the object of the study, were also observed vertebrates present in the cavity. Among the mammals the only vampire bat *Diphylla ecaudata* was observed (a small rodent, mocó – *Kerodon rupestris*, dead probably due to the fall in the abyss of entry was also observed), with small groups (usually fewer than ten individuals) and stains guano spread across the entire length sampled. Among birds, only the church owl (*Tyto alba*) was observed (local food pellets and regurgitation, inclusive), between reptiles only a green snake (unidentified) and between amphibians frogs (Ranidae), "gias" (Leptodactylidae) and frogs "cururu" (Bufonidae), the latter being found in areas far from the entrance.

There were large differences between the invertebrate communities observed in two campaigns: At the end of the dry season were observed 603 individuals from at least 28 different taxa, while at the end of the rainy season were 1,699 individuals of at least 42 taxa (Table 1). Therefore, there was a significant increase in species richness and abundance in virtually all populations, which is probably a result of increased seasonal availability of resources imported from the external environment. These results were also expected in view of the dependency on imported ecosystem cave resources and, likewise, similar responses are well documented in the literature for the surface invertebrates, particularly with strong rainfall seasonality within dry dry forests environments called caatinga.

The list of species of Trapiá Cave has 47 morphospecies and is the region's average (for a total of 47 caves surveyed, the average wealth observed was 44.21 ± 19.76 species per well, and the cave of Crotes also in Felipe Guerra, with 101 species is the richest).

Regarding troglobite species (exclusively cave), we found an earthworm (Annelida: Oligochaeta) and a collembola (Collembola: Entomobryomorpha), both in puddles of water dripping with patches of guano *Diphylla* the "dome of the animals." Although the number of troglobitic species is not considered high (the cave of Troglobites also in Felipe Guerra, have so far 11 species troglobite and caves are common in the region with more than two species troglomorphic), these species were not found in any other cave and are probably new to science, having been sent to taxonomists for formal description.

Another aspect worth mentioning is the abundance of two of the most venomous spiders in Brazil, *Sicarius tropicus* and *Loxosceles* sp. (Both family Sicariidae). *Sicarius tropicus* were observed mainly near the entrance, but *Loxosceles* sp. (Brown spider) were observed throughout the sampled length of the cave, being particularly abundant in the north hall just inside the entrance (where the gypsum flowers) but also frequent throughout the Southern portion of conduit.

Figure 5. Earthworm with troglomorphic features.

Table 1. Taxa of species found in the cave Trapiá, Felipe Guerra. / RN, and population abundances in the two campaigns (end of dry season and late rainy season).

Morphospecies	1st Collection 06/01/2010	2nd Collection 04/08/2010
Acari		
Argasidae – *Ornithodoros* sp1	7	14
Laelapidae sp1	12	0
Melicharidae – *Proctolaelaps* sp1	0	72
Macronyssidae sp1	0	80
Sarcoptiforme sp1	0	14
Sarcoptiforme sp2	0	1
Sarcoptiforme sp3	0	1
Acaridae sp1	0	2
Anoetidae sp1	0	9
Amblypygi		
Phrinidae – *Heterophrynus* sp.	8	21
Charinidae – *Charinus* sp.	3	3
Araneae		
Ctenidae sp1	0	4
Gnaphosidae sp1	1	0
Pholcidae – *Mesabolivar* sp.	3	7
Pholcidae – *Metagonia* sp.	11	20
Salticidae sp1	0	1
Salticidae sp2	2	2
Scytodidae – *Scytodes* sp.	9	37
Sicariidae –*Loxosceles* sp.	35	125
Sicariidae – *Sicarius tropicus*	6	59
Theraphosidae sp1	1	2
Theridiidae –*Theridion* sp	9	61
Opiliones		
Gonyleptidae sp1	0	2
Pseudoscorpiones		
Garypidae sp1	0	11
Schizomida		
Hubardiidae – *Rowlandius* spn.	10	2
Diplopoda		
Polydesmida-Chelodesmidae sp1	3	0
Isopoda		
Isopoda sp1	0	1
Armadiliidae sp1	6	96
Plathyarthridae – *Trichorhina* sp.	9	117
Collembola		
Collembola (entomobryomorpha) sp.	2	37
Paronellidae – *Campylothorax* sp.	375	419
Blattodea		
Blattodea sp1	0	14
Coleoptera		
Carabidae sp1	0	1
Carabidae sp2	1	0
Carabidae sp3	1	0
Nitidulidae sp1	0	1
Tenebrionidae – *Zoophobas* sp.	3	1
Ensifera		
Ensifera sp1	0	2
Phalangopsidae – *Endecous* sp.	56	157
Hymenoptera		
Formicidae – Myrmicinae – *Acromyrmex sp.*	1*	1*
Isoptera		
Termitidae – Nasutitermitinae – *Nasutitermes corniger*	1*	1*
* - Colony (accounted as an individual)		

Highlighted lines correspond to troglomorphic taxa.

Morphospecies	1st Collection 06/01/2010	2nd Collection 04/08/2010
Lepidoptera		
Lepidoptera sp1	6	6
Tineidae sp1	0	3
Psocoptera		
Psyllipsocidae–*Psyllipsocus* sp.	21	183
Thysanura		
Nicoletiinae sp1	0	68
Oligochaeta		
Oligochaeta sp1	3	37
Gastropoda		
Streptaxidae-Streptaxis sp.	6	6

Highlighted lines correspond to troglomorphic taxa.

These spider occurences need caution especially because is necessary go crawling during exploration by the spelunkers to creep forward. Although accidents with these spiders in caves are relatively rare, such aspects should be taken into consideration in any work on cave Trapiá.

Figure 6. Amblypygi Heterophrynus sp with juveniles on the abdomen.

It should be noticed, again, that only about ¼ of the cave was biologically sampled, thereby, surveys in the areas after the siphon will be necessary.

Now, with the addition of biological data, besides the remarkable dimensions in length, area and volume and the presence of rare speleothems in the region, we can affirm that the cave is also an essential habitat for species of rare and endemic troglobitic fauna.

More than ever, there are many attributes to define the Cave Trapiá as the jewel of Rio Grande do Norte's caves.

4. Paleoclimate studies in the area of Felipe Guerra-RN

Studies of the past climate variations in the Rio Grande do Norte has been performed since 2004, using stalagmites from Rainha cave which is located nearby Trapiá cave.

The previous paleoclimate record is based on speleothem Isotope records dated by using U/Th geochnology technique of the last 26 thousand years (Cruz et al. 2009).

The most of dated speleothems stopped growing at about 4 thousand years ago which is consistent with the aridity trend and the establishment of semi-arid climate in the region suggested by higher values of oxygen isotope ratios in the record. The goal of this new study on Trapiá cave stalagmites is to understand the higher frequence climate variability in the region during the last three thousand years. This study can give new insights into the origin of intense droughts episodes tha has impacted human occupation since the first settements of immigrants in the region 400 years ago until today.

Samples were studied in America. The results were very interesting because it showed that almost all speleothems stopped graduating four thousand years ago, which indicates establishment of semi-arid climate in the region since then. In fact, the climate became drier in the northeast for the past four thousand years while in much of Brazil became increasingly humid. The paleoclimate data from the caves of the RN became central to discussion of the origin of climatic contrasts on the South American continent.

Working with a stalagmite of Furna Feia, also from Rio Grande do Norte, we had surprising results about the climate based on the variation of chemical composition over the past 3,700 years and completed a climate record of the last 26,000 years that was published in Nature Geoscience in 2009. However, this sample was an only child and this variability in chemical composition had to be tested in other samples to see if they really correspond. We needed more samples.

The first time we went to Trapiá cave was looking for a sample that was actively growing in the cave, something that had failed to find in Rainha cave. In the first trip, time was short, and only visited the starting areas of the cave. After the exploration and surveying expedition performed by of CECAV-RN and Meandros teams, we were informed that they had found active speleothems, but it tooks several visits to the cave until we could cross the siphon and reach the room where the stalagmites were.

I had particular interest in knowing that such conduct from "Chico's Paradise". Really that place is something quite unusual for the region as a cave high concentration of large candle shape stalagmites. In fact, we could find adequate active stalagmites that are already precisely dated and have been studied by a graduate student at University of Sao Paulo, under supervision of Prof. Cruz. These new speleothem records will soon provide precious informations on regional climate variability.

Acknowledgments

We would like to specially thank CECAV-RN staff for the constant support during expeditions (Jocy Cruz, Iatagan Freitas, Darcy Santos and Campos Uilson); we would also like to thank all cavers who attended the topography of the cave (Renata Andrade, Marcelo Kramer, Walter Cortez and Jocy Cruz): the topography performed in extreme temperatures, as we endure this cave, can be quite difficult. Francisco Cruz is also very grateful for Vladir Quintiliano and Fabio Simas for great assistance in the field.

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Session:

Speleological Research and Activities in Artificial Underground

THE MAN-MADE UNDERGROUND CAVITIES OF NORTH-WEST RUSSIA

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In this article we consider the largest, interesting and meaningful man-made underground structures of North-Western Russia, which are located on the territory of Leningrad and Pskov Regions and the Republic of Karelia. These are: Sablinskaya, Staroladozhsky man-made caves, Petrovskaya underground quarry, cult caves Svyataya ("The Saint cave") and Dolozhskaya, Taitsky sluice-way (Leningrad Region), underground complex of the Pskovo-Pechersky Dormition Monastery (Pskov Region), mine workings of Ruskeala and Rogoselga fields (Republic of Karelia). This review does not include fortifications and modern existing fields.

1. Introduction

The North-Western region of Russia is located at the junction of two major tectonic units – the Baltic Shield and the Russian Platform. The Baltic Shield is composed mainly of Upper Archean and Proterozoic igneous and metamorphic rocks. This region is characterized by minerals as iron, copper and tin ores, marble and granite. The majority of the Republic of Karelia territory is situated on the Baltic Shield, which determines the features of the history of mining here, as also a large number of old mine workings.

The territory to the south of the Baltic Shield is composed of rocks of the sedimentary cover of the Russian plate. In its structure, Lower Cambrian – Lower Carboniferous sedimentary rocks predominate, represented by sandstones, shales and limestones.

In this region numerous underground mine workings are present (Figure 1), which have been subdivided based upoin the types of minerals (Dolotov 2010). These mines were created for: 1 – Ore (iron, copper), 2 – Fossil fuel, 3 – Building material, 4 – Raw materials for the glass industry.

Among the underground architectural structures the following stand out: 1 – residential, 2 – manufacturing, 3 – protective (fortification), 4 – transport, 5 – cult sites.

The mining has received active development in this region since the XVIII century. Various ores (iron, copper, etc.) were mined in mines by underground method. The mines were used to extract fossil fuels (oil shale), in underground stone-pits – limestone and marble (for building purposes), sandstone (for glass industry). Part of the mine workings were carried out for mineral exploration.

In this region there are various types of architectural underground structures. The most common are underground structures of entertainment character in park ensembles, which were built from the XVIII century (grotto). During the war time natural caves could be used as a temporary shelter by the population.

Underground structures for manufacturing are rare. Most common are the protective (fortification) underground structures. From the Middle Ages, various underground cavities were built in castles: hiding-places (siege wells to provide water in the case of siege), mine galleries, passages for messages within the fortress walls. However, nowadays they are destroyed or inaccessible for a visit. During the XIX–XX centuries many facilities were built for military purposes: hideouts, communication trenches, fire positions, missile silos, warehouses.

Other types of structures are also quite common in the area. Basically they are underground hydraulic engineering constructions: sluice-ways, sewers, drainage structures. Complex systems have been preserved in manor-parks property, which were constructed in the XVIII century.

Underground cult structures are interesting enough, that are known from the XV–XVII centuries and are related to the Eastern Christian tradition (the Orthodox Church). There are the following types of sites: cave monasteries, cave temples, caves of hermits, burial structures, natural pseudokarst caves with revered holy springs.

For these purposes man-made underground structures were constructed and also natural caves were used, mainly in sandstones. The arches of natural caves sometimes were strengthened by stonework, and cavity volume was increased by mining penetration method (Agapov 2012).

2. Leningrad Region

The mining in the Leningrad region in pre-Petrine Period was weakly developed. Mine workings were preserved, which were created in the XIX–early XX centuries on deposits of Cambrian quartz sandstone of

the Ladoga and upper Sablinskaya formations. The largest deposit – Sablinskoye, is located 40 km to the SW from St. Petersburg, at the Leningrad Region. Layers of this deposit contain 95 to 99 % of quartz and could be used for the manufacturing of glass without enrichment. In Sablino 15 mines are known, the largest of which – the Levoberezhnaya (Fig. 2), has a length of 5,500 m (Lyakhnitsky 1990; Dolotov and Sokhin 2001).

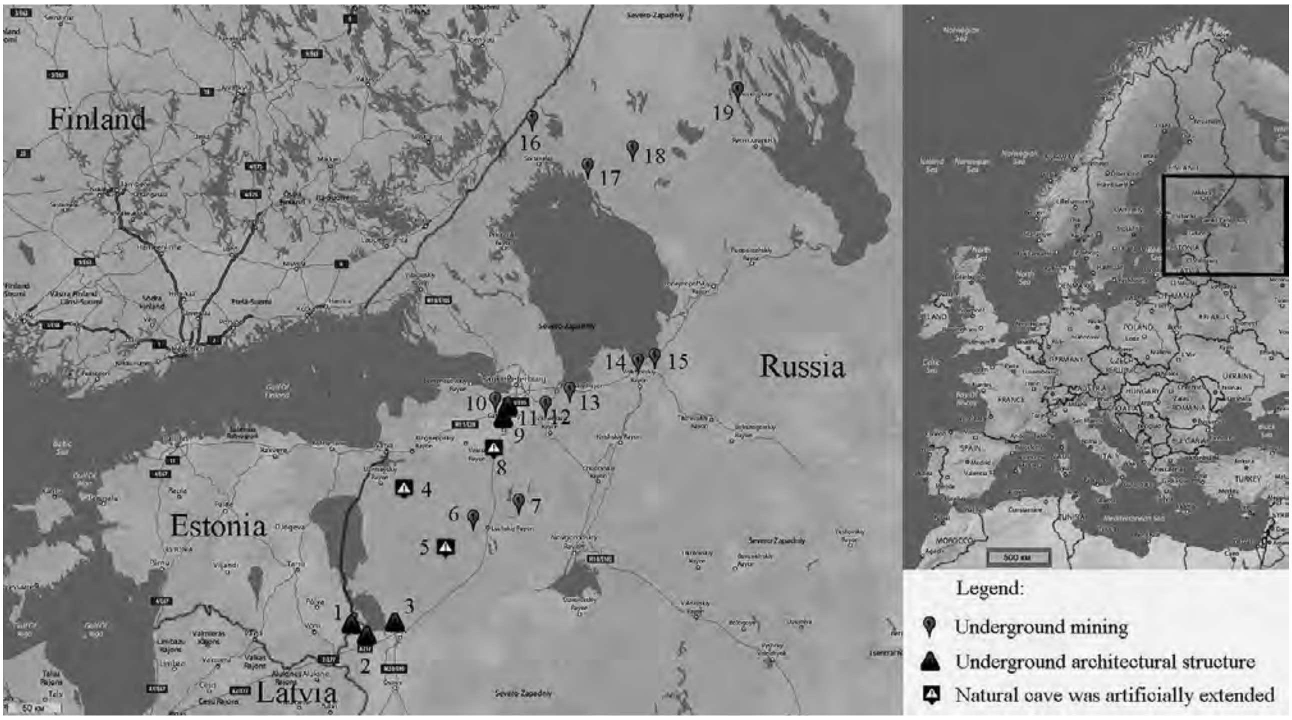

Figure 1. The overview map with the location of underground structures. Compiled by I. Agapov. Based on the 2013 Yahoo map. Legend:1 – Pskovo-Pechersky Monastery; 2 – Izborsk Fortress; 3 – Pskov City; 4 – Dolozhskaya Cave 5 – Posolotino Novye Pechora Cave; 6 – mines near of Korpovo Village; 7 – mines near of Borshevo Village; 8 – Svyataya Cave; 9 – underground passage from the Gatchina Palace; 10 – Petrovskaya Cave; 11 – Taitsky sluice-way; 12 – Levoberezhnaya Cave; 13 – mines near Apraksino; 14 – Quartz sandstone deposit StaroLadogskoye; 15 – Rebrovskoe Quartz sandstone deposit; 16 – Dvuglazka Marble Mine; 17 – mines near Pitkäranta City; 18 – Rogoselga Mine; 19 – Nadezhda Mine.

The deposit was worked by room-and-pillar method with free clearing space. The mines in the Sablinskiy field are horizontal, but because of breakdown from vaultss, their ceiling reaches heights up to 7 m. The height of adits and drifts reach about 2 meters, chamber height are 3–4 m, with a capacity of productive layer of sandstone of 3 m. The largest landslide halls reach in length some 20 m. Due to a collapse in the domes of the cavities, Ordovician limestones were exposed, thus starting the karst processes. Landslide processes have revealed the narrow slotted cavities in the limestones that arch the mine workings,which were formed under the influence of the glacier. In the Levoberezhnaya Cave were formed three lakes and a stream. In the Sablinskie caves 8 species of bats hybernate during the winter. The complex inspection of the underground cavities was carried out in the last century (Lyakhnitsky 2006). The Levoberezhnaya Cave was equipped for underground excursion routes. The work included the fixing of unstable areas, concreting of heads of inputs, regulation of the hydrological and microclimatic regimes, laying of the excursion trails, etc. On the surface a number of tour routes was also developed. Now it is one of the most valuable of the environmental and excursion centers – the Museum of Geology and Mining. In fact – this is the first geopark in Russia.

The Cambrian quartz sandstone deposits StaroLadogskoye and Rebrovskoe are located at the east of the Leningrad region. The method of processing and the geometry of the mine workings are similar to the Sablinskiy deposit.

The largest mine in StaroLadogskoye deposit has a length of about 6,000 m, by the topographical survey of the Speleology section of the Mining Institute, that was made in 1968–69. (Dolotov and Sokhin 2001). The largest mine in the Rebrovsky deposit is about 507 m long. Mining workings of Staraya Ladoga deposit are the largest reserve for wintering bats in northern Russia.

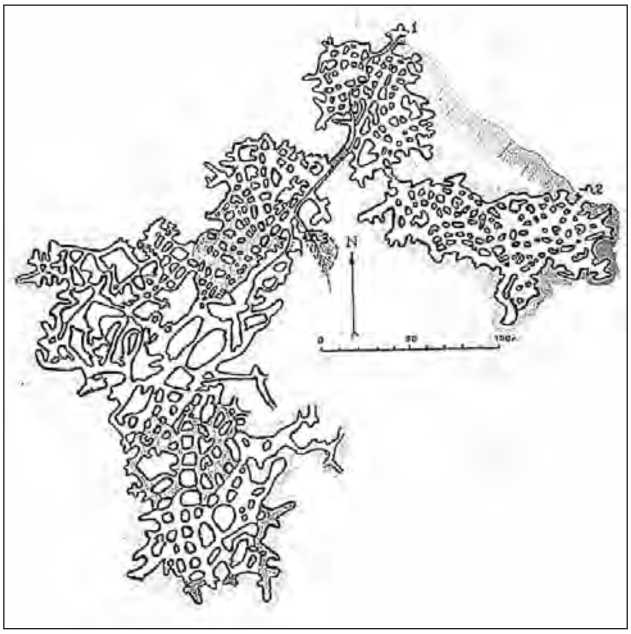

Figure 2. Levoberezhnaya Cave. Topographical survey by Y. S. Lyakhnitsky, 1990.

The minings for the extraction of Devonian quartz sandstone are located in the south-western districts of the Leningrad region. The major areas of minings are the surrounding of Borshevo Village and uninhabited Korpovo Village. They were worked out mainly at the beginning of XX century by the room-and-pillar method with free clearing space. From minings in Cambrian sandstones they are distinguished by the highest section of adits and drifts, which are up to 6 m high, whilst width is up to 5 m, which is associated with a greater capacity of the productive strata. The largest cave in the vicinity of Borschovo Village has a length of about 560 m, whilst in the vicinity of Korpovo Village the longest cave is about 400 m.

The main building material is a limestone,which was extracted since the first half of the XIX century through the first half of the XX century in underground mine workings in the Leningrad region. It was quarried on theIzhora Plateau near the villages of Telezi and Aropakkuzi from the layers of Llanvirnian tier. It was produced at more than 20 working sites, typically reaching in cross section from 5 to 3 m in height. The largest quarry is near the village Telezi, it is the Petrovskaya stone-pit. The entrance was long ago closed by a collapse. In 1980 it was found by members of the Leningrad Spelestologycal Party (Miroshnichenko 1992). Galleries and drifts in the Petrovskaya stone quarry have a total length of 360 m, they are located on two levels, with the altitude difference between the highest and the lowest marks of the floor level of the mine being about 5 metres. The width of adits and drifts is up to 6 m, the height is up to 4 m. An engineering and geological survey of the stone quarry showed that it is extremely dangerous because of the possibility of falls and collapses. The archs of the mine in many places is composed not from Ordovician limestones but from the overlying Quaternary moraines. In order to preserve this unique monument of the history of mining, it is necessary to strengthen the arches of the mine and cleaning it from garbage, left by the unorganized visitors. Near the station Apraksino, on the banks of the Nazia River was mined the limestone of the Arenigian stage of the Lower Ordovician. It was extracted through the method of developing room-and-pillar, with partial backfilling of the cleaning space. The galleries have a length up to 70 m. Adits and drifts are rectangular in cross section, high up to 2 m, and wide up to 4 m.

In the Leningrad region all types of architectural underground structures are known. The most common are a variety of underground fortification structures, built from the XIX to the early XX century. These are various types of forts and fortresses, that, however, will not be treated in this article.

Only one available underground passage of the XVIII century is known today, leading from the Gatchina Palace to the grotto “Echo” on the Silver Lake. Now it is used for excursions. The length of the passage is about 120 m

In the suburbs of St. Petersburg drainage systems of the XVIII to the early XX centuries are present, built under the city’s parks of Pushkin, Pavlovsk, Gatchina, Krasnoye Selo.

The largest-scale hydrotechnical structure is the Taitsky sluice-way, created in 1772–87 for the supplying of Tsarskoye Selo (Miroshnichenko 1992). The total length of the sluice-way is about 15 km. About 7 km of the way are in the form of so-called “Mine gallery”, traversed by in limestone at a depth of about 17 m. Along the route of the gallery has been made 59 mines for excavation. The water flowed from the Taitskie Springs. By 1905 the using of the sluice-way was stopped, and it went into decline.

For religious purposes mainly caves of natural erosion and suffusion in the Devonian sandstones were used. Their veneration is associated to the springs, which are considered as curative. Most of these caves are located in the area to the South-West of the Leningrad region. Some of them have been enlarged by man, and represent therefore nowadays a combination of natural and man-made cavities.

The biggest one is the Svyataya Cave, showing a total length of about 130 m.

This is a unique system of pseudokarst cavities, formed by suffusion and erosion processes, associated with underground streams in non-karst red Devonian sandstone, in the beautiful cliffs of a small stream – a tributary of the Oredezh River. It starts out from the spacious picturesque grotto with a height of up to 5 meters. The spring water, flowing out of the cave until the middle of the XX century, was considered curative and was revered by locals residents. Subsequently, because of its pollution, its worship was stopped. Now the Svyataya Cave is mostly used as a tourist site (Lyakhnitsky 2006; Agapov 2008).

The second longest (only about 21 m long) is the Dolozhskaya Cave, known since the XVIII century. According to legend, nearby the cave an appearance of the Virgin had occurred. Inside the cave there is a healing spring. This natural pseudokarst cave in the Devonian sandstone was also in this case enlarged by man. At the beginning of XX century at the entrance to the cave, the terraneous Church of the Assumption of the Blessed Virgin was built, which was destroyed later on, during the middle of the XX century. Out of the temple, by the covered gallery, the passage to the cave was built. Now the cave is widely used by people for religious purposes. Once a year a religious procession goes to the cave (Agapov 2008).

3. The Republic of Karelia

In Karelia the mining industry, as a matter of fact, did not exist during the pre-Petrine Period. Evidences of use of underground mining before the XVIII century, except for Ruskeala, have not been found up to today. The iron ore was mined in Karelia in several deposits, located in the North Ladoga, and the copper ore in deposits located near the Ladoga and Onega Lakes.

The largest area of mining of ore minerals is in the vicinity of the city Pitkäranta where deposits of copper, iron and tin were worked out. Most of the deposits in this area are of the skarn type.

The deposits around Pitkäranta were used from 1810 to 1940. Different methods of mining were used with free clearing space. Most mines have a vertical or inclined shafts, extending to a depth of 270 m from the ground surface. From the shaft, galleries head off at different levels. To this date, the vast majority of mines were flooded and are only available for study with the use of diving equipment. Very little is known about the morphology of these mines due to bad availability of the information.

In the Tulamozerskiy district a very interesting hematite deposit is situated at Rogoselga. It was used from 1870 to the 1900s. Its underground mines (Fig. 3) are relatively well preserved. After a short entrance gallery (about 18 m), a long haulage drift begins, in the ceiling of which are two huge sloping flattened cavities of a waste vein-shaped hematite body. In their upper part they have an access to the surface by the through-boreholes. Thanks to this exits, all the way down to the horizontal drift, it is illuminated by natural light. In the worked space rotten wooden chock are preserved. In the bottom part of the second ramp there are two small pillars, which are still supporting the arches above.

The 30-m deadlock transport drift is at the western drift. The total length of the horizontal galleries of the mine is about 200 m. The look of these old mines is very impressive: it is shined by a weak daylight, and covered in some places with moss and lichens. Not far from the mine there are the picturesque ruins of the Tulomozerskiy iron-smelting factory. The mine and factory ruins can be beautiful excursion sites, such as a museum of history of mining.

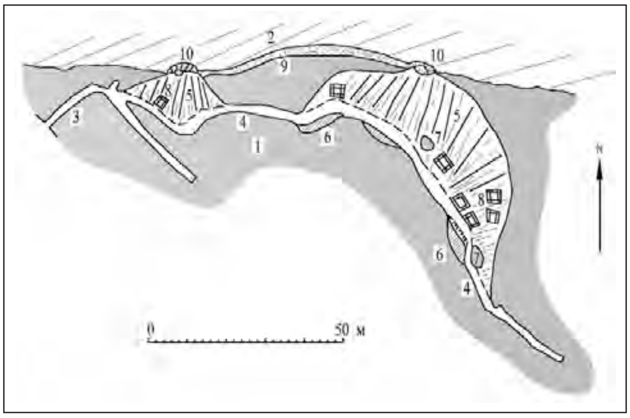

Figure 3. Schematic plan of mining by hematite field Rogoselga. Yuri Lyakhnitsky, with supporting KRPOSR "Kolos" (Karelian Republic Public Organization of Speleology Researches). 2007. The legend: 1 – host rocks, 2 – surface, 3 – entrance gallery, 4 – haulage drift, 5 – ramp – the worked space on the steep slopes of the hematite vein-shaped body, 6 – small lakes, 7 – pillars, 8 – wooden chock, 9 – trench on the surface, traversed by ore body, 10 – through-boreholes.

Most copper mines, typically small in size, are located near Onega Lake. The most famous – the horizontal mine "Nadezhda" – functioned since the beginning of the XVIII century to 1750–1754 (Miroshnichenko and Khlebalin 2011). Its adits and galleries cover on an area of 52 × 30 m. In the mine chalcopyrite, chalcocite and oxide copper were extracted.

Karelia is extremely rich in various construction cladding and ornamental stones, so there are widespread quarries for their extraction. Large amounts of granite and marble were especially extracted. The largest deposit of marble – Ruskeala – is located in the Northern Ladoga area, at 40 km from Sortavala city, near the border with Finland. This is the ancient Novgorod territory, but the village Ruysselka was firstly mentioned at Nikolsko-Serdobol'sky Pogost in the Census Book of Korelsky County (Swedish) in 1590. The first information about its use is related to the XVII century. In 1766 in Ruskeala the pilot production of blocks of Proterozoic gray marble began for the construction of St. Petersburg. In 1817, Auguste Montferrand visited Ruskeala and chose the varieties of marble for the construction of St. Isaac's Cathedral. The Ruskeala marble was also used for the construction of the Marble Palace and other buildings and obelisks in St. Petersburg. Later the marble was quarried for lime burning. During the long years of work at the deposit, it resulted in several quarries and an extensive network of underground workings. It consists of three vertical shaft sinking, connected by galleries and drifts with large chambers, rooms, located on three levels. After completion of the work, the two lower levels of workings and, in part, the upper level, were flooded. The deepest drift of mine, no. 3, is at a depth of 38 m below the level of flooding and the shaft extends to a depth of 66 m. The largest flooded quarry has a length of about 370 m and a width of 15 by 105 m. The depth of the quarry to the flood level ranges from 6.4 to 24.4 m, and even up to 25 m to the flooded floor. It was called the Marble Canyon. Nearby is another picturesque flooded "Monferranovskiy" quarry and a beautiful lake. Now on the base of the deposit, the mountain park "Ruskeala." is present. It is one of the most valued geological heritage sites in north-west Russia. In the primary equipping of the tourist route around the quarry an excursion trail and a pier with promenade boats were constructed. The underground space of the deposit – galleries and large cameras – halls are not used yet. The largest hall has a length of about 115 m and a width reaching a maximum of 55 m (Figs. 4 and 5). The arch of the hall rests on 8 massive columns. The height of the hall over the water is about 8 m, up to 12 m. including the depth of the flooded part. To create the underground route it is planning to use at least two galleries and this huge room. By combining underground and surface routes, a beautiful Geopark can be created, which will become one of the best in Europe (Lyakhnitsky 2006).

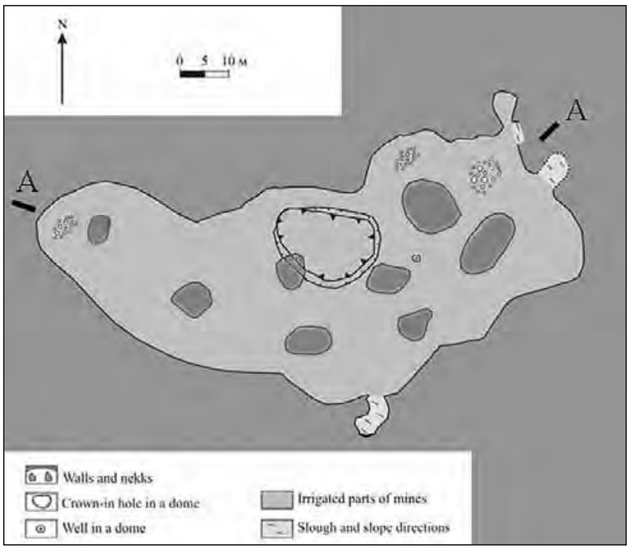

Figure 4. Dvuglazka Marble Quarry. Yuri Lyakhnitsky, Igor Khlebalin, Oleg Minnikov 2010.

4. Pskov Region

In the Pskov region the underground mining is weakly developed. In the area the quarries are spread for the extraction of building materials and for the construction of fortresses and cities. However, the production was produced mainly by the ground mining method along the sides of the river valleys. Underground mining of stone was private and fragmented. The length of the underground quarries do not exceed an average of 10–20 m. Cases of alabaster underground mining in the XIX century are known.

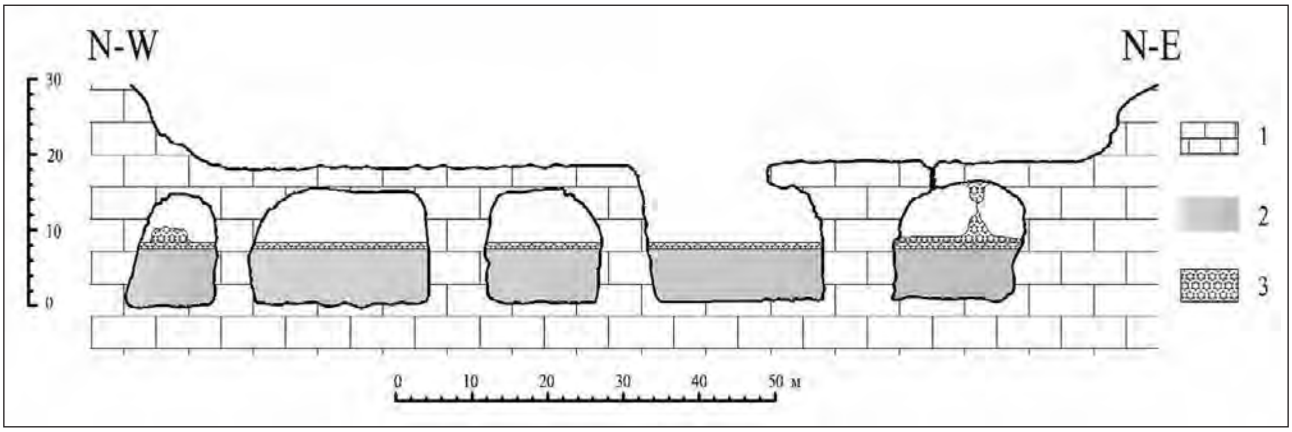

Figure 5. The longitudinal section (section A-A) through the Hall of Columns in the underground marble quarry Dvuglazka (Dvuglazka marble quarry) in Ruskeala (flooded volume is darkened). Yuri Lyakhnitsky, 2010. Legend: 1 – the host rock, 2 – water, 3 – ice (in winter).

Alabaster mining was conducted in the winter. In the spring such minings are often flooded with water, and subjected to likely collapses of rocks.

In the region there are various architectural underground structures. The largest is the cult and household underground complex of Pskovo-Pechersky Dormition Monastery of the XV century (Agapov 2011). It is one of the largest Orthodox cave monasteries of Russia. This is the only monastery in the history of Russia that at any time since its founding has never been closed. It is constantly in use and developed over more than 600 years. The underground complex (Fig. 6) consists of several cavities: an underground necropolis, cave church, cave cells.

The total length of the passages of the underground necropolis is 177 m. About 10,000 people are buried there. It is a system of galleries with burial chambers that have been cut in the Devonian sandstone. The necropolis is used as intended to this day.

The cave Temple, the Assumption Cathedral, evolved during the XV–XVIII centuries. Restorers opened in 1971 frescoes of the XVI century in the altar of the temple. The temple has length of 18 m and is 20 m deep. The arches of the church are resting on 10 massive pillars of sandstone, overlaid with brick. The temple has a terrestrial facade, in which five windows are made.

The cave monastery cells, where hermits lived, emerged during the expansion of natural erosion and suffusion caves by monks. The length of the cells ranges from 4.5 to 13 m.

On the monastery grounds underground structures for household purposes are known: cellars and subterranean reservoirs, in which the Kamenetz brook is running, flowing through the monastery. Apparently there were also tunnels for military use, as a monastery in the past performed the function of a fortress.

In the Pskov region several cult caves of natural origin are present. These erosion-suffusion caves were formed in sandstone and were later expanded by man. In the northwest of the Pskov region in one of these caves, in the XVI century people from the Pskovo-Pechersky Dormition Monastery founded a new monastery, "Posolotino Novye Pechori". The monastery was abolished in the XVIII century. The length of the cave is about 21 m. The arches of the cave were strengthened by brickwork. Over the masonry one burial chamber was built. At the cave entrance, a bell tower with cell (destroyed in XX century) was built. Inside the cave there is a healing water spring.

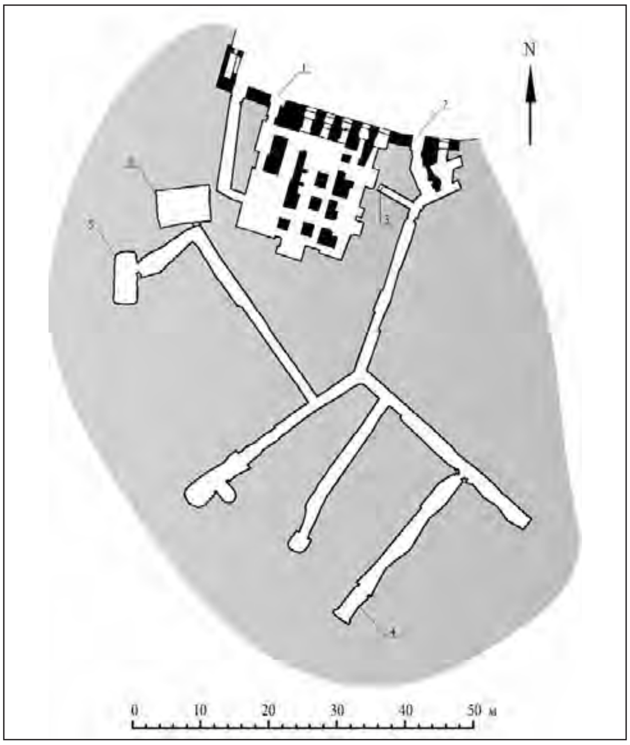

Figure 6. Plan of cult underground complex of the Pskovo-Pechersky Dormition Monastery. Computer processing – I. Agapov. 2013.

The scheme is based on the plans from the archives of the Institute "Spetsproektrestavratsiya" (Special Project of Restoration): Mikhail Semenov 1966. Drawing by Mikhailov S.P. 1977, Semenov M.I., Mikhailov S.P. 1975. Drawing by – Mikhailov SP.

Legend: 1 – entrance to the Assumption Cathedral of the XV–XVIII centuries. 2 – entrance to the underground necropolis of the XV–XXI centuries. ("Bogom Sdanniya Pesheri"), 3 – the rise to the second (upper) layer in the Church of the Protection, of the XVIII century, 4 – the Church of the Resurrection, 5 – the old common cemetery before 1700, 6 – new common cemetery after 1700.

The medieval fortresses of the Pskov region were equipped with a variety of underground fortifications, the so-called hiding-places. These are underground passages, intended to deliver water during a siege. For the most part they have not been preserved. They are most probably in the fortresses of Pskov and Izborsk. In Izborsk the beginning of the course has been preserved. In the fortress of Pskov underground tunnels were built within the city walls. Also mine galleries are known, built to fight during the siege.

In the city of Pskov some famous historical drainage and sewerage underground facilities can be found (for example, the tunnel from the Pogankiny Chambers with a length of about 400 m), which have not survived. In the Pskovo-Pechersky Dormition Monastery a brook is enclosed in the underground channel.

5. Conclusions

In the north-west of Russia a large variety of underground cavities of different origin and use is present. Some of these cavities are enlarged pseudokarst structures of natural origin. Many of them are wonderful excursion locations, on basis of which nature protection and museum centers could be planned and organized. We are being prepared for inclusion of new sites in the register of monuments of a natural and geological heritage. Work of the members of our committee of Karstology and Speleology of the Russian Geographical Society seeks to study, preserve and promote of these interesting objects and to the organization of this basis and educational tourism. Some of these sites are already equipped for the regulated tour use. Unfortunately, up today this was only made possible at the Sablinskiy natural monument and at the Ruskeala marble deposits. These works are ongoing. To achieve better results, for saving the other monuments financial help from the state or sponsors is needed.

For more than 600 years the Pskovo-Pechersky Dormition Monastery had been in use – one of the main shrines of Russia.

Our Commission is doing its utmost to the study, the discovery of new caves, their conservation and wise thought out using on the basis of scientifically based standards and professional projects.

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GOLD MINES OF THE 18TH CENTURY: PAST AND PRESENT

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In Ouro Preto, the gold extraction was started in alluviums and terraces, later interesting slopes rock masses, through underground mining. This mining left its marks, which are visible in the surroundings and inside the city. The discovery of gold in 1711 boosted the socio-economic life in Brazil, especially in Minas Gerais State, creating a new center of production and consumption. However, the fast population growth generated serious supply crisis in which the miners could not find food to buy. From the second half of the 17th century, with the gold decline, the Portuguese Royal Family came to Brazil, and a policy of attention to the mines was started, sending a specialist to observe the mistakes of the miners and to study and implement methods which could increase the production again. At first, the exploration was limited to the alluvial deposits, looking for the auriferous gravel. As the time passed, associated to the impoverishment of the alluvial deposits, the exploration of other kinds of deposits began, and new extraction techniques appeared, in which the workers opened galleries and tunnels following the layers with gold in all directions. At the slightest sign of impoverishment of these layers, the miners abandoned that workplace and opened another mine. This lack of technical knowledge accounted for the existence of several mines with varied extensions. The total number of mines opened during the gold cycle in Ouro Preto is not known, with some estimates ranging from 1,000 to 2,000 mine openings. Nowadays, many mines have inaccessible and/or hidden entrances. Some are still used as touristic attraction and/or as source of water collection for urban supply. The Sociedade Excursionista e Espeleológica (SEE; Excursion and Speleological Society) develops projects together with the Federal University of Ouro Preto (UFOP) and the local communities. The projects include hikes and visits to the places with remains of mining activities, aiming to locate and identify these remains, besides raising awareness of the local population about the importance of their preservation and also intending to recover some of the history of a time which was essential for the development of the country.

1. Introduction

It is not possible to define who was responsible for discovering gold in Brazil, and where and when the gold rush started. Some researchers report about a mulatto from Taubaté City who found gold in Tripuí Stream, in Ouro Preto. However, in the last decade of the 17th century, hundreds of alluvial gold deposits were found in the rivers and streams in the surroundings of the mining cities of Ouro Preto, Mariana, Sabará and Caeté, thus starting the gold rush in Brazil.

The search for the metal also had a great impact on the life of the colony and the metropolis itself. Thousands of people from all over the country moved to Minas Gerais in search of wealth. In Portugal, it is estimated that around 750 thousand people migrated to Brazil. Although the numbers seem exaggerated, it is known that it was large enough for the Portuguese Crown to restrict the coming of the Portuguese to Brazil, in 1720.

The gold cycle meant the colonization and definitive settlement of a vast region inside the colony, changing deeply the standard of land occupation and the economic activity of Brazil-Portugal and of the world. It marked the beginning of the demographic, economic and political hegemony of the Central-South region of Brazil, represented by the transference of the colony capital from Salvador (BA) to Rio de Janeiro (RJ) in 1763.

In Ouro Preto, the gold extraction started in the alluviual and terrace deposits, and later affected the slopes, generally through the wash down of deposits and more friable rocks, finally reching the rock masses through underground mining. Mining activities were developed for over a century in the place where today lie the cities of Ouro Preto and Mariana (Domingues et al. 2006).

These activities left marks still today visible in Ouro Preto Range (Fig. 1). In the surroundings and inside the urban area of Ouro Preto there are several records of the gold extraction. They are cut mountains, aqueducts which cross the slopes to carry water for the wash down of gold deposits, and huge reservoirs called “mundeus”, intended to collect the auriferous mud that came down from the mountains and underground galleries.

This work focuses on the underground galleries which besides having a little of the history of the early days of mining in Brazil, are part of the touristic routes of the city. They have extensions ranging from just a few meters to hundreds of meters, and have been object of study due to their historical and touristic importance and need of preservation.

2. Characterization of the physical environment

Geologically the city of Ouro Preto is located in the south part of Quadrilátero Ferrífero, in a large regional structure known as Anticlinal de Mariana. Ouro Preto is located in the south corner of this structure. Ouro Preto grew in a large valley limited by the mountains of Ouro Preto Range in the north and Itacolomi in the south, where the Funil Stream runs. The local morphology is characterized by high

Figure 1. View of Ouro Preto Range.

mountains of linear development, plain areas of different altitudes and long valleys. Approximately 40 % of the area shows slopes traits between 20 % to 45 % and only 30 % with gradients between 5 % and 20 %. Steep zones are common in all urban area (Gomes et al. 1998).

The traces of the relief, rugged with very steep slopes and deep valleys show a clear dependence on the local geology. The main element of the landscape in the urban area is the Ouro Preto Range, the north limit of the urban area and watershed of two large regional hydrographic basins, the Rio das Velhas and Rio Doce – Ouro Preto is on the headwaters of this last river. The altitudes are around 1,400 meters a.s.l. at the highest parts of the city, with Itacolomi Peak, the highest point of the region, at 1,760 m a.s.l.

The bedrock consists of metasediments of Paleo-Proterozoic age – phyllite, quartzite, schist, and iron formations – deeply affected by tectonics. The regional structure is oriented in East – West direction, having the general dip layers to south, in the order of 30º, at the south corner of the structure, and has similar values, dipping to north in the north corner of it. There is a common occurrence on the top of the slope of the hills, the superficial cover of lateritic crust, usually called “canga”. These materials, of Tertiary – Quaternary age, are products of supergenic alteration in tropical climates. The soils, when occurring, are thick, on the order of centimeters, except for some larger spots of colluvial material. The lithology feature, besides marked metamorphic exfoliation, planar discontinuities (faults and cracks), which deeply influence the geotechnical behavior (Sobreira and Fonseca 2001).

3. Historical context of the gold cycle in Brazil

With the Portuguese arrival in Brazil in 1500, an intense campaign in search for gold, silver and precious stones was started. However, the settlements were concentrated on the coast. Due to the mountainous relief, existence of a dense forest and several tribes of fierce and even some anthropophagic native indians, the colonization of the interior of the country seemed impossible. But, from the mid-17th century, the residents of the Province of São Vicente (São Paulo State nowadays), started the incursions to the interior of Brazil, looking for indians as slaves and for gold. These incursions were called “bandeiras” (flags) since they carried a flag of the King of Portugal as a passport for the conquest of the country and as an authorization to search for gold in the name of the Crown (Eschwege 1883, reedited in 1979). It is in this context that gold was discovered in Brazi (Figure 2) and the colonization of the interior of the country developed, culminating on the foundation of Minas Gerais State, from the cities of Ouro Preto, Mariana, Sabará, Caeté, among others, which were nothing more than gold-rich regions.

The gold cycle in Brazil represented the largest surge in the production of this metal at the time in the world history. This production remained unparalleled until the great discoveries in California (USA) in 1848, Australia in 1851, and especially the discoveries of Witwatersrand, Transvaal, South Africa in 1886. The gold extracted here between 1700 and 1770 was equivalent to the whole production in the rest of America, from the discovery until 1850, or yet, to half of the world production in the 16th, 17th and 18th centuries.

Figure 2. Historical photo of mining.

During the first half of the 18th century, the development of the captaincy of Minas Gerais and the wealth generated for the Crown made Ouro Preto, then called Vila Rica, capital of the province and one of the largest populated centers in the interior of Brazil. According to Ferrand (1894, reedited in 1998), in 1750, a period that can be considered the heyday of gold extraction in the region, there were around 80,000 workers extracting gold in Ouro Preto.

In the second half of the 18th century the gold production started to decline due to the precarious techniques and lack of investment in technology. At that time, the Portuguese Crown was only focused in charging taxes on the gold production – named “Quinto do Ouro” (Fifth of Gold – 20 % of the production). When Napoleon invaded Portugal, the Portuguese Crown sought out for refuge in Brazil and a new policy of attention to the mines was started. With the arrival of Baron Von Ezchwege in 1811, a new era in the history of gold mining in the country began.

4. Formation of mines

Right after the discovery of gold, the extraction works were limited to the alluvial deposits in the riverbeds. The prospectors, “faiscadores” as they were called, searched for the gold gravel, revolving the riverbeds using small tin, sometimes wooden, plates to separate the visible gold with their hands. Later, slaves from Africa, who knew better mining techniques, led to an increase in the gold production.

With the impoverishment depletion of alluvial deposits, the miners were forced to mine colluviums along the Ouro Preto Range, and built several aqueducts to carry water to wash down the rich deposits. The last stage of technological evolution of gold mining was the development of underground mines.

The underground mines were open, usually, in the middle of banded iron formations (BIF) (Figure 3), locally known as itabirite and in some points in quartzite and phyllite. In general, they followed the several layers of quartz rich in gold, although, the banded iron formations also had some gold.

Figure 3. Entrance of a mine open in the iron formation.

The workers opened galleries and tunnels following the layers with gold in all directions. At the slightest sign of disappearance of this layer, they abandoned the works and opened another mine. The tunnels and saloons opened by these workers varied from mine to mine but usually the tunnels were 1 meter wide by 1.8 meter high and the saloons had an average area of 30 m^2. This clearly demonstrates the low geological knowledge of the miners who did not observe the dip direction of the mineralized layers. This generated, in some mines, saloons of considerable dimensions (saloons with areas of up to 120 m^2), because when removing material with unknown dip, the miners had to widen the galleries to look for the correct angle. Depending on the country rock, some mines could present stability problems such as landslides or loose blocks, but the mines rearely have these problems.

This lack of technical knowledge accounted for the existence of several mines with varied extensions. The largest are over 400 meters long on average, with some mines over 1,000 meters long of development.

The total number of mines opened during the gold cycle in Ouro Preto is unknown, and it is difficult to quantify them today, due to the growth of the city that makes it difficult to access many of the entrances. However, Lacourt (1937) surveyed 2,350 mines or mine entrances in the Ouro Preto Range. Nowadays many mines have their entrances inaccessible and/or hidden for several reasons.

5. Current use of the mines and activities developed by SEE

The Sociedade Excursionista Espeleológica (SEE), known for its research activities in different karstic environments, also develops activities in these galleries. In this context, the old gold mines, characterized as artificial underground cavities, make excellent sites to train speleological techniques and to conduct researches in the diverse areas that involve speleology. This study presents the works carried out by the SEE, which include the use of old underground gold mines of Ouro Preto City to train the speleologists in the mapping techniques and activities from the scientific and broad points of view of the works focusing on the preservation of old mines and their cultural importance as a memorial of the gold cycle in Minas Gerais.

Almost after 200 years of opening, some mines have become touristic attractions and/or as source for water supply (although the consumption of water from mines have been restricted by public administration due to high arsenic content). The mines dedicated to tourism (Figure 4) have artificial light among other modifications inside, in order to be more pleasant for the tourists.The guided tours describe the mining techniques employed, present a historical view of the activity through the years, and tell, in many cases, a little of the local folklore and legends involving the gold rush.

Naturally, there are water infiltrations in the mines that locally are so intense that to generate a great water flow inside the mines. Other mines reached the groundwater and after the end of the activities were partially flooded forming large water reservoirs. In January, 2012, intense rain caused several landslides in the slopes in Ouro Preto. In one of these landslides, a flooded mine used for water supply in the 18th century was rediscovered. The entrance of this mine is covered with bricks dating back to the beginning of the 20th century, and there is a pipeline that still supplies the main water reservoir of one of the main neighborhoods of Ouro Preto.

SEE performs activities of research and training of speleological techniques with its members in the old gold mines in Ouro Preto. The main activity is the prospection and mapping of the mines. Some mines present magnetic interference due to the iron formations where they were excavated. This interference prevents us from using the compass, thus it is necessary the use and improvement of mapping techniques without a compass.

Figure 4. Mine used for tourism by the owner of the area.

An interesting aspect in the mines is the presence of "pseudo-speleothems" formed from the dripping and leakage of water containing iron oxides, manganese oxides, clays and sand (Figure 5). The mixture of these substances gives rise to stalactites, stalagmites, draperies and micro-rimstones. They are delicate structures, which fall apart to the slightest contact because they lack a cement substance such as calcium carbonate. Their color varies in tones of red, yellow, gray and even blue when there the presence of arsenic.

The environment within the mines is very similar to that of a natural cave, with little or no light, constant temperature, presence of water and energetic support. Many mines are today the habitat of bats, crickets, moths, and opiliones.

Figure 5. Speleothems being formed inside a mine.

SEE has recently carried out a project together with the community of Veloso Hill in Ouro Preto. In this work, trails were made along the ruins and mines in the area for the community. The project had many visits to many structures remaining from the 18th century mining specially the aqueducts, water reservoirs, "mundéus", abandoned buildings and mines. These works involved the location and positioning of these structures, followed by the mapping of the mines with greater cultural and historical expression. Five mines were mapped in total.

One of the mines selected for mapping, called Mina Felipe dos Santos, has many levels, with the first being used for touristic visits. The mine is also used for water harvesting. (Figure 6) shows the volume of water that overflows from one opening that serves as access to a higher level of the mine. The mapping works have not been concluded in this mine. So far, 400 meters of galleries have been mapped and it is estimated that there are more than 1,000 meters left to conclude the work.

Another mine studied in this project is called Mina do Du. In this mine, the mapping was concluded unveiling a linear development of 290 meters (Figure 7). This mine has a well which leads to a lower level (nowadays flooded). In this well it is possible to see a wooden ladder that connects the levels. However, because of safety reasons and lack of equipment, the lower level was not explored.

6. Conclusions

The several remains of mining, including the underground mines, are part of the tourist routes of the city of Ouro Preto and are an important landmark in the gold rush history in Brazil. The objective of this work was to introduce and spread the works of SEE on speleological mapping, besides providing its members with an important field for training.

Figure 6. Waterfall from a higher level in Mina Felipe dos Santos.

SEE seeks yet in these works to draw the attention for the importance of preservation of the old gold mines in Ouro Preto given its historical importance, and nowadays, as a source of income for the local residents as touristic attractions. Moreover, the knowledge and mapping of these mines enabled the identification of old water reservoirs still in use. This has drawn the attention of the authorities due to the high content of arsenic in these waters, making them inadequate for consumption.

The authorities and institutions responsible for ensuring the preservation of this heritage should implement measures of preservation and awareness raising about the importance to preserve these monuments and to encourage controlled visits in these places in order to spread the knowledge and the spirit of preservation of the Brazilian historical and cultural heritage.

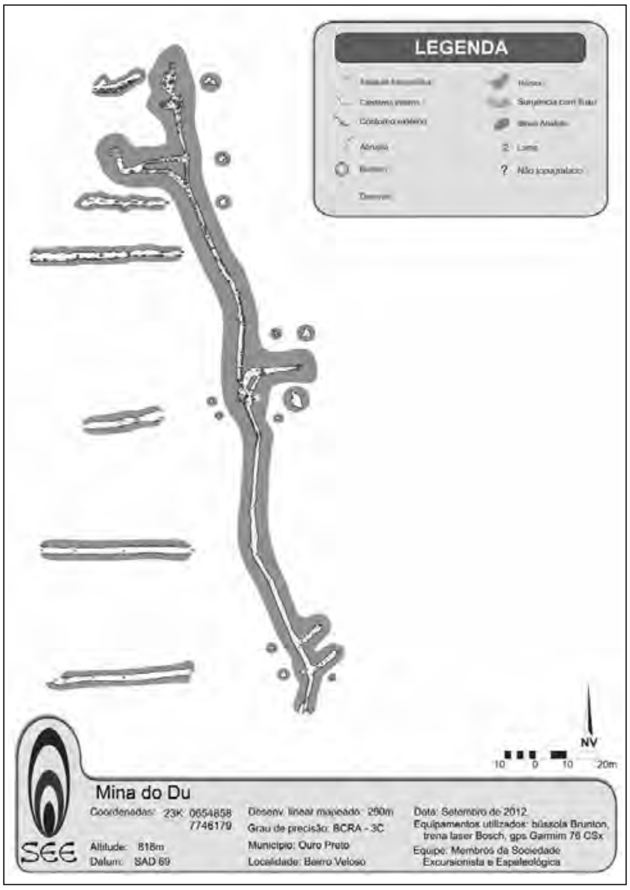

Figure 7. Map of Mina do Du.

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THE SUGANO MINES OF ORVIETO (ITALY): ALUMINIUM FROM VOLCANIC FIRE

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A speleo-minerary research discovered two mines in the Orvieto district, in Central Italy, where was extracted a leucite rich ore, a mineral formerly used to obtain alumina, an intermediate in the aluminium industry. The mining works started in the early 30s, and reached the peak in the mid-thirties till 1937, when the veconomic conditions imposed the abandonment of the exploitation. For the processing of this specific mineral G.A. Blanc developed an acid treatment. Blanc was an italian scientist known to the scientific community for his studies in ethnology, but almost unknown for his important researches in the mining industry and radioactive elements, in fact he was for two years a collaborator of the Curies in their laboratory in Paris. Here is given a short description of the site and the mineral, and a few aspects of the alumina extraction are represented with the process registered by Blanc.

Eventually, the results of a series of radioactivity measures of the leucitic ore, a phonolytic tephra, are presented. Some aspects have dealt with a short text demands here, and will be developed in a further research text.

Introduction

The aim of this work is the description of a leucite mine, located a few kilometers west of Orvieto, Central Italy, at about two hours drive north of Rome.

The geological substrate is volcanic, typical of the Volsinian system, at the edge between the above-mentioned volcanoes and the low sea sediments of a Quaternary Thyrrenian gulf.

The Volsinian was a system whose activity spans from 600,000 to about 100,000 years ago, consisting of several eruption centres, mostly explosive, whose products are alkaline and very rich in potassium, consisting mainly in tephra.

The volcanic events underwent four phases, the second one of which is responsible of the calderic collapse that formed the basin of Bolsena lake, the biggest european volcanic lake (Varekamp 1980).

During the eruptions that formed the rocks of these ores, the calderas depression were not formed yet, and in the place of the lake, there were several volcanoes erupting clouds of ashes and lapilli.

Description

The mining site consists of two galleries named Sugano 1 and 2, respectively 142 and 76 metres long, the storage squares and the washing plant with hoppers, where raw material was crushed and enriched.

In the area there are hydraulic tunnels of etruscan age, over 20 centuries ol; one of these was restored and kept in working conditions during the Middle Age, by monks of the nearby monastery of Holy Trinity. Nowadays they are still functioning and serving drinkable water to several households around the place.

There is a third tunnel, named Saggio Sorgente, formerly a mine changed in use when a burst opened a crack from which water is still plentifully leaking, thus opening a spring.

The tunnel named Sugano 1 deeps horizontally in the rock bank for a lenght of 142 meters; the rock is phonolitic tephra with big leucite crystals.

Along the tunnel there are two couples of recesses, opening at the opposite sides of the tunnel axis. On the vault there are two shafts heading upwards, the smallest halfway along the tunnel, and a deeper one at the end, the walls of which were populated of hundreds of bats hanging upside down. These bats were recognized as Miniopteris Scheibersii (Fig. 1).

Figure 1. Miniopteris Schreibersii bats by the end of Sugano 1 tunnel.

The end of the mine presents a layer of red sandy flint rising gradually. We think this could be a fossil seashore of a Thyrrenian gulf in the Ionian (780,000–126,000 years ago), the chrono-stratigraphic stage corresponding to the Middle Pleistocene, a period in which the vast Thyrrenian basin, filled with the sediments originated from the dismantle of the newly formed Appenine chain, emerged from the sea and became mainland (Del Monaco et al. 2005).

The other mine, Sugano 2, turns of 45° to deep inside the bank some metres after the entrance. With its 76 metres, it is shorter than Sugano 1, and at the end its floor is made of a layer of thin ashes and pyroclastic flow debris.

This tunnel has one recess and two shafts, the first at 2/3 of the lenght, and the other one at the end. On the end-wall the bore of a big drill is clearly visible. In this gallery too there are big leucite crystals on the walls and the vault.

The third tunnel is a test in order to open a new mining work, it was interruped when an explosion broke the stone wall confinating a water vein, that broke through as soon as the way outside opened. So a spring was opened and nowadays water is still flowing thorugh it.

This tunnel is 27 metres long, and has two wide recesses some metres before the end, witnessing the mining origin of the tunnel, later turned to a spring. At the end wall there are beautiful white crystals of leucite contrasting with the black tephra rock, and with the colours highlighted by the water.

What is leucite?

In this section we provide some information about the ore and the historical context of the mines object of the study.

The mineral is leucite, a tectosilicate feldspathoid of the tetragonal system corresponding to the formula $KAlSi_2O_6$ (Fig. 2). This mineral occurs in the unsaturated potassium rich alkaline lavas of the Roman Magmatic District. The probable place of emission was not a real crater, but a narrow long volcanic vent located a few kilometers SW of these mines. The flowing direction was likely towards NE, because at that time (430,000 years ago) there was not yet the caldera depression occupied by the Bolsena lake, the largest european volcanic lake,was not yet formed and in its place there were several craters, with very unstable slopes.

The presence of blocks of scoriae in the tephra is an indication of the proximity of the emitting vent.

The abundance of so many crystals of leucite, some of which over 1 cm large, uniformly distributed in a tephra matrix, means that the crystallization process of leucite took place in the orto-magmatic phase, before the open air discharge. Leucite crystallization process starts at about 1,600 °C, enriching progressively in silica the molten residue, so when the magma is emitted consists of a two-phase system solid/melt in which, at lower temperatures, several more phases crystallize in lower amounts.

The more leucite leaves the molten phase, the more the liquid residue is rich in silica; this process reaches a level in which the concentration of silica allows the crystallization of a new mineral: sanidine, $KAlSi_3O_8$, high temperature potassium feldspar.

The crystallization of sanidine consumes the rest of the silica still present in the liquid phase and eventually a part of it in the leucite molecule, according to the equilibrium:

$$KAlSi_2O_6 + SiO_2 = KAlSi_3O_8$$

Leucite Silica Sanidine

The crystallization of sanidine from the melt and partial trasformation of leucite into sanidine itself is called *peritectic reaction* and the point of the diagram at which this happens is called *peritectic point*, a triple point in which very particular conditions occur and a slight variation of a single parameter changes completely the composition of the solid and the melt.

Bowen studied this equilibrium and elaborated the state diagram bearing his name.

A study of the Bowen diagram goes far beyond the scope of our research; let’s say that leucite-sanidine is not the only peritectic system known in volcanic geochemistry, another peritectic is the system forsterite-enstatite.

Figure 2. White leucite crystals clearly visible in a slab of rock in Sugano 2 tunnel.

Autarchy and mining in Italy in the 1930s’

After the invasion of Abyssinia in 1935 the Society of Nations declared trade embargoes towards Italy at the time ruled by Mussolini, so, to overcome the increasing demand of minerals for the fast growing industry, the italian mining industry reached a peak never seen before.

The italian industry at the time required increasing quantities of aluminium, whose main mineral is bauxite, a reddish earthy oxide present in laterite layers.

Another exploitable mineral is leucite.

Indeed, in these mines they extracted leucite ore.

Blanc and Alumina

The difference between bauxite and leucite for alumina extraction is not merely formal.

Bauxite is extracted from open air mines while leucite is extracted in underground mines.

Bauxite is worked by caterpillars, due to his nature of earthy silicate oxide seldom mixed with iron, while leucite is worked with dinamite, being crystals in a hard rocky ore.

Metal aluminium is obtained in two stages: a first chemical stage in which alumina is obtained, Al_2O_3, and a second electrochemical stage, in which alumina is processed in particular cells with melted criolite Na_3AlF_6 with graphite electrodes, the Hall-Heroult process.

Metal aluminium is not obtainable by fusion and reduction like other metals, but only by electrochemical way.

Much has been discussed about the bauxite alumina alkaline process, the Bayer method, but not quite the same occurred about the leucite acid process, that is the Blanc method.

Nowadays this process belongs to industrial archaeology, but it represented a milestone in the industrial chemistry of the 30s'.

Blanc submitted his project of alumina production from leucite at the National Congress of Industrial Chemistry of Milan in 1924 (Blanc 1924).

The raw ore, made of a dark lava rich in leucite crystals, was transferred to the crushing plant, close to the mining site, and then to the hoppers.

The ore was not crushed to a fine powder, but rather to small gravel, and this is exactly what we found by the plant; the reason of this is described in the text reported in bibliography: Blanc in his experiments found out that treating a fine powder of leucite with hydrocloric acid resulted in a colloidal dispersion that coul not be filtered (Blanc 1924).

The method developed is exposed in detail in the aforementioned text of 1924 reported in bibliography.

When is treated with concentrated hydrocloric acid, leucite dissolves in it very exothermically, and the products are ionic aluminium Al^{3+} and potassium K^{+} in the acidic medium and finely dispersed colloidal silica SiO_2. Due to the colloidal nature, silica could not be taken away from the acidic solution, impairing further treatments for alumina isolation.

This happens because leucite in fine powder releases silica hydrosol; Blanc discovered that when leucite in gravel grains is treated with recirculating concentrated hydrocloric acid, silica generates a gel at the bottom of the tank, thus making alumina and potassium in acidic media more easily removable.

The enrichment of the mineral from the ore was reached through magnetic separators, being the raw material attracted by magnetic fields while leucite is not a magnetic mineral.

Blanc developed this method after his experience as a chemist in the Curies' laboratory in Paris.

At the time (about 1920) it was well known that some kinds of lava (basaltic mainly) could be magnetized applying a magnetic field, and they gained "memory" of the induced magnetization.

Blanc served two years at the Curies', where he determined the constant decay of thorium.

Radioactivity was not the only field of interest of the Curies', since also magnetism was another interest for them. Marie discovered that a ferromagnetic mineral loses his magnetic properties above a typical temperature, named Curie Temperature after her.

Then Blanc came back to Italy and developed further studies about magnetism posing the bases to a very useful method of geochronology: Paleomagnetism.

Blanc realized that magnetic vectors line up with the Earth's pole in the interval between two temperatures: the Curie Temperature (about 600 °C) above which vectors are completely disorganized, and the Blocking Temperature (about 150 °C) below which vectors have fixed positions. In this interval lava solidifies, and this is the gangue of the leucite ore. During the solidification process it acquires ferromagnetic properties as the vectors align with the Earth's Pole's direction while the process was going on, 430.000 years ago in our leucites, according to the dating given by Evernden and Curtis in 1965.

Radioactivity

In these mines there is a pretty high level of radioactivity background, concentrated in the gangue.

This is a common feature in several minig sites in the estern area of the Bolsena lake, object in the 70s' of mineral exploration for uranium ore in old marcasite mines at NE of Viterbo.

When spending time inside these mines, we had to wear gas masks to prevent alpha rays inhalation, but no filter can prevent beta and gamma rays.

The Geiger counter registers a total radioactivity emission in air of about 2,5–3 microGray per hour, a level about 30 times over the normal background.

We tested the surface emission of rock samples just outside the mines using a military instrument especially designed for measuring solid matter, equipped with a lead shielded probe not of Geiger type, that can reveal particles only from the bottom, thus excluding the cosmic radiation component of the background. Such instrument is able to discriminate and count separately alpha, beta and gamma rays. We found a surprinsingly high level in beta rays. We think that Radon 222 is not the only responsible for such level, but there is the presence of Uranium and Thorium widespread in the rock, as suggested in a previous research in a hydraulic tunnel nearby performed by nuclear track detectors LR115 type (Bellocchi et al. 2009).

Acknowledgements

We wish to thank some people that somehow, even indirectly, took part to this project: Antonello Baccelloni, Emanuele Ioppolo, Giancarlo "Gec" Marchetto. A special thank to Prof. Paolo Mietto, in the 50^{th} anniversary of the foundation of our speleologic group.

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WORKSHOPS AND SURVEY RESULTS IN THE CHRIMA CINP PROJECT (EU PROGRAMME CULTURE 2007–2013)

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The activities carried out under the project activity of Crhima-cinp, an acronym standing for "Cultural Rupestrian Heritage in circum Mediterranean Area. Common Identity-New Perspective" is described in this paper. It has been financed with funds from the Culture Programme 2007–2013, Budget 2010, Strand 1.1 Multi-annual cooperation projects, Strand 1.2.1 – Cooperation measures. The project responds to the unitary purpose of the invitation Culture 2007–2013: contribute to enhancement of a cultural area shared by Europeans, the development of cooperation between the creators, operators, and cultural institutions of the countries participating in the Programme. The activities have promoted a new interest in the rediscovery of the rupestrian villages that characterize many countries of Europe and of the Mediterranean, populated until the last century, memory of layers tangible and intangible of great interest that is likely to be permanently compromised or destroyed. The project increased the exchange of information between the various Mediterranean countries by producing monographic studies on different sites, publishing new studies of little-known areas, and contributing with new materials at the scientific deepening of topics and at the dissemination of information. The report summarizes the experiences of the workshops carried out in some centers chosen as the site of the work, (Massafra in Italy, Saumur in France, Santorini in Greece and Ortahisar in Turkey). The work summarizes the major activities in the area with drawings and photographs that illustrate the differences and similarities of rupestrian settlements of each region under study.

1. Introduction

1.1. CRHIMA-cinp project

Theme of the project is the Rupestrian Heritage, a distinctive feature of the Mediterranean landscape.

The works show how the rupestrian culture is widespread an across the Mediterranean area, a heritage developed over time with environmental, architectural and artistic emergencies that are known only to scholars and enthusiasts of the subject, still though without having an overall picture of this cultural event.

The project, with the various activities organized, presents a synthetic framework of the influences and events that have contributed to the diffusion of the phenomenon and the arts that characterize it. It favored a greater awareness about the extension of the different features present in the sites chosen as study areas. It also encouraged interdisciplinary knowledge, which contributes to the understanding of a complex heritage, lasted over time, responding to practical needs, spiritual and contingent of everyday life for many people. The project supported the transnational mobility of cultural operators who, through their activities, have strengthened the knowledge of the known territories and focused the attention of the authorities and the local population on the value of the indigenous patrimony, often not fully known. New operators educated to the respect for cultural diversity that enriches the regions of the same country or of countries of the Union were also formed.

The partnership CRHIMA-cinp project. Project Coordinator: (coordinator): (IT) Università Di Firenze – Department of Architecture dsp – Project manager Prof. Carmela Crescenzi. Project co-organiser (co-organiser): (EL) Dep of Energy Physics National, NKUA – Project manager: Prof. Assimakopoulou Margarita (ES) Dep. De Expresión Gráfica Arquitectónica, UPV – Project manager: Prof George Llopis; (FR) Dep. of Sciences Humaines and Department of Science and Techniques for Architecture ENSAP "La Villette" – Project manager: Prof Edith Crescenzi; (IT) Archeogruppo "E. Jacovelli" onlus Project manager: Avv. Giulio Mastrangelo; (TR) "Kadir Has" University Of Istanbul – Virtu Art Faculty Project manager:

Figure 1. Palagianello. Troglodyte village.

Prof. Mehemet Alper.Additional partners (IT): Centro Studi Sotterranei – Genova, Museo del Territorio di Palagianello e Centro Unesco di Firenze Onlus.

1.2. Rupestrian culture

Man has excavated structures in the rocks from the Anatolian highlands to the Egyptian deserts, from the Balkans to Italy, from France to Spain. In this anthropological and ethnographic context, the cave is the "common house" of Mediterranean cultures. Medieval caves – rupestrian houses and churches – massively characterize the landscape of the plateau of Cappadocia in Turkey, several regions of Spain, Greece and the Loire Valley in France, and many other places in the Mediterranean area and in other regions the world.

All these settlements are the micro cells of the wider Mediterranean rupestrian habitats that encompasses diversity but also many common aspects. The rupestrian civil structures were considered an expression of inferior classes, since UNESCO included Cappadocia (Turkey) and the rupestrian districts of the city of Matera (Italy), in the World Heritage list. From that moment, the valley of the Loire and other centers, have considerably increased scientific studies on the rupestrian structures and the preservation of monuments and environmental contexts.

The cultural unity of rupestrian settlements was, in some cases, damaged or destroyed, but their relevance as open air eco-museums has never been underestimated, despite anthropogenic deterioration caused by weather conditions.

Recently, the attention was focused on urban settlements, on the typologies and on subterranean shelters. These structures are certainly less monumental than churches, but they are more numerous and more ancient.

2. Geography and geology

The geology of the five examined sites has geologic and morphologic characteristics which allowed the excavation of rocks to create spaces for daily activities. These places developed mainly because of volcanic eruptions, which deposited soft materials (as tuffs) that could be excavated with rudimental tools. This was the case, for instance, for Turkey and Greece. In Cappadocia, Turkey, volcanic eruptions formed plateaus. The water and wind erosion created the characteristic valleys of the area.

Santorini, in Greece, is constituted by a crater, which was destroyed by a prehistoric earthquake. Later, it has been eroded by external agents and then covered by the sea. The building activity has always been based on the different rocks of the island. The different mechanical and chemical characteristics of the rocks offered different solutions.

Figure 2. Geological materials of studied areas.

In Italy and France, on the other hand, the bedrock is represented by different types of limestone rocks, from calcarenite deposits (Italy) to chalk (France).

The water and wind erosion in the area of Massafra, Palagianello and Mottola (Italy) have eroded the calcarenite on the Ionian coast, creating ravines. Many rupestrian settlements were realized in these ravines.

The geological constitution of the cliffs in the Loire Valley, France, has been influenced by the typical chalk of Turonian age. The Lower Turonian chalk is the most typical, whilst the Upper Turonian has a greater content in sands.

3. Troglodyte Settlements

The man has always responded, according to historical periods, with "built form" to its security, defense and spiritual needs. The original "rock shelter" and natural cavities were transformed into dwellings functional to daily life. The provisions of natural shelters were transformed with additional excavations or expanded with the construction of spaces extended outward. He decorated the caves with wall art (graffiti, paint dry, frescoes, etc.), satisfying the need to tell great, superhuman and mystical events.

The adaptation of the needs is expressed by simple interventions in the natural setting to create a troglodyte site included: the natural caves are enriched by a hearth; the rock shelters are protected by a wall, in cracks between rocks are built homes, a village situated protection and backed by a natural wall. Cave builders were able to combine different solutions, adapting and improving technical construction and different materials to the natural features of the sites.

Figure 3. France, "carrière de falun".

3.1. Hollowing out settlements

The realizations of the underground volumes are obtained by subtraction of materials. There are two methods of excavation:

1. Horizontal excavation in the sides of valleys and cliffs: there are rupestrian dwellings.
2. Vertical excavation in the plateau, originating hypogean settlements.

Each of these solutions confirm the versatility of the troglodytic architecture to the geological, climatic and anthropogenic settings.

3.2. Typology of troglodytes settlements:

1. Rocky villages in terraces or on the wall. It is the most common settlement system. The number of households is variable and takes full advantage of the valley slopes. These architectures are usually carried out with particular attention to insolation during the different seasons.

Important achievements of this kind are in the complex linear in France in dwellings carved into the cliffs of the Loire Valley; in Spain, in the many buildings that characterize Andalusia; in Turkey where one example is the village of Zelve or the valley of Selime; in Puglia with the villages in the ravines of Massafra and Ginosa; in the districts of Caveoso and Barisano at Matera, Basilicata; in the villages of Santorini Votonos and Finikia.

Figure 4. Wall village, Bocairent, Valencia, Spain.

2. Villages on the surface. They are found in Cappadocia; these villages are carved into the cones, called "fairy chimneys", pyramids of rock (tuff, silt or volcanic boulders), showing a caprock consisting of a more compact slab of the same material, which protects the underlying rock from erosion.

The rock cones are distributed in a natural setting that reproduces, in fact, the village's structure. These villages, having the buildings excavated in rock blocks, are considered surface settlements.

Figure 5. Ortahisar, Villages on the surface.

3. Hipogean villages. The residential units are organized around wells drilled vertically and called courts or patios or vicinanza. The courts are connected to each other trough underground passages or at the surface. Common areas of aggregation and distribution to homes and their annexes, the courts regulate the entry of sun, light and heat, and ensure, with fireplaces, the ventilation. Typical of settlements in North Africa, the emblematic example is the village of Matmata, Tunisia. The court system or "neighborhood" was imported in Massafra in the fifth century. In the Comuniad of Valencia is known the settlement of Paterna; in Turkey an exemple of these structures is the Gümüşler Monastery, in the province of Niğde; finally, in Santorini, there are small groups of villages on the plateau of Oia.

4. Underground villages. In some cases, the imperatives of defense led to totally conceal the urban structure. The communication with the outside are limited to few accesses and outlets required for ventilation. The cities of Derinkuyu and Kaymakli (Turkey), on several levels, are representative of this undergroundvillages. In France it is known the city of Naours.

4. Documentation

The heterogeneity of the public to involve requires different tools for the graphic and multimedia description, to understand bot It is the most common settlement system. The number of households is variable and takes full advantage of the valley slopes employing his good orientation. h the continuity of living in a cave, and representation of the architecture and the environment.

The representation, in all its modalities, is one of the most useful tools for the documentation of monuments already ruined by the passing of time and that are destined to destroy.

The acceleration of degradation is clear: in the environments of the monastery of Hallach (Hortahisar – Cappadocia), in a few years, there has been a loss of quality of the drawings (Fig. 5) and the integrity of the rock appears heavily compromised. In 2007 the village of Zelve was accessible, while in 2010 it was closed to the public.

Failing to safeguard and restore the abundance of cave sites, any form of documentation, even if only photographic or aimed at a simple survey, it would be desirable in order not to lose the memory of the legacy left to us over the centuries.

It is nowadays possible to use softwares to recreate the three-dimensional reality of the caves, in order to let people appreciate the environmental and architectural features with sure effect and involvement. Furthermore, the softwares, with the data processing, are able to produce models from which the site can be quantitatively measured and analyzed.

The same places require several readings and the main instrument for this documentation is represented by photographs. It is necessary that the photos are shot in peculiar ways, according to the used software. Therefore, the effectiveness and efficiency of data acquisition must be supported and integrated with the data processing, in order to effectively produce integrate geometric information, attribute of matter, excavation techniques, state of decay, etc. Further, the difficulties in classification and processing of the amount of data that may contribute to the knowledge of the sites have not to be underestimated.

The major activities carried out within the CHRIMA-cinp consisted in analysis of different rupestrian sites.

Through experience, different operating modes and methodological approaches have been tested, aimed at identifying the most proper conceptual data collection plan, and the related cartographic products. The critical analysis of the project results, conducted with basic documentation, has tested the critical importance of a fast survey to obtain satisfactory results to document the rupestrian heritage.

4.1. Methods and data survey of some heritage.

4.1.1. Traditional survey. Surveying in France contributed to collection of data at Bourg-Neuf, Saumurois.

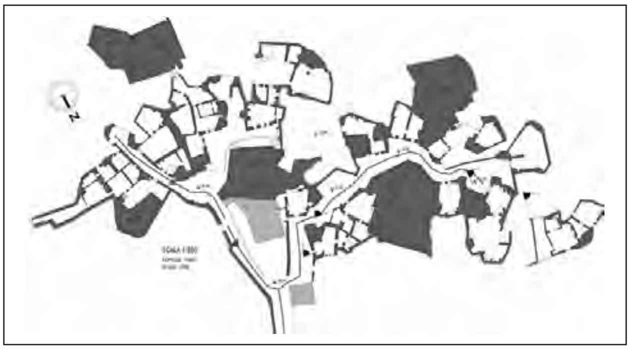

Figure 6. Bourg-Neuf, plan.
Bourg-Neuf is a town in the municipality of Dampierre-sur-Loire. Its origin dates back to the fifteenth century, when the ligerians dug dwellings into the tufa creating a small village away by the floods of the Loire. More and more modest families inhabited these houses until the 60s of the twentieth century, finally abandoning them for newer and more comfortable spaces.
The village of Bourg-Neuf develops along the winding path of "Rue Haute" located half way up the cliff. At the entrance of the village, the Rue Haute divides into two paths that serve all the houses in the village and is part of the old mining tunnels of tuff, serving other houses and gardens overlooking the valley. Sixteen of the private homes in Bourg-Neuf have real possibilities for restructuring despite the decay: one has already been renovated and upgraded to "holiday home", two are in the process of restructuring, the remaining thirteen are abandoned. The houses are troglodytic and partly semi-troglodytic. Bourg-Neuf differs from the typical wall troglodytic settlements of the area: it has the characteristics of rock settlements but has some of the characteristics of the underground settlements, such as underground galleries opening into courts. All homes have at least one fireplace, some have a "potager" or a bread oven; all have a small green space; some of them consist of a single large compartment, other have multiple rooms and levels.

4.1.2. Speditive survey. The experiment carried out on Hallac highlighted some issues about facing cameras like as daylight factor, definition and dept of field and the quality of metric reading of homologous points. It is highlighted the need, in critical location such as the aisles of building basilican Allac, of a traditional topographic survey (closed profile of plan or section) and sufficient measures for the development of the third dimension.

In Allach (2010) metric measurements in the courtyard of the church, in the hall with a dome and in the basilica were carried out, together with the photographic survey for the construction of a tridimensional model and a panoramic view. The textual description of the court highlighted the architectural features, revealing decorative elements that cannot be appreciated in the short time of the survey.

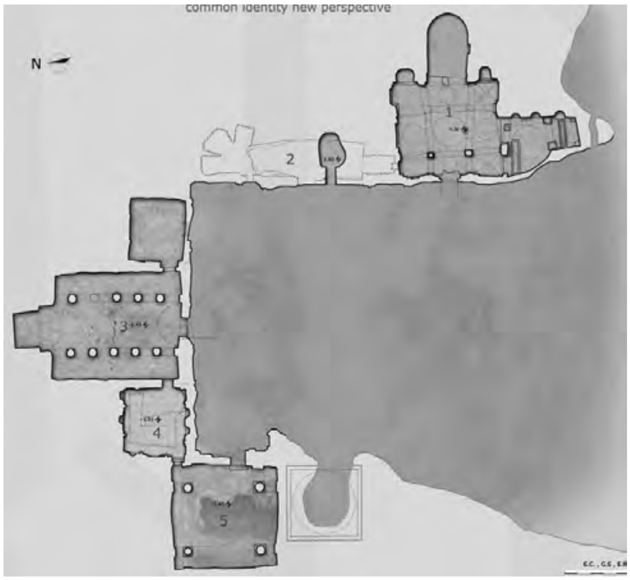

Figure 7. Hallac Monastery, the top.
Hallac Monastery is located to the north-northeast of the Ortahisar village, in the area between the road connecting Nevshehir to Urgup and Yolu and that connecting Ortahisar to Nevshehir. The complex has an open courtyard on the south side (Pic. 2) on which seven rooms open on the ground floor and others on a second level. The court has partially oxidized pink and cream walls and it is cut into a spur limited by a crown of brown cones.The original core was probably a closed court, accessed by a narrow passage on the SE edge; the southern front was probably closed by small cones eroded by time. The original ground level of the courtyard is covered by a 1–1.5 m pile of debris.
Today, the court disengages four entrances: at north there is a three-room complex, which is located at the bottom (no. 2, 3, 4), while at the top there are openings of unvisited rooms. A church is located at east with an inscribed cross plan church with a funerary narthex; on the eastern side, at the top, there are entrances to the house of the monks, which were successively used as pigeon house (no. 7); at west, there are an inscribed cross plan large square room (no. 5) and a second room, probably used as kitchen (no. 6).

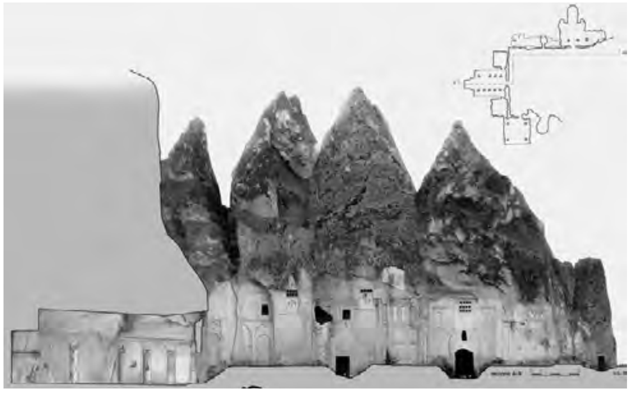

Figure 8. Hallac Monastery, the front-section.

The photogrammetric survey was also applied to the Chapel of S. Pietro and Paolo in Balkan monastery (Ortahisar – Turkey). Despite the photographic documentation was heterogeneous and not aimed at the photogrammetric restitution, it was possible to obtain relevant data to an understanding of its architecture.

The same technique was applied to survey of some caves in the territory of Casabona in Calabria (Italy). Casabona has three rupestrian villages. The first is Valle Cupa, located in the ravine of the Malolacco valley, and contains about 250 rupestrian environment developed along linear terraces with an extensive network of trails. Then, there is the site of Timpa Tallarico and the Rione Croce with 80 caves; in the site of Montagna Piana, moreover, there is a village with 15 caves.

The cave with spirals presents in Valle cupa is very interesting: spirals, concentric circles and moon are carved into the sandstone.

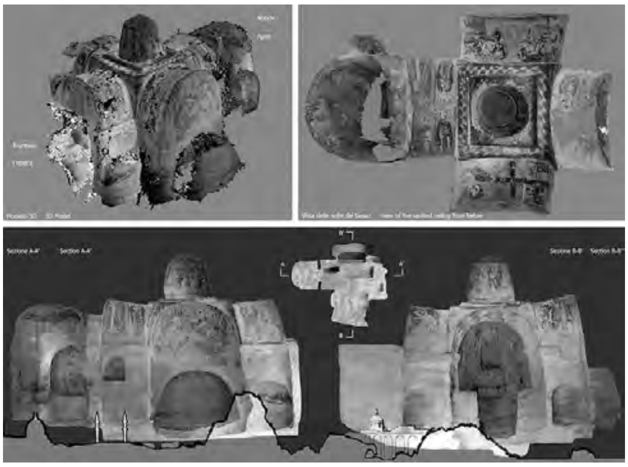

Figure 9. Chapel of S. Pietro and Paolo in Balkan monastery.

4.1.3. 3D scanner survey. Different architectures, religious and civil, have been object of 3D survey in Spain and Italy (Massafra and Ginosa).

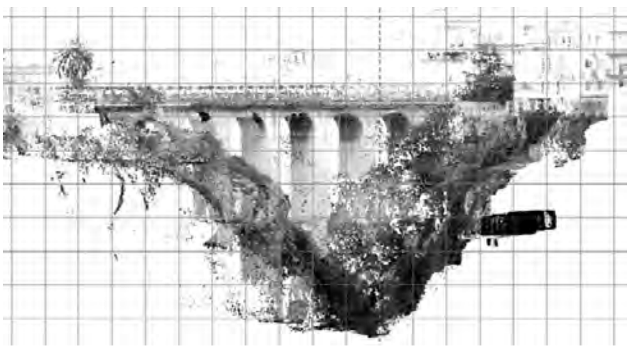

Figure 10. The San Marco ravines, 3DS architectures and hosting environment survey.
The San Marco Ravine is north of Massafra, and originates near the Masseria Pantaleo. It is on the east side of the old town, dividing it in two parts. It is part of the town, and is named after the rupestrian church of San Marco.
In the past it was called (the Greek word paradeisos means garden), because Paradise cliffs and terraces are covered with blooming spontaneous vegetation, gardens, orange gardens. The suggestive view from the Ponte Vecchio shows terraces, cliffs, caves and cactuses. Many of these caves were inhabited in the Middle Age; were important crypts are San Marco, the Candelora and Santa Marina.

Other important caves are the Hegumen's house and the anonymous crypt in Vico III Canali, used as an oil mill until few decades ago. The ravine is surmounted by the severe and majestic Castle from the 16th century (but founded before), with a square plan, three cylindrical towers and one octangular tower.

Figure 12. Ginosa, top the ravine.

4.1.4. Virtual Tour – 360° photos. Different architectures, religious and civil, and the hosting environment have been object of these analysis in Turkey and Italy.

Figure 13. Gravina di Trovanza, environment virtual tour.
In Massafra, was detected the little "gravina" of Trovanza, in Mastropaolo area. Some caves were part of the settlement, on two levels, used as residence and outbuildings; one of the caves has a rectangular plan and it has one wall entirely covered by small square niches arranged in parallel rows (dovecot/herbarium). The common interpretation describes it as a room for the conservation of medicinal herbs, hence the popular name of "pharmacy".
Faced with this cave is a small rupestrian church with a rectangular plan (about 4.60 x 3.20 m, height 2.30 m) and a single orthogonal basis (2.75 x 1.20 m) to the east, with an altar against the wall. There are some frescos (in fair condition). The canal system is well conserved.

5. Annotations

In Cappadocia, from surveys made in some places with rupestrian sites in terraces like Ortahisar, the structural decay of the sites has accelerated with the change of the population during the first half of the twentieth century.

The conservative wisdom and culture of land hard rock has been lost; the necessity to build on the surface prevailed though lacked the technical bases of support for good land management. The voussoirs for new homes quarried from the rock on which he was edified: emptying of the rock, and the overhead of the underlying structures are contributing factors of the collapse.

These collapses were further favored by lack in water management that, taking advantage of the network of collection and distribution, found new paths seeping into the rock, thus causing erosion. In many countries, the lack of a network of wastewater collection, together with the excavation for the restoration of some houses, continues to heavily contribute to the collapses.

The villages were abandoned in the wall, and the lack of care led to the loss of many settlements of considerable architectural value.

Presumably, the same phenomena have occurred in previous eras in rupestrian sites of the different states; negligence over the time and the ignorance of the value of cultural and environmental rupestrian heritage contributed to the loss of the cultural heritage of living in a cave.

In various countries restoration and environmental rehabilitation are ongoing for cultural needs or, more often, for economic interests related to tourism activity. For instance, significant interventions are occurring at Saumoirs and Matera. However, in several sites it is not yet clear the bioarchitectonical value of the rock; therefore, the rock is coated with plastic and anti-perspirants fabrics and then laid in plaster supported by wire mesh. In other countries, the exposed rock is an aesthetic value required by tourists, but is completely ignored the need for ventilation systems for the health of the environment and of the same rock.

Figure 14. Restoration of a cave. Finikia Oìa.

6. Results of the project Chrima-cinp

The activities of the partnership were intense and continuous; the specific activities of the partners are published in the:

- *The rupestrian settlements in the circum-Mediterranean area*, published by DAdsp, typ. Il David, Florence, September 2012. isbn: 978-88-96080-09-2. The texts discuss: historical and cultural features; studies of some settlements with unpublished drawings of the architectural emergencies; thematic studies on the rupestrian culture.
- CD documentary *Journey through the rupestrian cultures*. The CD contains a video presenting the three territories of the Workshop: Puglia, Santorini and Cappadocia; 3D virtual video of the rupestrian environments with architectural and landscape values in Cappadocia and Puglia. It collects photographic material representing the qualities of the territories: rupestrian settlements, humanized villages, architectural emergencies; moments of socialization and activities of Crhima-CINP.
- CD "Music for bagpipes in the Mediterranean Area", with sounds and music of the Mediterranean area;
- Web site www.rupestrianmed.eu. The site is an important data source that promotes the activities of the Crhima-CINP project, collects drawings and papers developed during its activities, as also the data from the censuses that have been carried out or are still in progress.

The results of the project activities, including the works on the rupestrian heritage by the participating students, are published in:

- *Days of Study on the Jonica Earth. Rupestrian habitat in the Mediterranean. From archeology to new practices for its protectionand recovery*. Massafra 29–31 October 2010. Antonio Dellisanti publisher, May 2012. isbn: 978-88-89220-92-4
- *Days of Study on the Jonica Earth. Rupestrian habitat in the Mediterranean. From archeology to new practices for its protection and recovery.* Massafra April–May 2011 published by DAdsp, typ. Il David, Florence, June 2012. isbn: 978-88-96080-06-1.
- *Crhima Cultural Rupestrian Heritage in the Circum-Mediterranean Area, Conference Firenze 21–23 Giugno 2012, Abstracts,* published by DAdsp, typ. Il David, Firenze June 2012. isbn: 978-88-96080-07-8.
- Exbition: Massafra 2010, Massafra 2011, Ortahisar 2011, Mustafapasha 2011.
- Final exibition: Firenze 2012, Sorano 2012.
- *Rupestrian Landscapes and Settlements Chrima Cinp Project Workshops and Survey Results.* published by DAdsp, typ. Il David, Florence September 2012. isbn: 978-88-96080-08-5.The volume contains descriptive graphic papers of the Crhima-CINP project; general information about the rupestrian sites of the partner countries; general information about the rupestrian territories and emergencies.

Credits

Figure 6. http://www.pixelistes.com/…/ souterraine-t24158.html

Figure 6. Bourg-Neuf, plan – by Giovanni M.Vampa, Nicola Pacini.

Excerpt from the thesis: Studi e riqualificazione della Loira troglodita. Il bourg-neuf: "La Loire a velo" elemento di riqualificazione. *Relatore*: Carmela Crescenzi, *Correlatore*: Bernard Tobie. *Laureandi*: Giovanni M.Vampa, Nicola Pacini.

Figure 9. Chapel of S. Pietro and Paolo in Balkan monastery Fotogrammetry Survey by Simone Beneventi, UniFI.

Figure 10–12 M. Manganaro, A. Altadonna, G. Martello, A. Nastasi, N. Siragusa. DiSIA. UniME.

THE AUGUSTEAN AQUEDUCT IN THE PHLEGRAEAN FIELDS (NAPLES, SOUTHERN ITALY)

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Romans built the 96 km long Campanian Augustean Aqueduct to bring fresh water from Southern Italy mountain springs to the densely populated areas of *Puteoli* and *Baiae* in the Phlegraean Fields. In the XVI and XIX centuries the ancient aqueduct was investigated in order to restore it to bring water to Naples, with no result. The section after Naples was never seriously investigated. From 2010 we are performing researches about underground hydraulic systems in the Phlegraean Fields. The paper reports about several findings in the area. Up to now, only few hundred meters of aqueduct are documented, out of more than 22 km. However, the little information gained already contributes to the comprehension of a very important ancient settlement area.

1. Introduction

The Phlegraean Fields are an active volcanic caldera, composed by several craters in an area of about 65 Km² in the surroundings of the town of Naples (Campania, southern Italy). Presently, the volcanic activity is limited to fumaroles and thermal springs but in 1538 a new crater erupted and destroyed a large area. Main eruptions are dated at 39/35 ky b.p. and 15 ky b.p., while several minor volcanoes erupted in pre-historical times (Rosi and Sbrana 1987; Orsi et al. 1999; Fedele et al. 2011; Scarpati et al. 2012). The area is affected by bradiseismic effects: a long-period raising and lowering of the land, related to variations in the underlying magmatic chamber. In Roman times the land was at higher elevation than today, so many coastal structures, villas, palaces and harbour plants are presently underwater.

In ancient times the presence of safe harbours, thermal springs and a temperate and fertile land raised attention by Greeks and Romans. In the last years of the first century B. C. the area was fully exploited with leisure establishments, fisheries, storehouses and with the Navy harbour plants. Many caves were opened in Roman times, as tunnels, aqueducts, water tanks, hot water catchments, steam tubes to warm spas. A major drawback in the Phlegraean Fields was its lack of fresh water. The volcanic land produced just thermal salt springs. In order to support a growing population and the demanding military and commercial fleets, the Romans designed a long aqueduct, tapping important springs in the calcareous Appennines. The aqueduct course was largely underground. Side branches reached the ancient cities of *Pompeii*, *Nola*, *Atella*. The main branch skirted *Neapolis* (the present Naples) and reached the important commercial harbour of *Puteoli* (today Pozzuoli), the *Portus Julius* Navy harbour, the wealthy settlement of *Baia* and the *Misenus* harbour, after leaving a side branch to the ancient Greek city of *Cuma*. Total length was about 96 km (De Feo and Napoli 2007).

The ancient aqueduct ceased functioning at an undetermined date in the Middle Age. In the XVI century, the city of Naples required more water to support its growing population, so the Spanish viceroy Don Pedro de Toledo appointed the Neapolitan architect Pietro Antonio Lettieri with the task to investigate the ancient aqueduct in order to restore it. Lettieri research lasted four years but the restoration effort proved too large. We are just left with a hand written relation (Lettieri, ab. 1560) describing the course from the springs to Naples, with some hints about the course after Naples in the Phlegraean Fields. The same happened between 1840 and 1880, when architect Felice Abate performed a similar research (Abate 1864). Finally, in 1885 a modern aqueduct was completed, tapping the same sources as the Roman aqueduct.

2. Aqueduct explorations in the Phlegraean Fields

Since the restoration of the Phlegraean Fields section held no special interest, the ancient aqueduct was neglected in the area. Even the dating was uncertain. In 1938 a celebration stone was found at the springs, which attributes the aqueduct to Augustus (Sgobbo 1938). Finally, in the XX century second half a wall inscription was found in a tunnel at Scalandrone, between Pozzuoli and Baia, bearing a date corresponding to 10 A.D. for the opening of a water catchment from the Augustean Aqueduct (Camodeca 1997).

Very few bibliographic references to aqueduct sections in the Phlegraean Fields were found. We began research on the aqueduct in 2010, with the support of the Special Superintendency for Archaeological Heritage of Naples and Pompeii and of the Phlegraean Fields Regional Park. The following sections will report briefly about the first results of these studies. Sections are reported in flowing progression, from Naples to the aqueduct end in Miseno (Fig. 1).

The ongoing research aims at providing a small contribution to the Italian map of ancient underground aqueducts (Parise et al. 1999).

2.1. Crypta Neapolitana

The *Crypta Neapolitana* is a 709 m long tunnel which in Roman times connected *Puteoli* with *Neapolis*. The aqueduct runs parallel to the *Crypta*, few meters deep within its north wall (Amato et al. 2002). The *Crypta* pavement

Figure 1. The Phlegraean Fields. In black: the explored sections.

was lowered several times, mainly on the Naples side; presently, the elevation of the Naples entrance is 34 m a.s.l. The entrance toward Pozzuoli opens in a place called Fuorigrotta; its elevation is 45.5 m a.s.l. The *Crypta* pavement raises from Naples to Fuorigrotta. On the contrary, the aqueduct slopes slightly from Naples to Fuorigrotta, beginning at an elevation of 39.5 m a.s.l. This means that at the Naples entrance the aqueduct opens at about 4.5 m above the present pavement, while at the Fuorigrotta entrance it is supposed to run 6 to 7 meters below the pavement.

On the Naples side, four entrances open on the *Crypta* wall, reachable with a ladder. In 2012 we were able to explore and survey a 120 m-long section of the aqueduct. Its cross-section is rectangular with a vaulted roof. The width is about 0.7 m and the heigth is about 1.8 m, but the aqueduct is partly filled with a variable thickness of fine tuff sand (mean heigth about 1 m), so explorers are required to crawl. The hydraulic plaster is intact; its height reaches the point in which the walls join the vault (vault impost). The usual calcareous deposit lines the hydraulic plaster. The exploration ended where a big wall collapse exposed the aqueduct, revealing interesting details about the building techniques, which are presently under investigation by archaeologists. A further section of the aqueduct is visible after the wall collapse, to be reached in the near future with a long ladder. However, large parts of the *Crypta* central section were affected by wall collapses, so the aqueduct could be inaccessible or destroyed in this section.

In the Fuorigrotta entrance some cubicles are present on the north wall. They are filled with rubble; just the second one was only partly filled, revealing a descending shaft. We dug out some rubbish and nearly three meters of rubble to reach the bottom, 6.5 m below the *Crypta*

pavement. A passage similar to an aqueduct *specus* was revealed, 0.8 m wide and 2.2 m high, but no hydraulic plaster is present. The passage top is not vaulted but angled. However, just the angled mark in the tuff is visible. Evidently, the terra-cotta tiles usually employed in angled vaults were removed.

Both the entrance "windows" in the Naples side and the cubicles in the Fuorigrotta side are roughly evenly spaced. Distances range from 36 to 41 meters. The lesser value is very near to one Roman *actus*, corresponding to 120 Roman feet, that is 35.6 meters. The "windows" and the shafts

Figure 2. Crypta neapolitana: the aqueduct at a junction between two digging teams.

evidently acted as digging and inspection entrances. In the Naples side section slight misalignments of the *specus* are evident nearly halfway between two consecutive “windows”. They were the connection points between the excavation teams working in opposite directions from consecutive entrances (Fig. 2).

Lettieri and later researchers report that at Fuorigrotta a side branch ran from the *Crypta* to Nisida island. Sgobbo (1938) claims to have traveled into long sections of this branch, but unfortunately he left no entrance position, description or survey.

2.2. Agnano

Past improvements in via Vecchia Agnano, an old road between Fuorigrotta and Bagnoli in the Municipality of Naples, cut the aqueduct. Presently, the *specus* emerges from the north-east under a hillside at about 2 meters above the road and continues in south-western direction across the

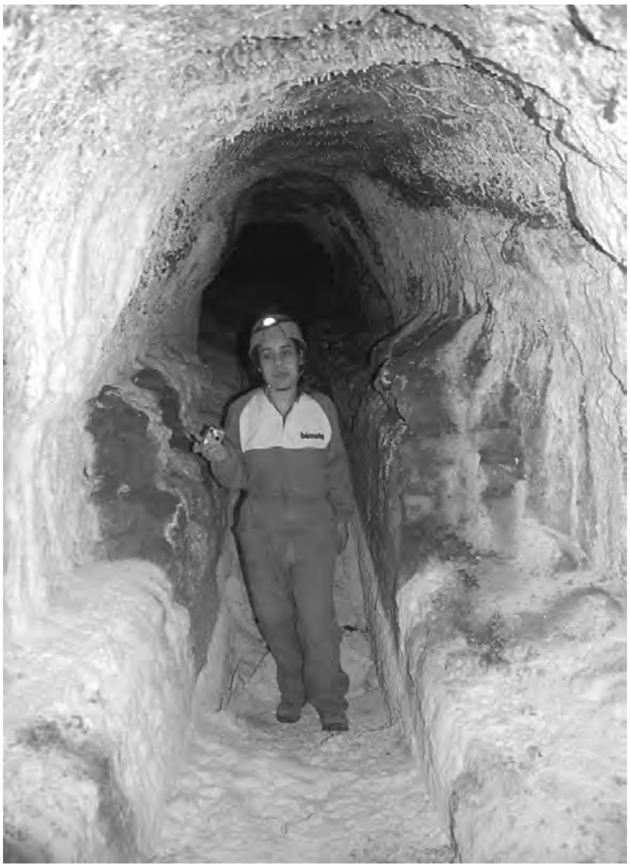

Figure 3. Agnano: the masonry lining was partly removed; calcareous water seepage decorates the passage.

road under a plain within the boundaries of a school in construction. We examined both the entrances, and found that both structure and dimensions are the same as in the *Crypta Neapolitana*. The only difference is in the enclosing terrain: solid tuff in the *Crypta*, volcanic sand and soil in via Vecchia Agnano. The former entrance is choked by fine sand and debris after three meters; the latter one is choked after 6 meters. Here again we started a digging operation.

400 meters north-west, past a small ridge, the remnants of the Roman Agnano baths stand. They were an ancient spa exploiting hot natural steam from underground. Here in 2012 we explored some sloping passages which operated as steam catchments and a 140 m-long aqueduct branch running to the south-east toward via Vecchia Agnano. It was evidently a side branch bringing fresh water to the baths. The passage is cut into volcanic ashes; the vault collapsed, so it is quite difficult to determine the geometry of the aqueduct and the hydraulic plaster height. In two places, water seepage, possibly from the modern aqueduct, produced white calcareous courtains (Fig. 3) and pisolites. A small bat colony dwells in the passage.

2.3. La Pietra

La Pietra is a coastal area in the Municipality of Pozzuoli. It owes the name (meaning “the rock”) to a hard volcanic rock reef in the sea. Land ridges are composed by several layers of tuffs, with different hardness. The Augustean Aqueduct was reported in nearby trachyte caves. At the beginning of 2012 we identified a cave entrance on the cliff

Figure 4. La Pietra. White: the cave; dashed black: inferred upstream aqueduct; dotted black: the destroyed downstream aqueduct; solid black: railway tunnel.

over La Pietra. Exploration revealed a 175 m-long aqueduct section with two side branches, for a 279 m overall cave development (Fig. 4). The two side branches are a horizontal unplastered service tunnel and a modern tunnel sloping down, probably related to a nearby railway tunnel. The first half of the cave was mined in a soft and altered rock, while the second half opens in a hard tuff. The hydraulic duct shows different building characteristics: the first half is lined with tuff masonry up to the vault impost (about 1.35 m); the hydraulic plaster is applied over the masonry, while the vault is just lined with a thin layer of plaster over the encasing tuff. In the second half, the hydraulic plaster is applied directly on the rock walls. The cave was half filled by tuff dust and sand. The first half was cleared up, possibly to allow the recent mining of the sloping down branch. Exploration in the second half requires to proceed on all fours. Both the aqueduct and the service branch end with earth fillings, near to the surface.

Graffiti letters are present at four sites on the vault plaster; they were probably length measurements. As far as natural sciences are concerned, the cave hosts a small bat colony. Very interesting depositional phenomena are present on the hydraulic plaster, such as extruded cave flowers. Furthermore, a luckily inactive volcanic gas fumarole is present in a side branch. A detailed description of the cave is reported by Ferrari and Lamagna (2012).

2.4. Pozzuoli Amphitheater

The Flavian Amphitheater in Pozzuoli is a large arena, the third largest in Italy. Its speleological interest lies in the nicely preserved underground level, with rooms for services, wild animals, gladiators and so on. A 70 m-long tunnel connects this underground level to an aqueduct running north-east of the Amphitheater (Fig. 5), placed at an elevation of 35 m a.s.l. The *specus* was filled with dried tuff mud for three quarters. A 83 m-long section was cleared in 1951 to reveal a rectangular cross-section with vaulted roof, 0.6 m wide and 1.5 to 1.7 m high. The hydraulic plaster reaches the vault impost, to suggest that the section belongs to the main Augustean Aqueduct branch. The north-western part is still filled up to the vault impost. In 2011 we crawled into a vaulted space 0.6 m wide and 0.4 m high, to explore a 80 m-long aqueduct section. Two square inspection shafts were found, each lined with reused marble stones. The passage continues, but forced ventilation is needed to further proceed in safety.

Figure 5. Pozzuoli Amphitheater. In black: the explored section.

2.5. Grotta di Cocceio

Lucius Cocceius Auctus was a renowned imperial architect in Augustean time (Strabo, V, 4, 5). His name is related to several important and ambitious projects in the Phlegraean Fields. Cocceius' Cave is the name of a 920 m-long tunnel connecting Lake Avernus to Cuma. The reported length is comprehensive of sections where the original vault collapsed. In the north side of Cocceius' Cave an aqueduct is reported. It was first identified and explored in 1844 (Scherillo 1844) when a peasant was lowered down a 11 m deep shaft to reach an aqueduct. Caputo (2004) reports about the aqueduct and stresses the similar topography of tunnel and parallel aqueduct between Cocceius' Cave and *Crypta Neapolitana*. A common development plan can be easily inferred, so Cocceius could reasonably be the actual designer of the tunnels and the aqueduct system. The specus parallel to Cocceius' Cave is probably the beginning of an Augustean Aqueduct side branch to Cuma. Caputo (2004) reports also about a settling and distribution plant (*castellum aquae*) just at the Cuma entrance of Cocceius' Cave. However, we have not examined this branch yet, because Cocceius' Cave hosts two bat species in the Red List, so its access is strictly regulated.

2.6. Scalandrone

A little known roman tunnel is placed in the municipality of Bacoli (Naples, Italy), in an area historically called Scalandrone. The tunnel was designed as an underground road communication over an impervious cliff slope. Originally it was about 200 m-long, but at present only 75 m can be explored, due to dust fillings. The cross-section is rectangular, with a vaulted roof and no masonry or plaster. It is 2.5 m wide and 3.5 m high. Five inclined light shafts are present, one of them being the present-days entrance. A small square opening, 1 m-wide and 1.5 m-high, stands on the left tunnel wall. Just above the opening, an inscription is engraved on the tuff wall, celebrating the inauguration of the opening as an *haustus* (passage intended as a water catchment) connected to the Augustean aqueduct (Fig. 6). The date of the event is reported as December 30th, 10 A.D (Camodeca 1997). So, on December 30th, 2010 we celebrated the bimillennial "birthday" of the *haustus*. Thanks to the cooperation between A.R.I.N. (Naples water resources company) and the Special Archaeological Superintendency of Naples and Pompei, an event was organized in order to celebrate the tunnel and the inscription at the same time. The birthday celebration summed up with a monumental cake inspired to Roman and modern aqueducts.

Figure 6. Scalandrone: the Haustus *and the superposed inscription.*

Three days later, on January 2nd, 2011, we succeeded in digging the filling in the *haustus*, to reveal a 0.5 m-high hydraulic plaster lining and a 53 m-long aqueduct section, partly filled by tuff sand and lapilli. The aqueduct elevation is 34 m a.s.l. Researches need to be continued. A detailed description of the cave is reported by Ferrari and Lamagna (2011).

2.7. Baia Archaeological Park

The Baia Archaeological Park is a large area completely built in Roman times as a thermal establishment. Several underground sources of hot water and steam were exploited by the thermal plants. Three large vaulted domes stand in the area; they were *calidaria* (hot rooms). Fresh water was provided by the Augustean Aqueduct and by long rows of water tanks holding rain water. The area is open to tourists and it is managed by the Special Superintendency for Archaeological Heritages of Naples and Pompeii, local office of the Ministry of Cultural Heritage.

In 2010 we began investigating underground cavities in the Park, both thermal and hydraulic. Just outside the Park entrance, the public road enters a trench in the ridge. The trench cut the ancient aqueduct. An entrance closed by a wall shows on the north wall, at about 5 m over the road. In the south wall, a similar entrance is covered by a steel cliff-containment wire-net. This entrance is choked by dust after 2 meters.

Some 230 meters south, within the Park, an 18 m-long passage leads to an underground vaulted room lined with *opus reticulatum* masonry, 7 m-wide, 4 m-long and 3 m-high. In the middle of the room, a section of the aqueduct runs. It is completely enclosed in masonry; just a small door allows access to the *specus*. As usual, the aqueduct is partly filled with dust and rubble. We succeeded to explore about 25 m south and 5 m north. The hydraulic plaster is only 0.5 m-high. Careful digging is needed.

2.8. Fondi di Baia

Fondi di Baia are two small twin craters (diameter 500 m). Vineyards grow on the inner slopes. A cave entrance is visible at about 30 m a.s.l. of elevation in a small artificial cliff in the north crater (north-western side). In 2010 we performed a rope descent to reach the entrance (Fig. 7). We were able to explore just 16 m of cave, which opens in a whitish coarse volcanic deposit. The cave is a straight passage 1 m-wide and 1.3 m-high with rough walls and roof, and no plaster. The cave turns left and ends abruptly on a small masonry wall built with tuff stones. The cave shows no trace of an aqueduct, but both location and elevation are coherent with the expected position of the Augustean Aqueduct.

More than 2 km of unknown aqueduct separate this site from the renowned *Piscina Mirabilis*, a large water tank designed to provide fresh water from the Augustean Aqueduct to the Roman Navy at anchor in the Miseno harbour. It could store 12,700 cubic meters of water (De Feo et al. 2009). The water intake is still visible 10 meters high in the monument wall.

3. Discussion

The little information gained so far shows good uniformity. The general cross-section is rectangular with vaulted roof, usually 0.64 m-wide and 1.5 to 1.8 m-high. A fine hydraulic plaster is nearly always well preserved; its height is about 1.3 m between Naples and Pozzuoli and 0.5 m between Pozzuoli and Miseno. However, the available data are not sufficient to make a rule, and further observations are needed. About the encasing ground, there are four cases. In solid tuff rocks the hydraulic plaster is directly lined over the walls, usually with a thin plain plaster on the vault (*Crypta*, La Pietra, Scalandrone). In less coherent volcanic rocks, the bottom part of the walls is lined with tuff masonry which bears the hydraulic plaster, while the vault plaster is lined on the bare rock (La Pietra, Agnano). In little coherent volcanic deposits (lapilli, pumices) a full masonry tube was employed (Agnano, Baia). Finally, in soil or earth the full tube was built in a trench and covered (Agnano). Up to now, the measured elevations are coherent with a progressive sloping of the aqueduct. However, data are too few and inaccurate to provide a reliable dip.

Figure 7. Fondi di Baia: rope descent to reach the entrance.

4. Conclusions

Few hundred meters of aqueduct have been explored so far, out of an expected development of more than 22 km in the Phlegraean Fields. Interesting data have been collected, but more researches are needed. Some other potential entrances are known from literature and research on the field could bring some new exploration. However, long and demanding digging operations in narrow places are required to proceed. A general idea of the whole aqueduct course is already defined. Present data show that the underground structures resisted eruptions and earthquakes;only human abuses succeeded in destroying sections of the aqueduct. A strong concerted action is needed in order to explore the yet unknown sections, preserve them and exploit their cultural heritage value.

Acknowledgments

We are grateful to the Special Superintendency for Archaeological Heritage of Naples and Pompeii, especially to the Heads of the local offices at Baia (Ms. Miniero and Mr. Talamo), Naples (Mr. Vecchio) and Pozzuoli (Ms. Gialanella) and their staff. The Phlegraean Fields Regional Park (Past-Presidents Mr. Escalona and Mr. Giuliani) enthusiastically supported our researches. The Municipality of Naples, Direction for Cultural Heritage (Ms. Dello Russo) and the Province of Naples, School Building Offices (Mr. Parravicini) allowed access to the areas they manage. Similarly, the owners of the business premises called Tonga (La Pietra, Pozzuoli) and Villa Espero (Scalandrone, Pozzuoli-Bacoli) authorized access to their areas and the Neapolitan Archaeological Group (President Mr. Giglio) supported us in the ancient Agnano Thermal area. Mr. Martinelli, Mr. Schiano di Cola and Mr. Wenner showed us some underground sites in the Baia Archeological Park, while the members of the Aquae Ductae Association (Mr. Luca Ciardiello, Mr. Uberto Potenza, Mr. Ugo Potenza) supported us in the explorations at La Pietra. Last but not least, we are indebted with the caving friends which shared emotions and digging dust with us: Berardino, Elena, Ivana, Norma, Rossana, Rosario.

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NERO'S OVEN: TEN SURVEYS ARE NOT ENOUGH

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Nero's Oven is an artificial cave placed in the Municipality of Bacoli (Naples, Southern Italy). A small network of passages leads to an underground pool of hot water. The passages were dug in Roman times as a sweater: hot steam was used to cure several ailments. The place was highly renowned also in medieval to modern times; wealthy foreigners in the "Grand Tour" to Rome and Naples were shown the passages and the hot water. The first printed survey of a cave (1546) is a rough plan sketch of Nero's Oven passages. Subsequently, several researchers tried to cope with the internal temperature and steam to produce a graphic representation of the cave. The paper reports about the ten known surveys produced between 1546 and 2000 and the information they provide to modern speleological and archaeological research. Some information about the present state of the cave are presented. A modern cave survey has not been produced yet, since the outer rooms are used as a private dwelling.

Author rerum naturae curiosus indagator montem intrat (Theodoricus aus Nieheim, 1532).

1. Introduction

Nero's Oven is a 400 m long maze of small tunnels. It opens in the Phlegraean Fields, 16 km west of the center of Naples, Italy, in the Municipality of Bacoli (Fig. 1).

The Phlegraean Fields are an active volcanic area. Catastrophic eruptions occurred 39/35 ky b.p. and 15 ky b.p., while several minor volcanoes erupted in pre-historical times and again in 1538 (Rosi and Sbrana 1987). Presently, the volcanic activity is limited to fumaroles and thermal springs as the one which is present within Nero's Oven. The area is affected by the characteristic bradiseismic effect: a long-period raising and lowering of the land, related to variations in the underlying magmatic chamber. In Roman times the land was at higher elevation than today, so many coastal structures, villas, palaces and harbour plants are presently underwater.

The mild climate, the fertile land and the safe harbours raised attention by Greeks and Romans. Furthermore, the area was blessed by several thermal springs. In the Augustean period (end of the 1st century b. C.) the area was fully exploited with leisure establishments, fisheries, storehouses and harbour plants. Many caves were opened in Roman times, as tunnels, aqueducts, water tanks, hot water catchments, steam tubes to warm thermal establishments. Among ancient writers, Cassius Dio, Celsus, Martialis, Plinius the Elder and Vitruvius report about sweating places at Baia, employing natural steam sources from underground.

2. The cave

Nero's Oven is the most important establishment in the area. It bores through Punta Epitaffio, a small tuff headland over the sea. Ancient ruins are still visible on the top and the cliffs; a medieval tradition reportedly attributes them to a luxurious villa which belonged to emperor Nero. He attempted his mother murder in the nearby sea waters.

The actual place name is Tritoli, maybe a corruption of *cryptulae* (Latin term for "small caves"). Nero's Oven is called also Tritoli Sweater, as opposed to Tritoli Bath, an underground bathing room placed on the beach at the roots of Punta Epitaffio. Tritoli Sweater opens on the cliff; in medieval times it was reached from the sea, through 43 steps. Therapeutic use of the place continued after Roman times. In the XV century Tritoli was the hottest establishment in an area where more than 40 baths were reported. The site was shown to foreign visitors. A local peasant stripped, entered the hot passages and brought back a buckle of nearly boiling water. Some eggs were dropped in it and they were quickly cooked. Some visitors tried to enter the hot passages following the guide. Usually they had to retreat; few succeeded in reaching the hot pool with great effort, due to the air temperature which reached 50 to 60 °C. In the XIX century water temperature was frequently measured at more than 80 °C; in 1975 it reached 92 °C, just after a period of increased volcanic activity in the Phlegraean Fields. On May, 8th, 2010 we measured temperature at 65 °C. Presently the cave is composed of three parts: the so-called Grotta di Baia, the outer rooms and the inner passages. The Grotta di Baia is a 70 m long tunnel, parallel to the cliff, with several windows and six underground rooms aligned along the tunnel internal side. It was opened by order of viceroy Pedro Antonio de Aragón (1666–1671) to allow road communication through Punta Epitaffio cliffs. The rooms were used as resting places for patients after exposition to the Sweater steam. The outer rooms are five vaulted caves aligned along the cliff, just out

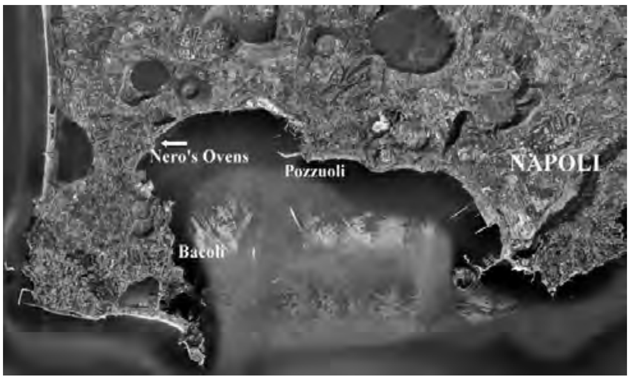

Figure 1. The Phlegraean Fields.

the northern entrance of Grotta di Baia. They too were resting places, but their origin is obscure. Theodoricus aus Nieheim, a German historian, visited the place in 1404 and reported (1532) about large rooms dug in the rock. The inner passages are a set of small horizontal tunnels, with a rectangular section about 0,8 m wide and 1,7 m high. The rightmost passage slopes down as a stairway to a pool of hot water covered with salt crystals. The air temperature reaches 40 °C. The outer rooms are inhabited by the descendants of a family which found shelter from World War II bombing on Pozzuoli. We had the chance to enter the inner passages but once, so we were unable to produce a modern survey.

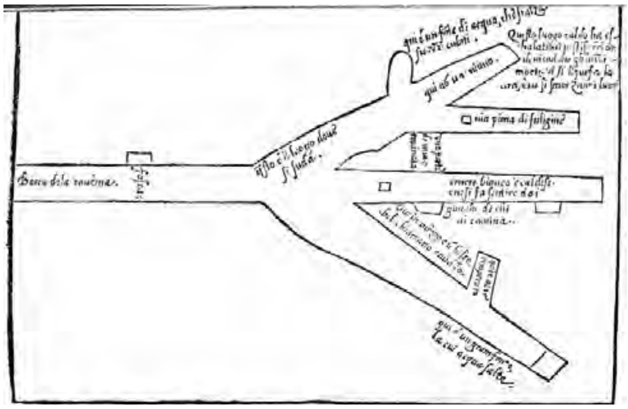

Figure 2. Nero's Oven survey n. 1 in the italian version (Agricola 1550).

3. The surveys

The caving historian Trevor Shaw (1992, p. 13) states that the earliest printed cave survey belongs to the Tritoli Sweater. The exceptional interest of the place raised attention by several scholars, antiquarians and researchers, and up to ten different surveys were produced in the past.

3.1. 1546

In 1538 a new volcano erupted in the area, less than 1,5 km distant from the Tritoli Sweater. The accident prompted attention by European scholars. Georg Fabricius (1516–1571), a German historian and archaeologist, visited the area in 1543. In his travel report (Fabricius, 1547) he composed a poetical description of the Sweater. In 1546 Georg Agricola, also author of the renowned *De Re Metallica*, published a collation of booklets in latin about subterranean matters. Information about the Sweater was provided by an unnamed inhabitant of Pozzuoli to Georg Fabricius who transmitted it to Agricola. The cave development was reported as a largely overestimated three miles length. Information was accompanied by a plan sketch woodcut of the cave (Agricola 1546, p. 146) with several captions. The cave is represented as a single entrance passage which splits in three. The rightmost one leads to a boiling spring. The woodcut was reprinted in several subsequent editions, also in an Italian translation (1550, Fig. 2). The survey and its captions are described by Cigna and Middleton (2005).

3.2. 1558

The 1546 plan sketch was evidently a low quality one. A reprint of Agricola work contains a wonderful woodcut (Agricola 1558, p. 142, Fig. 3) which represents a pictorial view of Punta Epitaffio with a ship arriving at the foot of the 43 steps stairway and a cut-away view of the Sweater, called *Sudatorium Magnum* (most important sweater). This woodcut too was published in Cigna and Middleton (2005).

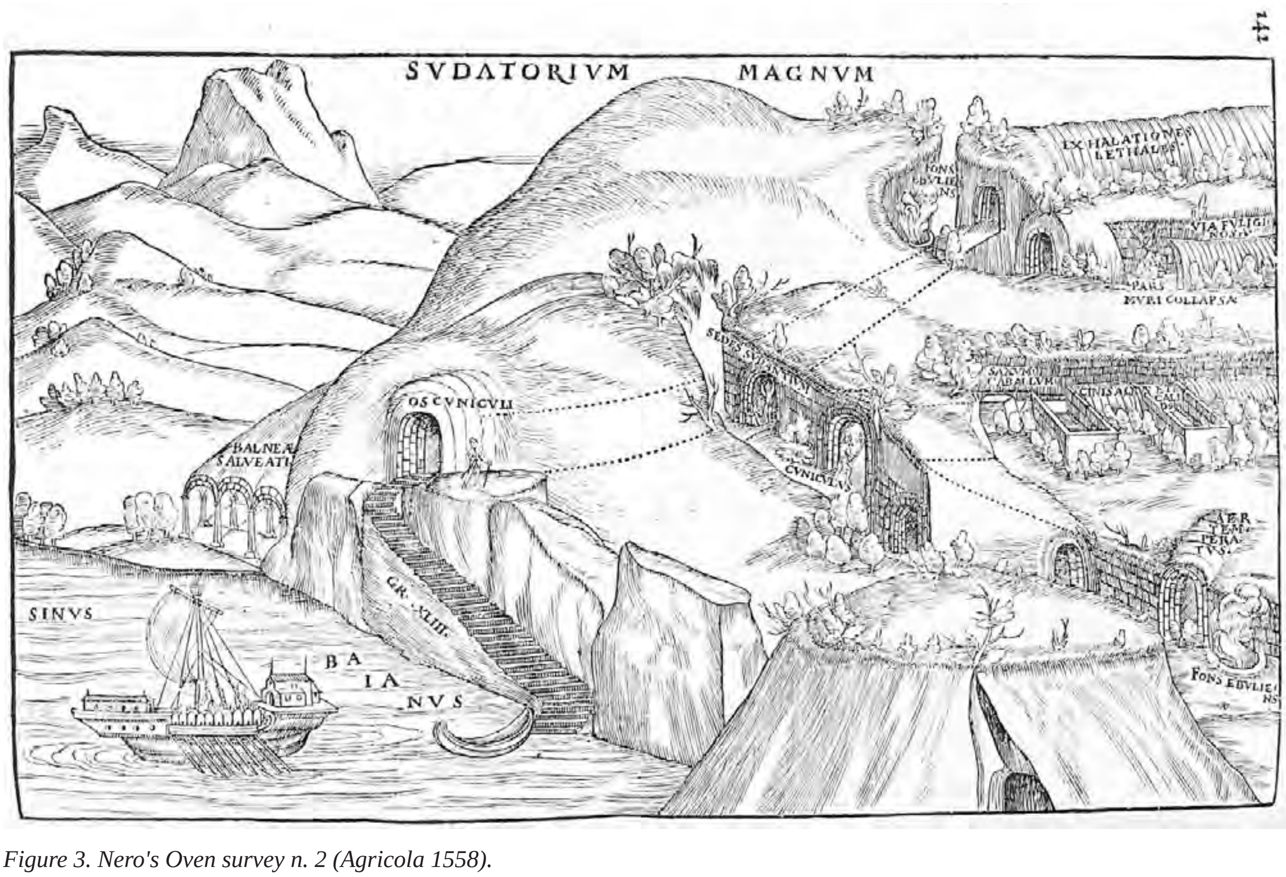

Figure 3. Nero's Oven survey n. 2 (Agricola 1558).

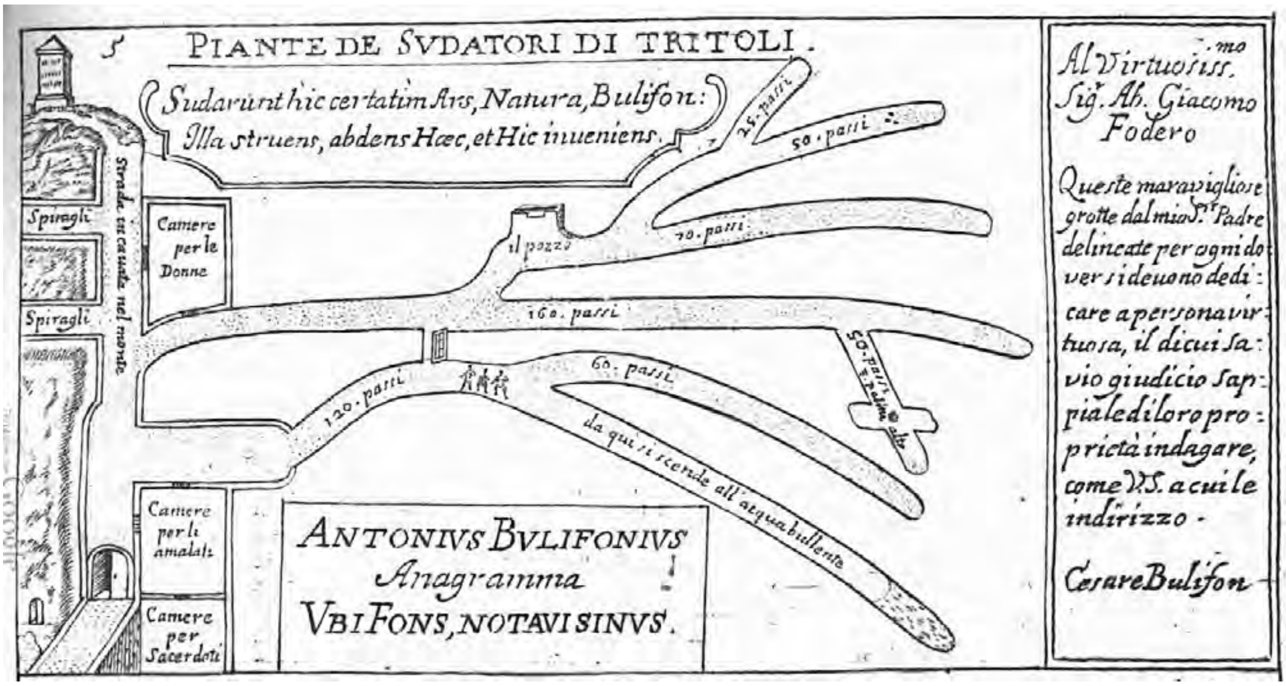

Figure 4. Nero's Oven survey n. 3 (Sarnelli 1691).

3.3. 1687

Antonio Bulifon was a French learned publisher, with plants in Naples and Pozzuoli. He realized that the Agricola plan was incorrect, so he decided to produce a more accurate one together with a detailed description. On June, 24th, 1687 he entered the Sweater with a local guide. A copper engraving was first published in the 1688 edition of a Pozzuoli guidebook by Pompeo Sarnelli (pl. 7) and in a reprint in 1691 (Fig. 4).

The survey is a plan representing some of the outer rooms as separate resting places for women, men and priests. At the time, the cave was actively employed for therapeutic use by a hospital in Naples. The inner passages are represented as two main branches connected by a gated passage. The right branch splits in two and contains the hot spring. The left branch splits in five and contains a shaft. The total development is estimated at slightly more than half a mile. No scale is shown, but partial lengths of several passages are reported, expressed in paces. Bulifon reports also that one of his employees recovered from blindness thanks to the Sweater hot steam.

This survey was reprinted several times; Cigna and Middleton (2005) report a 1818 reprint by Panvini.

3.4. 1697

Bulifon produced a slightly different and more accurate version of the survey to be published in a detailed Sweater description (Bulifon 1697). The same copper engraving appeared in further editions of Sarnelli guidebooks (1697, Fig. 5; 1702; 1709). Perhaps the original copper was worn out, so a new one was needed. Both the outer rooms and the

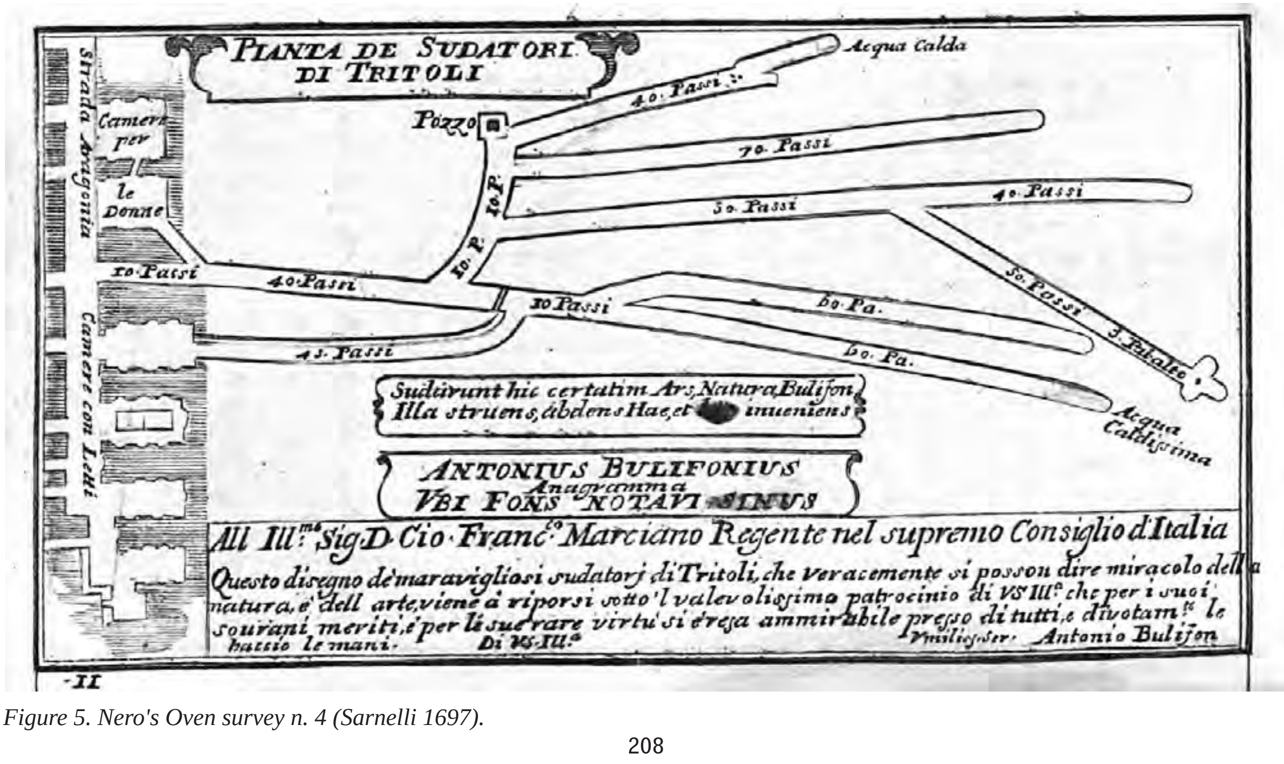

Figure 5. Nero's Oven survey n. 4 (Sarnelli 1697).

inner passages layout are more realistic; all passages are provided with length in paces. It seems that Bulifon decided to re-entered the Sweater in order to improve the first version of his plan.

3.5. 1753

Jerome Charles Bellicard, a French architect, published a research about Herculaneum and other antiquities in the neighbourhood of Naples. The book was produced in English and appeared in 1753. Further editions were published in French or in English in 1754, 1755, 1757 and they bear also the name of the designer Cochin. Only the plan of the Sweater entrance room is represented, together with the very beginning of the hot inner passages. However, beside the entrance room, an undescribed spiral staircase is represented (Bellicard 1753, pl. 37). No scale is shown. It is worth noting that in the 1757 (Fig. 6) edition the plate is flipped in the vertical sense, producing a more realistic representation on the place.

3.6. 1830

In 1817, canon Andrea De Jorio, a renowned Neapolitan archaeologist, published a tourist handbook on antiquities in Pozzuoli and its neighbourhood. The first edition, as well as a second (1822), mention Nero’s Ovens but no graphical representation is enclosed. In the third edition (1830) a separate atlas of plates was printed. It contains a survey of Tritoli Sweater (Fig. 7) with a plan of the outer rooms and the inner passages. A longitudinal section of the rooms and the main passage to the hot spring is enclosed. It is the only section ever published of the Sweater. The survey was produced by Friedrich Heller, a German archaeologist, and the scale is in French toises, which corresponded exactly to 2 meters at that time, due to a Napoleonic measurement units reform.

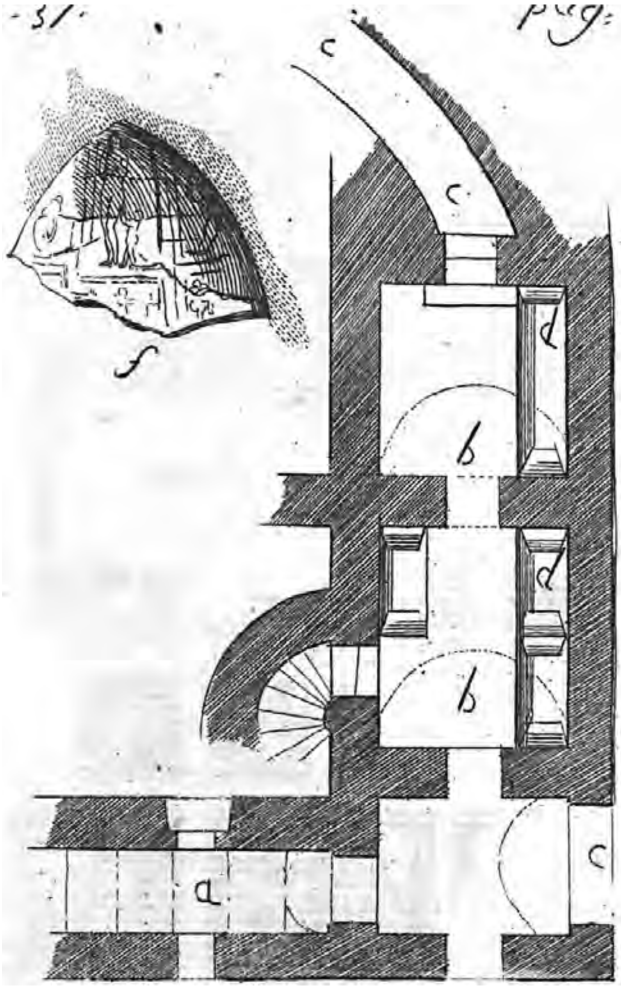

Figure 6. Nero's Oven survey n. 5 (Cochin and Bellicard 1757).

The plan is inaccurate: passages are tree-like and not straight as in reality. The connection between the two main branches is missing and a three-lobed passage termination is in the wrong place. However, both the plan and the section show a round room at the end of the main passage.

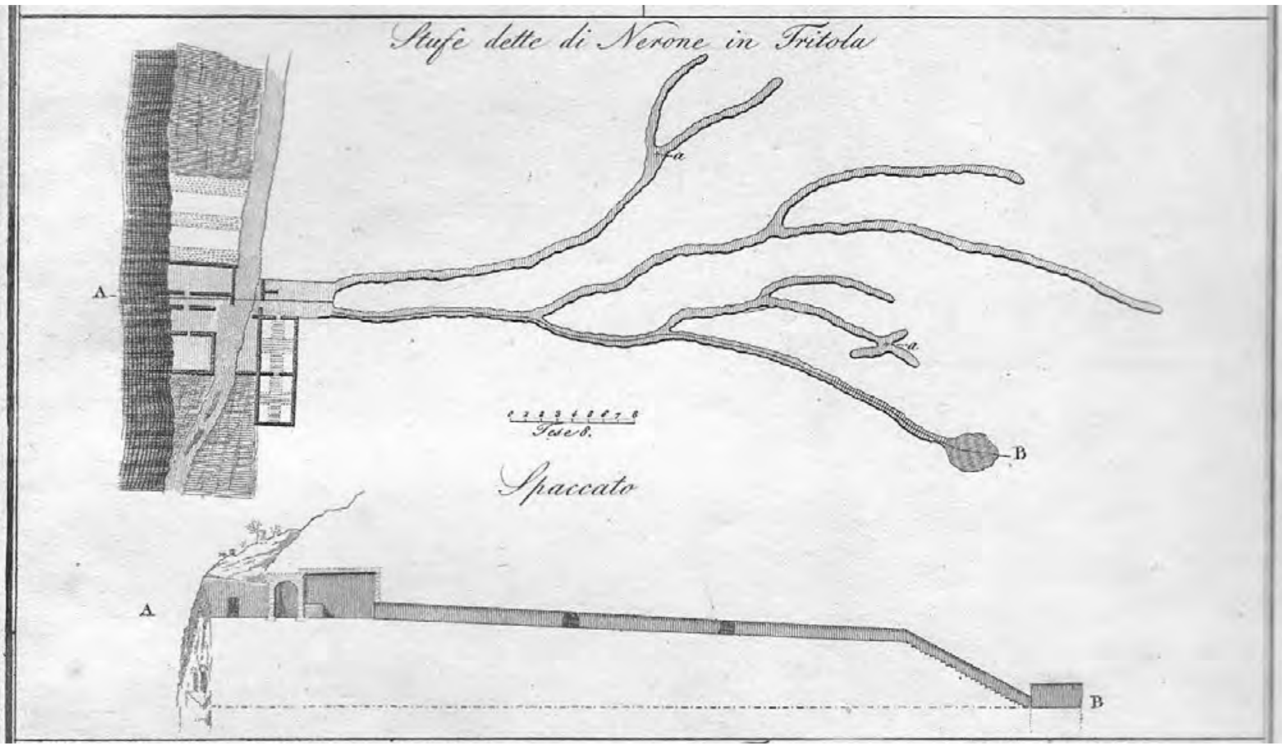

Figure 7. Nero's Oven survey n. 6 (De Jorio 1830).

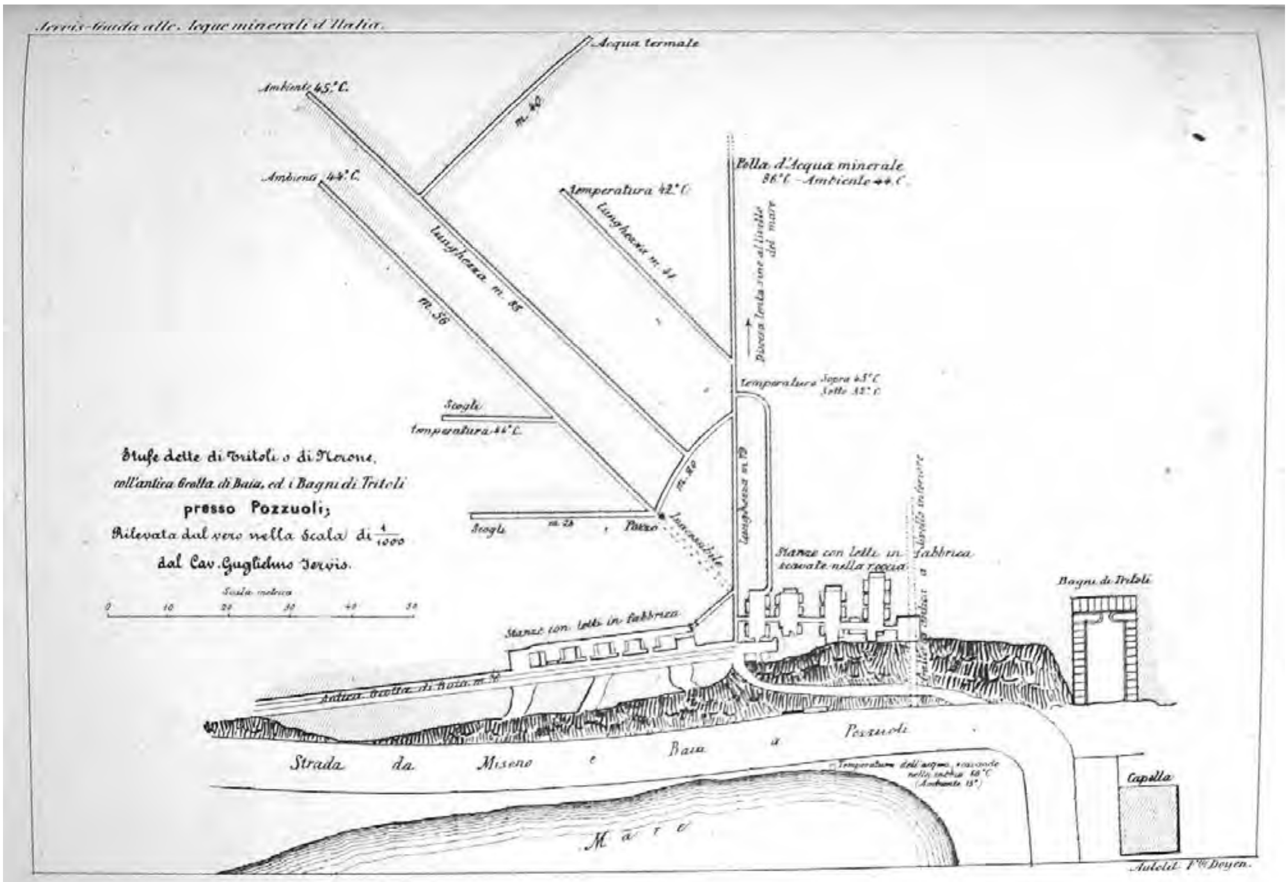

Figure 8. Nero's Oven survey n. 7 (Jervis 1876).

In 1843, Constantin James, a French physician, reported the hot pool as divided in three basins, with an estimated depth of about 0.5 m (James 1844). Presently, the land is lower, so the hot water pool raised up the stairway. This means that a real room could be present at the end of the passage. On the other hand, we should note that James observations were performed amidst hot vapours, with an air temperature of 50 °C and with heart pulse higher than 150.

3.7. 1869

William Jervis compiled a multi-volume guide to Italian mineral waters. In the southern Italy volume, he added a chapter on natural sweaters. Nero's Oven was described and surveyed (Jervis 1876, pp. 180–182). The water temperature was 86 °C. A plate reports the survey; it is a very accurate plan, with the outer rooms, the Baia Tunnel, the main passages and the side passages (Fig. 8). The scale is in meters.

3.8. 1957

The geologist Renato Sinno performed a geologic and petrologic research on Punta Epitaffio area. He entered the site and sampled the salt deposits. A plan survey was published, limited to the main passages, as far as the hot pool (Sinno 1957). No scale is provided.

3.9. 1975

Cavers from the Naples Alpine Club explored the cave. They measured air temperature and moisture at several places and sampled water, in which a thermophilic bacterium was found. Water temperature was 92 °C, while the maximum air temperature was 58 °C. A survey was produced, limited to the main passages, as far as the hot pool; the plan only was published, but the picture reports also the clinometer data (Abbruzzese Saccardi 1976). The scale is in meters.

3.10. 1999

Finally, Greg Middleton, an Australian caver, visited the place in 1999. He was aware that the cave owned the oldest printed survey and he aimed at producing a modern one. Unfortunately, he was forbidden to enter the hot passages; he was just able to produce a few photos and a grade 1 plan sketch of the visited parts (Middleton 2000).

A further library research induced Cigna and Middleton (2005) to produce a paper in which four of the above mentioned survey (n. 1, 2, 3 in the Panvini 1818 version, 9) are discussed. The present paper is a natural follow-up of their work.

4. Discussion

The ten produced surveys had very different objectives, so results are quite divergent. Oddly enough, no. 1 and no. 10 are both grade 1 sketches, conditioned by the little information available. No. 5 is simply an architectonic documentation of the initial room. Its value relies on the elusive spiral staircase. No. 8 and no. 9 were oriented to specific studies on the hot pool branch. This means we have no recent information on the other branches.

No. 2 derives directly from no. 1. Its value is in the pionieristic pseudo-3D view of Punta Epitaffio, with the cave cross-cut.

Nos. 3, 4, 6 and 7 are the most complete and detailed surveys. Their comparison shows the following information:

- errors and imprecisions are clearly related to the very demanding survey conditions. Honor should be paid to these surveyors of the past.
- The general situation of the inner passages shows very little changes in the last four centuries.
- Survey no. 6 seems to show that in the first half of the XIX century a terminal room was reachable. The point deserves further investigation, but this means some sort of hot underwater exploration, possibly with a video probe or a temperature-resistant ROV in the hot spring (Fig. 9).

Another interesting point to note is the wide international research interest in Nero's Oven: in the past five centuries, scores of scholars and researchers from France, Germany, Great Britain, Italy and even Australia converged to perform researches on the place.

5. Conclusions

Nero's Oven is evidently a very special place. It shows several scientific and cultural fields of relevance: archaeological, historical, geologic, geochemical, volcanologic, petrologic, hydrologic, biologic. Speleology aims at gathering past information and providing reliable, complete and detailed information about the place, to be employed by researchers in sectorial studies.

Nero's Oven deserves a multi-disciplinary research project; the first step should be the production of a modern, complete and reliable survey, within the limits imposed by local environmental conditions. Luckily, present time low volcanic activity produces a less demanding environment with respect to the near past.

Acknowledgments

We wish to thank Silvana, Leonardo and Luigi, who inhabit into this extraordinary place. They preserve memories of it and they allowed us to begin its studies.

Many real and virtual libraries helped in providing old and recent books and publications. The list is too long; the main providers were: Naples National Library, Pozzuoli Diocesan Library, www.archive.org, Google Books.

We are also grateful to Arrigo Cigna, for his invaluable support and suggestions about historical and scientific relevance of Nero's Oven.

Figure 9. The hot spring (photo by G. Ferrari). Libri III. Petreius, Norimbergae.

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RESEARCH PROSPECTS OF OLD MINE WORKINGS IN THE URAL MOUNTAINS

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Mine development in the Ural Mountains (Russia) started 4–3 thousand years B.C. In the XVII–XVIIIth centuries commercial mining began. A lot of mines and adits have been retained till now. These mining old relics are of great interest not only for speleologist, but also for historians, biologists and geologists. On the Western and Eastern slopes of the Urals – copper, iron, gold, asbest, sulphur pyrite, alabaster, coal were extracted. The depth of some excavations reached 300 m and the area of some mine fields – reached 500 km². The total number of developed underground mines of the Urals at the beginning of the XIXth century exceeded 15–20 thousand. Speleologists are only at the very beginning of investigation of this rich region in artificial caves.

1. Introduction

The Urals are a mountain range that reaches a height of 1,895 m asl, located in Russia 1,100 km east of Moscow. The Ural Mountains stretch from the north to the south for 2,000 km, forming the boundary between Europe and Asia.

Mining crafts of the Ural Mountains find their origin a long time ago. According to A.A. Shtukenberg copper sandstones of the Pre Ural area and the Western slopes of the Urals already were a source of raw materials for the local population since 4–3 thousand years B.C. (Shtukenberg 1901). Intense activity of the first miners in prospection and mine-working already caused the discovery of practically all the most significant deposits of copper of the Ural by the beginning of the industrial revolution. Such ancient mine-workings received the collective name of “chudsky mines” by the Russian population. Chudy refers to the name of the tribes that occupied the Urals in earlier times.

From the beginning of the XVIIth century a new age in the development of the Ural mineral deposits started. Expeditions financed by Moscow actively investigated the western slopes of Northern and Central Ural Mountains. In 1628 iron ore was found near the river Nitsa, and in 1635 the Kunzhursky field of iron ores near the river Yayva and the Grigoryevsky field of copper ores near Solikamsk were discovered. In 1631 the so-called Nitsinsky plant started its work becoming the first Russian iron industry. By 1633 at the Grigoryevsky mountain the first copper enterprise of Ural was founded, and in 1640 the Russia’s first Pyskorsky state copper-melting plant was erected near the river Kamgorka, attached to the Pyskorosky monastery.

Quite often ancient works were an indication of the presence of ores, and their discovery often lead to the development of detailed researches. For example, in 1702 the Ural settlers led by Sergey Babin found “chudsky mines” near the river Polevaya and opened the well-known Gumeshevsky copper field. Later, during excavations in the Gumeshevsky mine, ancient mines over 20 m in depth, the remains of timbering, and also numerous labor tools such as mining picks, copper hammers, leather bags for ore transport, were discovered. A wooden shovel was found in Sergiyevsky mine at a depth of 32 m.

The XVIII–XIXth centuries were marked by a rapid development of ore deposits that were explored thoroughly, and tens of foundries were erected across all Urals. Besides production of metals, an important share in mining was represented by non metallic ore deposits. By the end of the XIXth century the Ural mountain enterprises mined copper, iron, gold, asbest, sulphur pyrite, alabaster, coal and so forth (Fig. 1).

Mineral resources of the Urals attracted public and private investments. The mining industries inherited many European traditions and, although with a certain delay, started to use advanced technologies. Innovations allowed extracting minerals in complex hydrogeological conditions and underground production was pushed deeper and deeper. In the early XXth century many deposits were exhausted or found unprofitable, and most mines were slowly forgotten.

2. Geography of mines

The total number of underground mines of the Urals developed in the beginning of XIXth century exceeds 15–20 thousand. Details of the exact location, size and morphology of most of them is poor or irretrievably lost. Archival and published sources, as well as current research in general, can provide an enormous amount of documentation on mine works in the Urals – thousands of miles of underground spaces.

In the XXth century a rediscovery of the mines was attempted. Coverage of objects was quite small. Often only facilities near settlements and highways were inspected. Basically the entrances of the mines and tunnels, and dams and ditches were described. Thus most of the workings and their real dimension and morphology remain unexplored.

2.1. Cisurals

Cisurals is the marginal part of the East European Plain, adjacent to the western slope of the Ural Mountains, within the river basin of the Kama and Pechora. The main minerals derived here up to the XIXth century were copper ores. They are confined to sandstones of Permian age. Thousands of copper mines spread from the city of Orenburg in the south to the northern borders of Perm region.

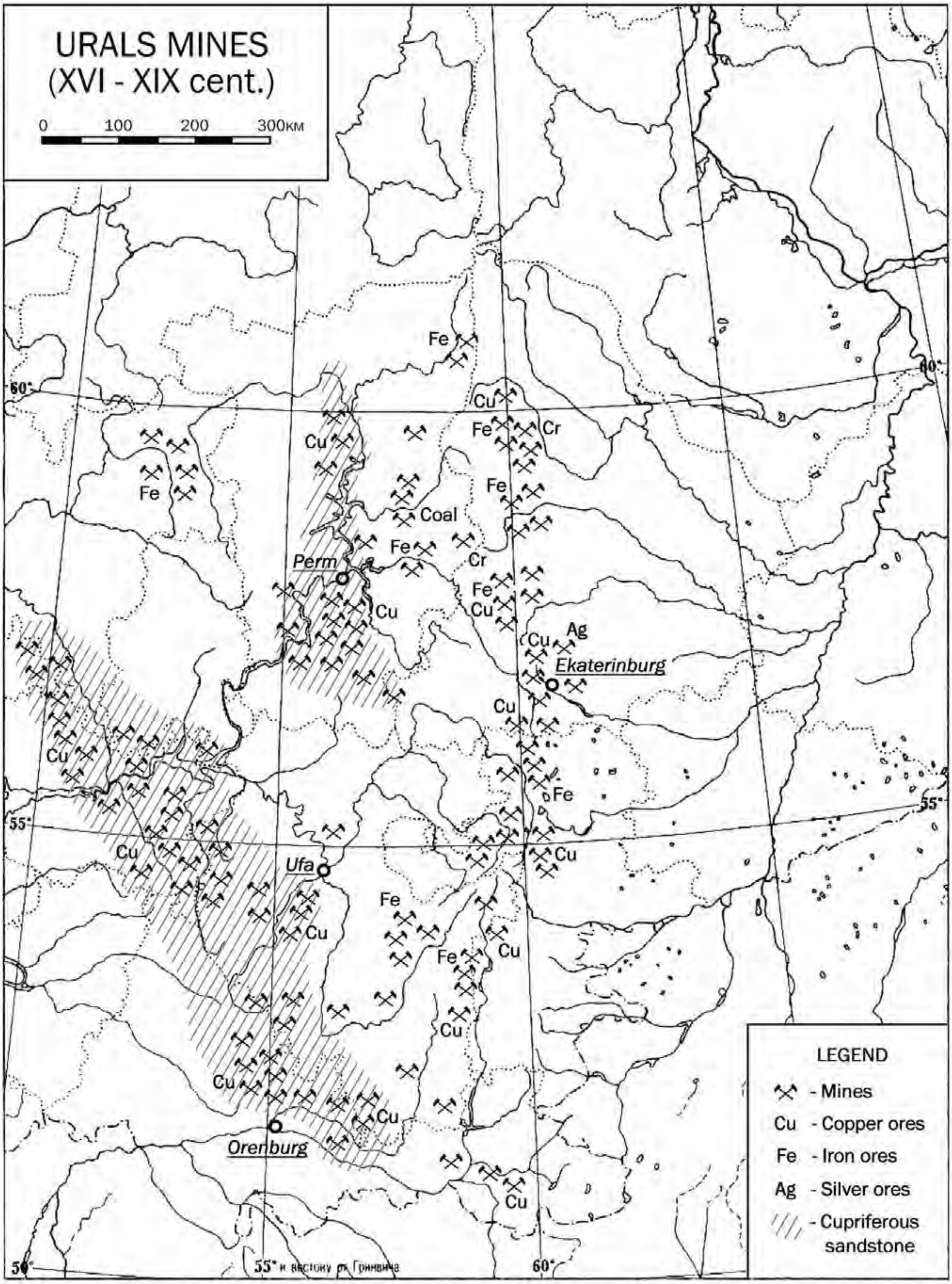

Figure 1. Map of location of mine workings (XVI–XIX cent.) in the Ural Mountains.

A strip of copper sandstones passes through Kirov region and the Republics of Tatarstan, Udmurtia and Bashkortostan.

Mining works have a depth of 5–70 m. Their size and shape are quite diverse from a few meters straight exploration adits and shafts, up to hundreds and thousands of meters of multi-level systems. Minings near the village Kargaly north of Orenburg cover an area of approximately 500 km ². This is one of the world's oldest mining complexes, consisting of hundreds of large mines and tunnels, developed in the IVth century B.C., and active until the end of the XIXth century. In Tatarstan, the study revealed dumps and large and complex workings connecting the two river valleys located at a distance of about 5 km. Here, several galleries

Figure 2. Inclined workings of Voskresensky mine.

and a chain of more than 40 mines stretch between the rivers Arbashi and Ucha. The largest of the copper mines hosted in sandstones is Sarmanovskiy, located 220 km south-east of the city of Kazan. We studied this mine in 1998 for a length of 2.1 km (Gunko 2008). It has several layers of well-preserved sections of the arched galleries. According to some literature sources, captured Swedes participated in its development at the beginning of the XVIIIth century (Rychkov 1770)

In the east of Kirov region in the upper reaches of the rivers Vyatka and Kama, and in the south of the area on the left bank of the Vyatka was being developed iron ore. Mining works were produced by small mines and sloping tunnels. There are numerous gaps and wells, the study of which is complicated by the remoteness of the villages.

2.2. The western slopes of the Urals

This territory includes the eastern part of the Perm Territory, the Republic of Bashkortostan and a part of Orenburg region. Iron mines are widespread in this region. They were developed in Perm region, in the upper reaches of the river Vishera, and in the middle parts of the rivers Vijay and Koiva (river basin Chusovaya). The deepest mines in this area are Isakovsky (-70 m), Koyvinsky (-90 m), and Kurtymsky (-128 m). Active mining of iron ore was carried out in the basin of the rivers Belaya and Inzer in Bashkortostan.

Partially developed underground chromite ore was exploited near the village Sarayu on the river Vijay in Perm region. At the end of the XIXth century this area was the world's largest supplier of chromite. There are numerous mine workings, the entrances to which are located in the walls of the pits and valleys.

Since 1796 coal was mined underground in Perm region. In the river basins Usva, Kosva and Yaiva are located numerous workings. In 1892 there were 22 mines and tunnels here. In the XXth century many mines have continued to work at great depths. Older mine works are present on the mountain Krestovay near the town of Gubaha.

2.3. Central and eastern slopes of the Urals

This territory includes Sverdlovsk and Chelyabinsk regions, the eastern part of the Republic of Bashkortostan and Orenburg region. Exploitation of copper was carried out throughout the whole easten slope of the Urals. The preserved copper mines in the northern part of Sverdlovsk region are of great interest. In 2007 north of Severouralsk a group of researchers led by M.V. Tsyganko found and opened the entrance to the mine Voskresensky (XVIII–XIXth centuries). Several mine galleries are well preserved here (Fig. 2), still containing several miner tools: mining picks, fragments of drag harrows, sump pans and lamps were assembled. There are great prospects for further exploration of the mine.

Thousands of mines surround the towns of Severouralsk, Krasnoturinsk (Fig. 3), Nizhny Tagil and Yekaterinburg. These are mine workings of copper, iron, chromium, silver, etc. The deepest mine goes down to 300 meters below surface. The famous Rudyansky Copper mine on the river Rudyanka near Nizhny Tagil had 10 mines with a depth of 300 m spread over an area of about 520 × 670 m. The famous Turinskie mines reaches depths in Frolovskiy 230 m, Rashetovsky 210 m, and Vasilevsky 160 m. Increasing urbanization has englobed these mine adits in the suburbs, and the mines are now located in the cities.

Large excavations of copper and iron are located near the towns of Zlatoust, Miass, and Magnitogorsk (Chelyabinsk region).

3. Conclusions

Since the end of the XXth and the beginning of the XXIst century with the development of scientific disciplines such as spelestology and industrial archaeology, underground mine workings are seen as unique objects – monuments and mining technologies that have survived to the present day.

Figure 3. Mining shaft of chrome ore to the east of the town Krasnoturyinsk.

Artifacts representative of past mining periods are often preserved inside ancient mine workings: tools, personal items of miners, elements of mine ventilation, lighting, and many others. Collapse, flooding, secondary mineralization, settling of living organisms: all this leads to the formation of a special underground landscape, the fragility of which is similar to that of the natural karst landscapes.

However, some of the old mine workings are a problem for the development of cities in the Urals. A number of large Ural settlements were built close to or around the XVIII–XIXth century ore deposit exploitations. Later, population growth has led to urban development in the mining areas. Public safety issues related to, first of all, the construction in such territories, began to emerge as early as the 1960s. As in Perm entire districts of the city are in danger. In the town of Berezovsky, the lack of historical data and the haphazard urbanization over old mine workings led to subsidence and deformation phenonema of the built structures. The town Krasnoturinsk central residential area was built right on the mine field. Several houses were located right on the mouth of the mine. A possible solution of a number of geo-ecological problems associated with mining, is based on prevention. It should be based on the collection and analysis of historical information, as well as targeted research and speleological and geophysical methods.

Speleologists are only at the very beginning of investigation of this region rich in the artificial caves. It is a well established location and to date only 10 % of the old mines of the Ural Mountains have been investigated.

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KUNGSTRÄDGÅRDEN, A GRANITIC SUBWAY STATION IN STOCKHOLM: ITS ECOSYSTEM AND SPELEOTHEMS

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At a depth of 30 m, Kungsträdgårdens subway station is the deepest station in Stockholm. It is also one of the few with easily accessible walls that are not covered in concrete, but where the Stockholm granite is exposed. On the granite wall a simple but complete and unique ecosystem has developed since the station was constructed in the mid-1970's. The constant artificial light is a unique energy source in this subsurface environment and enables the occurrence of microbial communities dependent on photosynthesis with the primary producers being cyanobacteria, several species of diatoms as well as the bryophyte *Eucladium verticillatum*, not known from other locations in Stockholm. Top predator is the spider *Lessertia dentichelis*, with its only known population in Sweden. Closely associated with the ecosystem are secondary mineral precipitations forming flowstone, coralloids and small stalactites. The most common mineral is calcium carbonate, but there are also sodium sulfate depositions. A significant proportion of the mineralisations has been mediated by the present microorganisms, especially fungi. Characteristic for the microbial communities on the granite wall is that they appear to give rise to local geochemical conditions that influence microbial diversity, mineral precipitation and mineral dissolution, such as diatom ooze with calcium carbonates or a fungal – cyanobacterial community that might be responsible for speleothem formation.

1. Introduction

In most environments, lampenflora is considered as detrimental. This is not the case in the Kungsträdgården subway station in Stockholm, Sweden (Figure 1). As in most of the subway stations in town, Kungsträdgården subway station has an artistic decoration. At Kungsträdgården, the artist Ulrik Samuelson wanted to infer a sense of a (romantic) "granite cave", leaving most of the bedrock in the station exposed and decorating with mascarons from the 17-century palace Makalös (De la Gardie's Palace) that was situated close to the place where the subway station is today, until it was destroyed by fire in 1825. The artist also introduced some plants associated with a romantic view of caves, in particular ivy (*Hedera helix*) that is planted near the entrance to the platform. The station was finished in 1977 as the end station of the newest subway line in the Stockholm Metro system (the "Blue Line"), and was opened for use on October 30th the same year. The platform is one of the deepest in Stockholm, located approximately 34 m underground and 29 m under sea level. The station is entirely constructed in about 1.8 Ga old granite (Ivarsson and Johansson 1995) (thus the artist's "granite cave"). As in caves, there are rich secondary mineralizations ("speleothems"), forming various flowstones and coralloids (but only a few very small stalactites).

Earlier studies on granite speleothems (Vidal Romaní et al. 2010) have revealed a diversity in speleothem forming minerals (in particular opal-A and pigotite, but not calcite) and a close association with various microorganisms. In the station there is also a small ecosystem first noticed in the early 1980's when the first and so far only population in Sweden of the small spider *Lessertia dentichelis* (Linyphiidae) was discovered in the station (Kronstedt 1992). It is obvious that the ecosystem to a large extent is driven by the energy from the lights on the platform. This prompted our recently commenced research in this artificial "cave", this time with focus on the speleothems, but using a systems approach, trying to survey the station from minerals to top-predator.

Figure 1. Kungsträdgårdens subway station, located more than 30 m below the surface in central Stockholm, Sweden. A large part of the wall is covered with the moss Eucladium verticillatum. *There are also several distinct biofilms and speleothems.*

2. Material and Methods

We sampled the speleothems in several places along the platform, making sure not to handle the specimens with ungloved hands. The specimens were transferred to freezer

(-20 °C) within two hours from the sampling, and stored at the Swedish Museum of Natural History, Stockholm, until later investigation. It was noted that the flowstones were exclusively formed where water was seeping out of the granite. In these places there was also a higher biological diversity, and we collected specimens of animals, moss and biofilms (brown "algae" mats and "calcareous slam"). The animals were stored in alcohol (70 % Et-OH), while the moss was dried, and the biofilm samples transferred to freezer. In some places we observed a slightly discolored (yellowish) salt precipitation. This, too, was sampled for later analysis.

The animals and the moss were determined by experts at the Swedish Museum of Natural History, where voucher specimens are stored. Speleothems and the salt were analysed using Environmental Scanning Electron Microscopy (ESEM) coupled with Energy Dispersive Spectometry (EDS).

Diatoms were sampled from the walls of the station, using a common spoon and spatula. Samples were cleaned in 30 % H_2O_2 and 10 % HCl and then mounted using Naphrax™ for light microscopy analyses (using a Leitz orthoplan light microscope at 1,000× and oil immersion), and dried directly onto the stub for Scanning Electron Microscopy (SEM) analyses. The samples were analyzed with the aim of identifying everything to species level by one of us (LNI). Additionally, 400 valves were counted in each sample to estimate the relative abundance of species.

3. Results

Even if our investigation of the subway station has only recently started, we have some noteworthy results. We observed several individuals of the spider *Lessertia dentichelis* (Simon), including egg sacks. Crane flies (Diptera: Tipuloidea) collected were determined to *Tipula lateralis* Meigen (Tipulidae), and the moss to *Eucladium verticillatum* (Brid.) Bruch and Schimp. The crane fly larvae collected could not be identified to species (Figure 2), but it is likely that they are *T. lateralis*. Of diatoms, 12 species have so far been identified. For an overview of the biodiversity in the station, as known today (including previous reports), see Table 1.

The speleothems consist mainly or entirely of calcite. Characteristic for the speleothems are the close associations with biology including cyanobacteria, fungal mycelia and diatoms. Especially fungi appear to play an important role in the formation of speleothems. It is possible to follow a gradual increase of calcite precipitation from non-mineralized fungal mycelia to well-defined speleothems with less presence of active fungal colonies (Figure 3). In between these opposites are various stages of calcite precipitation with direct precipitation on the fungal hyphae as a first stage, successively forming more and more elaborate calcite precipitates in between the hyphae until large parts of the mycelia is completely mineralized. Whether fungi precipitate calcite directly as a result of their metabolism or if calcite is precipitated indirectly as a response to favorable geochemical conditions in the vicinity of fungi is not yet concluded. Furthermore, cyanobacteria have been observed to live in close association with the fungal communities. Results from DNA analyses of both fungi and cyanobacteria are pending.

The EDS analysis of the salt showed that it is composed mainly of Na, S and O, thus tentatively determined as a sodium sulfate salt.

4. Discussion

The ecosystem at Kungsträdgården subway station seems to be more or less self-sufficient, driven by the energy from the fluorescent lamps used for lightening the station, and water from the bedrock. The autotrophs in this system have been identified as cyanobacteria (in close association with heterotrophic fungi), diatoms, and the moss *Eucladium verticillatum*. This moss is a common component of lampenflora in many caves (Mulec 2012). In these the presence of the moss is unwanted, but the population in Kungsträdgården subway station is the only known from the Stockholm area and an important component in the ecosystem. The moss is tufa-forming, and normally grows on limestone; the presence here on a granite wall was thus not expected. However, at a closer examination, it was clear that all individuals were growing on speleothems and not directly on the wall. *E. verticillatum* is commonly associated with tufa deposits (e.g., Pentacost 1987), but it is not known if the moss contributes in any way to the formation of the speleothem.

The diatom flora of Kungsträdgården subway station (Figure 2) is dominated by aerophilous taxa. *Diadesmis perpusilla* (Grunow) Mann and *Diadesmis contenta* (Grunow) Mann are species often found in caves and they are both characteristic of environments with low light availability. Other species found were e.g., *Pinnularia appendiculata* (Agardh) Cleve, *Diploneis ovalis* (Hilse) Cleve, *Amphora normannii* Rabenhorst, *Cymbella laevis* Naegeli, *Nitzschia sinuata* (Smith) Grunow, *Nitzschia amphibia* Grunow and *Caloneis* cf. *aerophila* Bock. *Caloneis aerophila* is a rare species, to our knowledge not previously reported from Sweden. In addition, a small *Caloneis* species was found, which might represent a yet undescribed species. All diatom species found were pennate diatoms with at least one raphe. This indicates the importance of being able to move around on the substrate. The results show a clear biogeography in the metro station. The species composition of the calcareous slam was not the same as of the brown "algae" mat. It is likely that the diatoms found in the calcareous slam in some way contribute to the making of this specialized habitat.

The top-predator in Kungsträdgården subway station has been identified as the small spider *Lessertia dentichelis* (Kronstedt 1992). It seems to have a viable and stable population on the walls of the platform, mostly found in close association with the moss where the nets and egg sacs can easily be spotted. Due to the small size, it is more difficult to observe the adults. The population at the subway station is the only known in Sweden (Kronstedt 1992), but it is possible that it has been overlooked. Kronstedt (1992) reported a microfauna living among the moss, consisting of nematods, annelids, harpacticids, and collembols (Table 1). It is likely that the spider feeds on the collembols and the harpacticids, and that they in turn lives on the diatoms, fungi

Table 1. Organisms identified from Kungsträdgården subway station, Stockholm, Sweden.

Taxon	Reference	Remark
Mammalia: Hominidae		
Homo sapiens Linnaeus	This Investigation (TI)	temporarily in high density, not stationary; adults and juvenils
Arachnidae: Linyphiidae		
Lessertia dentichelis (Simon)	Kronstedt 1992, TI	several individuals, including egg sacs
Insecta: Diptera: Tipulidae		
Tipula lateralis Meigen	TI	several adults, numerous larvae
Collembola: Hypogastruridae		
Hypogastrura purpurescens (Lubbock)	Kronstedt 1992	
Collembola: Isotomidae		
Proisotoma minuta (Tullberg)	Kronstedt 1992	
Crustacea: Copepoda		
Harpacticidae	Kronstedt 1992	
Nematoda	Kronstedt 1992	
Annelida	Kronstedt 1992, TI	
Plantae: Bryophyta: Pottiaceae		
Eucladium verticillatum (Brid.) Bruch & Schimp	TI	locally abundant on sinter
Heterokontophyta: Bacillariophyceae		
Amphora normannii Rabenhorst	TI	
Caloneis cf. *aerophila* Bock	TI	first record for Sweden?
Caloneis cf. *bacillum* (Grunow) Cleve	TI	
Caloneis sp.	TI	new species?
Cymbella laevis Naegeli	TI	
Diadesmis contenta (Grunow) Mann	TI	low light environments
Diadesmis perpusilla (Grunow) Mann	TI	low light environments
Diploneis ovalis (Hilse) Cleve	TI	
Navicula sp.	TI	
Nitzschia amphibia Grunow	TI	
Nitzshia sinuata (Smith) Grunow	TI	
Pinnularia appendiculata (Agardh) Cleve	TI	
Fungi	TI	
Cyanobacteria	TI	

and cyanobacteria, as well as decomposing parts of the moss. We attempt to follow up on Kronstedt's inventory, trying to identify more components of the microfauna and their roles in the ecosystem.

In the background, but as an integral part in the local environment, are the speleothems (Figure 3). We expected the usual granite speleothem forming minerals (Vidal Romaní et al. 2010); instead we could only identify calcite from the samples. The source of the calcium is not yet identified. The bedrock is granite, but the ceiling is covered in concrete and would be the obvious source. However, most of the speleothems form only some distance below the ceiling, without visible contact with the concrete, and the impression is that the seeping water is the source of the calcium. Granites contain only a fraction of Ca compared to mafic rocks and the groundwater in the Stockholm usually contains small amounts of Ca: 4–6°dH (grad deutscher Härte) where 1°dH correspond to 10 mg CaO/1 litre of water. This can vary locally, especially in the nearby Stockholm archipelago with measured values of 7–13°dH. In such areas Ca precipitations in washing machines, saucepans and pipes can be a problem. Perhaps the degree of CaO is high enough to precipitate speleothems on the granitic walls of the subway station Kungsträdgården, at least with support of microorganisms.

Acknowledgement

We want to thank AB Storstockholms Lokaltrafik (SL) for permission to survey the station and its fascinating environment; especially Gülsüm Kaya at SL must be thanked for support and assistance during the project. Thanks also to Lars Hedenäs and Yngve Brodin, both at the Swedish Museum of Natural History (NRM), who determined the moss and the crane fly, respectively, and to Mario Parise, National Research Council of Italy, for valuable comments on an earlier version of the manuscript. The ESEM/EDS analyses were done at Stockholm University; in particular we would like to thank Marianne Ahlbom at the Department of Geological Sciences for assistance during the ESEM. Some of the light microscopy analyses of the diatomes were done at the Paleobotany department at NRM, and we would like to thank Prof. Else-Marie Friis and Dr. Christian Pott for help with the microscopy. At NRM we had much help from Veneta Belivanova and Yvonne Arremo with the SEM, many thanks to both of you!

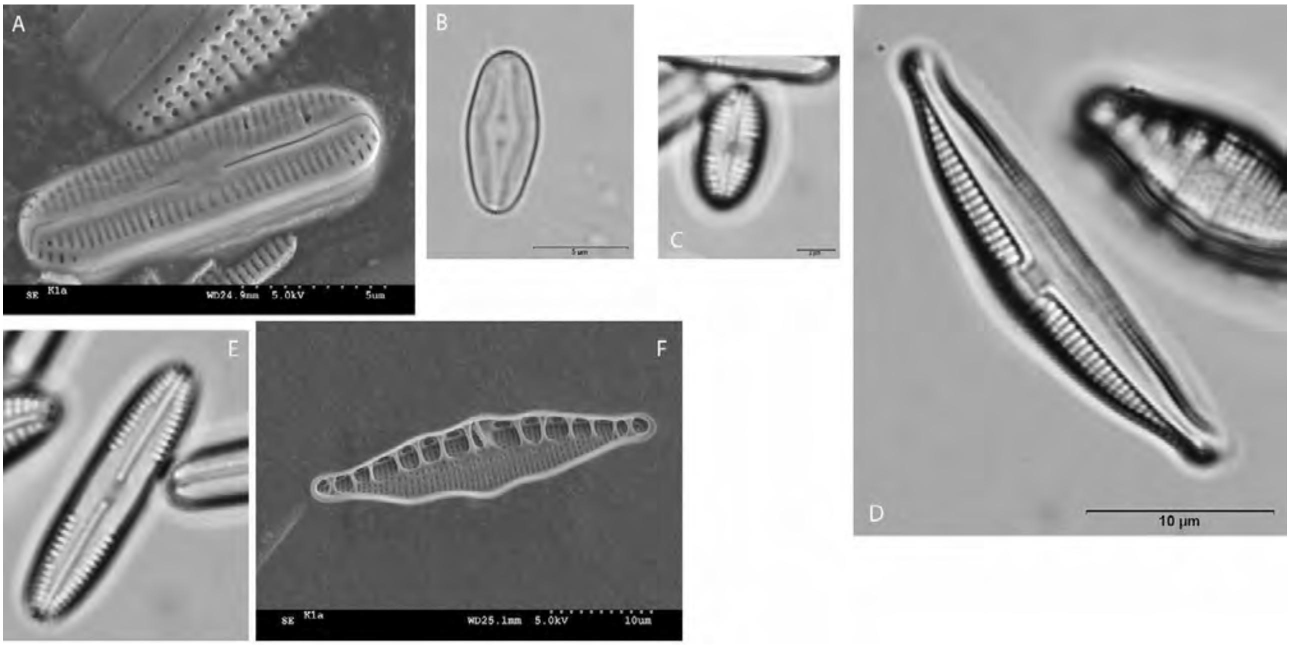

Figure 2. Some of the species from the diatom flora of Kungsträdgården subway station, Stockholm, Sweden. A: Diadesmis contenta *(Grunow) Mann. B:* Diadesmis perpusilla *(Grunow) Mann. C:* Caloneis *sp. D:* Amphora normannii *Rabenhorst. E:* Caloneis *cf.* aerophila *Bock. F:* Nitzschia sinuata *(Smith) Grunow.*

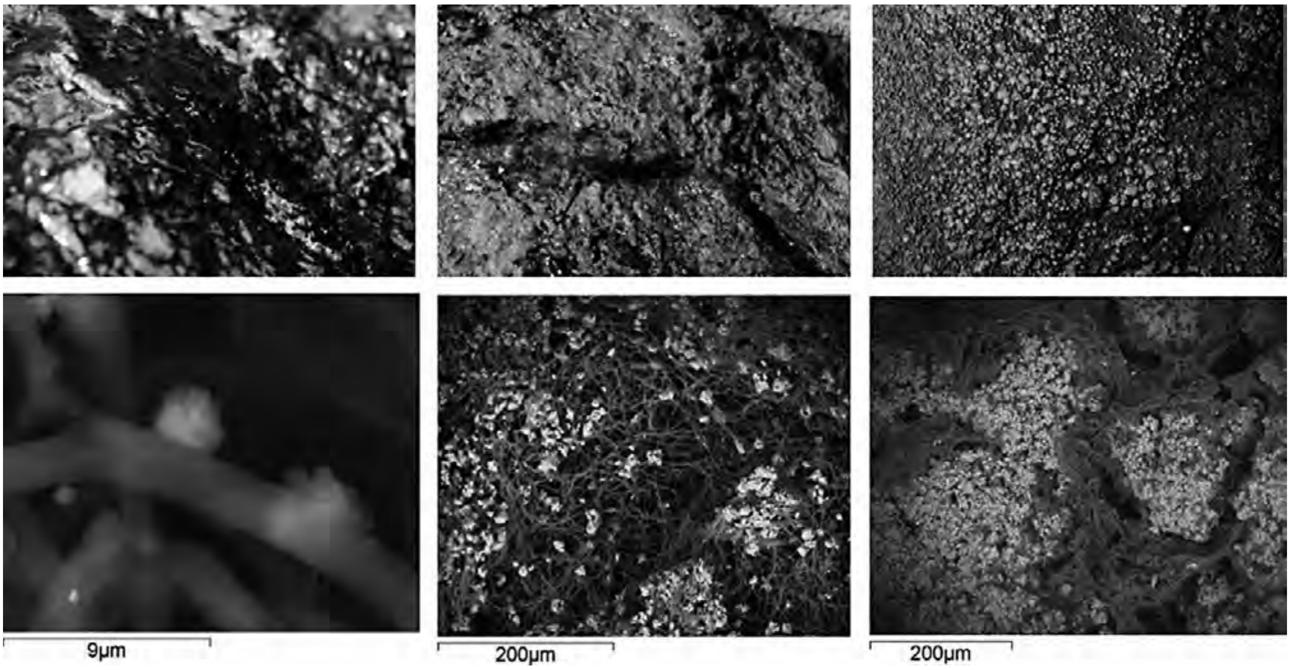

Figure 3. Microphotographs and ESEM images showing gradual increase (from left to right) of calcite precipitation on fungal hyphae with the final result of speleothem formation.

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UNFINISHED RAILWAY TUNNEL AND BUNKER AT GODOVIČ

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To enable better supply of the front line during the First World War, the military command started to build a standard-gauge railway line from the main line at Logatec. The project began in April 1917 but in October the front line was pushed far to the west. The railway was no longer needed, so all work stopped and most structures remained unfinished. After the war, the new border between Italy and Yugoslavia passed close to the unfinished tunnel. Part of the tunnel was transformed into a bunker, one of many within the system of fortifications known as the Alpine Wall. After the Second World War the border moved away and both tunnel and bunker were forgotten and overgrown by forest. Apart from its unusual history, the structure is notable because work on it was halted in mid-construction, with the result that all stages of construction of the tunnel are well preserved.

1. Introduction

During the First World War, following the Italian attack on Austria-Hungary, the Isonzo front line formed in the western part of what is now Slovenia. To enable better supply of the front line, the military command ordered the special Imperial and Royal Railway Regiment to build a standard-gauge railway line to Črni Vrh, beginning at the junction with the main railroad at Logatec. The project began in April 1917, but after the Battle of Caporetto in October of that year the front line was pushed west to the river Piave, with the result that the railway was no longer needed. All work on the railway was stopped and the line and most structures remained unfinished and abandoned in the middle of the forest.

Figure 1. Position of the tunnel.

When the war ended in year 1918, the newly established border between Yugoslavia and Italy cut through the area and there was no need to continue building the railway. Among the unfinished structures along the line was a tunnel near the village of Godovič. Because of its position in Italy near the new border, part of the tunnel was converted into a bunker after 1931. It was part of the Alpine Wall, the system of fortifications created by the Fascist regime to protect Italy's borders.

After the Second World War the border moved west and both the tunnel and bunker were forgotten and overgrown by forest. Apart from its unusual history, the structure is notable because work on it was halted mid-construction, with the result that all stages of construction of the tunnel are well preserved.

2. The tunnel

The plans, including the longitudinal section and ground plan, were drawn up in April 1917 by J. Kolmann (Kolmann 1917). Construction work started at about the same time. The main workforce consisted of prisoners of war, mostly Russians. Work proceeded simultaneously along the entire length of the railway, and in the autumn, when work was abandoned, many sections of the railway were already finished. Completed structures included a tunnel in Logatec, which was later filled with waste, and a tunnel close to the village of Godovič that is today used as road tunnel (Frelih 1999).

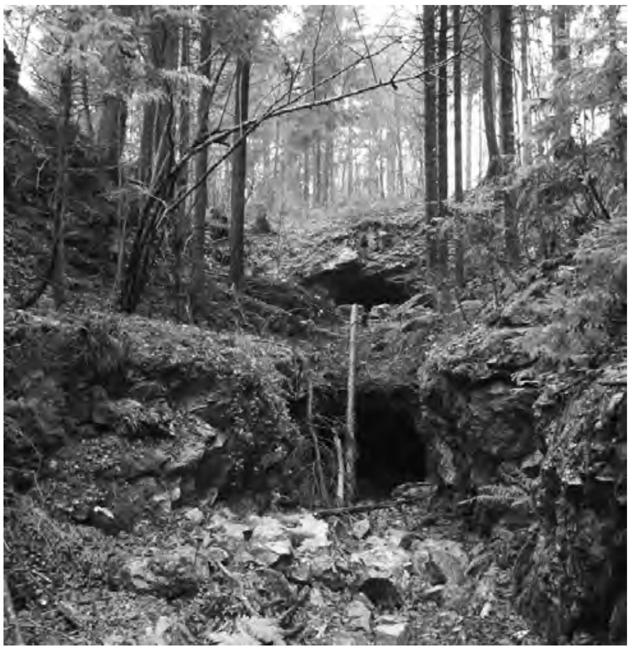

Figure 2. Southern entrance showing the pioneer tunnel (lower aperture) and crown (upper aperture).

The unfinished tunnel (south entrance: 45° 56' 58" N 14° 4' 48.4" E) lies about 2 km west of the village of Godovič. The tunnel is constructed through karstified Cretaceous limestone below a rough, rocky karst surface with numerous dolines. A number of caves are known in the vicinity and one natural cavity was encountered by the tunnel.

According to the building plan, the tunnel was 388 m long. The north entrance was at 613 m above sea level, and the southern at 618 m. The incline of the railway was 13‰. The thickness of the rock above the tunnel ceiling is for the most part around 15 m, with a maximum thickness of 26 m. There is also one doline above the tunnel, where the ceiling is only about 10 m thick.

Digging of the tunnel began from both ends simultaneously, and at three different heights. At the height of the tunnel floor, a small pioneer tunnel was dug to transport excavated rock. It is about 2 m high and 2 m wide. A narrow-gauge railway track ran through it.

Figure 3. The unfinished crown of the tunnel. The section in the background has already been lined with concrete.

Above it, the tunnel crown was excavated. The crown section is connected to the pioneer tunnel by several vertical shafts through which the excavated rock was poured into the small wagons below for removal. Timber supports and wooden loading structures were placed at intervals. Once the crown was excavated, scaffolding was erected and the crown was lined with concrete. When this was done, the invert was only completed in the northern part of the tunnel. The height of the tunnel is 6.5 m and the width is 4.6 m.

Figure 4. View of the pioneer tunnel and crown section and a section of nearly finished tunnel.

The tunnel was built in well-karstified limestone. This has resulted in drip points at several places in the tunnel and drainage of the water into the karst through the tunnel floor (Lajovic and Mihevc 2010). The tunnel also cuts through several natural caverns, one of which is still preserved for a length of 10 m and is entered in the Cave Register of Slovenia.

Because the work stopped before the tunnel was finished, nearly all phases of excavation and construction have been preserved. More work was completed at the north end of the tunnel: about half of this section was fully or partly concreted and, according to locals, the tunnel portal was also finished. The southern end remained at the earlier stages (digging of two tunnels, excavation of the crown, erection of scaffolding for the purposes of cementing).

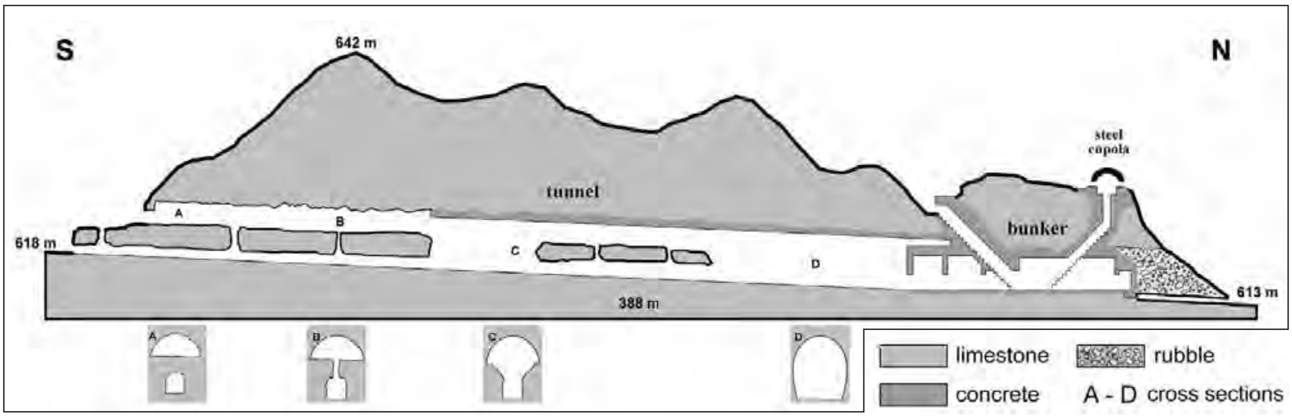

Figure 5. Shematic cross section through the tunnel. All building phases and the bunker are preserved.

tunnel builders dug down and began to shape the main tunnel, all the time using the pioneer tunnel. The scaffolding and cementing of the walls was done in sections. The invert

After the war, when the Treaty of Rapallo fixed the new borders, the tunnel found itself about 3 km inside Italian territory. After 1931 the Italian army started to build a bunker in the northern part of the tunnel. The bunker is a concrete cube, with a staircase and a shaft leading to a surface outpost covered by a steel cupola. Access to the bunker is through the tunnel from the south or via the staircase from the surface. There are toilets in the bunker and a sewage pipeline that drains it. To hide the bunker, the northern tunnel portal was filled with rubble and camouflaged.

Figure 6. Bunker in the finished part of the tunnel.

It seems that the bunker was not completely finished when Italy attacked Yugoslavia in 1941 and the Second World War started in the area. It was not used during the war. After the war, the national border moved to the west and both the bunker and the tunnel were abandoned and forgotten in the forest. The tunnel was looted by the inhabitants of the area, who carried off all usable items and mined the concrete in order to extract the steel for building purposes.

3. Conclusion

The tunnel and the bunker are witnesses to the turbulent times of the first half of the 20th century, including wars and border changes. The unfinished tunnel also reveals interesting phases of tunnel building and helps illustrate the knowledge and techniques that were developed and used in the 19th century.

Figure 7. Steel cupola on top of the bunker. Below it, the northern portal of the tunnel is filled with rubble and hidden.

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RECOGNITION OF INSTABILITY FEATURES IN ARTIFICIAL CAVITIES

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Instability features may be observed in underground settings, including both natural and artificial caves. Recognition, mapping and documentation of such elements is of crucial importance to understand the likely evolution of the caves in terms of instability, and to evaluate the possibility of a direct involvement of the built-up areas above. Many towns and important communication routes are located in Italy above caves, which makes knowledge of the instability conditions an absolute priority for civil protection issues and land management. The role of cavers in the identification of instability features has been rarely taken into account, and always considered as a minor, often unnecessary, element in the stability assessment. Nevertheless, cavers are the only "eyes" underground, and have the opportunity to document what is really occurring. The present article aims at pointing out this crucial role of cavers, and illustrates some of the most common instability features in underground settings, both related to already occurred failures and to incipient signs of deformations. The issue is dealt with focusing on artificial caves, since these have been in the last decades at the origin of several problems in many towns and rural areas of southern Italy.

1. Introduction

Cavers carry out an activity that is often lowly considered, or thought of in negative terms because of the breaking news reporting accidents involving difficult and high-cost rescue operations. Nevertheless, caving has a very important value: cavers are the only people having the possibility, due to their technical skills and ability to move in a subterranean environment, to explore and document the underground world in safety. Documentation, in particular, is extremely important, since it provides all those people that are in charge of decisions (local authorities, land use planners, etc.) but never will directly enter a cave, the necessary material (maps, photographs, videos) to make their own choices.

Even more than for natural caves, the matter becomes of extreme importance for artificial cavities, since these are more frequently located below or in the proximities of inhabited areas or infrastructures. As a consequence, any problem occurring within the underground setting may have direct, sometimes catastrophic, consequences, on the built-up areas above (Waltham and Swift 2004; Parise and Gunn 2007; De Waele et al. 2011; Parise 2012).

Starting from these considerations, the present article intends to point out the importance of cave surveying, mapping and documentation, with particular regard to all those elements related to instability processes that can be observed in natural and artificial caves (Andrejchuk and Klimchouk 2002; Palmer 2007). Being well aware that instability phenomena are rarely sudden, but in most of the cases they are preceded by deformations, it comes out that having the possibility to collect direct observations about the precursory signs of failures may result in the possibility to understand what is going on underground, predict the likely evolution toward the ground surface, and plan interventions to reduce the hazard, or at least to mitigate the risk to people and society.

The present article will illustrate both features related to already occurred instability, and incipient signs of deformations. The combined analysis of these elements might be useful, together with the necessary geotechnical data about the involved materials, to determine the most suitable geological model for instability evolution at the specific site. It is our firm opinion that such documentation is crucial for understanding the instability problems, but, at the same time, cannot be considered the only scientific material on which to base a practical mitigating action.

Figure 1. Massive fall from the vault in a calcarenite quarry.

2. Natural vs. artificial caves

The issue of instability is of interest for both natural and artificial caves, and as such a number of studies have been published over the years in the speleological scientific literature in the attempt to describe and model the process (Davies 1951; White and White 1969; Palmer 1991; White 2005). However, the direct link existing between many artificial cavities and the environment at present used by man for his activities make artificial cavities of particular interest, since these are generally the type of underground voids creating problems, and causing economic losses and damage, to the society. The recent cases of a sequence of collapse sinkholes at Guatemala City in 2006 and 2010 is straightforward at this regard (Hermosilla 2012).

With this, it is not our intention at all to diminish the relevance of instability observations carried out in natural caves. Some of the most common processes of cave evolution, for instance, derive from progressive failures in the rock mass constituting the roof of the cave, until reaching the ground surface, and thus originating collapse sinkholes (Tharp 1995; Klimchouk and Andrejchuk 2002; Delle Rose et al. 2004; Canakci 2007; Waltham and Lu 2007; Parise 2008). Observing and documenting features related to such processes is of crucial importance, for both the understanding of the cave evolution, and the likely consequences this may have in terms of risk as well. But the focus will be in this article essentially on artificial caves, since these are those that have produced the greatest alarm and worrying in many regions of southern Italy during the last 15–20 years, due to a number of sinkholes that had to be recorded in Apulia, Campania and Sicily (Parise and Fiore 2011).

3. Mapping instability features

Due to the geological and morphological setting, many regions of southern Italy presented features such as to allow man since historical times to excavate and use several types of the local rocks for building purposes, and to create underground voids for different uses (Del Prete and Parise 2013). As a consequence, wide areas are characterized by the presence of a huge number of man-made cavities, that have to be added to the natural caves, present in the same regions because of karst processes. As concerns Apulia, the most extensive systems, and the most dangerous in terms of instability, are represented by underground quarries, located at variable depths in a high number of towns, even below urban areas (Parise 2010). The working activity stopped in most of these quarries few decades ago, and since that time many sinkholes have been recorded, due to upward propagation of failures occurring within the underground sites (Parise 2012).

Evolution of instability processes in underground caves is generally dependent upon internal factors, such as the low mechanical strength of soft rocks (Andriani and Walsh 2006), or external natural and/or anthropogenic factors that can modify the boundary conditions, the loading, or the physical and mechanical properties of involved materials. Changes in loading can be, for instance, represented by construction of buildings or infrastructures above the ground surface, that can modify the stress state around the cave, the destruction of pillars within underground rooms with consequent increase in the cave span, as well as seismic loading conditions or man-made vibrations due to traffic, construction works, etc. Changes in the boundary conditions may be represented by the variation of the wetting conditions within the cave due to large incomes of water inside the cave, to condensation processes, and to water percolation from the ground surface. These processes generally promote weathering processes of the rock mass and of the joints leading to a gradual reduction of the corresponding mechanical strength, as also observed in many cases of slope instabilities worldwide (Fookes and Hawkins 1998; Zupan Hajna 2003; see also Calcaterra and Parise 2010, and references therein).

Underground caves can be involved in instability processes affecting the whole overburden, or simply by local failures that may induce a progressive increase in the height of the cave up to eventually reaching a critical configuration which later on can develop towards the complete collapse. The failures or instability mechanisms observed in many caves of southern Italy may be described by grouping them into two main categories (Diederichs and Kaiser 1999a, 1999b; Hatzor et al. 2002; Ghabezloo and Pouya 2006): failures within continuous media (intact rock mass or highly jointed rock mass), and failures within discontinuous media (anisotropic rock mass with specific joint sets). Whilst the first category characterizes soft rock masses such as calcarenites, chalk, and evaporites, the second one relates to stratified and fissured limestone rock masses affected by karst.

Figure 2. Examples of detachments from the vault of natural caves.

In the following we describe the main mechanisms of failure that can be observed in caves:

Falls from the vault, developing the formation of a single or double arch. This type of failure can be generated by a reduction of the rock strength in the cave roof due to wetting or additional loading. The strength of the rock forming the roof reduced down to the maximum stresses existing in the area, leading to the development of the first fractures. These new joints may propagate through the roof, leading to a complete or local failure mechanism (Fig. 1). This process has also been observed in natural caves, where is characterized by the failure of the central part of the roof and the consequent collapse of blocks from the same area which is followed by failure of the remaining ledges along the sidewalls (Lollino et al. 2004; Lollino and Parise 2005; Parise and Trisciuzzi 2007). The resulting shape in the roof is generally circular, but it may have one or more rectilinear sides, due to control exerted by tectonic discontinuities. Further evolution may lead to upward stoping, with size of the failure decreasing toward the ground surface (Fig. 2).

Falls from the vault, due to lack of support from previously existing pillars. This type of fall is actually an induced failure, since it occurs with the same mechanism as above, but generated by failure of one or more pillars, so that the roof span becomes too long to be sustained by the rock strength (Hutchinson et al. 2002; Fraldi and Guarracino 2009; Ferrero et al. 2010).

Failures from the pillar corners. This type of failure is generated by local accumulation of compressive stress too high with respect to the rock strength (Fig. 3).

Figure 3. Failure at the upper corner of the pillar.

Lateral failures along sliding surfaces parallel to the walls. This mechanism is generated by the low confinement of the rock mass along the vertical boundaries of the cave, which leads to the development of fractures parallel to the direction of the maximum compressional stress (Fig. 4). This process generally is not directly at the origin of a sinkhole, but may work in producing the progressive enlargement of the cave until it reaches a critical configuration which then leads to general failure.

4. Upcoming instabilities: the incipient signs of deformations

Failures in underground caves do not occur without warning, and measures of the effects produced by the processes active in deforming the rock mass can be generally observed before major displacement occurs (Liu et al. 2000). This has also been documented for slope failures (D'Elia et al. 1998; Senfaute et al. 2003), and is at the origin of the design and implementation of alert system for landslides. As concerns underground caves, the main problem lies in the possibility to observe and recognize such phenomena. Further, it has to be noted that scarce attention has been given in the scientific literature to the issue of precursory signs, as pointed out by Szwedzicki (2000).

Figure 4. Lateral failures from the wall in a calcarenite quarry. Note the development of linear sliding surfaces.

Many studies have documented that the structural damage in the rock mass, eventually leading to collapse, requires a long time, and generally occurs through gradual progression in time, intensity, and appearance of recorded precursors. These latter, in the early stages of deformation, may consist of surface cracking, crack opening, shear movement along planes of weakness or vertical and horizontal displacement (Kowalski 1991; Parise and Lollino 2011). Further evolution of the process may lead to ground surface subsidence and the occurrence of localized signs of stress within the underground caves, in the form of floor heaving and roof lowering. In some cases, the last hours before the final collapse have been accompanied by rock noises and falls in the ground.

In the following we describe the main evidence of deformations that can be observed in caves:

Cave walls. Localized swelling can be observed along the walls as a result of pressure by the rock mass close to the cave boundaries (Fig. 5). It may be noticed as aligned bulging and slight deformation, which as a whole bound the sector prone to failure. Locally, the increasing deformation results in outward protrusion of wedges, or, eventually, in a continuous fracture bounding the mass detached or prone

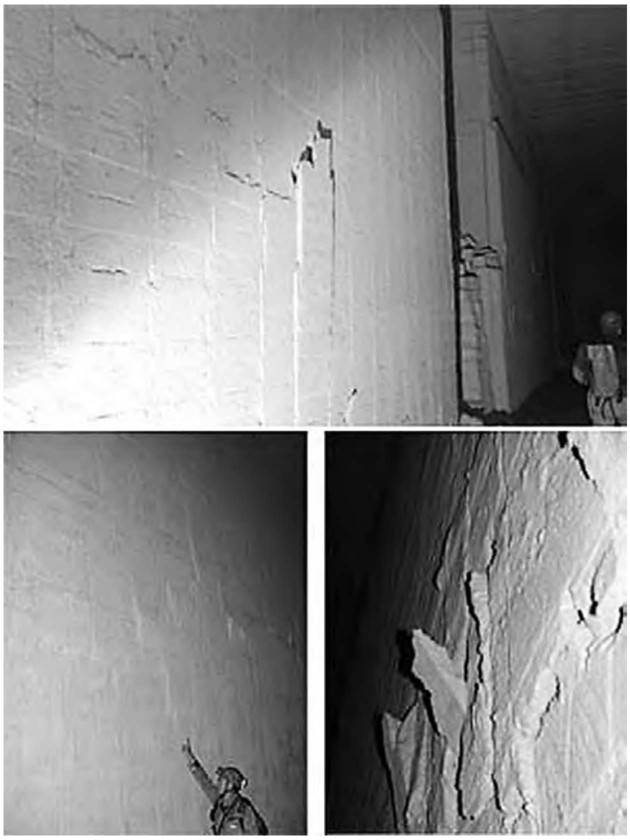

Figure 5. Incipient signs of instability: localized swellings (above, and lower left), and wedges protruding from walls (lower right).

to be detached. All of this generally precedes occurrence of local failures in the wall, with sliding surfaces parallel to the wall itself.

Pillar corners. Regardless of the size of pillars, different stages of deformation may be observed at the corners of pillars: the first are *en echelon* cracks (Fig. 6), from incipient to a few mm in aperture, similar to those observed at the flanks of active landslides as precursory sign of the exposure of the sliding surface at the ground (Fleming and Johnson 1989; Parise 2003). Progression in the deformation brings to developing a well-defined fracture, thus preparing the upcoming detachment, which may occur at the base or at the top of the pillar, or along its entire height. When the vertical stress becomes unsustainable for a pillar, open cracks may develop, even along pre-existing discontinuities, and a network of crossed fractures may be formed (Fig. 7).

Figure 6. Examples of cracks developing at the pillar corners.

Figure 7. Cracks crossing a pillar, along primary (clino-stratification, dipping to the right in the picture) and secondary (open cracks) discontinuities.

Vault. Precursory evidence of failure appear in the vault as long and continuous cracks, locally opened a few mm, and often ending in an already occurred fall (mostly located at the crossing between two discontinuity systems; Fig. 8). Massive falls from the vaults may determine the formation of a single arch covering the whole span of the cave, or of a doube arch in the case a more resistant spur in the rock mass subdivides the detached area (Fig. 9). On the basis of the data so far collected, no clear relationship has been ascertained between shape and size of the passage and the development of a single or double arch.

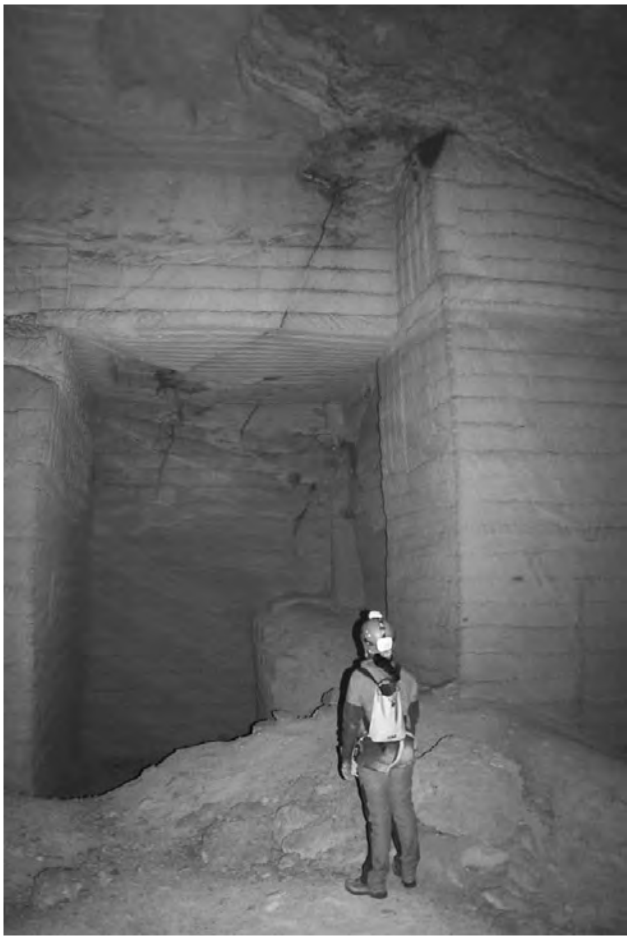

Figure 8. Fall from the vault, occurred at the intersection between two discontinuities.

Figure 9. Double (above) and single (below) arches produced by failures at the vault.

5. Conclusions

There are of course several topics that have not been dealt with in the present article. First of all, the type of failures depends also upon type and characteristics of rocks. In this sense, there are great differences among hard rocks as limestones, and soft rocks as calcarenite, and in turn between carbonates and evaporites, which respond to stresses with more plastic behavior (Iovine et al. 2010; Fig. 10). All these should be properly taken into account for evaluating the stability conditions of underground voids, and the likely evolution to sinkhole occurrence.

Nevertheless, aimed at an audience of cavers, the focus was here dedicated to direct observations in caves, that are considered a precious, and very difficult to obtain, element in the evaluation of the hazard related to failures occurring in underground settings.

Acknowledgments

Without mentioning any name, I am indebted to many cavers for having been my companions during long surveys underground. While I was looking at strange and unfriendly features they had the patience to wait, asking some of the most difficult questions I had to answer in my geologist experience; at the same time, they were crucial for allowing me the possibility to make observations in safety, and develop some thoughts about the topic here dealt with. Without these people, the present article would never have seen the light.

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Figure 10. Plastic and fragile deformations in evaporite rocks of a gypsum cave of Calabria.

CLASSIFICATION OF ARTIFICIAL CAVITIES: A FIRST CONTRIBUTION BY THE UIS COMMISSION

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The article representes a contribution by the Commission on Artificial Cavities of the Union Internationale de Speleologie (UIS) aimed at defining a general classification of artificial cavities. The amount and variety of cavities realized underground by man is extremely high, and cover with variable peculiarities many areas of the world. Nevertheless, it is important to perform an attempt in classifying such great variety, through a classification comprising at least the main categories of observed situations. Starting from the work carried out in past years by the Italian Speleological Society, it is here presented a classification of artificial cavities based upon time and modality of realization, and organized through a typological tree where seven main categories are defined, each one of them in turn subdivided into sub-types. We hope that, referring in the next future to this classification, it will be possible to better organize and describe the works and researches on artificial cavities, and compare the situations present in different areas of the world.

1. Introduction

In several occasions, attempts have been made to develop a classification of artificial cavities, as a common base to describe the underground cavities produced by man's activities over time, and to share the related knowledge and great amount of researches done, that embrace many different fields of science (from geology and geomorphology, to archaeology, anthropology, history, and so on). In the past, more than one classification has been proposed. In most of the cases, the main drawback of these attempts relied in their strong dependence on the country of provenance of the authors (with, in turn, a stronger attention paid upon the most typical cavities of that country).

In very few occasions the proposed classifications derived from the work of an international group where different countries were effectively represented. Nevertheless, some attempts have been done to put together international teams, with outcomes such as the lexicon of terms dealing with underground works presented at the International Symposium on Underground Quarries in Naples (Capuano et al. 1991).

In Italy, a strong effort was produced during the last decades to put together the cavers and researchers interested in the topic of artificial cavities, by creating a dedicated Commission within the framework of the Italian Speleological Society (SSI). The Commission started its works in 1981, focusing on the issues of producing a preliminary classification of artificial cavities and, at the same time, preparing a form to be filled for inclusion of each artificial cave in the Italian register, managed by the SSI Commission itself (for further details, see www.ssi.speleo.it). In the years, many meetings and discussions were the object of the matter, until in the late 1990s a preliminary classification was proposed.

Following the last International Congress of Speleology, held in Kerrville (Texas, USA) in 2009, and the re-start of the activity of the new UIS Commission on Artificial Cavities, the issue of producing a general classification of artificial cavities became again matter of discussion. At this aim, a specific workshop was organized in May 2011, and held in Turin (Italy), with the outcomes presented in a special issue of the journal Opera Ipogea, published by SSI (Parise 2013). On that occasion, starting from the Italian classification, some adjustments were produced, both in the organization of the structure, and as linguistic improvements; further, inclusion of new typologies was also considered, which brought to the present classification, that will be described in detail in the following sections, and is illustrated in the flow chart of Figure 1.

2. Definition of artificial cave

Artificial cavities are defined as underground works of historical and anthropological interest, realized by man or positively readjusted for his needs. Thus, artificial cavities include both man-made works (excavated, built underground or turned into underground structures by stratigraphic overlap) and natural caves, when these latter are readjusted to human needs in significant parts. To provide some examples to this regard, the natural caves used as shelters in the Alps during the First World War, and the hermitages in natural shelters can be mentioned.

Size, development and frequency of artificial cavities at a given place are directly dependent upon the hardness of the rock, and, as a consequence, easiness of excavation. The characteristics of the cavities present in a given urban area are also closely related to the peculiarities of the site itself, and to its evolution and transformation as well. In many cases artificial cavities go back to a historical period of which there is no longer evidence at the surface. Therefore, cavities are often the only evidence left of pre-existing territorial organisations and of a lifestyle wiped out by the present urban development, owing to new and different needs developed in the course of time.

The main reasons at the origin of the realization of artificial cavities in different epochs were the need to:

- obtain water and/or minerals;
- exploit the natural thermal properties of underground sites to survive in adverse weather conditions (Givoni and Katz 1985);
- overcome the shortage of timber for building and/or heating;
- bury the dead;
- find conditions of ascetic isolation;
- defend against raids, persecution, war;
- hide from justice;
- exploit the economy and/or ease of excavation of some types of rock compared to other construction techniques;
- take advantage of the shape of some rocky hills;
- obtain free areas for productive activities.

2. Classification of artificial cavities

The main criteria at the origin of the present classification of artificial cavities have to be found in the need to characterize each man-made cave in terms of age of realization, technique of construction, and use of the cavity itself.

As concerns the first issue above (that is, age of realization), it has to be noted that artificial cavities have been constructed for over thousands of years without interruptions since the remote past to the present days. Even our modern civilisation is still "colonising" the subsoil with a variety of works, that include but are not limited to: subways, car parks, road tunnels, shopping centres, scientific laboratories, military works, mines, etc.

To provide an indication about age, following the standards in use in Italy the underground facilities can be distinguished as follows (lettering is the reference used in the Italian Register of Artificial Cavities):

a = prehistoric
b = protohistoric
c = pre-Roman
d = Roman kingdom / Republican
e = Roman Imperial
f = Late Antiquity (Sunset of the Roman Empire)
g = high-Medieval (until about 1000)
h = middle-late Middle Ages
i = Renaissance (approximately, 1400–1600)
l = Modern Ages (until the French Revolution)
m = XIX century
n = XX century and later

Apart from age, other elements have to be identified. These include:

- the technique of construction;
- the function (or purpose);
- the shape and development of the underground structure;
- the spatial correlation with the surrounding environment;
- the temporal correlation with the general historical events on a general, regional and local scale.

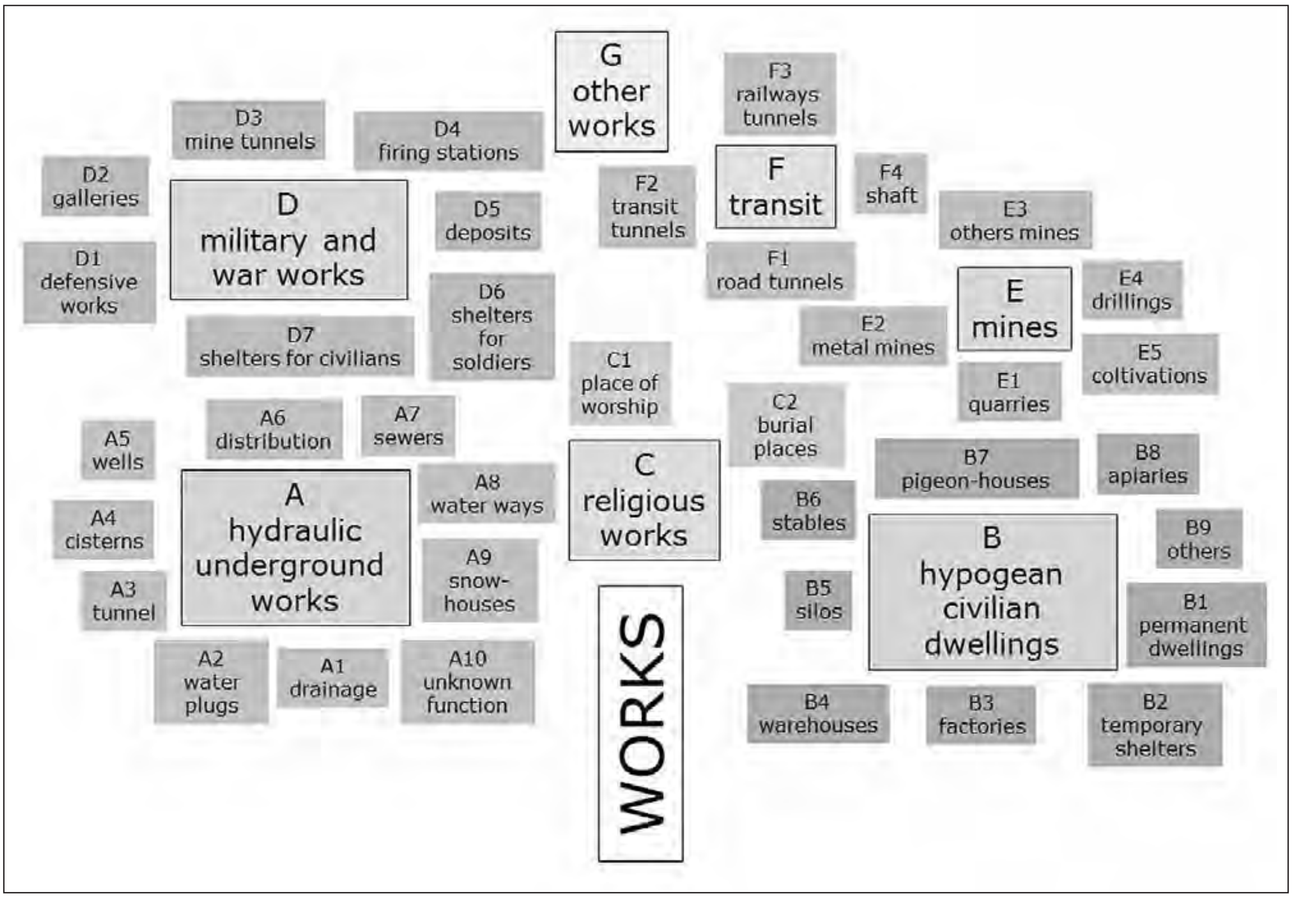

Figure 1. Typological tree for the classification of artificial cavities.

3. Categories

Taking into consideration the construction technique, several situations can be considered:
• cavities dug in the subsoil;
• cavities constructed in the subsoil;
• cavities obtained by re-covering;
• anomalous artificial cavities;
• mixed artificial cavities;
• natural caves modified by men.

Cavities dug in the subsoil. These are underground structures in the strict sense: rooms obtained by removing stone materials (rocks) under the surface level, or inside rocky hills, or carved close to the surface of the cliff faces, canyons, ravines (for example, troglodytic structures).

Cavities constructed in the subsoil. Excavation in trenches is realised with an open air excavation, followed by coating of the walls and construction of the vault. Excavation in gallery is realised by removing the rock entirely underground. The walls are then coated with different masonry techniques.

Re-covered cavities. Human activity in urban areas often produces the covering, natural or artificial, of structures originally located on the surface.

Anomalous artificial cavities. These structures are built on the surface, but with characteristics similar to those underground (for example, some military bunkers).

*Mixed artificial cavities***.** They are the result of the digging to reach, extend or alter natural caves.

Caves with anthropogenic interventions. Natural caves that have undergone limited human interventions. They represent the boundary between the natural caves and those of artificial origin (anthropogenic). In general, they are of limited extent.

4. Types

According to the function for which an artificial cavity was, or is still, used, it can be classified in a specific type.

The variety of underground artificial structures is very large. Consequently, the classification is organised like a tree, based on seven main types, in turn divided into sub-types (Fig. 1). The use is made easy by alphanumeric codes. Often different uses overlap in time; thus, a single site may have multiple classifications representing different periods in its life.

4.1. Type A – Hydraulic underground works

A.1 – Water level control, drainage-ways
Tunnels dug for the reclamation of marshlands and to stabilise the level of lakes (emissaries) and reservoirs (Judson and Kahani 1963; Castellani and Dragoni 1991, 1997; Caloi and Castellani 1991; Galeazzi et al. 2012).

A.2 – Underground stream interception structures
Tunnels and galleries designed to capture underground water veins or dripping waters (Sadaf Yazdi and Labbaf Khaneiki 2010). The work of interception can consist either of a simple duct cut into the rock, or of a complex system integrated with building works.

A.3 – Underground water ducts: aqueducts
Galleries and tunnels to carry water from the stream interceptions or other body of water to the users (Ashby 1935; Hodge 1992; Bodon et al. 1994; Parise et al. 2009). Deviations into galleries of water courses can allow the construction of bridges: the so-called *Ponti Terra* or *Ponti Sodi* (Etruscan technique).

A.4 – Cisterns, water reservoirs
Underground spaces to store water, usually completed with waterproofing of the walls (Fig. 2).

Figure 2. Cistern at Albano (Italy). Photo: G. Marchesi.

A.5 – Wells
Vertical shaft to reach the water table and carry water to the surface. Those located within other underground structures are considered an integral part thereof.

A.6 – Hydraulic distribution works
Tanks or other underground rooms in which one or more ducts converge and from which other ducts go out to distribute water to the users (*castellum aquae*).

A.7 – Sewer
Tunnels or galleries for the discharge of grey or black waters produced by human settlements and industrial facilities.

A.8 – Ship, boat canals
Canals built for passage of ships or boats (Fig. 3). They are found mainly in central Europe and the United Kingdom.

A.9 –Ice wells, snow-houses
Deposits and/or manufacture of ice in the subsoil. Both natural cavities and artificial cavities were used for ice conservation, and use during the dry seasons.

A.10 – Tunnels or ducts with unknown function
This sub-type include those traces of ducts that are identified as water works, but which specific function is not known with certainty.

4.2. Type B – Hypogean civilian dwellings

B.1 – Permanent dwellings
The sub-type comprises long term settlements, cave dwellings, and underground houses (i.e. Bixio 2012). Most cavities of this type have nowadays been abandoned. However, the historic Sassi of Matera (Southern Italy) are recovering thanks to recent, extensive renovation works. In

Figure 3. Canal at Cotswold (England). Photo: J. Orbons.

China public buildings and private houses are still being digged into the rocks, and are inhabited by about thirty million people. In antiquity some sites have achieved the size and organisation of real urban hypogean areas, often complemented by brickworks (Golany 1988).

B.2 – Temporary shelters
Seasonal settlements, shelters for shepherds during the transhumance, hiding-places of bandits, places of temporary detention.

B.3 – Underground plants, factories
Rope-makers caves, oil mills, factories, working places no longer in use (Fig. 4). Military factories are classified D.1.

B.4 – Warehouses, stores, cellars
Storage for farming equipment, wine cellars, storage for fruits and vegetables. If military, they are classified in D.5.

B.5 – Underground silos
Cavities general accessed from above, carved into the rock and carefully closed by a stone to guarantee the preservation of food from animals or humidity. Sometimes they are bell-shaped.

B.6 – Stables for any kind of animals
Shelters for animals of any size: horses, chickens, other birds (except pigeons, see B7, and bees, see B8).

B.7 – Pigeon-houses
Dovecote or pigeon-house are synonyms to indicate rocky structure used for the housing of pigeons, doves or similar birds (Fig. 5).

B.8 – Apiaries
This sub-type has been recently included, following the proposal by Bixio and De Pascale (2013). Rock apiaries are widespread in many countries of the Mediterranean Basin.

B.8 – Any other kind of civilian settlements
It is difficult to establish a complete list of all the types of settlements. Unusual or not understood works can be included here.

4.3. Type C – Religioust structures, veneration works

C.1 Nymphaeum, Mithraea, temples, sacred wells, shrines, monasteries, churches and chapels, etc.
This category includes the main structures built for religious purposes (Rodley 2010; Fig. 6). In case they contain many burials, they are also classified in C.2. Conversely, if in a catacomb there are clear traces of the altar the site is also classified as type C.1.

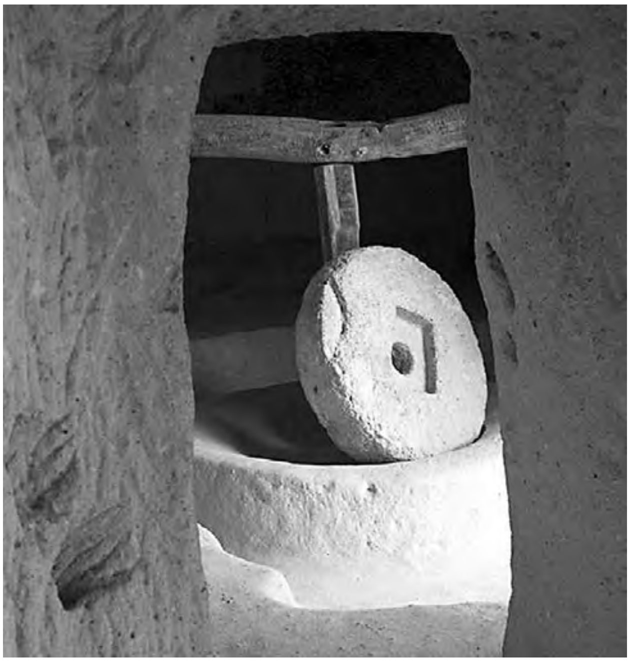

Figure 4. Oil mill factory at Zelve (Turkey). Photo: R. Bixio.

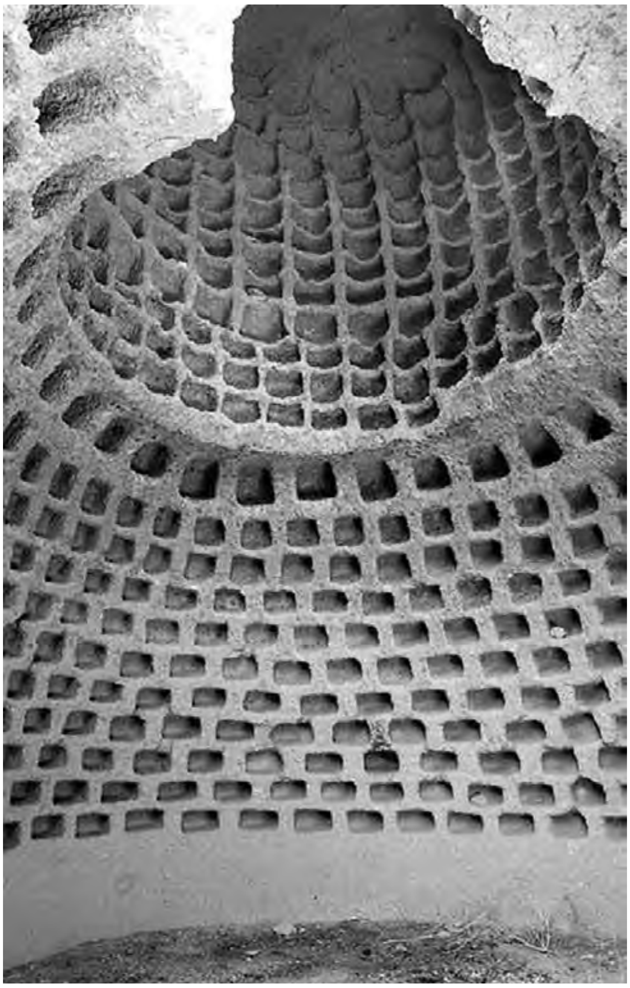

Figure 5. Pigeon-house at Anì (Turkey). Photo: R. Bixio.

C.2 – Burial Places
Crypts, chamber tombs, complex systems such as funerary columbaria, catacombs, and necropolis.

Figure 6. Church at Kizil Cukur (Turkey). Photo: M. Traverso.

4.4. Type D – Military and war works

D.1 – Defensive works
Underground fortifications and linked works.

D.2 – Galleries and connecting passages
Military structures for the transit of soldiers and arms; tunnels with military purposes, dating back to a number of different age and in many countries worldwide (Triolet and Triolet 2011).

D.3 – Mine and countermine tunnels
Military tunnels and trenches with a specific role.

Mine galleries: tunnels dug by the attackers to reach and undermine the foundations of the walls or defences of the defenders, or dug by the defenders to reach and undermine the artillery of the enemy (Fig. 7).

Countermine galleries: tunnels dug by the defenders to intercept the mined tunnels and prevent the attack.

D.4 – Firing stations
Rifles, machine guns, cannons and weapons of earlier periods, such as crossbows. In the First and Second World Wars many defensive structures were built underground: some of them were very large (like the Maginot Line, the Siegfried, the Metaxas etc.), whilst many others were isolated sites where the guns and other weapons were located.

D.5 – Deposits
Underground military stores of ammunition, food or other commodities. It is not always easy to determine the intended use of some of these facilities.

D.6 – Sheltered accommodation for soldiers
Shelters from the bombing, dormitories, military command posts.

D.7 – War shelters for civilians
Underground places where the civilian population sought refuge during raids, invasion, shelling, and (particularly) air bombing. They can consist of a single room or develop for many hundred metres.

Figure 7. Bastione Verde tunnel at Torino (Italy). Photo: F. Milla.

4.5. Type E – Mining works

These structures can reach huge depths and development (Craddock 1980).

E.1 – Aggregate quarries
Quarries of sandstone, pozzolana, limestone blocks, building stone or ornamental. The structures of this type which are no longer active, frequently have been or are still employed for other uses: cultivation, refugee, sport, tourism, scientific purposes, etc.

E.2 – Metal mines
Mines of copper, iron, tin, lead, gold, etc.

E.3 – Mines and quarries of other materials (non-metallic)
Underground quarries of flint, alum, sulphur, coal, sand for glass, ochre, salt, etc.

E.4 – Non-specific mining surveys
Traces of excavation activities aimed at the identification of mineral deposits. They are typically exploratory tunnels of limited size.

E.5 – Underground spaces to grow vegetables
In these spaces plant products are grown, typically mushrooms and vegetables.

4.6. Type F – Transit underground works

F.1 – Tunnels for vehicles, pedestrian or horses
Galleries at least a couple of metres wide, used in the past for the transit of carriages, wagons, horses.

F.2 – Transit works, not military
The function is the same as F.1, but the dimensions are such as to not allow the transit of wagons and large animals. Only for pedestrian use: tunnels related to villas, castles, monasteries, tunnels to escape, and so on. They certainly do not include military works.

F.3 – Railway tunnels, tramways or funicular (out of use)
Although fairly recent, many are already out of use. They include mine tunnels intended solely for haulage purposes and not for mining.

Figure 8. Well at M. Loreto (Italy). Photo: R. Bixio.

F.4 – Non-hydraulic wells, shafts etc.
The wells created for the access, the inspection, or the maintenance of artificial cavities (Fig. 8), today no longer in use because of occlusions or other reasons.

4.7. Type G – Other works

This final and generic category is intended to include all those underground works that do not directly belong to one of the before mentioned types. For instance, the wells that are not part of other undergrounds structures with unknown function (ventilation wells, light wells, cavities for technical spaces, passages, wells for alignment) find space in this typology.

5. Conclusions

The classification here presented, derived from that defined by the Italian Commission, and with further work by the UIS Commission, is not exhaustive, but can represent a starting point for further work and discussion by other scholars interested in artificial cavities.

We hope it may be widely used, as it is mostly aimed at facilitating the discussion among researchers, and at stimulating other cavers and scientists interested in artificial cavities.

Acknowledgments

We are deeply indebted to many people that in the past years have worked and discussed with us about the need to classifying artificial cavities: among them, we would like here to mention Vittoria Caloi, Giulio Cappa, Vittorio Castellani, Carlo Germani, Joep Orbons, Jerome and Laurent Triolet.

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AN OVERVIEW OF THE GEOLOGICAL AND MORPHOLOGICAL CONSTRAINTS IN THE EXCAVATION OF ARTIFICIAL CAVITIES

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The habit of man to excavate artificial cavities began a very long time ago. Man's efforts were initially moved by the need to have a safe place to live, to control the surrounding territory, to collect and transport water, to exploit the natural resources. For all these purposes, he had to face a number of geological and morphological constraints that, depending on site characteristics, guided, favored or complicated the excavation. Therefore, all the phases in the "life" of an artificial cavity, from the original idea, to planning and realization, up to its later evolution and possible conservation, depend in some ways on geology and morphology. Lithology of hosting rock is the first aspect to consider: the rock mass must allow hand excavation but, at the same time, it should present physical-mechanical characteristics such to support the newly-formed cavity. The geological and structural setting, including the main faults and the discontinuity systems in the rock mass, have to be particularly taken into account. Choice of the site where to locate an artificial cavity is also dictated by morphology, the morphological factors being, in turn, strictly related to land management and control. When safety reasons were considered to be the main priority, for instance, those sites that apparently were extremely difficult to excavate and to settle in were chosen. Morphology is also strictly related to slope instability. Several rock settlements situated at the borders of deep valleys and ravines are directly involved in mass movements, due to natural evolution of the slopes and to open cracks produced by the tensional release in the unsupported rock mass. Inside the artificial cavities, in turn, problems of instability may be observed. Locally, these may become so significant to compromise the overall stability of the structure. Slope instability processes deserve a greater attention from cavers and scientists, since their effects might be extremely dangerous for people visiting and working in artificial cavities, and for the cultural heritage therein contained as well. Availability of water resources is a further factor that controlled during historical times the choice of sites for settlements and towns. As a consequence, the hydrogeology plays a crucial role for artificial cavities, and particularly for those works intended to collect and transport water to settlers and inhabitants. Aqueducts, tunnels, fountains are, for the reasons above, very important to study in the context of the geological and hydrogeological setting, considering at the same time the social and historical aspects of the community that designed and realized them. The present contribution is an attempt in categorizing the aforementioned factors that play a role in the realization of artificial cavities. The topic is very wide, covering several interrelated disciplines and field of research, and should deserve to be treated with much greater detail and thoroughness. Our goal is therefore to stimulate with this article cavers and interested scientists in carrying out studies about the crucial role that geology and morphology have in the development of artificial cavities

1. Introduction

Artificial cavities have been realized in many different parts of the world, in different epochs and for a variety of purposes. Whatever the sites, and the purpose of the excavation, man had to face a number of natural constraints in order to properly realize the cavity, and to assure its stability for a given time. The local landforms, as well as the processes active in changing it, had to be well known, in order to avoid dangerous situations, eventually resulting in partial or total destruction of the cavity, or in catastrophic failures during its excavation. In turn, the morphological features are related to geology at the site (Fig. 1), and to the hydrologic regime. All of these elements played a very important role in the choice of the sites where to dig the cave, and had to be considered in combination with other factors such as the strategic location and the control of the surrounding territory.

Over time, a great variety of people and culture had developed remarkable capabilities to adapt to even extreme environments, and to subtract rocks from the original landscape in order to create a place to be used as shelter, house, storage site, etc. There are in fact many reasons that brought different cultures to develop subtractive techniques and technologies: among the main ones, we recall here war (with both the goals of offense and defense), religion, economical and social reasons. In any case, the development of real underground cities was strongly influenced by geographical, climate and geological aspects.

As concerns the geological setting, many factors have to be taken into account in the realization of artificial caves and underground settlements. Their importance may vary as a

Figure 1. The flank of one of the many gravine-type valleys at Ginosa di Puglia, showing a number of artificial cavities located following the several flat surfaces degrading toward the valley thalweg.

function of the use of the artificial cave and the intended benefits. Generally, the presence of the so-called "weak rocks" (that is, materials easy to excavate, but at the same time with technical properties such to use them for construction) granted for underground quarries, from where building stones were extracted for troglodyte and religious settlements. Location and development of mines for the extraction of metal bearing rocks was, on the other hand, conditioned by the deposit and the strength of the mineral vein (Fig. 2), as well as by the industrial technologies available at the time of the mine activity.

Moving to other typologies of artificial cavities, such as hydraulic and military works, it has to be noted that during the realization of aqueducts (Ashby 1935; Bodon et al. 1994) or military corridors (Gherlizza and Radacich 2005), the difficulties of excavating more resistant rocks (for instance, hard carbonate rocks as limestones) were less important than the goal (that is, to bring water to a civil or military settlement). In these cases, the morphological factors greatly affected the choice of the path, and the development of the work as well. The greater difficulties encountered during the excavation because of the lithologic characteristics were generally balanced out by the realization of cavities with a reduced section, though with an important spatial development.

In the case of communication routes and roads, the need to overcome morphological obstacles led to the realization of tunnels. Ancient Etruscan and Romans were masters in building narrow tunnels, where a single file of wagons and horses could pass (see Vitruvio, De Architectura). Big underground cavities, on the other hand, and in particular cisterns and quarries, changed frequently destination, turning into manufactories, bomb shelters, underground deposits, cemeteries, etc.

Figure 2. The bauxite level interbedded in the Mesozoic limestone sequence controls location and development of mines.

2. Lithology and technical properties

The use of an underground cavity in time is strongly affected by the mechanic characteristics of the rock mass, which in turn controls the more proper excavation section. The latter has to play a primary role for self-bearing vaults, thus allowing the safe use of the cavity.

Searching the rocks with the best characteristics (Fig. 3) was the first step to fulfill in order to have the possibility to realize a long-lasting cavity. Volcanic rocks present generally good mechanical properties, and have often been used in antiquity as sites for developing human settlements. The variety of volcanic rocks, in turn, showing quite different strength and physical properties, was another important factor that made possible, in a limited territory, to look for rocks to be used in different situations and for different purposes. For instance, volcanic rocks are associated to the Quaternary volcanic activity along the Tyrrhenian coastlines of central-southern Italy in Tuscany, Latium, and Campania. These territories had volcanic deposits consisting of a limited lava layer, with extended tephra (the so-called *pozzolana*) and pyroclastic rocks (tuffs of different varieties, such as *piperno* in the Campanian area). Those are classified as weak rocks, but they are suitable building materials with good physical and mechanical properties, easily workable and acting as good heat insulators (AAVV 1967). Further, the great amount of available material made them the most common building and ornamental materials in the Greek and Roman periods (Zevi 1994; Piciocchi and Piciocchi 2005), as many monuments still testify.

Figure 3. Artificial cavities in a coastal area of southern Italy: note that all the caves open at the same level, characterized by easy-to be worked rock, and overlain by a stiffer layer, that constitutes the roof of the cave.

Another type of rocks that used to be excavated is represented by sedimentary rocks, in particular the variously cemented and porous calcarenites of Pliocene – Pleistocene age (Fig. 4); in many cases, these rocks are of biogenic origin, showing many fragments of Bryozoans, Echinids, Crustacea and Mollusks. Calcarenite rocks also played a primary role in the subtractive architecture, representing the main available material in those regions of Italy without presence of volcanic rocks (Apulia, and sectors of Basilicata and Sicily). These rocks are improperly known as calcareous tuffs, due to similarities in fabric and appearance with volcanic tuffs; with these latter, they also share the characteristic of having suitable physical and mechanical properties, are easy to be excavated and sufficiently porous (Andriani and Walsh 2002, 2003).

Other lithotypes are easy to be excavated, and can self-sustain vaults. Thus, the presence of volcanic tuffs, sandstones and calcarenites, when combined with availability of water and the proper morphological setting, possibly with sub-vertical walls granting good strategic defense, represented the first element for the choice of the sites where to locate a settlement.

When considering other types of artificial cavity, however, the things are quite different. As concerns mines, for instance, the fundamental geological element required to be known is the stratigraphic and structural setting, that determines the presence of a mineral vein along a particular direction. Underground mines had to definitely follow this strike, once determined. This is evident especially in prehistoric caves, where technological limits brought to narrow galleries in compact rocks. The flint mines of Defensola (5500–2500 B.C.) in Gargano (Galiberti 2005; Tarantini 2007) are characterized by sub-horizontal excavations of a few calcareous layers in passages 60 cm-high, quite low but sufficient to extract flint stones. The copper mine in Monte Loreto (3500–3100 B.C.) has a copper vein in a fracture wide from 0.4 to 1 m (Bixio et al. 1999).

Figure 4. An artificial cavity in calcarenite rock, strongly controlled by a tectonic disconituity.

In underground mines, stability problems may arise when a passage develops through different materials (Fig. 5) with very different mechanical characteristic (Bieniawski 1979). At the contact between the different rocks it may be necessary to cover and/or sustain the walls and vaults, or to reduce the section of the gallery (Del Prete and Di Crescenzo 2008). In some cases, this may also happen in the same lithology, due to the presence of water veins, draining fractures, or frequent discontinuities which cause a high degree of fracturing in the rock mass.

3. Water: its availability, hydrology and hydrogeology

Water availability is a crucial factor for establishing any human settlement, as it granted solutions for drinking and sanitary needs. It was therefore necessary to have a good knowledge of the basic hydrological features of a given territory to decide where to settle and how to manage the water collection, transport and storage (Parise et al. 2009; Parise 2011). For this reason, very long channels were generally realized by carving the rocks, which branched in underground tunnels and cisterns as they reached the settlement. Ancient aqueducts were exclusively open air; the choice of the springs to tap, and the path of the aqueduct as well, were conditioned by the difference in elevation

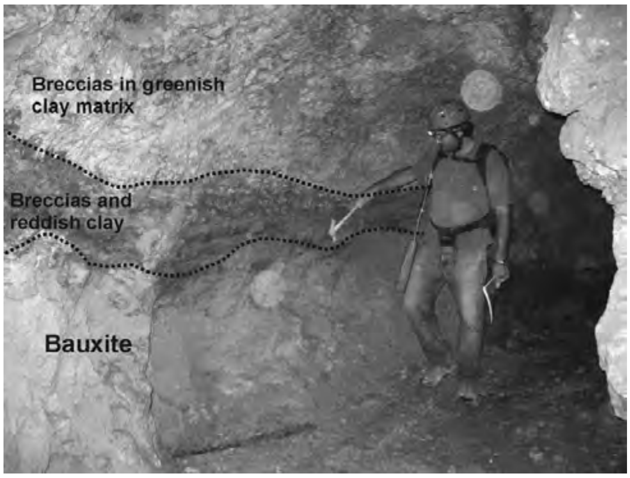

Figure 5. Lithotypes with different technical properties can influence the stability, size and morphology of the cavity.

between the source and the final destination (Castellani 1999). This granted the right water load for public and private fountains. An interesting example can be drawn from the town of Naples, when during the Spanish vice – Realm, at the end of the 17th century, human settlements in the hilly quarters had to withdraw waters from wells, because ancient aqueducts had not the necessary water loads (Fiengo 1990).

The subterranean hydrogeological circulation plays a primary role for the realization, the stability and the preservation of an underground work (Delle Rose et al. 2006). The groundwater circulation is an important conditioning aspect during the realization and the fruition of the work. It is a function of primary and secondary permeability of each rock formation. In case of lithoid rocks, the presence of draining or plugging fractures can create serious risks of flooding and make impossible the actual fruition of the cave.

In other situations (i.e. mines), deepening the excavation may result in intercepting the water table (Fig. 6), with the evident necessity of lowering it by pumping out waters; if this solution is not economically convenient, works will be abandoned. If, on the other hand, the richness or interest of the deposit brings to lower the piezometric surface, once the extraction activity ends the underground works will be totally submerged (as at the Naica caves, in Mexico; Lang 1995).

In addition to aqueducts, that have always been considered as one of the most typical engineering works characterizing past civilizations, control of the lake levels and reclaiming of marsh lands are other important hydraulic works. The possibility of restoring unhealthy, marsh lands has always been a determining aspect for the realization of drainage tunnels, as at the Lakes of Nemi (Castellani et al. 2003), Albano (Castellani and Dragoni 1991, 1997; Caloi et al. 2012), and Fucino (Burri 1987; 2005). There are many geological and structural factors that affect the distribution of springs and their discharge, depending on the subterranean groundwater catchment. Their quality is important for capturing and transporting waters through aqueducts. If walls and the bottom of these works are not covered, after years of abandonment they can be remodeled by water erosion. Thus, very particular speleogenetic features can be observed, where the formation of a natural cavity in rocks is due to mechanical

Figure 6. A passage flooded by water in a lignite mine.

erosion, which is induced by the pre-existence of an abandoned artificial cavity.

4. Morphology: the need to integrate the natural landscape

The erosion and degradation processes that model the landscape have a primary role in the definition of rupestrian structures and subterranean works and in their preservation in time. Earth pyramids, butte, mesa, plateau are morphologies produced by the action of weathering (physical disintegration and chemical alteration), of gravity (landslides) and of water erosion; for this same reasons, they are destined to decay. The same process that generated particularly suitable morphologies can destroy the rupestrian settlements, sometimes very quickly, as in the case of landslides (Fig. 7). They may also generate accumulations that are more suitable than the original morphology to the development of rupestrian architecture. A tuff cliff can collapse, and this bring in turn to underground rooms to open air, but a further evolution of the process may lead to a total loss of the hypogeal heritage. Some collapses due to landslides produce big tuff blocks (thousands of cubic metres) that can produce the realization of another particular rupestrian settlement. To provide an example, green tuff blocks in the island of Ischia island detached from the tuff ridge of Mount Epomeo: they were excavated to realize different rupestrian structures, including multi-stories habitations (D'Arbitrio and Ziviello 1991; Mele and Del Prete 1998). The stone blocks were used in their original morphology without plaster, leaving the rude tuff surface covered with lichens and altered by the erosion of rain and wind. This helped the adaptation of the structures to the environment in search of a defensive mimesis.

Some areas are characterized by frequent thermal variations of freeze/thaw cycles: in these areas physical disintegration due to constant heating and freezing occur, whose effects are gradually evident in time. The level of porosity and the kind of fissuring characterize the attitude of rocks to suffer these processes, leading to the crumbling of the rock in small blocks or flakes (exfoliation). The effect of exfoliation in the Valley of Meskendir (Cappadocia, Turkey) on the walls of draining tunnels contributed to remodeling the original sections during thousands of years (Bertucci et al. 1995).

Figure 7. Rock failures in a gravina at Massafra (Apulia), threatening several artificial cavities.

5. From beneath the Earth: the endogenous factors

Volcanic eruptions deposit tuff and pyroclastic material: this is one of the main influences of endogenous strengths, as it is the generating event of one of the most suitable rock layer of hypogeal works.

Another interesting and risky endogenous aspect, which is associated to mines and especially to carbon mines, is the presence of gas (also known as grisou), which is difficult to localize and has caused so many deaths in different times. Similar problems can rise during the excavation of tunnels in clay formations, if they are rich of organic substances. Locally, hypogea in volcanic areas can intercept the uprising of endogenous gas: a very famous example is the Cave of the Dog in Agnano (Baldi 2001).

As concerns endogenous factors, there is also the influence of fossil fumaroles (degassing pipes) on the lithotechnique characteristics of tuff formations, since degassing can occur when the pyroclastic falls cool down. This may bring to removal of the fine matrix, leaving rough incoherent elements. These fumaroles are sub-vertical and irregularly shaped. Their grain size is similar to melted gravel deposits, which has very different load characteristics from the tuff layers. Bradyseism is also associated to internal dynamics of the Earth, and it may affect the use of an artificial hypogeum in time. The artificial cavities on the coasts of a volcanic area may be under sea level because of negative movements of the Earth's crust. Thus, they may be confused with natural cavities, which were generated by the sea erosion. In the Phlegraean Fields of Campania, many ancient Greek and Roman villages are now under the sea level. The same happened to some tunnels from the Greek era near Castel dell'Ovo in Naples (Cilek et al. 1992), to the cave called Spuntatore or Varule, in the island of Ischia (Buchner 1943), and to many others cavities (Simeone et al. 2008; Ferrari and Lamagna 2011) which in 2000 years has sunk some meters under the sea level.

6. How long will the cavity last? The stability of subterranean works

Artificial cavities are often abandoned, but the necessary precautions about their preservation are rarely taken. For this reason many cavities suffer of instability problems, also creating a risk for the above territory. The closure of the original entrances may aggravate the situation, as well as the loss of memory and information about the spatial distributions of the hypogea is at the origin of an increase in the related risk.

The more frequent failures in cavities are detachments of blocks or slabs (up to dozens square meters) from the vaults (Fig. 8) and/or from the pillars (Parise 2013). These partial collapses are frequently sudden and without premonition, and may occur even hundreds of years after the excavation. The instability of slopes where cavities are present, due to the thinning of pillars is particularly risky when they endanger archaeological sites, as in many gravine-type valleys in Apulia and Basilicata. In many cases, the external walls of cavities partially collapsed (Bertucci et al. 1995; Bixio et al. 2002; Pecorella et al. 2004; Parise 2007, 2012), and the stability of many cavities is seriously compromised by open cracks in pillars and vaults.

With the exception of the above mentioned situations, the general effect of collapses is localized to the underground cavity and its nearby areas, with moderate damage to people and things; even so, the alteration of the static conditions can be extremely dangerous and originate a general collapse, with severe consequences on the structures at the ground surface. These situations occur in areas where the intense subterranean excavation has caused slow subsidence or sinkholes (anthropogenic sinkhole). Such a phenomenon has been observed in several quarrying areas of Apulia (Bruno and Cherubini 2005; Parise and Lollino 2011; Parise 2012), where the intensive extraction of local calcarenite and of overhanging clay has caused serious instability in the last decades. Similar situations occur in the urban area

Figure 8. Slab detachment from the vault in lacustrine deposits of a lignite mine.

of Naples and the surrounding plain (AAVV 1967; Evangelista 1991; Evangelista et al. 1980).

The discontinuities within a hypogeum can be of different nature: they can be pre-existing and strictly connected to the genesis of the rock formation (such as syngenetic fractures in a tuff formation, which can be caused by rapid cooling of melted deposits); others can be successive, due to the tensional redistribution after the excavation, to tectonic vicissitude that involved the formation and to tensional releases in correspondence of sub-vertical cliffs. The discontinuities in a rock mass work as sites of stress concentration and activate a progressive long-term reduction of the material resistance. Knowledge of the effective stability conditions of a cavity (for instance, the study of the fissured vaults) and of the possible causes of collapse is necessary for a correct evaluation of the risks in subterranean failures. The study on stability conditions is indispensable to set the priorities to plan consolidating works, while the analysis of the possible causes of collapse help to choose the most suitable techniques for the monitoring of the failures.

7. Conclusions

Influence of geological and geomorphological features on the realization of subterranean works is a complex and wide topic. Generally, the roles of the various factors can be examined singularly, but they overlap and act together in combinations that depend also on environmental factors (geography and climate) and on time. For instance, mechanical erosion of running waters and thermal fractures contribute to the remodeling of the section in a draining gallery. Techniques of subterranean excavation are conditioned by geomechanical and/or hydrogeological aspects, which affect times and future usability of the works. Underground water influences the realization and the use of a subterranean structure. A settlement or a warehouse can be used only if they were realized in well draining rocks, which granted for suitable humidity levels. An economical interest can suggest the drainage of a great quantity of water in mine works or in the construction of an important road. The overlapping endogenous (resurfacing of fluids at high temperatures) and structural (such as draining or filled tectonic structures) factors can complicate the realization of underground works, with repercussions on times of realization and costs. It is generally evident that the study of geological aspects supplies for important indications about the socio-economic aspects that brought populations and cultures to realize and use subterranean structures.

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THE ANCIENT MINES OF USSEGLIO (TORINO, ITALY) MULTI-YEAR PROGRAMME OF RECORDING, STUDY, PRESERVATION AND CULTURAL DEVELOPMENT OF THE ARCHAEOLOGICAL MINING HERITAGE IN AN ALPINE VALLEY

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The programme started in 2001 and developed a large set of operations in order to create a geo-topographic and historical-environmental database, to rebuild the chronology (relative and absolute) of mining works in the Punta Corna complex (high Arnàs and Servìn valleys) and the extractive activities' effects on the Usseglio economy and more broadly on Lanzo Valleys economy.

The main part of the operations has been conducted directly by the Civic Alpine Museum staff, but in some aspects (such as deciphering medieval documents, mineralogy, petrography, GNSS surveys, aerial photography, restoration of the steel archaeo-mining finds, and so on), a strict co-operation with university teachers and other specialists or qualified technical figures was requested and realized.

This open and multi-disciplinary approach will guarantee, also into the future, the best exploration and knowledge of this enormous heritage.

According to the experience of the senior archaeologists (responsible to the Civic Alpine Museum), a group of underground experts – mining engineers and speleologists specialized in artificial cavities – will carry out explorations and surveys, to collect precious information connected to the external records.

1. Topography and Geology

The Punta Corna mountain mining complex is located on the left side of the Arnàs stream valley (western Po basin), spreading from 2,250 to 2,900 m a.s.l. (main peaks attain 2,930 up to 3,108 m a.s.l.), between Rossa Lake (hydroelectric storage near French border, 2,718 m a.s.l.) westwards and Torre d'Ovarda mountain group (3,075 m a.s.l.) eastwards.

The siderite and Co-Fe-Ni arsenides mineralisations belong to a trending system of post-metamorphic hydrothermal veins, mainly within the metabasites of the Piemonte Zone. These veins formed because of the circulation of hydrothermal fluids along extensional structures linked to brittle deformation events which affected the rocks at the end of the Alpine orogenesis.

The mining complex is protected by the institution of a 10 km² area, wherein the mineral collection and the removal of man-made objects are totally forbidden.

2. Aerial reconnaissance and field survey of archaic mines

Aerial reconnaissance and field survey point out a strip of some kilometres long, up to 10 m wide and 12 m deep, open air trenches, issued from archaic iron ores mining; their order of magnitude is equal to today's industrial plants, like roads, hydroelectric power plants or dams.

These trenches are associated with pits, ditches, descending galleries (often intentionally back-filled after the end of the exploitation), sinkholes, undermined boulders, spoil banks, remnants of little rough-stone half-buried buildings and also walls, used for terracing, ore crushing and picking, sheltering gallery entrances and closing natural rock-shelters.

3. Technical features of archaic exploitation

The exploitation was focused on iron hydroxides (limonite, goethite), resulting from siderite decay. The fragmentation was strictly limited to mineralised veins, particularly in upper and softer levels; it halted when reaching inner and harder levels of massive, un-weathered iron carbonates (siderite). No drill holes and only rare tool marks are visible on the trench sidewalls. Miners used steel hand tools, occasionally found near the trenches during field survey.

4. Present look of trenches

Today, iron ores are seldom visible in the open air, because they have been nearly completely removed by the exploiters. Trenches are partly occupied by unremoved boulders and panels of the embedding rock, so their bottom is presently unattainable; nevertheless, they seem sometimes to be connected to descending gallery entrances in lower levels. Sidewalls are generally stable; widespread spoil banks run along the ditches.

5. Present look of pits, ditches and sink-holes

All these features are excavated under main boulders, which shelter the access to veins; they are circular, oval or funnel-shaped, placed above buried veins, flanked by little, mound-shaped spoil banks, obstructed by post-functional collapses

Figure 1. Trenches R1-201 and R1-202 (left); iron hydroxides and embedding rock panels in trench T1-202 (right).

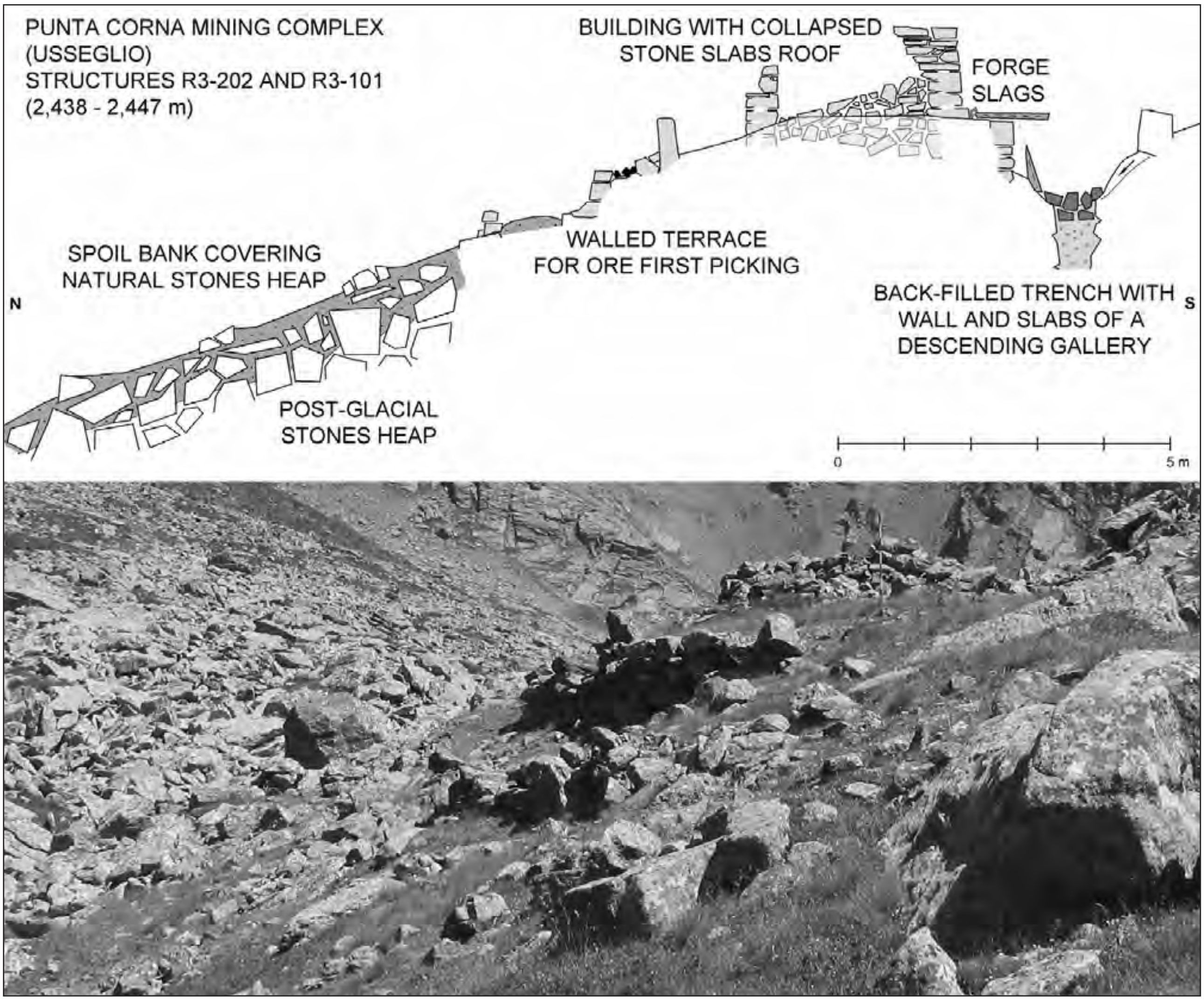

Figure 2. Vertical section and photographic view of a typical archaic plant.

or back-filled after the end of the exploitation. Underground, rough-stone walls, slabs and stairs are preserved for few metres.

In general, the structures are well preserved in comparison with their working time, because of scarce post-functional colluvium.

6. Pre-blasting mining

Gunpowder use in mining activities begins in the 17th century: the first statements in the Duchy of Savoy date from 1671, in the Duchy of Milan from 1665.

The organization of a pre-blasting mining exploitation, possibly similar to the Usseglio examples, can be observed in the polyptych by Hans Hesse (1522) for the altar of mine workers in the Church of St. Anne at Annaberg-Buchholz (Herzgebirge, Sachsen, Germany).

7. Chronology

The dating of archaic exploitation to the middle ages is based on archaeological finds, particularly steel tools (12th–14th century) and pottery (11th–13th century), and on historical documents, referring to mining activity, cast iron, steel and silver production, and ore thefts, in the years 1264 (already carrying on previous contracts), 1316, 1318, 1333, 1335, 1402, 1438, and 1515.

8. The age of cobalt

Since 1753, after a long period of scarce production, a new chapter begins, because of the discovery of cobalt ores, exploited by Counts Rebuffo di Traves alongside copper and silver (cobalt-iron-nickel arsenides with tetrahedrites).

Two maps, dating to 1758–1772, mark the exact positions and directions of several veins. In 1758, a building named "*Casere*", much larger than medieval ones, was built at an altitude of 2,625 m a.s.l. near Veil Lake to house the workers.

9. A proto-industrial perspective

The exploitation is no longer opencast mining, but moves mainly underground, with several multi-level grids, sometimes intercepting former works, in an incoming proto-industrial perspective.

Two new buildings are constructed before 1815, at 2,374 and 2,439 m a.s.l. respectively. Both are recorded in a mine section dating to 1823, near the entrance of crosscuts.

10. Paper maps and material reality

Even today, veins, galleries, spoil banks and buildings reported by mine sections and maps can be identified in the field. However, galleries and stopes are mostly inaccessible, because of landslides, or dangerous, because of the collapse of timbering.

Documents reveal to us that sometimes miners lived in very hard conditions: the "Dwelling of Workers" ("*Abitatione de Lauoranti*"), recorded by a map, in 1758–1772, at the foot of "St. Mary Mine" ("*Caua di S. Maria*"), was a walled prehistory-like rock-shelter, still used occasionally in the 1920s by the last prospectors.

11. Protecting the entrances

To reach the deposit bed, that was hidden by a thick layer of debris, miners built some long galleries into such sediments, protected by side walls and roofed by rough-stone slabs. One of the most impressive linked a dwelling to the real lower entrance of a mine, that was cut in hard rock: in that way, miners avoided blockages of the entrance by landslides or by avalanches and avoided long removal works in spring, when restarting the exploitation after the

Figure 3. Ruins of a modern dwelling, linked to an underground grid by a gallery, built into the debris (left); an example of a subterranean vein (right).

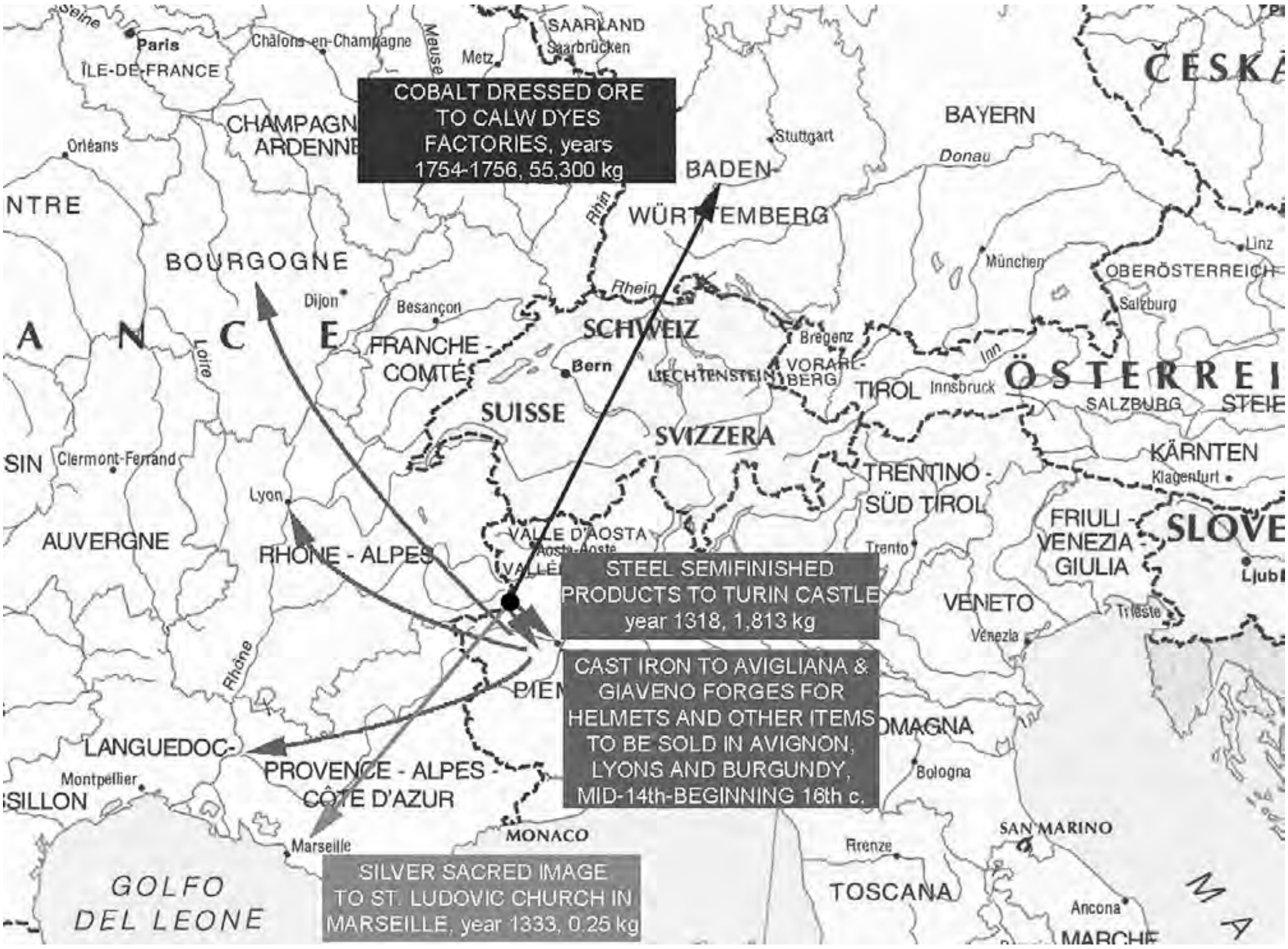

Figure 4. Not just a local market: international routes from Usseglio to European destinations.

winter inactivity (documents inform us that the season lasted no more than four to six months).

12. Observing the veins

Veins can be observed underground, where the exploitation stopped: they show a series of parallel, almost vertical bands, with a lot of gangue.

13. The "cobalt factory"

The Usseglio built-up area still hosts the "*Cobalt Factory*", at 1,290 m a.s.l. in Crot hamlet, built in 1755–1757 according to a plant model imported from Saxony and Bohemia by S.B. Nicolis di Robilant (1724–1801), general inspector of the mines of the Kingdom of Sardinia (1752–1773).

The dressed ore that was produced by this plant was exported to Württemberg (55 tons up to 1756). The original look of the building is recorded by maps and drawings dating to the period 1823–1854.

14. From factory to hotel

The factory was then enlarged and modified, in 1896 becoming one of the earlier hotels devoted to the rising mountain tourism, with the evocative appellation "*Albergo Miniere*" ("*Mines Hotel*"). Today it is a stop on the external itinerary of the Civic Alpine Museum.

15. Working plan 2013

Following the Museum programmes, in order to increase and to develop our knowledge of the territory, in summer 2013 a lot of new studies are going to start:

- recording and topography of archaic mines located in the area, in safe conditions;
- underground survey of mining, according to speleological/archaeological standards;
- multidisciplinary study of cavities and associated evidence (mineralogical, mining, wildlife, archaeobotanic, etc.).

16. In conclusion

One of the statutory aims of the Civic Alpine Museum of Usseglio, entirely volunteer-conducted, is the "systematic recording and cultural development of the historic heritage of sciences and techniques". The Museum's researchers, with the decisive aid of several colleagues of other institutions, are carrying out a full survey of archaeological mining structures in relationship to geological, technological, historical and iconographic data.

The state of preservation of this heritage is remarkably good, as the area is geologically stable, vegetation is almost absent, mining has been suddenly abandoned and no subsequent activities but pastoral farming have taken place.

Several sites are accessible to the public in summer and at the beginning of autumn, as the Museum organizes workshops including guided tours in the Punta Corna protected area.

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SAFE CAVES: THE DISTINCTIVE FEATURES OF HIDEOUT COMPLEXES IN THE GALILEE IN THE EARLY ROMAN PERIOD AND PARALLELS IN THE JUDEAN LOWLANDS (SHEPHELAH)

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Two types of subterranean chambers found in the Galilee – natural caves at the tops of cliffs ("cliffside shelters") and rock-cut "hideout complexes" – shed light on Jewish defense methods there in the Hellenistic and Early Roman periods. The plans of 65 caves that may have served as hideout complexes are sketched, presented, and compared with hideout complexes in Judea. The subterranean complexes are divided into six categories:

1. *Simple hideout complexes* – crudely hewn, with dark, narrow passages.
2. *Elaborate hideout complexes,* hewn with great care and attractively finished and smoothed.
3. *Hideout complexes hewn out of rock-cut subterranean chambers that had been used as storage facilities for agricultural products, cisterns, olive presses, or ritual baths.*
4. *Hideout complexes hewn out of burial caves.*
5. *Escape crawlways.* These are rare, but Josephus describes one used during the siege of Jotapata during the Great Revolt to bring in goods and news.
6. *Subterranean cavities that should not be identified as hideout complexes.* This category includes cavities that some scholars have thought were hideouts but in my opinion are not because they lack the features of hideouts.

1. Introduction

From the standpoint of archaeological and historical research, the caves in the Galilee (northern Israel) are less well known than those in the Judean Desert in central Israel and in the rest of Judea (Weiss 2007). Studies and surveys have been conducted in the Judean Desert ever since the discovery of the first Dead Sea Scrolls in 1947. The caves there have been surveyed systematically, and the finds shed light on many details about the late Second Temple period and Great Revolt (2nd c. BCE–1st c. CE) and the Bar Kokhba Revolt (2nd c. CE) (Yadin 1957/58, 1963, 1971; Bar-Adon 1980; Eshel and Amit 1998; Eshel and Zissu 2001; Porat et al. 2003/04, 2005/06; Eshel et al. 2005/06; Eshel and Porat 2009). Gradually, a particular pattern of natural karst caves containing networks of crawlways and chambers was discerned in the Judean Desert; because Jews fled to them especially in the Early Roman period (63 BCE–136 CE), they were termed "refuge caves." These caves are located in the steep cliffs of large riverbeds that descend from the Judean Desert toward the fault scarp near the Dead Sea (Eshel and Amit 1998).[1] Another type of cave used as a hideout, known as a "hideout complex," is also found in Judea. These complexes were hewn out of the ground adjacent to towns and homes. Hideout complexes in Judea were first defined by David Alon in 1978 (Kloner 1984), and have since been studied extensively (Kloner et al. 1982; Kloner and Tepper 1987; Zissu 2001; Kloner and Zissu 2005).

In this paper I discuss hideout complexes in northern Israel because a great deal of information has accumulated on the subject since the studies of Aviam (1983), Tepper and Shahar (1987), and Shahar (2003). In addition, I will propose a categorization and characterization of the hideout complexes based on well-defined criteria, and I will consider whether they are comparable with those in the Judean lowlands and Judean Hills.

Hideout complexes in the Galilee were discovered back in the 1960s, but at that time no historical importance was attributed to them. To the best of our knowledge, Antiquities Department inspector Netanel Tefilinsky was the first to report the existence of subterranean crawlways (Aviam 1983; Tefilinsky 1983). In 1974, Dan Bahat excavated a hideout complex at Horbat Hazon. Although at first he thought it was an aqueduct, in 1983 he published the pit and tunnel that he had excavated as a hideout (Bahat 1974, 1983). In the 1980s Michael Even-Esh, who had surveyed hideout complexes in the Hebron Hills, conducted a survey of hideout complexes at Khirbet Ruma and Beit Netofa in the Galilee. The elaborate hideout at Khirbet Ruma was first studied and mapped by a team from the Hebrew University, and a salvage excavation was carried out there, headed by Arieh Rochman. At the same time, Tepper and Shahar surveyed and mapped it as part of a preliminary survey of Galilean hideout complexes (Cohen 1983; Rochman 1985/86; Tepper and Shahar 1987d). The Beit Netofa hideout was mapped by Amos Frumkin (Eshel 1983). In 1983 Aviam published an article about the five Galilean hideout complexes known at the time, discussing their dating and the connection between these caves and the revolts against Rome (Aviam 1983). In the 1980s and 1990s, workers from the Israel Antiquities Authority (IAA) reported the discovery of hideout complexes throughout the Galilee,[2] four of which – at Ibillin, Migdal Ha'emeq, Khirbet Ruma, and el-Khirbe – have since been excavated (Rochman 1985/86; Shalem 1995; Muqari 1998/99; Alexandre 2003). Recently, salvage excavations at Kafr

Kanna uncovered a hideout complex beneath the ruins of a structure from the Early Roman period (Alexandre 2008).

In a paper published in 2003, Shahar listed approximately 20 hideout complexes in the Galilee and argued that they should be dated to the time of the Bar Kokhba Revolt (Shahar 2003). In 2008, Kloner, Zissu, and Shahar stated that 27 hideout complexes had been found in the Galilee. Based on the finds at Jotapata (Yodfat) and Kafr Kanna, they asserted that hideout complexes were first hewn in the Galilee even before the Great Revolt and were probably used in various periods (Kloner et al. 2008).

2. Recent Research on Hideout Complexes

In the present paper, I report on 35 sites in the Galilee at which 65 hideout complexes have been found (Fig. 1). The presentation of the new data constitutes a significant update of the scope of the hideout phenomenon in the Galilee. For the purpose of reexamining the hideouts, the subterranean chambers were documented according to the rules of speleology. In this study the hideout complexes previously discovered in the Galilee have been redocumented and remapped (since in some cases data were omitted from the surveys), and new hideout complexes have been documented and mapped following a careful examination of their crawlways and chambers. Because the mapping encoutered technical problems, I do not have complete plans of all the caves. Nevertheless, I was able to survey the hideout complexes thoroughly and identify them according to the categories below.

The following sites and subterranean cavities in the Galilee have been identified as hideout complexes:[3] Gush Halav (three complexes); Meroth (two complexes); Qiyyuma; Nabratein (Nevoraya); Iyei Me’arot – Hatzor Hagelilit (ten complexes); Mt. Hazon; Hukok (two complexes); Mimlah (two complexes); Ravid; Illabun; Mistah; Jotapata (two complexes); Ibillin (five complexes); Beit Netofa; Lubiya; El-Khirbe (two complexes); Ruma; Kafr Kanna (six complexes); Tur’an (two complexes); Ilaniya; Khirbet Bessum; Jebel Qat; Shikhin; Sepphoris (two complexes); Horbat Bina; Horbat Tiria; Nazareth; Horbat Devora (Khirbet Dabbura) (two complexes); Beit She’arim; Migdal Ha’emeq; Horbat Riv; Shunem (Sulam); Horbat Bolek (Buleiq); Horbat Nurit (Nuris); Tel Amal tunnel; Nahal Amal crawlways.

Additional sites that have been described as hideout complexes are located in private areas and are inaccesible. These are therefore not included on the map of hideout complexes in the Galilee.[4] One exception is Yafa, where Guérin reported seeing two subterranean hideout complexes near the Orthodox Mission building in 1870; in them were three stories of rock-cut rooms entered via round openings. One of the complexes, he noted, contained a cache of 200 coins of Roman emperors (Guérin 1880). But because the area is now densely built up, no evidence remains of the hideouts.

Like the hideout complexes in the Judean lowlands, those in the Galilee can be divided into six main categories:[5]

1. *Simple hideout complexes:* Subterranean chambers hewn roughly for hiding purposes, without attractive finishing. These small hideouts resemble the Judean ones discovered by Kloner at an unnamed site and by Zissu at Horbat Ethri, as well as the one beneath the synagogue at Susya (Chamber 8); all of these complexes are from the Second Temple period (Kloner 1987b; Zissu 2001; Kloner and Zissu 2005). The openings and crawlways were smoothed hastily, and effort was clearly put into making it as hard as possible for uninvited guests to get in. Turns are not necessarily at right angles, and there is nothing systematic about the way the different levels of the caves were hewn. In these dark, narrow complexes, one has to crawl to get anywhere. Twenty-one such complexes were hewn in

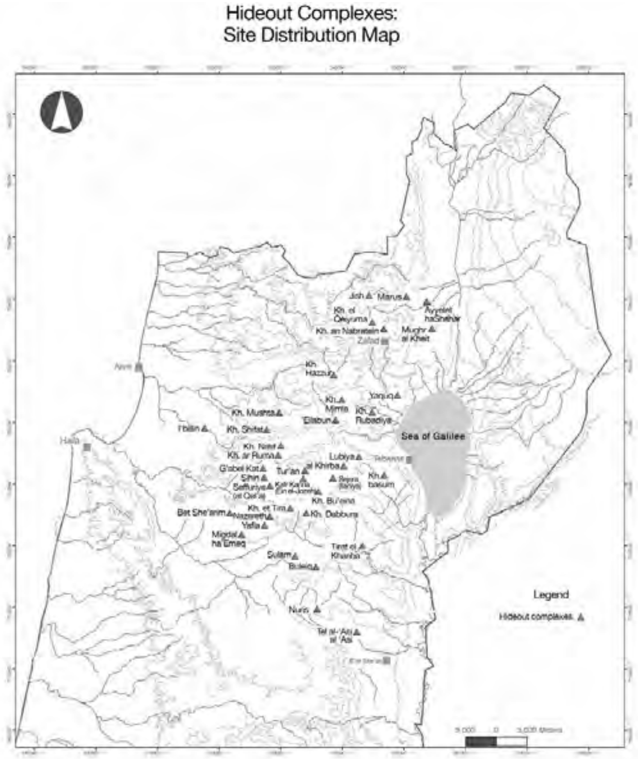

Figure 1. Map showing location of the sites mentioned in the text.

Galilee villages in anticipation of bad times; the finds indicate that some of them date from the late Second Temple period. It seems, then, that these complexes were created in preparation for the Great Revolt.

2. *Elaborate hideout complexes:* These complexes, hewn with great care and attractively finished and smoothed, resemble hideouts at Horbat Ga’ada, Horbat Beit Loya, and Rasm er-Rusum in the Judean lowlands (Tepper and Shahar 1987a, 1987b; Kloner and Zoran 1987). The elaborate hideout complexes investigated in the Judean lowlands have been dated to the time of the Bar Kokhba Revolt, and the 24 surveyed in the Galilee may also have been hewn in the second century CE.

3. *Hideout complexes hewn out of rock-cut subterranean chambers that had been used as storage facilities for agricultural produce, cisterns, olive presses, or ritual baths:* These chambers were closed, cool, and rainproof, and it was relatively simple to convert them into hideouts. Similar hideout complexes have been found in the Judean lowlands at Ahuzat Hazan and Horbat Shem Tov, among other places (Avni et al. 1987; Tepper and Shahar 1987c). In the Galilee, most hideout complexes of this type have been found in subterranean chambers originally hewn to serve as cisterns

or storage facilities; a minority are in chambers used as olive presses (e.g., at el-Khirbe and Ilaniya). In 19 of them I found narrow crawlways, some of them nicely finished and others simple, leading to additional rock-cut chambers. Most of these hideout complexes were designed to incorporate preexisting cisterns or ritual baths, such as at Meroth and Sepphoris. In some places, certain installations were rendered unusable when the narrow crawlways were added. Similar cases are documented in the Judean lowlands, e.g., at Horbat Loya, Horbat Midras, and Khirbet el-Aqed (Kloner 1987a, c; Tepper and Shahar 1987a). In a few cases, such as the complex at Horbat Mistah and one at Sepphoris, the openings of the crawlways were hewn a few meters above the floor of a cistern, and water continued to be stored up to the height of the openings. The fact that only the water could be seen from above provided camouflage. This phenomenon is found at Khirbet el-Aqed in the Judean lowlands, at Horbat Naqiq, and at the Nahal Yattir site (Gichon 1982; Zissu 2001). Presumably, in a time of emergency, when the Galileans realized that hideout complexes could save lives, they decided to do without the subterranean facilities and hewed crawlways in them.

4. *Hideout complexes hewn out of burial caves:* Such complexes are extremely rare in Judea as well; they are found there only at Horbat Burgin (Khirbet Umm Burj) and Horbat Benaya (Kloner and Zissu 2005). Three of the six burial caves turned into hideouts in the Galilee were located within the village of Iyei Me'arot. The other three were outside or on the outskirts of villages.

5. *Escape crawlways:* This type of subterranean cavity is rare in both Judea and the Galilee; consequently, it is hard to know how and to what extent they were used. The only written document in our possession that may describe the use of an escape crawlway in the Second Temple period is by Josephus, who recounts how the besieged people of Jotapata in the Great Revolt used a narrow, hidden crevice as a crawlway for transporting commodities and bringing news (Josephus 1956). The escape crawlway at Gush Halav had a specific purpose: to serve as a hidden route to a spring and a hidden exit from the village. In contrast, Gichon (1982) has suggested, based on Cassius Dio's description of the Bar Kokhba Revolt, that the rebels during that war used the hideout complexes and escape crawlways in two stages and for two different purposes: at first the hideout complexes served as bases for surprise attacks and ambushes, whereas later the rebels used the crawlways to escape from walled towns. As an example of such dual-use complexes, Gichon points to Khirbet el-Aqed, which was surrounded by a wall. Gush Halav was also walled, and dual use may have been made of the escape crawlway there as well (Gichon 1982). Another escape system is found at the Nahal Yattir site, where two crawlways were hewn: one leading to a cistern so that water could be drawn secretly, and the other leading out of town, to the slope of Nahal Yattir (Zissu 2001).

6. *Subterranean cavities that should not be identified as hideout complexes*: This category includes subterranean cavities that Tepper and Shahar believe were hideouts, but in my opinion were not. Those at Jebel Qat, at Illabun, in the Nahal Amal crawlways, and in the Tel Amal tunnel do not have features of hideout complexes. Although the Jebel Qat complex belongs to the bloc of towns around Sepphoris, it lacks the central feature of a hideout – a crawlway, or at least a narrow, relatively inaccessible passage. It is a rock-cut cistern from whose floor a natural cave is accessible. The tunnels at Illabun, described by Tefilinsky, were up to 60 m deep (Tepper and Shahar 1987d), not a depth typical of hideout complexes. The crawlway entrances that Tepper and Shahar found at Tel Amal and Nahal Amal are far from the ruins of the ancient villages, whereas a salient characteristic of hideout complexes is their location beneath a village. The Tel Amal tunnel and the Nahal Amal crawlways were evidently used for transporting water and may have been also used as escape crawlways. In any case, we have no basis for dating them to the Early Roman period, and they were not located within Jewish localities.

3. Discussion

Given the similarities between the hideout complexes in the Galilee and those in the Judean lowlands, some scholars have dated the Galilean ones to the Bar Kokhba Revolt (Gichon 1982; Tepper and Shahar 1987d; Shahar 2003). It is very hard to date the complexes since they incorporate chambers that antedate the crawlways and contain signs of later activity. Moreover, ceramic objects and other items got into most of the complexes in various periods and antiquities thieves broke in before the complexes were studied scientifically. In this study ceramic finds are not used to date the hideout complexes on the assumption that they originate in later disturbances.

Recently it became clear that some of the small, simple hideouts in the Judean lowlands were hewn before the Great Revolt. Therefore, some of the hideouts in the Galilee may also have been hewn before or during the Great Revolt.[6] About a third of the hideout complexes in the Galilee, 21 in all, are of the simple type. The finds in the hideout on the lower slope of Jotapata and in the hideout in Area W at Kafr Kanna attest clearly that these complexes were hewn during the Great Revolt (Alexandre 2008). Additional unsophisticated hideout complexes in the Galilee, such as those at Meroth, Gush Halav, Tur'an, Horbat Nurit, and Horbat Devora, may have been hewn in the late Second Temple period; the nature of these complexes may reinforce the suggestion that they were hewn in a hurry during the Great Revolt.

On the other hand, some of the Galilean hideout complexes may have been hewn in preparation for the Bar Kokhba Revolt. Because most of the hideouts in the Judean lowlands were used by the Jews during the Bar Kokhba Revolt, we cannot rule out the possibility that some Jews in the Galilee prepared for the revolt in the same way (Shahar 2001). Presumably, some of the Jews who had been in hideouts in the Judean lowlands at the end of the Bar Kokhba Revolt survived and fled to the Galilee (see Samet 1985/86). Historical sources indicate that some of the Judean population moved to the Galilee following the Bar Kokhba Revolt; this is apparently reflected in a list of the 24 priestly shifts (Safrai 1980/81).[7] Indeed, an inscription discovered in Tiberias refers to a Jewish family from Horsha in southern Judea who moved to the Galilee

(Stepansky 1999). This migration may also explain the hewing of hideout complexes in the Galilee: refugees from Judea brought with them knowledge that had helped them survive in Judea, so in the Galilee, too, they turned storage cellars and burial caves into hideout complexes. The large concentration of caves in Iyei Me'arot that were used for various purposes may be indicative of this. The scholars who hypothesized that the Galilean hideout complexes were hewn during the Bar Kokhba Revolt saw them as preparations for the revolt, even if the Galilee did not ultimately take part in the fighting. This hypothesis was based on similarity in plans and hewing methods to the complexes discovered in the Judean lowlands, even though no finds have come to light that support this dating (Kloner 1987d; Tepper and Shahar 1987d; Shahar 2003). Mor rejects this hypothesis, claiming that if the Galileans had been preparing for the revolt, they would presumably have taken part in it (Mor 1991). Dickstein notes that the hideout complexes are not unique to the Bar Kokhba Revolt in terms of either place or time, and they should not be viewed as an element of Bar Kokhba's tactical conception (Dickstein 1995/96).

Interesting evidence about hideout complexes is presented by Josephus (1956), who uses two different terms for rock-cut chambers: He refers to the people of Jotapata seeking refuge in "subterranean vaults and caverns". In this phrase Josephus draws a distinction between ὑπονόμοις (subterranean vaults) and σπηλαίοις (natural caverns).[8] Thus, there were both hideout complexes and natural caves in Jotapata.

Based on the new information presented in this paper on the Galilean hideout complexes and their distribution, we see that the subject is worth discussing, and that the hideouts are evidence of fear of the Roman government at various times, not only of preparations for the Bar Kokhba Revolt. Hence, presumably, the simple hideout complexes were hewn during the Great Revolt, whereas the smoother, elaborate ones, such as those at Ibillin, Khirbet Ruma, and Khirbet Khueha (Kafr Kanna), are from the second century CE – although we do not know yet whether they were created in preparation for the Bar Kokhba Revolt or hewn by Judean refugees who knew they could save lives. The relatively large number of hideout complexes hewn out of cisterns – which rendered them unusable as cisterns – seems to indicate that the Galilean Jews were in such distress in the Early Roman period that they valued places to hide over water sources.

4. Conclusions

Several conclusions can be drawn regarding the Galilean hideout complexes. Those at Ibillin, Khirbet Ruma, Khirbet Khueha, and Iyei Me'arot (Complex 54) have all the typical features of elaborate hideout complexes in Judea. In the other complexes surveyed in the Galilee, the outstanding features of the elaborate Judean complexes were not found. In contrast, the Galilean hideouts seem to have unique features of their own: (1) In many cases hideouts were hewn out of older facilities, causing the cessation of activity of those facilities. (2) Most of the crawlways in the Galilean hideout complexes were hewn roughly without attractive finishing. (3) The crawlways in the Galilean hideouts are neither winding nor particularly long and do not have sharp angles.

The two types of hiding places found in both Judea and the Galilee – refuge caves/cliffside shelters (Eshel and Amit 1998; Shivtiel 2008) and hideout complexes – are indicative of a highly motivated Jewish population with impressive organizational ability. In some cases we can compare the preparation of the hideout complexes in the Galilee to activity in Judea between the two revolts: subterranean complexes were hewn and hiding places were prepared, sometimes eliminating important subterranean facilities such as cisterns, storehouses, and even tombs. These activities were motivated by increased concern for personal safety and attest to the distress of the Jews of the Galilee.

We cannot date the hewing of the Galilean hideout complexes with precision. Presumably, some date from as early as the Second Temple period (with the hewing activity intensifying during the Great Revolt); others were hewn before the Bar Kokhba Revolt, and still others afterwards. It is incorrect to date all the hideout complexes discovered in Judea to the time of the Bar Kokhba Revolt; the number of Judean hideout complexes shown to have been hewn in the late Second Temple period, on the eve of the Great Revolt, is growing. It seems that the Jews of the Galilee prepared subterranean chambers for refuge and hiding at times when they sensed a real physical threat to their lives from the Roman authorities, and this occurred frequently during the Early Roman period in Palestine.

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[1] On refuge caves in the Galilee (known as "cliffside shelters"), see Shivtiel 2009, 2011.

[2] For a summary of the data, see Aviam 2004.

[3] Some of the sites on this list lack certain characteristics of hideouts; below I explain why I am not convinced that they are hideouts.

[4] Since this article was written, more hideouts have been discovered at Ayelet Hashahar, Hukok, Sepphoris, Yafa, Kabul, Illabun, Lubiya (Golani Junction), and Horbat Bata (Karmiel), but these have not been documented or published.

[5] On the similar categories and other ways of categorizing the hideout complexes, see Tepper 1987; Zissu 2001.

[6] On simple hideouts from the early first century CE, see Zissu and Ganor 2001/02; Kloner and Zissu 2005. Yadin, Oppenheimer, Foerster, and Aviam noted that the Galilean hideouts may have been created in preparation for the Great Revolt; see Aviam 1983; Oppenheimer 1982; Yadin 1982.

[7] On the ties between Judea and the Galilee, see also Urbach 2002.

[8] He is consistent in this terminology elsewhere as well. See, e.g., Josephus 1956, I: 304, 307, 310–311; II: 573; III: 336; Josephus 1957, XIV: 415–417, 420–430; Josephus 1926, 188; I am grateful to Prof. Bezalel Bar-Kochva for making me aware of this.

ARTIFICIAL CAVITIES OF GAZIANTEP (SOUTHEASTERN TURKEY)

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After the Hagia Sophia and Topkapi Palace of Istanbul (Turkey) underground structures project that we carried out in 2008–2009 as OBRUK Cave Research Group, we began to prepare "Gaziantep Underground Structures Inventory" offered us by Gaziantep Municipality and CEKUL Foundation in November 2011.

The aim of this project was to research, document, survey and making an inventory of the entire underground structure heritage which is within the borders of Gaziantep city and disappearing day by day because of the new constructions. It has been long known that Gaziantep, possessing a continuous inhabitancy since 3000 BC, has hundreds of underground structures which were carved in sandy limestone. Some of those underground structures were used as storage facilities or cisterns, while some others are as yarn ateliers today. Furthermore, despite forming a huge and complex system, underground water structures whose small part can be researched due to destructions are another important phase of that project. This study will provide an assessment of the underground structures, aimed at protecting this cultural heritage. Additionally, it is known that some of the caves dug mostly in soft limestone may collapse. This inventory study will be a reference for the future for preventing such potential hazards. The abovementioned project is basically aimed at detecting, measuring, mapping and studying all underground structures in the old settlement area of Gaziantep, with an Autocad program. Thereby, the relation between all the underground and aboveground structures would not be lost. As a result of the studies carried up to date, 48 artificial caves and water structures have been explored and mapped. The project is planned to be completed by the end of 2013.

1. Introduction

As OBRUK Cave Research Group, we have carried out surveying and mapping of Hagia Sophia and Topkapı Palace underground galleries and chambers at Istanbul during the years 2008–2009, headed by Dr. Çigdem Aygun. It can be accepted as a milestone that those structures, having great historical importance and heritage, have been researched by expert cavers without producing any harm through using "Single Rope Techniques". Within the scope of this project, 32 underground cisterns have been measured and mapped in the Historical Peninsula of Istanbul, and a total length of 2,000 m of tunnels has been explored and measured.

After this project and another study carried out in Hasankeyf's underground structures in March 2010, a project was offered to our group for the exploration of underground structures at Gaziantep (Fig. 1). The basics of the project and how to apply it were planned during the following meetings. After signing the protocol between Gaziantep Municipality and CEKUL Foundation, the studies were launched in the city.

2. Execution of the Project

- At the beginning of the study, a main zone was selected in the city. This study zone was indicated by Gaziantep Municipality and CEKUL Foundation together.
- In the first stage; all underground structures in the main zone, which had been already known, were detected and underground studies started.
- In the second stage, all detected underground structures were measured and processed into the main city plan. Water structures, on the other hand, were searched for level and directions besides architectural measurements are processed into a surface map accordingly, by taking surface related points as reference.
- The local people were constantly communicated and all notifications were taken into consideration. As a result of the whole information, the first detected fields were crossed and various studies in different regions were carried out.
- During the study, plans, features and photographs of each underground structure were recorded as the separate tags. Structures and tunnels were processed into the map.
- The project is coordinated by OBRUK Cave Research Group's architect-cavers.

3. Geology of Gaziantep

The geological units near and around Gaziantep can be classified in three groups:

3.1. Gaziantep Formation

This unit comprises limestone and chalk. The places where the most typical outcrops are seen are Gaziantep and its surrounding area. It is mixed with Fırat Formation in the region. Although it is mostly consisting of soft rocks as argillaceous limestone and chalk limestone, thicker layered massive limestones can also be found. Argillaceous limestones comprise whitish, grey and yellow, loose and thin-middle layered and chalky levels. The unit is dated as Upper Eocene–Middle Eocene (MTA 1997).

3.2. Fırat Formation

This formation crops out in discordance with Gaziantep Formation. The formation starts with a thick layered limestone with cream, white and yellow in the lower part

Figure 1. Project area.

and goes on with more fossiliferous limestone above. In the upper formation, it comprises thick layered limestone. Limestones are generally fractured, and the fractures are filled by calcite. Fırat Formation is of Miocene age.

3.3. Yavuzeli Basalt

This Middle-Upper Miocene formation can be found in the south of Gaziantep. It generally comprises lava flow, which is dark brown to dark gray and blackish. Despite its large outcrop area, it presents thickness ranging between 10 m and 50 m.

4. Tectonics

The East Anatolian Fault, one of the most important faults in Turkey, extending from 50 km north of Gaziantep to the west, and the Dead Sea Rift, which is below this fault from the south to the north, still resume their activities in Turkey. These main faults and all the minor faults between them are active. It is known that, as a consequence of the strong earthquakes in 1526, 1760 and 1822, most of the buildings in Gaziantep were destroyed (Ambraseys and Finkel 1995).

5. Artificial Underground Structures of Gaziantep

48 artificial cavities which were detected in Gaziantep up to now can be classified into 2 groups.

The first group is the underground water structures which were widely used in the past. There are numerous water resources around the plateau where Gaziantep is located. Despite all these resources, there is no water table under the city. Therefore, long tunnels were dug a long time ago in order to bring water to Gaziantep.

To date, some 700 m of the total tunnel length have been explored and several shafts have been investigated. These tunnels, which are for miles and called *"livas"* locally (Fig. 2), are very similar to the ancient *"qanat"* or *"karez"* which were initially realized 2000–3000 years ago in Iran and can today be seen in many countries like Morocco, Algeria, Egypt and China (Wessels 2000; Castellani 2001). The tunnels of Gaziantep some of which are longer than 7 kilometres carried the water from the springs to the town.

There are numerous shafts (or wells) opened from the surface to these tunnels. Unfortunately, the modern settlements in Gaziantep seem to have destroyed most of these shafts and wells.

Apart from these shafts; other underground structures peculiar to Gaziantep are represented by washing pools which are connected to the surface with stairs, and by public places with small baths and lavatories. These public water areas, locally called "*kastel*", were mostly built near the mosques. Although there were at least 15 "*kastels*" until 50 years ago, only 5 examples remain today (Çam 1982).

Nevertheless, the remaining structures give an idea about the impressive architecture of these interesting underground features. Among these structures, Pisirici (Fig. 3) is one of the oldest, together with an underground mosque built in 1283. The *"livas"* bringing water to this structure cannot be precisely followed due to subsidence in the area. Among the other *"kastel"*s, only Ahmet Celebi Kastel, with a slight change, fits for purpose.

The remaining 3 kastels; İhsan Bey, Kozluca and Nadir Bey, are unprotected and have been the victims of wrong modifications.

Figure 2. A typical "livas" under Gaziantep (photo: AE Keskin).

Various water tunnels (*livas*) likewise the ones in Gaziantep War Museum Cave, Tütün Han Cave, Fethullah Mosque Kastel and Ömer Ersoy Culture Centre are all connected to the same underground water system. On the other hand, it was also found that many shafts searched during the project are also connected to those water tunnels. For example, there are two different tunnel connections in the depths of a 44 m deep well of the American Hospital.

Additionally, the soft limestones of Gaziantep are particularly suitable for digging tunnels and other underground structures. Nearly all of the old houses have an underlying cave used as storage (Çanakçı and Güllü 2004). The stones coming out as a result of the excavation were used in the construction of the upper structure. Though most of the caves explored and mapped up to now belong to this group, there are some extraordinarily large structures which were excavated as quarries and then used as yarn or ceramic factories. For example; Akbulut Cave, used as an underground ceramic factory for a long time, covers a total area of 9,500 m^2 and is one of the largest artificial cavities of Turkey. On the other hand, Uzumcu, Iplikci and Sulu caves are still being used as yarn ateliers.

Figure 3. Pisirici Kastel (photo AE Keskin).

As to mention Cemetery Caves (Figs. 5 and 6), it is a gigantic system located under the modern cemetery of Gaziantep, a total area of more than 60,000 m^2, with 14 entries and used as a yarn manufacture and barn previously. It can be considered as the largest known artificial cavity of Turkey.

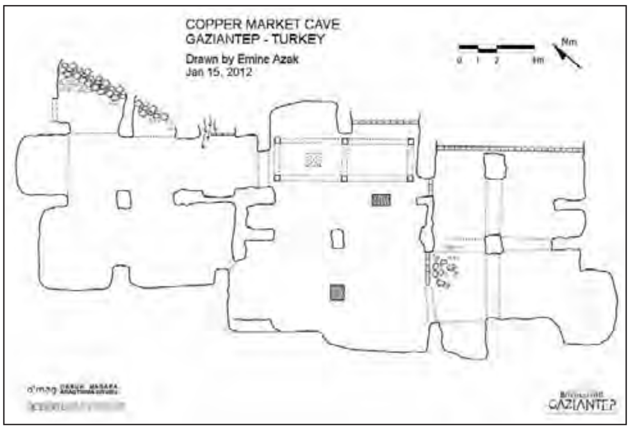

Figure 4. Plan of Copper Market Cave.

The unique example different from the two groups of underground structures mentioned above, is represented by the tunnels located under the Castle of Gaziantep. These tunnels, with a total lenght of 280 m, reach the cisterns at the bottom. Age of the tunnels is unknown, but archaeological researches are continuing at the castle.

Figure 5. Plan of Cemetery Caves of Gaziantep.

6. Future of Artificial Cavities in Gaziantep

Gaziantep is probably the richest region in terms of historical underground structures of Turkey after Cappadocia. Most of the structures that we surveyed during this project either continue to be used for their original purpose or have a new function as a cafe or restaurant. Yeni Han and Tutun Han caves are beautiful examples of those underground structures which are used as cafes today.

Traditional yarn manufacturers still continue to work in some caves. It will be a preferable application that this branch of business, having an ancient tradition, would maintain its activities in the same places after the restoration of their caves.

Furthermore, Gaziantep Municipality is looking forward at the end of this project, to have useful information about the future usage of the empty Akbulut Cave, Copper Market Cave or Cemetery Caves.

Figure 6. Cemetery Cave A5 Main Gallery (photo AE Keskin).

On the other hand, some protected parts of the underground water systems, namely “*livas*” and “*kastel*” will be restored and open to public.

Our main purpose is to protect the available underground structures of Gaziantep and transfer them to the next generations.

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SUBTERRANEAN "BELL-SHAPED" QUARRIES IN THE JUDEAN FOOTHILLS, ISRAEL

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The paper focuses on bell-shaped underground quarries, which were rock-cut in the soft limestone of the Judean Foothills during the Late Roman, Byzantine and especially the Early Islamic periods. These large and imposing artificial caves, typical to this region, located south-west of Jerusalem, were first described by scholars and explorers who visited the area in the 19th century. They were extremely impressed by the caves and suggested various theories regarding their function: cistern, granaries, dwellings, stables and underground churches. The phenomenon was discussed in a pioneering study, undertaken more than fifty years ago by Y. Ben-Arieh (1962) who explained the function of the subterranean caves as quarries, used for the extraction of the local chalky limestone. In the largest cave-clusters, around Beth Govrin, where the region's biggest quarries operated, scholars estimate that their total number is over 800. Others estimate their total number in the region as being about 3,000.

The aim of this paper is to present and describe the phenomenon according to new archaeological and speleological surveys. The current study focuses, among other issues, on the method of quarrying and on a re-examination of the chronology of the phenomenon, the carving methods, and the use and reuse of the caves.

1. Introduction

Throughout ancient Israel, and especially in the Judean Foothills subterranean chambers were cut in the bedrock as part of the economic and physical infrastructure of towns and villages. The hewing technique was refined in the Hellenistic, Roman, Byzantine and Early Islamic periods.

This paper focuses on the phenomenon of bell-shaped underground quarries, which were rock-cut in the soft limestone of the Judean Foothills from the Late Roman to the Byzantine and especially the Early Islamic period. These large and imposing artificial caves, typical to this region, located south-west of Jerusalem, were first described by scholars and explorers who visited the area in the 19th century. The visitors were extremely impressed by the caves and suggested various theories regarding their function: cistern, granaries, dwellings, stables and underground churches (Robinson 1841: 352–355; 395–396; Guérin 1868: 104–106; Conder and Kitchener 1883: 264–293; Smith 1900: 239–244; Bliss and Macalister 1902: 188–270). The phenomenon was discussed in a pioneering study, undertaken more than fifty years ago by Ben-Arieh (1962) who explained the function of the subterranean caves as quarries, for the extraction of the local chalky limestone. In the largest cave-clusters, around Beth Govrin, where the region's biggest quarries operated, we estimate that their total number is over 800 (Kloner 1996: 50–53). Y. Dagan estimated their total number in the region as being about 3000 (Dagan 1982: 35) but this number probably includes other types of caves as well.

The aim of this paper is to present and describe the phenomenon according to new archaeological and speleological surveys. The current study focuses, among other issues, on the method of quarrying and on a re-examination of the chronology of the phenomenon, the carving methods, the use and reuse of the caves.

2. The Geology of the Judean Foothills

The Judean Foothills are characterized by layers of soft limestone and chalky rocks from the Senonian, Paleocene and Eocene periods. The prevailing bedrock is the soft, chalky limestone of the Maresha detail of the Tzor'a Formation, dating to the Eocene, of a 30–100 m thickness. This white, relatively soft and homogenous rock (locally known as "*kirton*") is protected from erosion by a crust of harder limestone, of up to 3 m thickness ("*nari*"). This fissured layer is harder, non-homogeneous, and has a tendency to collapse relatively easy (Kloner 2003).

Throughout the region thousands of underground chambers were cut during various periods. Throughout the relatively easy process of cutting the chalky limestone, a large variety of artificial subterranean chambers was created. In addition, through the quarrying process, good quality blocks of building material were produced (Oren 1965; Kloner and Zissu 2009).

The caves typical to this region served as quarries, silos, water cisterns, columbaria, oil presses, stables, cult rooms, hiding systems and burial caves (Bliss and Macalister 1902; Dagan 1982). The bell-shaped caves are just one of these types of underground chambers.

When the stone-cutters planned to create an extensive quarrying site, they avoided damage to already existing sites and caves. Locations where underground quarrying had not yet taken place were preferred. The location of bell-shaped caves was chosen by carvers who knew how to identify geologically the chalky limestone deposits suitable for quarrying good quality material. Most of the bell-shaped caves were quarried in high-quality Maresha detail *kirton* and only a few of them were cut in lower quality *kirton*, like Adollam and Beth Govrin. It is also apparent that the carvers chose the appropriate topography for quarrying a cave: slope or spurs were typically preferred.

At most bell-shaped caves sites, the method of quarrying was rather similar and there are common defining outlines to the whole phenomenon. The geological characteristics of the region, which combined an upper harder crust and a deeper soft but compact chalk was well known to the stonecutters in antiquity. The first stage of creating a bell-shaped cave was to cut a rounded opening in the upper limestone crust. From the opening a vertical shaft led through the hard limestone layer to the soft chalk below. The shafts were similar in size and their purpose was the penetration of the relatively hard *nari* crust. The average diameter of the top opening is between 0.8–1.2 m. The depth of the vertical shaft varies from two to four meters, according to the width of the crust. In some caves the round shape of the top opening was not kept, for a number of reasons, as quarrying into an already existing, earlier artificial cavity (e.g., at Kh. el-Ein: Zissu 2005) or the quality and specific features of local bedrock. A reason for the "cylindrical" shape of the shaft not being kept in certain cases, may derive from difficulties experienced by the stone-cutters trying to penetrate into the *nari*.

Upon reaching the soft limestone layer, the carvers started widening out the cave downwards and laterally in a circular shape. That method of quarrying gave the caves their typical bell-like shape, which created a large but relatively stable underground cavity.

3. The Quarrying Method

The underground quarrying was carried out using carving tools, as pick-axes, hammers, chisels and crowbars, under natural lighting entering the cavity from the upper shaft, and enhanced, when needed, by oil-lamps. The quarrying operation has left well-marked traces, which appear as parallel rows of oblique chisel marks on the walls. The limestone was extracted as blocks detached from the walls of the cave by narrow and deep channels (Fig. 1).

Figure 1. Bell-shaped cave at Horvat Burgin. Note the chisel-marks and the negatives of blocks extracted (B. Zissu).

The 30–40 cm-high blocks of *kirton* were transported and used as building material elsewhere. When these blocks are used for external walls they require a thick coating of plaster as protection from the elements. The straightening and "finishing" of the cave walls was done by removing limestone chips, apparently burned in kilns and used as a raw material in the manufacture of lime and cement.

This characteristic bell-shaped plan was in our opinion a development and enlargement of an earlier, smaller form of subterranean installation – the typical bottle-shaped silo found in Judea from the Iron Age, (e.g., the "winery" at Giveon: Pritchard 1964) throughout the Hellenistic and Early Roman periods (certain installations at Horvat Burgin: Zissu and Ganor 2008; and at Horvat Ethri: Zissu and Ganor 2009).

Figure 2. Typical cluster of large bell-shaped caves at Luzit (Deir Dubban); (B. Zissu).

In some cases, the typical bell-shape was lost. Changes in the angle of quarrying were made by the stone-cutters due to the appearance of cracks and fear of collapsing. Sometimes, a side opening would have been created because of natural collapse or artificial quarrying that allowed additional entry.

The dimension of caves that functioned as a single quarry is smaller than of those which are part of a cluster of bell-shaped caves. The average depth of a cave is about 5–7 m. and the diameter of its bottom is about 4–5 m. The reason for the smaller size caves appears to be the limited ability to extract the quarried material from the caves and the mobility of the cutters.

Figure 3. Smaller sized bell-shaped cave at Horvat Sgafim (B. Zissu).

Certain clusters of bell-shaped caves, especially in the area of Bet Guvrin and Deir Duban – Luzit, exceed these dimensions. The caves in such groups are characteristically larger in size (Figs. 2, 4 and 5). Their average depth ranges from 10–15 meters and the diameter of their bottom ranges from 6 to 12 m. Few caves are much deeper – up to 20 meters (Kloner 1996). Usually the caves in these clusters were quarried adjacently and were joined to one another in

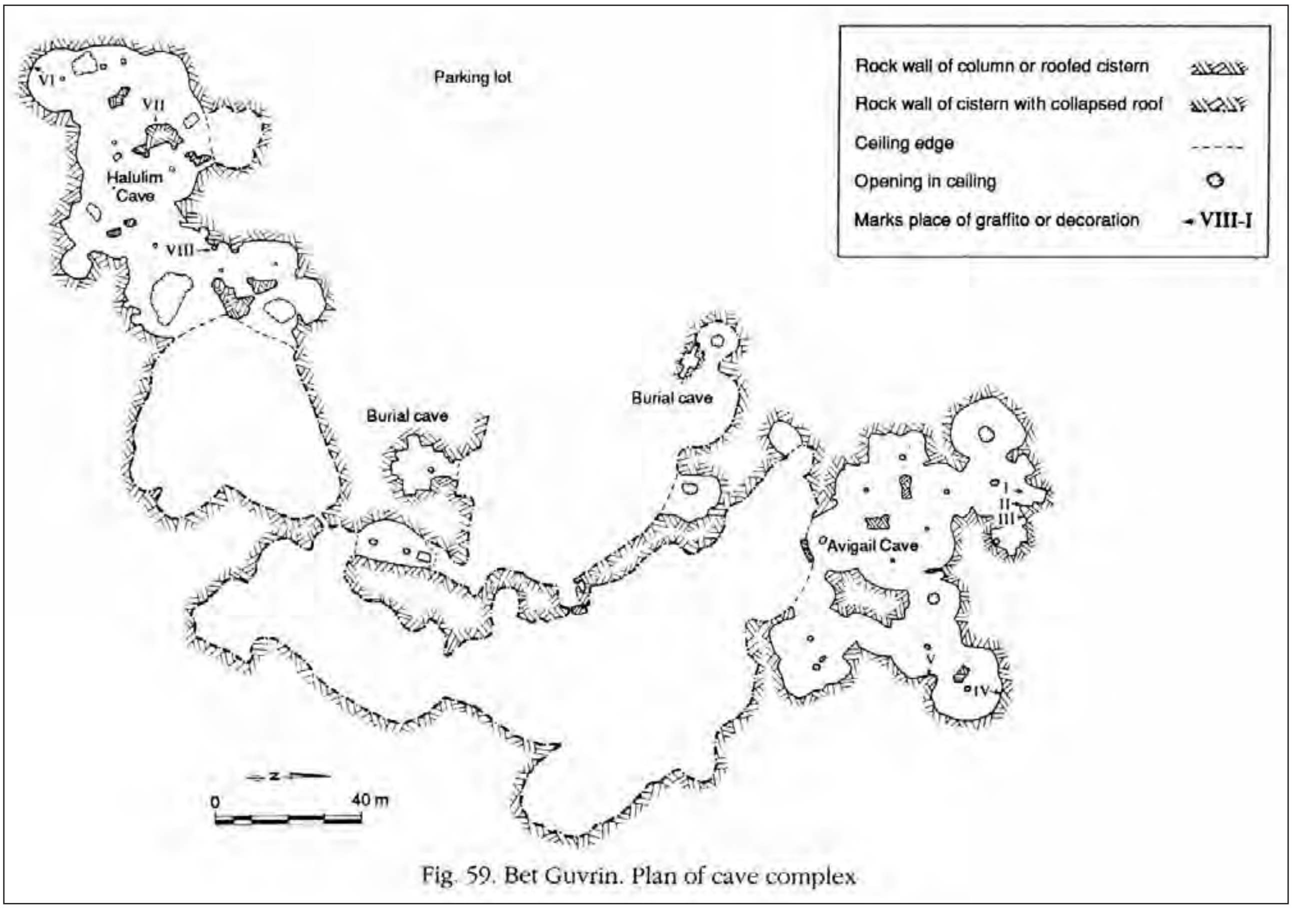

Figure 4. Plan of cluster of large sized bell-shaped caves at Bet Govrin (after Kloner 1989/90: 66).

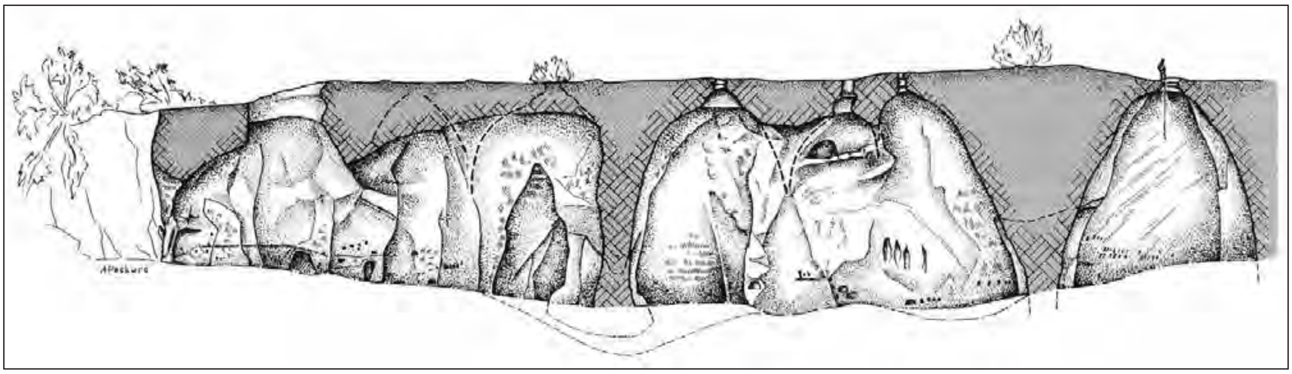

Figure 5. Section of cluster of large sized bell-shaped caves at Bet Govrin (after Kloner 1996: 53).

the course of carving. This was as a result of the cave walls collapsing naturally, an act initiated by the stone-cutters or a combination of both (Figs. 4 and 5).

The caves were connected by a variety of horizontal or oblique tunnels, aimed to allow easy passage of workers, blocks and other carved material and perhaps even pack mules between the cavities to the surface level (Fig. 6).

Staircases were cut into the depth of the wall in some caves. This particular type of staircase is entirely different from the staircases installed in the Hellenistic period "Maresha type" cisterns and quarries, found in the same region. The "Maresha type" bell-shaped caves have typical steps with parapets, spiralling along their inner walls (Kloner 2005). The staircases have no common characteristics and they were created during the digging of the bell, out of mobility considerations.

Quarried into the bottom part of the wall in some of the caves are various niches, hooks for hanging sacks, and devices for holding animals. These features were made when bell-shaped cave quarrying was at its peak, or alternatively when the caves were connected to one another. Some of the installations were probably added after the main quarrying activity.

Quarrying the bell-shaped caves created large underground spaces. A substantial number of the caves were later converted for a variety of uses. After the quarrying was completed, the underground quarries were transformed into animal pens, columbaria installations – some of them of a large scale (Fig. 7). In few caves, agricultural installations such as oil presses were installed. A very small part of the caves were converted into water cisterns. Other caves were used by squatters for residence.

Figure 6. Bell-shaped cave at Horvat Burgin. Nos. 1, 2 mark tunnels, cut in the walls in order to extract the quarried material horizontally (B. Zissu).

4. Chronology of bell-shaped caves

Dating the quarrying operations is somewhat difficult due to very few mentions in the written sources and few findings relating to the period the caves were used. A re-evaluation of the bell-shaped caves chronology is desirable by using various features such as crosses, inscriptions and incisions left on the cave walls and the relative stratigraphy of bell shaped caves and adjacent rock-cut caves and installations.

Figure 7. Bell-shaped cave at Luzit-Deir Dubban – converted into columbarium installation (B. Zissu).

Excluding the "Maresha-type" caves, which belong to the Hellenistic period, the findings show that the bell shaped caves phenomenon post-dates the Second Jewish Revolt against the Romans (The Bar Kokhba Revolt – 132–136 CE). The stratigraphic relation of the bell-shaped caves to adjacent caves shows that the caves cut into and damaged earlier underground facilities, which were probably cut and used by the local population, living in the area prior to the Bar Kokhba revolt, e.g., hiding systems, burial caves (from the Hellenistic, Early Roman and Byzantine periods near Bet Govrin and at Horvat Segafim (Kloner 1989/90), agricultural facilities etc. (Kloner and Zissu 2009; Zissu and Ganor 2008). In certain cases, inscriptions and crosses cut or painted on the upper, now inaccessible part of caves' walls point to a clear Byzantine date (4^{th} to 7^{th} c. CE; e.g., at Tel Lavnin: Zissu 1999' at Luzit-see Figs. 8 and 9). These crosses and Greek inscriptions were incised by the cutters when the cave was still in a shallow phase (Dagan 1982).

In other cases the crosses, carved or incised on the upper part of the cave walls, are accompanied by Arab (Kufic) and Greek graffiti and inscriptions (as in Fig. 10), which support the dating of the bell-shaped caves to the Late Byzantine/ Early Islamic period (7^{th} to 11th c. CE; Dagan 1982: 38–39). Some oil-lamps and pottery vessels found in situ in caves east of Beth Govrin belong to the initial cutting activity and point to a similar Late-Byzantine – Early Islamic dating (Frumkin and Kloner 1989; Kloner and Frumkin 1989).

Figure 8. Cross incised on wall of Bell-shaped cave at Luzit-Deir Dubban – note the greek letters IC/XC/A/W which stand for the christian formula: Iesous Christ, Alpha Omega, (Jesus Christ, beginning and end; photo A. Graicer).

Figure 9. Greek inscription, incised on upper part of bell-shaped cave at Luzit-Deir Dubban – the inscription reads: Holy Isidore, help Stephanos. We assume Isidore was a local saint (B. Zissu).

The Muslim geographer Al-Muqaddasi mentioned in his book (from 985 CE), the "marble quarries" of the Bayt Jibrin district – referring most probably to the bell-shaped caves discussed here. The traveller Nassiri Khosrau visited the region in the year 1035 and referred to the same phenomenon (Dagan 1982: 38–39 and references therein).

Few graffiti were made by hermits, squatters or visitors during or after the Early Islamic period (e.g., at Horvat Burgin: Tchekhanovets 2010).

Figure 10. Kufic inscription, incised on wall of bell-shaped cave at Luzit-Deir Dubban – the inscription reads: "O Allah, forgive Habib's sin" (photo by A. Graicer; Sharon 1997: 365; no. 7).

5. Summary

From the above mentioned data it is apparent that there are clear typological characteristics of the bell-shaped quarries phenomenon. The scattered caves resemble in their characteristics the impressive cluster of over 800 caves, situated near Beth Govrin, where the areas' biggest quarries operated (Kloner 1996; 1993).

In our opinion, the main purpose of the subterraneous quarries was the extraction of blocks of stone. The lime was apparently only a by-product of this industry. The "rock scars" and "block remains" apparent on the walls and on the floor of many caves testify to this purpose.

The mixed Greek and Arab (Kufic) inscriptions, found on the upper part of the walls of some caves testify to the cultural process of the assimilation of the Arabic culture. Following the Arab conquest of the country in 634–640 CE, during the 7th to 10th centuries, the Arabic language gradually became the language of Christians, Jews and Samaritans.

In summary, the re-examination of the findings enable us to suggest the start of the large-scale underground bell-shaped quarries phenomenon to the Late Roman – Byzantine period (4th–5th centuries CE). It appears that the peak of this process occurred during the late Byzantine and Early-Islamic periods, during the 7th to 10th centuries CE.

In order to fully understan additional aspects of the phenomenon, one needs to examine other components of the landscape of the Judean Foothills and their link to the geographical distribution of bell-shaped caves, as settlements, road network and limestone kilns (Ben-Arieh 1962: 58–61; Dagan 1982: 35–39; Dagan 2006: 16*–27*; Kloner 1993: 200–201). This examination is beyond the scope of the present paper.

The outstanding phenomenon of the bell-shaped quarries awaits further study.

Acknowledgments

We are grateful to Yair Zoran, Alon Klein, Elinor Rahel Hajaj, Abraham and Nili Graicer, for their assistance in the field. The article was prepared with the support of the Krauthammer and Moskovitz Cathedra at Bar Ilan University.

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THE ETHNO-CULTURAL FEATURES OF MAN-MADE CAVES CARVED IN THE NEOGENE PYROCLASTIC FORMATION WITHIN THE ARMENIAN HIGHLAND AND NEIGHBORING AREAS

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Pyroclastic rocks of the Neogene Period with numerous dugout cave dwellings are widely spread in the Armenian Highland, Iranian and Anatolian plateaus. There are different types of structures in the cave dwellings (rooms for living, churches, monasteries, tombs, household and auxiliary structures, underground paths), which have been created in the Middle Ages by Armenians, Georgians, Byzantines. The same type of rock-cave culture had been developed in the same geological unit by different ethnic formations located hundreds of kilometers far from each other.

1. Introduction

Pyroclastic rocks of the Neogene age are commonly spread over the Armenian Highland and neighboring areas (the Iranian and Anatolian plateaus): in literature they are referred to as the Goderdz-Voghjaberd volcanogenic-sedimentary suite. By its stratigraphy and lithology, it has analogies in Cappadocia, Ani, Goris, and in the northwestern. Generally, the thickness of this rock suite is about a few hundreds of meters, and includes individual strata of ignimbrite tuffs, tuff breccias, tuff conglomerates and other units related to volcanic activity (Balyan 1969). Underground cavities within the mentioned tuff and pyroclastic rocks have diverse origin. Some of them were formed by suffusion processes, which cause dissolution in the subterranean water of the substances cementing the pyroclastic deposits and subsequent reduction of the rock strength. The rocks became easy to disintegrate and by the effects of water and gravity they were removed, causing formation of voids– cavities and caves of variable sizes. Many of these were enlarged by humans and the created cavities served different purposes. The rest of the caves were created by human activity: humans excavated the rock intentionally, to create underground structures of varying size and form, which would meet their specific needs (housing, cult-related, food storing and other). Creation of such structures in tuffs could be explained by the following considerations:

Tuffs are easy to process and this rock becomes harder upon contact with air;

In structures carved in tuffs, microclimate is stable throughout the year.

2. Cave settlements

The caves are located on the slopes of tableland plateaus of Cappadocia and Ani (Turkey), Vardzia (Georgia), Ghehardadzor, Voghjaberd, Goris and Kh'n'dzoresk (Armenia), and and Maragha (Iran). In the listed areas, the caves are represented by carved-in-rock structures of varying sizes, forming entire cave settlements. In some of these settlements, the number of structures carved in rock is more than several hundreds. For instance, in the period of its flourishing, Ani had about one thousands of rock-carved structures. The richest is the area of, where more than 40 cave towns are known, with as much as about 2000 underground structures of various types recorded just in one of them, in Derinkuyu.

All cave settlements are arranged in tiers, the number of which is sometimes up to 20. Despite the fact that many of these settlements were founded as far back as before the common era, the greater part of the caves were built in the Middle Ages and were related to spreading of the Christian culture. The caves carved in rock had been used both by the monks, and by secular population. The rock-carved structures in Cappadocia are related with the Byzantine culture, in Vardzia they are associated with the Georgian culture, while in Ani, Ghehardadzor, Voghjaberd, Goris, and Kh'n'dzoresk with the Armenian culture.

3. Underground structures

Experts identify the following types of underground structures (Gaprindashvili 1960; Tokarsky 1966; Erdem and Erdem 2005):

- rooms for living (residential);
- churches;
- monasteries;
- tombs;
- household and auxiliary structures; and
- underground paths.

Rooms for living have simple design with rectangular layout, but rooms of oval-shaped or irregular layouts are also encountered sometimes. Their areas are commonly in the range from a few square meters up to a few tens of square meters. Residential rooms had very simple furniture: a few cavities of different size were carved on the walls and served for household purposes (storage of tableware or placing a light source). Decoration elements are lacking. Prayer rooms are a different type of residential rooms.

Churches are represented by a kind of rock-carved structures of varying layout, and different spatial and structural design. Most common are the single-nave churches that have a hall and an apse. Double-nave and three-nave basilica churches are relatively less common. Their halls are partitioned into two or three naves by means of rows of pillars. Church design of more complex layout and spatial and structural concept (cross-shaped, cross-shaped rectangular, domed) are known by a few examples. There are also churches of irregular design, whose spatial concept is determined by the character of the rocks.

Monasteries include not only church buildings, but also other different structures such as *gavit* (narthex), dining rooms, cells and household structures. Their existence bears evidence of an organized monastery life.

Tombs are represented by several types. They are either like open halls, or corridors, or like *gavits*, where burials were made in the cavities located on the floor or on the walls.

Household and auxiliary structures have many types. There could be livestock enclosures, dovecots, caves intended for production of wine, pantries, dairies, water wells and other. These rooms have different forms and sizes. The household and auxiliary structures provided for autonomous life of the underground settlements.

Underground paths linked different parts of underground settlements thus playing the role of streets. They were horizontal or inclined. Horizontal paths linked structures located at the same level (storey), while the inclined ones were stepped and linked different tiers of the settlement. They were often as much as a few hundred meters long.

4. Conclusions

The volcanogenic-sedimentary suite (especially tuffs) of the Neogene age is of high speleological importance for the Armenian Highland and the neighboring countries. Tuffs often had specific "attractiveness" and "appeal", offering the best environment for construction of rock-carved structures. The same type of rock-cave culture had been developed in the same geological unit by different ethnic formations located hundreds of kilometers one far from another.

Similar underground structures all have the same layout and spatial design concepts, albeit with certain differences determined by the historical, cultural and religious features. Armenian, Georgian and Byzantine rock-cave structures display common architectural features, attesting that they all have the same origin stemming from close interactions between Christianity and the culture.

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UNDERGROUND MINES IN MOSCOW CITY

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Within the modern administrative boundaries of Moscow, there is a significant quantity of abandoned underground mines which were the source of a relatively wide complex of natural resources: mainly limestones and subordinately sandstones, clays, and phosphorites. For that territory, the summary of the underground mines is provided, in accordance with the zoning scheme of speleology in artificial cavities (spelestology).

1. Introduction

The article provides an overview of the underground mine workings (UM) known in the modern administrative boundaries of Moscow that were expanded significantly in 2012.We define mine workings as the cavities excavated during extraction of mineral resources.

The major mineral resource widely excavated in this territory is the Carboniferous limestone also known as “Moscow white stone”. Its underground mining in Moscow neighborhood had been carried out at least from 12th century (Florenskiy 1984) up to the beginning of 20th century, with a peak in the 19th century. Underground minings of sandstones, clays, and phosphorites are less common, and date back mostly to the 19th and 20th centuries.

Describing the UM distribution, we use the zoning scheme of speleology in artificial cavities (defined as spelestology in the ex-USSR countries) and that has several hierarchy levels (Dolotov 2010). The description is given in accordance with Spelestological Sites (SpS) that belong to some Spelestological Regions (SpR) of such a hierarchy unit as Moscow Spelestological Division (SpD) of Srednerusskaya Spelestological Province (SpP).

Unambiguous SpS allocation here is hindered, at first, by a significant anthropogenic threatment of the urban landscape and, at second, by poor spelestological examination of most of Moscow city territory. So the scheme of spelestological zoning of the area should be considered as a preliminary one.

2. Overview of Moscow City SpR

In the territory of Moscow, within the Moscow Circular Motor Road, there is a significant number of mines that were used for excavation of relatively wide complex of natural resources i.e. limestones, sandstones, clays, and phosphorites, but only a few of these are located underground. The SpR lays within the confines of Moscow river valley, the upper boundary should be drawn upstreams from Tatarovskiye Highlands, the lower should be downsreams from Kapotnya.

2.1. Overview of Fili SpS

It is likely that within the territory of the Fili Park once a shaft existed that was used for clay mining. Local residents reported that in the early 1980s, along the shores of the Moscow river, there were many collapses, some of which led to semi-filled tunnels with round vaults, and semi-buried crawlways underneath the slope.

All the cavities were situated in argillaceous formations.

2.2. Overview of Dorogomilovo SpS

The quarries in Dorogomilovo are known by historical documents at least from the 17th century (Danshin 1947) and according to some information from the 14th century when the rubble from there was used for the foundations of Moscow Kremlin buildings. (Viktorov and Zvyagintsev 1989).

In the second half of the 19th century the abandoned underground quarries were locally re-opened. In 1860, a passage to a complicated system of tunnels deep in stone was discovered. Semi-flooded labyrinth stretched along the river alternating with halls with severalstone pillars up to 3 m height and collapses. The quarries in Dorogomilovo were also re-opened by a collapse in 1889. In 1892 a vast underground opened near Dorogomilovo cemetery. The entrances near the cemetery have been existed till the early 20th century (Belousova 1997). It looks like that due to water level rise of the Moscow river, with its regulation in the 20th century the Dorogomilovo quarries were totally flooded.

In 2002 when tunneling the subway near the Kiyevskaya station, an old flooded adit was revealed in the limestones (Petrunin 2002).

At the second half of 19th century in Dorogomilovo, there was a clay excavation at the depth of about 10 meters (Belousova 1997).

2.3. Overview of Vorobievy Gory SpS

There is no documentary evidence of an existence of underground UMs at Vorobievy Gory hills but there is a mention of mining sandstone there (Danshin 1947). First, the terrain does not allow to excavate at the site any significant quantity of minerals openly, and, secondly, there are reports about existence of chinks on the slope resembling semi-buried underground entrances. So the probability of the existence of underground minings there could not be omitted.

2.4. Overview of Kotly SpS

In the valley of the Kotlovka river there were large underground quarries representing a complex passage labyrinth (Bogatyryov 1989). It is known that the entrances to the quarry were blocked in 19th century to prevent a dwelling of criminals.

2.5. Overview of Kolomenskoye SpS

In Kolomenskoye in 1922–24, trial adits were started for phosphorite extraction, that were called Kolomenskiy district of Tsaritsynskiy mine. The mining stopped due to the very unfavourable conditions (Konstantinovich 1934a; Danshin 1947). Most likely, these minings are today destroyed.

2.6. Overview of Chagino SpS

In Kapotnya near the former Chagino village in the 1920s, there existed three adits of Chagino district of Tsaritsyno phosphorite mine (Konstantinovich 1934b).

2.7. Overview of Chertanovo SpS

In Bitsa woodland park, at the valley slope of Chertanovskiy stream, there is an excavation resembling a quarry. On its sides, karst sinks with up to 3–3.5 m in diameter are visible. It is likely that small adits existed there, and most likely sandstone have been mined there.

At the end of 19th century in the area of modern Bitsa park small stones quarried for paving roads had been quarried (Azancheyev 1894). The existence of mines in Chertanovo is likely associated with these works.

3. Overview of Upper Pakhra SpR

A small SpR in the upper Pakhra river, characterized by limestone mining, is totally unexplored and with unclear boundaries.

3.1. Overview of Mikhaylovskoye SpS

Near the village of Mikhailovskoye, limestones have been mined for lime burning (Zavidova 1932a).

4. Overview of Podolsk SpR

By the late 18th century this area is known as the site of the oldest white stone underground mining (Zuyev 1787), and the arms provided to Podolsk city in 1781 beared two picks in a blue field in a sign that the citizens are enriched in stone mining (Sokhin 1997). The SpR is situated in the middle part of the Pakhra river and involves the lower parts of the Desna and Mocha rivers. The region boundaries are drawn by the line of the Middle Carbon limestone surface explanation. The Northern boundary lays at Ryazanovo village by the Desna river, the Eastern one is layed near Krasnaya Pakhra settlement by the Pakhra river, the Southern one is near Klenovo village alongside the Mocha river, and eventually the Western one is downstream the Pakhra river from Pleshcheyevo village. The administrative boundaries of Moscow include only a part of the SpR.

In the area, local microrelief of ravines and river valleys is everywhere largely controlled by former minings of Podolsk and Myachkovo limestone. Quarries are widely represented, with a number of development trenches (one of the most important features for locating underground quarries), and collapse sinks. Within the SpR dozens of underground quarries are known.

4.1. Overview of Zhukovka SpS

Near Zhukovka village, some development trenches were observed.

4.2. Overview of Troitsk SpS

On the right bank of the Desna river downstream the city of Troitsk, the valley slope is dug by development trenches and small quarries.

Near the village of Bogorodskoe *Bogorodskaya* cave (*Vatutinki-2*) was found representing a part of a large quarry. Through low drift you can get to the main part of the cavity, a large pillared hall, cut with sliding workings. The height of the vault is up to 2 m. The length of the cave is 365 m.

Down the river, near Vatutinki village some development trenches were found.

4.3. Overview of Desna SpS

Apparently the underground stone mining was carried out here already during the 18th century (Zuyev 1787). The traces of such quarrying are situated alongshore the Desna river downstream from the Desna village. According to local residents in 1930s, there were available near-entrance adit parts of 10–15 m long Nowadays, all the entrances are nowadays buried.

4.4. Overview of Laptevo SpS

Laptevskiye quarries are located at the bank of the Desna river. According to local old residents, at the village of Laptevo there was a large underground quarry, with several small adits. The entrances were buried in the middle of the 20th century during a road construction. In 1989, three of these small adits were re-opened.

4.5. Overview of Mostovskoye SpS

In the village of Mostovskoye, some traces of UM including development trenches, apparently of different ages remained. In the late 19th century lime and rubble stone had been mined here (Azancheyev 1894).

4.6. Overview of Tarasovo SpS

To the Southeast of Tarasovo village, there are development and collapse trenches.

4.7. Overview of Alkhimovo SpS

Near Alkhimovo village, the bank slope of Desna river is strongly disturbed by development trenches and collapse sinks. Some opencast quarries are situated there. At present there are three caves known, apparently dated by the second half of the 19th century.

Alkhimovskaya-3 (*Gazprom*) is a fragment of a large quarry. Its entrance was opened by a collapse at the bottom of an opencast quarry. It differs by its structure from the rest of SpS caves. The cave consists of two sub-parallel drifts with walls that are strengthened by rubble. The drifts are connected by a narrow barely passable crawlway. The cave length is 115 m (Yanovskaya 2012).

Alhimovskaya-1 (*Ledyanaya*). The cave is a strongly collapsed fragment of a large quarry. The cavity represents a grid of mutually perpendicular passages with relatively small between-drift pillars. Low and narrow crawlways are alternated with collapse halls up to 5 m height, small fragments of preserved drifts have a height of about 1.6 m. Multiple collapses occupying at least 90 % of the preserved cavity part are caused apparently by blasting. The length of the cave is 157 m (Yanovskaya 2012).

Alkhimovskaya-2 (*Luna-Park*). Alhimovskaya-2 cave is a strongly destroyed fragment of a large quarry that included Alhimovskaya-1, as well. In accordance with that, the structures of the two cavities are similar – the quarry at that site originally was a grid of mutually perpendicular passages, some less regular than in Alhimovskaya-1. The cavity is strongly affected by collapses and represents a system of short drift fragments, often semi-filled by loose material, alternating with collapse halls and high piles of stone blocks. The length of the cavity is more than 160 m (Yanovskaya 2012).

4.8. Overview of Devyatovo SpS

All the slopes of the Desna river valley near the village of Devyatovo are broken by opencast minings, development trenches, and collapse sinks. The most interesting is *Silikatnaya-1* (*Devyatovskaya*), one of the largest man-made caves in the Moscow area that was developed till the early 20th century. The entrance is located in an old opencast quarry near Devyatovo village. In 2000s, the quarry was earthed up, but the access to the underground quarry has been preserved thanks to reinforced concrete well, erected over the entrance. The quarry deepens under the slope for about 650 m stretching for about 600 m in width. The length of the mining passages is more than 12 km. The quarry is characterized by a continuous development system and well-preserved rail network. The cavity has a complex configuration, it has two major developed and rubble piled volumes limited in most of the area by the faces. In the interior of backfill, sliding drifts are left forming a complex labyrinth. The systems are connected by only two passages. These areas are neighbored by smaller quarries, and in the entrance areas, there are fragments of older minings preserved. Passage width is about 2 m, the passages are characterized by heights of 1.1 m and 1.7 m.

4.9. Overview of Rybino SpS

Opposite to Rybino village, all the shore slopes of the Desna river valley are strongly disturbed by surface mining, development trenches, and collapse sinks. Underground limestone mining was carried out in large quantities, mineworks run deep under the slope. Several underground quarries are known there.

Rybinskaya-1 is the largest quarry of the SpS. Apparently it was developed in the late 19th century (Azancheyev 1894). The cavity runs under the slope for more than 400 m and stenches alongshore Desna river for more than 200 m. It consists of two branching drift systems developed independently and joined together by single connection hole. Drift walls are built of processed stone slabs. The entrance is located in the smaller system. Two of its drifts run under a ravine, in one of them a large hole formed filling actively the cavity with a material that comes from the surface. The drift that leads to the main system connection hole is blocked in two places with active sand-clay cones. Main system drifts are rather high, more than 1.5 m, the height of the faces is 0.8 m. The minework length is about 2,000 m.

Rybinskaya-2 (*Lisya*)**.** A small adit branching at the entrance for two well-preserved drifts, with walls that are reinforced by rubble masonry. The drifts are ending by faces. The mine is 40 m long.

Sobaka-2. The cave entrance is a crawlway within a collapse deposit. It leads to a tunnel which walls have been strengthened with rubble. At 30 m from the entrance the tunnel branches, the left drift leads to a collapse under a ravine. Collapses in the cavity are developed rather extensively. Cavity length is 80 m.

Sobaka-1. The quarry is a highly littered and crushed tunnel, that brings in 15 meters to a drift that runs along a face line. The mine working is 44 m long.

4.10. Overview of Yerino SpS

On the high bank of the Desna river near the village of Yerino, mining traces are found everywhere and on several levels. Stone extraction was carried out both underground, and openly, probably at two or three levels. Limestone was quarried for cement production, apparently blasting was used for the extraction (Parfyonov 2011). The extraction was carried out till 1930s (Zavidova 1932b). Three quarries were opened here in 2010:

Sredneyerinskaya-4 (*Tyotya Emma*). The quarry configuration is simple, it extends along the Desna river for 60–65 m, deepening under the slope for 25–30 m. A solid crosscut starting from a development trench and three drifts drived parallel to the riverside were a basis for the works. The excavated space represents a not fully formed grid that can be divided in three cells. Drift width is 3.5–4.0 m with a height of 1.6–1.8 m. Mine length is 128 m. Collapses in the cavity are developed rather widely and generally are represented by large and medium blocks (Parfyonov 2011).

Sredneyerinskaya-5 (*Belenkaya*). The cave stretches along the river for 30 m deepening to a slope for about 25–28 m. For a basis, some solid workings starting from a development trench were used. The eastern part of the working has a more complicated structure and consists of three mutually perpendicular segments with a length of 10–12 m. It is obvious that the initial design was grid-like. The length of this part is 95 m. The eastern part of the working is joined with the central one represented by a drift with a length of about 20 m. The northern part of the work has a length of about 25 m. Geometric elements of the workings are poorly kept up. Drift width is 3.5–4.0 m with a height of 1.4–1.7 m. Cavity collapses are relatively few and the vast majority of them are represented by large and medium blocks (Parfyonov 2011).

Sredneyerinskaya-3 (*Filifionka*). The quarry stretches for 110 m along the Desna river, deepening to slope for about 25–30 m. The cavity has a form of an irregular manifold. The southwestern part of the cavity is slightly different from the main one, being a fragment of an irregular grid. The work basis was a system of solid crosscuts and a drift that was run parallel to the riverside. Geometric elements of the system were not kept completely. Drift width is 3.5–4.0 m with 1.6–1.8 m height. Mine length is 260 m. Cavity collapses are widely developed, most of them are large and medium blocks (Parfyonov 2011).

The next two caves known since 1960s:

Sredneyerinskaya-1 (*Penaty*; *Mramornaya*; *Ninina Shchel).* The cave is a trapezoid-shaped chamber in a monolith that is connected with the surface by an inclined crawlway. The length is about 15 m.

Sredneyerinskaya-2 (*Lisya-2*). It is located near Sredneyerinskaya-1 up the Erinsky ravine. The cavity hss collapsed and is now explorable for a few meters only. In 1988, an attempt was made to enter the cave at the top. In a sink above the entrance, a pit was dug that penetrated a block pile at the depth of 7 m. Throughout the pile, along the complicated crawlway, it was possible to get to a dome-like secondary cavity that was probably formed over the collapsed volume. Total length of the cavity is about 15 m.

4.11. Overview of Salkovo SpS

Near the village of Salkovo there were a series of underground quarries (Zavidova 1932b). In 1960s there were found several open cave entrances: *Dubrovitskaya-1* – 15 m; *Dubrovitskaya-2*; *Dubrovitskaya-3*, a chasm with 3 m depth.

4.12. Overview of Krasnoye SpS

On Pakhra river, downstream of the village of Krasnoye, there were limestone mines. There development trenches and sinks are found. Some open quarry entrances still existed in the mid-1970s. In 1970s, near the village of Sofyino, there Sofyinskaya cave was known with a length of 20 m.

4.13. Overview of Podosinkovo SpS

Near the village of Podosinkovo, an underground limestone mining was carried out at least since late 18th (Zuyev 1787) till the beginning of 20th century (Zavidova 1932a).

Raevskaya cave is located in 0.2 km upstream from Raevo village. Quarrying had been observed there in the second half of the 19th century (Trautscholts 1870). In 1980s a cavity was rather large room (length of about 10 m and an area of about 50 m^2), heavily filled with sand (Sokhin 1997).

4.14. Overview of Shaganino SpS

In the area of Kuzenevo village, near the former Pishchery village *Pishcherskaya* underground quarry was opened with a length of 20 m.

In the village of Shaganino according to historical evidence (Azancheyev 1894), there existed a limestone adit mining. Its traces are now represented by development trenches.

4.15. Overview of Shalovo SpS

Upstream and opposite from the Shaganino village, on the high bank there is a series of quarries. In one of these, *Gagarinskaya* cave was opened with the length of about 20 m being a face ending drift.

4.16. Overview of Batybino SpS

There are records of underground limestone quarrying near the Troitskoe village on the Mocha river (Trautschold 1870; Zavidova 1932a). However, no traces of quarries were found on the left bank of the river near the village of Troitskoe. It is possible that these were minings on the right bank near the village of Batybino mentioned. To the south of Batybino there is Batybinskaya cave known, representing a drift fragment with the length of 15 m ending with a collapse.

4.17. Overview of Oznobishino SpS

Stone quarrying had been carried out here since old times, at least from the 16th century. There are adit stone quarrying in the 18th century records (Zuyev 1787). In the 20th century limestone was also adit quarried (Zavidova 1932a). Along the left bank of the Mocha river near Oznobishino village there are development trenches and open quarries along with a few of sinks situated. Along the right bank of Lubyanka river between Oznobishino village and Naumovo village quarries are severely damaged, the valley slope abounds in sink fields and collapse trenches.

4.18. Overview of Shchapovo SpS

Near Shchapovo village on both the banks of the Lubyanka river there are development and collapse trenches along with sinks found. According to some sources, underground minings were stretching up to the village of Aleksandrovo (Sokhin 1997).

4.19. Overview of Lubyanka SpS

Lubyanka SpS is located by the Lubyanka river upstream from Naumovo (former Lubyanka, Lubniki) village. The initial slope surface is complicated with development trenches and collapse sinks. In an area of up to 120 m width there are sites with numerous old collapse sinks. The sinks are often arranged in rows by several along the collapsed excavations. At the slope foot there are thick dumps of lime kilns. There are several known caves that are preserved parts of one large quarry. An opening of limestone layer was carried out by horizontal adits from the Lubyanka bank. Individual excavations were joined together to form a complex adit labyrinth. Quarry vault was supported by rubble walls and pillars of different shapes and sizes.

Lubyanka-5 (*Solnetsnaya*) – a large excavation that runs 100–120 m beneath the river slope and stretches for 130–150 m alongshore. It is bounded by a line of faces on the north and by impassable collapses on the west and east. The spatial structure of the cavity is very complex. Stone excavation was carried out in several stages and the direction of mining operations and main haulage drifts were changed accordingly. The cavity has many small pillar halls often partially embedded with rubble. In the eastern part there are three rather large areas that are separated by a collapse line from the main part and connected to it with a single passage. Ceramic pot shards with red spiral ornament made in Moscow workshops in the 16th century have been found in the cave. Collapses are widespread in the cavity, the largest are concentrated at the flanks. The total cave length is up to 4,000 m.

Lubyanka-4 (*Mandula*). The cavity runs beneath the slope for 10–15 m and stretches alongshore Lubyanka for 20–30 m. It is bounded by impassable collapses from all sides. There are only two haulage drifts remained. Collapses are widespread in the cavity. Its length is 55 m.

Lubyanka-2 (*Lisiy Laz*; *Lisya Nora; Oznobishenskaya*). The cave entrance is a pit of 1.2 m depth at the end of development trench. The cavity vault is located at the level of 1.2 m from the surface. The cavity runs beneath the slope for 40–50 m and stretches alongshore the Lubyanka for 20–30 m. It is bounded by impassable collapses from all sides. The spatial cave structure is quite complex. Intact areas are joined together by narrow crawlways throughout collapses, in the remote area there remain quite large halls. The near-entrance part is continually smeared out by soil coming from the surface. Collapses are widespread in the cavity and cover most of the total area. The cave was investigated for 200 m.

Lubyanka-1. A small quarry fragment with the length of 7 m actively smeared out by soil.

5. Conclusions

It should be noted that historic entrances of Moscow region UM are mainly confined to valley slopes and ravines, i.e. areas with high activity of geological and geomorphological processes and therefore as a rule have not survived to the present days and were often closed by collapses, landslides and slope deposits. In view of these circumstances and the fact that most of old-timed quarries had not been documented only a fraction of historic sites of quarrying are known, and available for visiting quarries are now a small part of their total number.

It should be also noted that the details and accuracy of the information provided above are not uniform because of different details in the site studies.

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Session:

Karst and Cave Survey, Mapping and Data Processing

1000 AND 1 CAVES IN "LEFKA ORI" MASSIF, ON CRETE, GREECE

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Crete, the fifth largest island in the Mediterranean sea has been subject to numerous speleological, archaeological and geological expeditions over the years. Nearly 50 % of the island is covered by limestones in the form of high rocky mountains. Lefka Ori massif is located to the west side (Chania district), it is the second highest on Crete (Pahnes, 2,454 m) but the largest in surface. The massif has a unique shape which is formulated by its 54 peaks – counting only those higher than 2,000 m altitude) and hosts some of the deepest caves in Greece including the deepest and the second deepest (both deeper than -1,000 m). Expedition reports from local or international teams targeting this amazing mountain are dating back in the early seventies and have revealed some unique caves and big shafts such us the well know Mavro Skiadi (shaft, -342 m), Drakolaki cave (+175 m), (Katavothra tou) Tzani (-280 m), Gourgouthakas (-1,208 m), Lion cave (-1,110 m) and others. The majority of these reports – especially those published before the year 2003 – are having limited information on the exact geographical location of the caves explored and/or located. With the world "exact" the author means coordinates of entrance recorded with a GPS (Global Positioning System) device which can be then re-used by other GPS or GIS (Geographic Information Systems) software. This fact (lack of entrance coordinates) influenced a new era of speleological projects in the area initiated by SELAS speleological club of Athens (in 2003) and a number of local and foreign contributors (clubs or individuals). Thanks to excellent cooperation developed between local and international teams (the contributors), **1,255 cave entrance coordinates** have been recorded and consolidated in one single database. The effort lasted 9 years so far and the author apart from taking part in many of the above field trips, has been also the person collecting and consolidating the datasets from the teams involved. If we take into account the known work of other teams that concern datasets which are due to be shared with the author, the number of validated cave entrances in the massif are (today) **more than 1,400.** The geocoded information provides new perspectives and opportunities in better understanding and exploiting speleological GIS datasets of the Lefka Ori massif. The subject of this paper is mainly presenting this dataset, the contributors and the effort and method used. Announcing the outcome of this project to the global speleological community is also interesting as a benchmark and to share experiences with other similar works carried out around the world.

1. Introduction

1.1. General

Lefka Ori is an amazing massif in an amazing island, Crete. When you are in the middle of this mountain e.g., *Pavlia Halara* area, there no roads, no trees (in high altitude) and no water. Based on the cave surveys recorded over the years, one may notice that the mountain has a high number of big vertical puits, especially when compared to mountain Idi (Psiloritis 2,456 m), to the east. The longest cave on the massif is *Tou Tzani o Spilios* with current length being more than 2.8 km. There are also some unique shafts (-342 is the deepest) and some super deep caves (more than -1,000 m) which attracting today's local and foreign cavers to organize expeditions in this mountain.

With GPS technology being available to the public in early 90s (and becoming reliable, for the public, after 2000) it is clear that all previous works in the area need revisiting in order to record cave locations with proper entrance coordinates. By having accurate coordinates of cave entrances, these can be used for GIS purposes, enabling the correlation of caves entrances to several geographical or geological information. Its existence is also helpful to resolve issues occurring when trying to count caves in a specific area.

1.2. The project

Having said the above, this paper is about a single database of cave entrance coordinates accompanied by some basic cave data collected between 2003 and 2012 by 17 expeditions and at least 8 trips in the area of Lefka Ori, on Crete. With the term "trip" we define the short expeditions usually lasting a weekend or long weekend (3–4 days) while proper expeditions usually last longer e.g., more than a week. Both trips and expeditions constitute the fundamental field work which was a key element of this effort. In parallel, there was a need in collecting, consolidating, clearing the datasets collected from field work which was also important. Part of this job was done in the field (Lefka Ori) during the expeditions and another part of it, was done afterwards at expedition level or at a cross expedition level (consolidation). Both the field work (expeditions) and the "homework" (consolidation of information) were fundamental for the subject of this paper which we call *"the project"*. The author apart from participating or leading in the many of the field expeditions or trips, took the role of the central point of contact for the above mentioned consolidation.

There was no written agreement between clubs/teams involved in this effort nor any central guidance or formal leadership on this project. It all came out of people from many countries working nicely together for a common goal, willing to share with each other. It is also worth mentioning that the project is not over yet as there at least 2 expeditions that are due to share their results with the project and of course there will be more future expeditions in the mountain. For now, this paper is just about sharing the outcome and some findings of this project with the public, as a first milestone (1,000+ caves) was reached.

1.2.1. The field work

The above mentioned **17 expeditions** contributed **928** cave entrance coordinates to the project. As stated above, several trips took place, some were preparatory steps for expeditions to follow in an area while others were local cavers activity for months or years in the same area. The trips contributed **327** cave entrances, leading to the total number of caves now available in the database to be **1,255.**

Table 1. Total caves in Lefka Ori, Crete between years 2003 and 2012.

Total caves in Lafka Ori Explorations 2003–2012	Total Caves
Validated and added in database	1,255
Not added yet to the database	185
Total	1,440
Estimated total	**1,400+**

It is also know that 2 expeditions that operated in the area are due to share their results. These expeditions reported that they located **188** caves, not included in the database. By adding the above the total number of caves (validated with coordinates) in the area of Lefka Ori should be above **1,400** caves. This is lower number that the sum of the above numbers as we anticipate there will be some overlapping of caves between the datasets.

The approximate time spent in the field was **308 days** (10 months) by approx. **308 cavers.** One may say that **for every day in Lefka Ori, more than 4 new caves were added** to the database. There were mainly 3 countries involved (Greece, Great Britain and France) with **9 clubs** taking the lead in organizing expeditions or field trips during these **9 years.** In addition cavers from **Romania, Italy, New Zealand** and **Israel** very actively and enthusiastically contributed by participating the above activities. More specifically, the table 2 indicates the clubs involved and their activities.

Several devices were used in the field for collecting data. The oldest type of GPS used (that came to our attention) it was a GARMIN GPS12XL The most frequently used devices were GARMINs e-trex family. Some minor GPS accuracy problems were detected but they are usually fewer when a modern device is used and when the user operating the device is more experienced. Using different devices means slightly different accuracy and somehow different information being recorded when in the field e.g., date is added on the remarks in some devices while this is not in case in some others.

In addition several methods were used in the field when collecting data. If we see the main contributors of the project we may notice that SELAS and FOS were using mainly in the field excel spreadsheets or paper forms or handheld PDAs. Every subject (a cave) was assigned with a code number (initially a continual number or a number with a prefix indicating the area). Later – after 2009 SELAS introduced different coding for its one use: first 2 digits indicating the year when the cave was found (e.g., 09 for 2009) followed by a 3 digit number non continual usually segregating teams (under the same expedition) to avoid assigning the same code in 2 different subjects while on expedition (e.g., 09100 to 09199 was assigned to team / GPS 1, 09200 to 09299 was assigned to team / GPS 2, etc). Both SELAS and FOS recorded existing coding when they were finding caves marked already by previous expedition e.g., GSO21 marked by GSO expedition in 1992 was recorded in GPS with the same code.

This code (number or other) was then used to link the coordinates in GPS to any drawing or relevant information about the subject in notes taken by expedition members. A similar approach was used by the second most significant contributor, SUSS. The SUSS coding appear to be based on the teams, with 2 first digits being letters, indicating the team leader / GPS, followed by numbers indicating the subject (cave). Coordinates and other cave information were consolidated in a more clever XML format (one file for coordinates and basic information).

Some teams of SPOK club (Mavrokosta, Gkiouzelis and Gigourtsis) contributed to the project mainly in the form of MS Word® documents containing the coordinates and some basic cave info. Some others (Valantis Vlachos and Augoustinos Economou) contributed with .KML (Google Earth file) containing both coordinates and some notes about each subject (on the comment field). The UK based RRCPC (Red Rose Caving and Potholing Club) also contributed with MS Word reports while the French GS Catamaran in some cases with a .pdf official report for the expedition, in other cases (e.g., 2010 expedition) with GPS files.

Table 2. Activity and contributions by club.

Club name and origin	Caves contributed	Days in field	Members
SUSS (Sheffield, UK)	435	56	40
SELAS (Athens, Greece)	348	95	123
FOS (Athens, Greece)	220	32	57
SPOK (Heraklion Crete, Greece)	102	37	27
GS CATAMARAN / DOUBS (Doubs, France)	94	56	27
OSCA (Heraklion Crete, Greece)	38	3	4
RRCPC (UK)	18	29	30
Total	**1,255**	**308**	**308**

Collecting data from the field can be challenging and requires proper organization and certain provisions by each expedition. If not organized well might lead in errors and that will require more effort to collect again.

1.2.2. The homework

The above mentioned "babel" of different approaches used in the field created a challenge in the consolidation phase (between datasets from different expeditions). This challenge was undertaken by the author starting with SELAS waypoints (as the author is a member of SELAS club). Waypoints were first loaded in OziExplorer® software by several GPS devices and a central file for all SELAS expeditions was formed. OziExplorer software has the ability to select waypoints "not on map" and this was one of the first filters used to efficiently remove waypoints not relevant to the project work. GPSBabel.exe software was then used to remove duplicates based on name/code and a "radius" range of 5 meters. This helped a lot to reduce the number of subjects to validate. Finally, by browsing notes taken by the expeditions and by visual analysis (on screen) the waypoint file was considered to have unique cave entries only. When that was accomplished for SELAS then SUSS data were added. It was necessary to create a custom converter from XML to .wpt for Ozi Explorer to be able to read the data contributed by SUSS. But when this was done the file nearly doubled. More entries followed in the years to come as the expeditions were developing. In some cases e.g., data from SPOK club were manually added while other data e.g., in .KML format were easily added by using the append function in OziExplorer software. This is mainly how the final file was created with 1,255 entries of cave objects. The file is kept in the form of .wpt (OziExplorer waypoint file) and .kml file (Google Earth waypoints). In addition cave information is kept in a basic .csv (Comma Seperated Values) format.

2. The evolution of the project

Inspired by former expeditions and the mountain itself, a few SELAS members which were already familiar with the area (since 1997) organized their first attempt to explore the central massif in 2003. In a few days they found 36 caves and this is how the project started. The club continued in 2004 with two short trips and recorded 78 caves more. By the end of 2005 the club had found more than 200 caves. The areas where SELAS focused were firstly Pavlia Halara and then Ammoutsera and Sternes. At that time only RRCPC (Red Rose Caving and Potholing Club) from UK and SPOK from Crete were sharing some info about their trips in Lefka Ori and contributed with a datasets of waypoints indicating cave entrances. During the UIS 14th ICS in Kalamos Athens Rob Eavis and Robbie Shone members of Sheffield University Speleological Society (SUSS), UK got in touch with SELAS, became aware of the project and decided to organized the return of SUSS to the mountain. As a result SUSS organized 2 trips in 2006, a preparatory expedition (March) and a proper expedition at summer (June–July). Both trips targeted *Mavri Lakki* area. As a results, the SUSS team contributed 174 waypoints that year. Same year, a joint expedition between SELAS and FOS club members operated in Ammoutsera, Sternes and Pavlia Halara area.

In 2007 it is again a mixed team between FOS and SELAS members returning to the mountain. This time FOS is taking the lead and operated in Kako Kasteli area (North East side of the massif). During the FOS club preparatory trip **50 caves were recorded in 1 single day (by 3 people)**. In total, by the end of 2007, another 98 caves were added, 83 by FOS and 15 by SPOK club which was operating short trips to the mountain during that year.

With **268** caves being contributed to the project, 2008 was definitely a very fruitful year. The result was mainly driven by SUSS's *"Crete 2008"* expedition (124 caves, Mavri Laki area). FOS also returned to Kako Kasteli area for the 2008 expedition and collected 103 new caves. Finally SELAS joined GS CATAMARAN (from France) in "Lion" expedition and they contributed with another 41 caves (Atzinolakas area, north side). Apart these caves, this expedition resulted in the exploration of Lion cave (-1,110 m), till today the second deepest cave in Greece. During the same year, the Hellenic Speleological Society of Crete (HSS Crete) organised an expedition to Psari peak area (North) and found 125 caves which are not shared with the project yet (pending publication). If we add HSS Crete findings, the caves found during 2008 were 393.

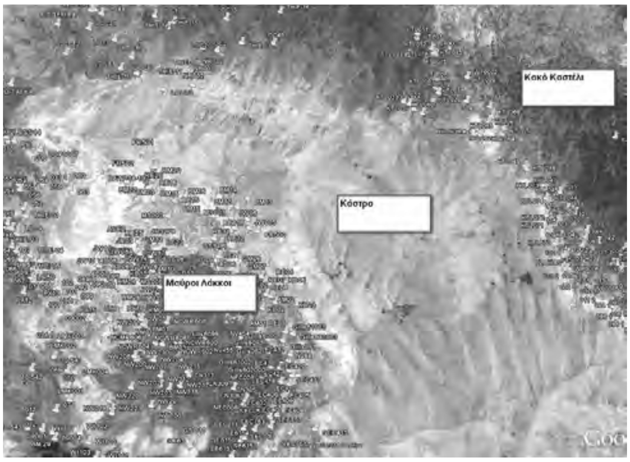

Figure 1. Dark dolomites of Mavri Lakki (bottom) and Kako Kasteli (top) appear to have significantly higher number of caves entrances when compared to e.g., Kastro Peak (middle) which is covered by pure limestones.

Late 2008 early 2009 was realized the first attempt to consolidate the above datasets in one unique database. The number of caves consolidated in the first attempt were slightly above 500 and it is the time when the aspiration to reach 1,000 cave entrances was formulated. The outcome is announced over the web together with a call for other teams – that worked in the area – to contribute. The field work continued of course, so in 2009 we witnessed 3 expeditions: one by SUSS which returned to COLOSUSS (together with a few SELAS and SPOK members, Mavri Laki area). This expedition had no significant contribution in terms of new caves found but was focused in exploring COLOSUSS, a very important cave – which found to stop in a boulder chock at -553 m. A few weeks later SELAS returns to Sternes area (and Sternes -463 m cave) after a while (together with FOS and SPOK members) and contributed with 44 new cave entrances in the areas of Sternes and Thodoris. Last but not least, FOS club returned to Kako Kasteli area for a last time since then and found 34 new caves. The same year (2009) Valantis Vlachos (SPOK member) contributed 55 caves and some notes for caves found around Korda peak (between Kako Kasteli and Atzinolakas, north side of the mountain). These caves were found in several weekend trips by small teams of 4 to 6 people in a period between 2007 and 2009. Finally, concerning, HSS Crete operated one more expedition to the mountain in 2009 and found 60 caves, with one being deeper than -400 m (PS7).

The following year (2010) two expeditions took place the same period (nearly identical dates) and they camped only 400 meters away from each other. These were the SELAS expedition *Sternes 2010* and the GS Catamaran / GS Doubs (FR) expedition in the area. There was very good cooperation between the two expeditions, besides members were well known on both sides for 10–15 years. The two expeditions were using the same coding principle for marking caves but the work in different areas. The French team was working in Rousies area while SELAS is working in the area between Sternes and Mesa Soros. SELAS was working in parallel Sternes cave (-463) by performing enlargements on some passages. SELAS was joined that year by a team of fellow Romanian cavers. The outcome of the year was: 53 caves found by the French team and 32 caves found by the SELAS (GR, RO) team. Same year (2010) the *SUSS Crete 2010* expedition took place in Mavri Lakki with significant findings (139 caves found).

The following year (2011) there was only SELAS returning in Sternes area, this time followed by French, Romanian, Italian cavers and a New Zealander. 54 more caves were added (and the majority explored) and the team was officially celebrating the achievement of the 1,000+ caves benchmark which was set as an aspiration in 2009. Finally, SELAS returned again in Sternes in 2012 with a small team but only 12 new caves are added to the database. Inch by inch, day by day the file reached 1,250+ entries and may reach more and the more in the future as the potential of the place seems to be great.

Table 3. Clubs by area, by surface covered and caves found by area (excluding Psari area).

Club	Code on map	Sq km	Caves	Caves/ km^3
SELAS	AM	10.3	348	33.8
SUSS	ML	6.8	435	64.0
FOS	KK	3	220	73.3
SPOK	ZR	4.2	65	15.5
SPOK	KR	2	55	27.5
CATAMARAN	RS	2.6	53	20.4
CATAMARAN	AT	2.6	41	15.8
Total		**31.5**	**1,217**	**38.6**

3. Geology and Geography of the project

The mountain and more specifically the areas in scope are mainly covered by limestone's (white) and dolomites (dark gray). When browsing the data one may notice a correlation between the caves entrances and the rock type: grey dolomites appear to have more cave entrances than the white limestones (see Figure 1). It worths elaborating more in this aspect in a future paper as well as understanding if there is any correlation between the depth / length of the cave and the rock type at the level of entrance. For now, experience says that the deepest caves in the area have been all found close to the junction between the two types of rock (white limestones and grey dolomites).

The expeditions included in the project were operating in different sides of the mountain. The area covered by the teams is around **30 square kilometers** and represents nearly 10 % of the total surface of the mountain. This segment of its surface has been searched by the expedition members but that doesn't mean that all caves existing in these areas have been found. In order to make this geographical distribution of expeditions visible to the reader the main area of the massif has been divided in 8 areas which are coded with a 2 letter code according to local name of the area / peak. In example KK stands for Kako Kasteli area. This coding is then linked to a color and a club which was operating expeditions in that particular area. Table 3 is the link between clubs and areas. On the same table you may find the surface of the area covered by each club (in square km) and the number of caves found in this part of Lefka Ori (so far). The area coding is presented in Figure 2.

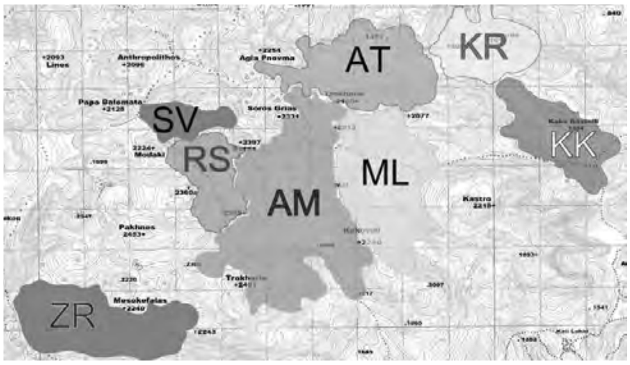

Figure 2. Target area by expedition as shown on Table 7.

The following figures are based on Google Earth® and represent some realistic views of the above color coded areas.

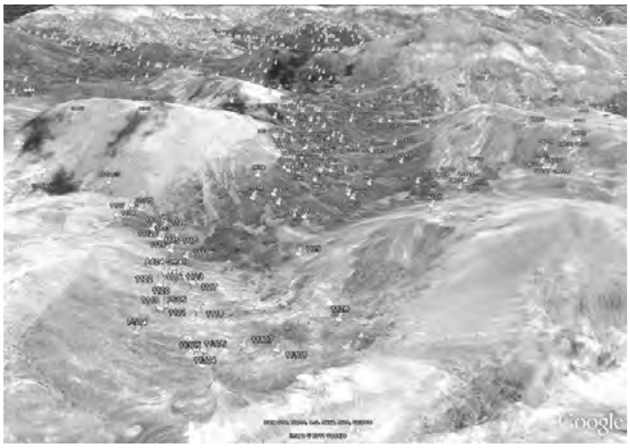

Figure 3. Satellite image (Google Earth) with the caves plotted on it AM area (SELAS).

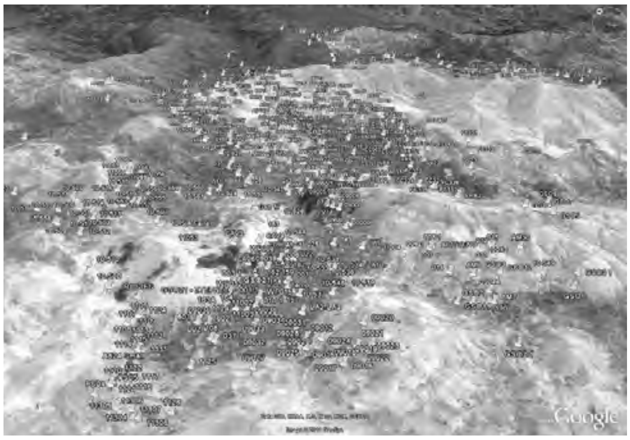

Figure 4. Satellite image (Google Earth) with the caves plotted on it. Areas shown are AM (SELAS) and ML (SUSS).

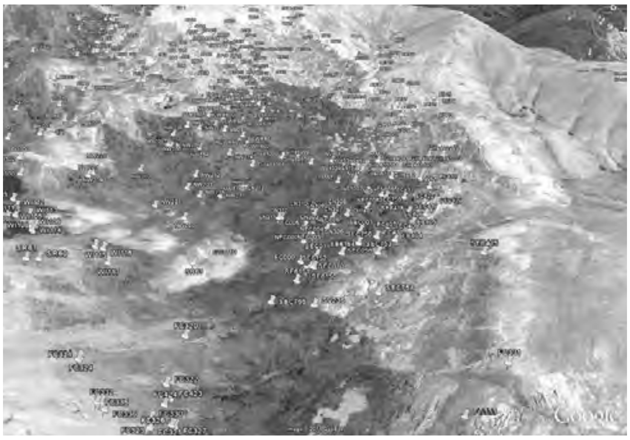

Figure 5. Satellite image (Google Earth) with the caves plotted on it, ML area (SUSS).

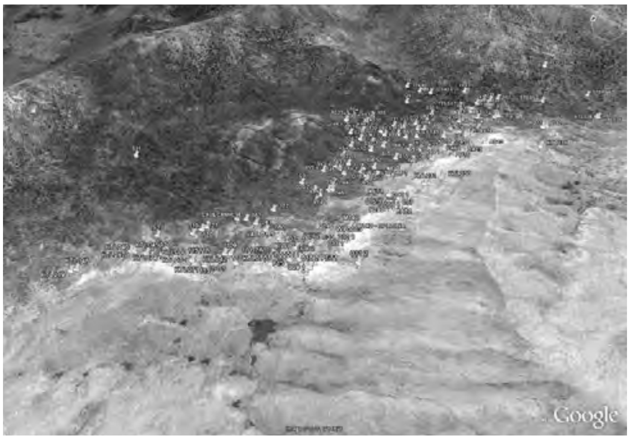

Figure 6. Satellite image (Google Earth) with the caves plotted on it, Kako Kasteli area (KK), FOS club.

4. Results

It is very safe to say that the dataset contains information about more than 1,001 caves. The dataset can have numerous uses and several studies can be made out of it. For example it can be used in correlation with the surface rock type and with the application of statistical techniques to make a forecast to calculate the potential of the entire mountain.

Figure 7. Satellite image (Google Earth) with the caves plotted on it, ZR and SV areas are shown on the lower right and the high left corner of the image (SPOK, SV and ZR areas). Upper right corner is showing RS (CATAMARAN) and AM areas (SELAS).

In addition out of these 1,255 caves around 740 have been explored (or at least partly explored). The majority of the caves are between 4 (minimum) and 20 m depth as it is shown on the histogram presented below. Several similar studies can be made on the dataset that may reveal patterns, correlations or other learning points that will allow us to better understand the cave environment of Lefka Ori but these are out of scope of this paper.

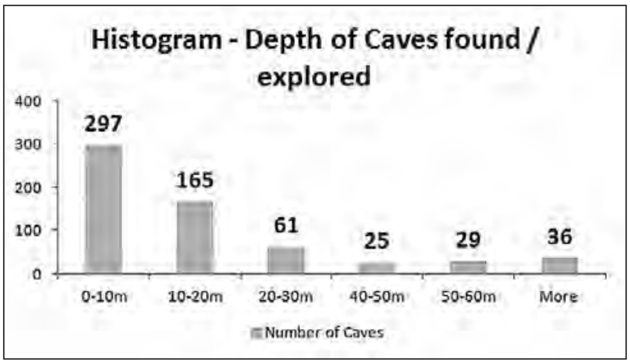

Figure 8. Histogram by depth of a dataset of 614 caves in Lefka Ori.

5. Conclusions

Reaching and exceeding the 1,000 caves milestone of the project revealed and confirmed the potential of the area and calls for more expeditions in the future. The potential of the area is significant and author's thesis is that the final number will be a multiple of the current number. In addition, only 60 % of the caves found have been explored and many out of these explored might reveal new leads in the future. It is worthy to continue with the exemplary cooperation that the above mentioned teams had shown. It will also be worthwhile in exchanging views with other similar projects around the world to see if this process of collecting these datasets can be more effective and more efficient.

It is definitely important to preserve Lefka Ori for the future generations. The wild environment of the massif is unique in Greece and in Europe, well known by people who walk it through as the "high desert". We welcome future expeditions to join our efforts provided that they will respect the environment, they will be having the kindness and the team spirit to contribute to this project and that they respect UIS code of ethics. Teams who are interested to contribute may contact the project and the author via (www.lefka-ori-caves.info) or SELAS club (www.selas.org). In addition EOS Chanion club situated in Chania will appreciate to be contacted / informed when expeditions are organized. The mountain is considered to be a protected National Park and as such it is surveilled by Samaria National Park (www.samaria.gr). Local authorities and municipalities are to be kept abreast as well – mainly municipalities of Sfakia to the South and Fre to the North side of the mountain. Lastly, please note that caves are protect by law in Greece.

Acknowledgments

The author would like to thank the members of the above mentioned expeditions for their contributions. Special thanks goes to EOS Chanion club located in the area and always contributing to the expeditions with membership and support. Especially Mr Antonis PLYMAKIS, George Fidikis and Michalis Polychronakis (all members of EOS Hanion) for their support and assistance from day 1 and for every single year. The clubs of SELAS, SUSS, FOS, SPOK, SPOK, GS CATAMARAN, OSCA for their ongoing support,

Giannis Orfanoudakis and his bakery in Anopolis for being the beginning and the end for all our expeditions as well as Nikos and Kostas for their support with the transportation to and from the mountain.

Peter Stavropoulos of SELAS for being together with Kostis Limakis (who is not with us anymore) the heart of this project for years between 2003 and 2006, Nikos Paspaliaris of FOS for being an exceptional leader and a fellow teammate in the expeditions with SELAS and FOS club. Grigoris Anastasopoulos and Yiannis Sourlatzis of SPOK for their active participation in the most difficult projects during this decade.

Rob Eavis and Robbie Shone (SUSS) for taking seriously this mountain, organizing 4 very important expeditions in the area and for promptly responding to any request for cooperation. Mr Jim Stevenson of RRCPC for being for so long in the area and keep on contributing to the society about its caves. Chrysa Mavrokosta, Nontas Gkiouzelis and Nikos gigourtsis of SPOK for sharing and the ongoing cooperations. Valantis Vlachos of SPOK for the contributions about Korda. Oana Chachula and our Romanian friends for their active involvement

Thierry Monges, Mouloud Koob, Leon Bonvalon, Marc Faverjon and the fellow cavers of GS CATAMARAN from France for “introducing” us to the mountain in 1997. Finally, all the former expeditions their reports and for the inspiration they gave us.

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MAQUINÉ CAVE, BRAZIL – OVER 170 YEARS OF CAVE MAPPING

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Abstract. The Maquiné Cave has great relevance in the Brazilian and international speleological context, and has been the subject of scientific studies and mapping work since 1835. This work rescued the historic line mapping this cave, composed of four distinct phases, and extending for more than 170 years. The current map, which corresponds to the fourth period mapping is not only more accurate than previous ones, but is an important tool for the management and protection of the cave. In the study it was possible to evaluate each of the four phases of mapping, analyzing the evolution of mapping techniques speleological in Brazil and the different uses of cartography produced.

Resumen. La Cueva Maquiné tiene gran relevancia en el contexto espeleológico brasileño e internacional, y ha sido objeto de estudios científicos y trabajos de mapeo desde 1835. En este trabajo se rescató a la línea histórica de cartografía, compuesto por cuatro fases distintas, y que se extiende por más de 170 años. El mapa actual, que corresponde a la asignación de cuarto período no sólo es más preciso que los anteriores, pero es una herramienta importante para el manejo y protección de la cueva. En el estudio se pudo evaluar cada una de las cuatro fases de la cartografía, el análisis de la evolución de las técnicas de mapeo espeleológicas en Brasil y los diferentes usos de la cartografía producida.

1. Introduction

The Maquiné Cave has great historical and speleological relevancein the Brazilian context, and in the scientific international context as well. The cave present rooms with significant volume, notable speleothems of rare beauty and an important archaeological site in the entrance area. Since 1908, most of the Maquiné is used for public visitation, being the first Brazilian cave to receive artificial light in 1967. In 2005 was created a protected area, the State Natural Monument Peter W. Lund, who was an important step to protect the cave and its surrounding area. In the first half of the nineteenth century the cave was studied by Danish scientist and naturalist Peter W. Lund, who revealed to the world the importance of this cave and its exceptional sedimentary deposits, where he found several specimens of extinct megafauna. Today the cave is visited by about 50,000 people per year, and the years 2009 and 2010 was conducted its Management Plan, an important step towards the protection and control of environmental impacts (IEF, 2010).

The history of Maquiné Cave mapping is unique in Brazil and presents a timeline composed of four distinct moments, extended for over 170 years. The cave has been mapped since 1835, when the artist and assistant to Peter W. Lund, the Norwegian Peter A. Brandt, conducted the first survey. About 100 years laterthis first effort, the cave was mapped again in 1940, by the geometer called A. Heberle. The third phase of mapping activities occurred in 1983, conduced by the first speleological group created in Brazil, SEE – Sociedade Excursionista Espeleológica (Speleological and Excursionist Society). The fourth and final phase of mapping coincides with the completion of the Management Plan. This new map, more accurately, is an important instrument for the analysis of the current situation of the cave and for planning its future use.

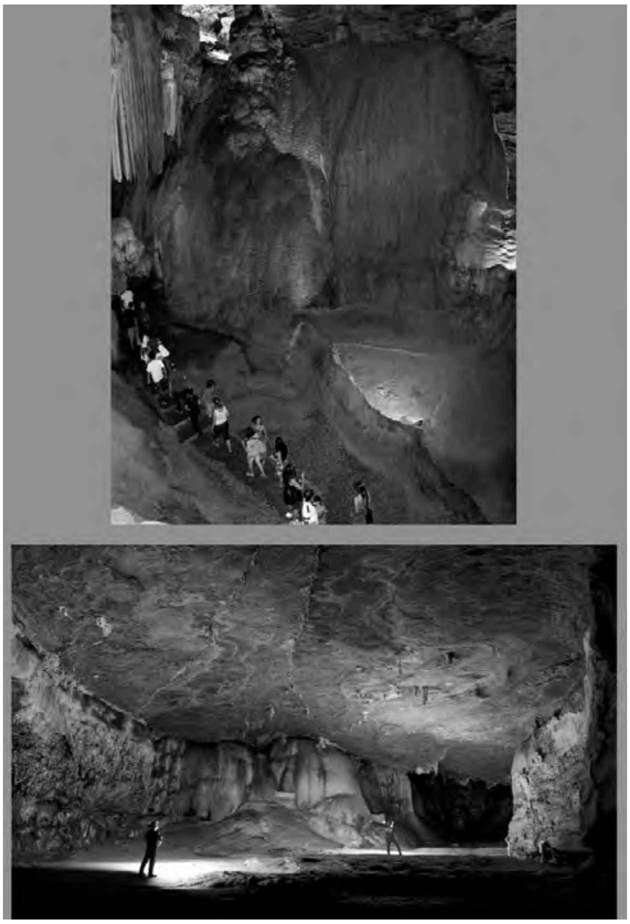

Figure 1. Above: view of the sixth room with flowstone and turistic catwalk; below: view of the large volume ofseventh room (photos: Luciana Alt).

2. Geology and morphology

The Maquiné Cave developed in limestones of the Neoproterozoic Era, deposited in tectonically stable area, called São Francisco River Craton, an important and extensive Brazilian river. The cave has 1,312 meters of linear development, being composed of seven distinct rooms, separated by sets of speleothems that creats restrictions on passages volume. Its development is preferably horizontal, which facilitated its exploration, scientific research and mapping. The first five rooms are actually distinct chambers within the same linear conduit, oriented in the N–S direction. On sixth room the structural conditioning passes to E–W direction also determining the development of the first portion of the seventh room, the larger volume of the cave. After this part the main body of this last room lap to take again the N–S direction of development (Fig. 2).

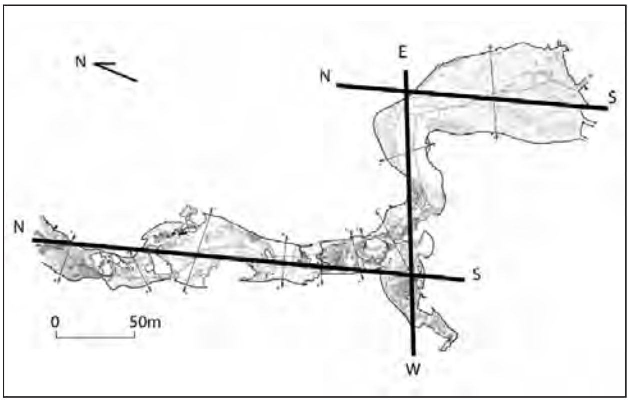

Figure 2. Maquiné Cave map of 2009 (IEF 2010) showing main structural alignments.

3. Methods

Methodologically the work was divided into two distinct stages, the historical research and the production of a new map. The first activity was the literature research on the basis of existing official maps. This was coupled to a field research to identify evidence of preterit mapping activities. Were found two examples of old topographic bases, one of 1904 and another of 1965, whose maps are not known. It was also identified bases from 1940 mapping works.

In the second step, the new mapping activitywas carried out through the method of fixed bases. As basic instruments were used bearing compass and clinometer (KB14 models and PM5, Suunto®) and a laser meter with a range of 50 m (model DLE 50, Bosch®). Combined with this system was performed a centerline additional mapping, using a Leica®Total Station. The work basis was a highly detailed sketch, with the hiring of numerous topographical bases for the faithful delineation of chemical, clastic deposits and other internal features. The sections and profiles were made with a irradiation method, using a combination of laser meter (model DLE 50, Bosch®) and clinometer (model PM5, Suunto®), both mounted on a three-way photographic tripod. This combination allowed the creation of accurate sections and profiles.

In the UIS classification for the map corresponds to grade 5-4-B but with centerline additional mapping the accuracy of the 2009 map isa actually between grades 5-4-B and 4-X-C, which increased accuracy. Considering BCRAclassification, this mapping is between 4C and 5D grades. Detailed measurements were made more than a conventional 4C mapping detailing, making measurements on topographic bases and also between them. However, this mapping does not reach the required precision in the 5D degree, which can only be obtained with the use of Total Station or a Theodolite across all the survey process.

The current map was drawn digitally by using two softwares. For the survey, was used the On Station 3.0a, with subsequent export of .dxf data format. The final cartography was produced with use of Autocad ® 2002.

4. Results and Discussion

4.1. Historical maps

The first known cartographic documentation is from the first half of the nineteenth century, made by Peter Andreas Brandt (Fig. 3). Despite some deviations of measuring angles and distances, the map made in 1835 shows good proportions between the galleries and is a work of great precision, mainly due to the working conditions of the time (Rubbioli and Auler 2002). Is remarkable Brandt's representation of the different features of the cave, as the main clastic sediments and speleothems sets. It is also remarkable the fidelity with which the Norwegian drew the longitudinal profile, with a variation in height, very close to the real, and an excellent illustration of the main sets of speleothems and their relationship with the galleries and halls. According Rubbioli and Auler (2002, p. 19) maps produced by Brandt, "constitute a record of pioneering space conditions of our caves and, as a whole, considering the time they were produced, they form a collection of international significance."

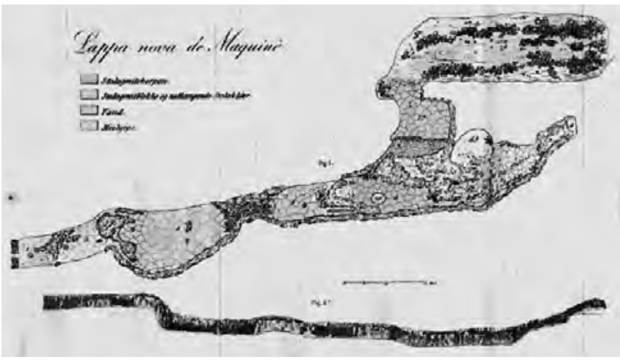

Figure 3. Maquiné Cave map of 1835 by Peter Andreas Brandt (Holten 2011).

It took over 100 years to the cave being target for a new detailed mapping. In 1940, the geometer Afonso de Guaira Heberle did a new map, already using theodolite to obtain precise angles, vertical and horizontal distances (Fig. 4). The Heberle's map introduces a good representation of the conduits and rooms delineation, but makes minimum references to chemical and clastic deposits and also to relief features. Even with a small number of topographic bases and few auxiliary measures, thegeometer madea quite accurate outline of passages and rooms, showing, as Brandt, great skill as a draftsman and a good understanding of the forms of the underground environment. According Rubbioli and Auler (2002) measures the average deviation angle between the horizontal maps Brandt and Heberle is around 10 degrees, confirming that Brandt used compass in your survey.

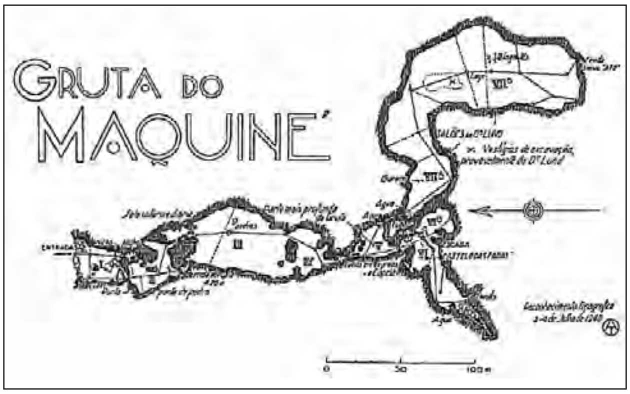

Figure 4. Maquiné Cave map of 1940 by Afonso de Guaíra Heberle (Heberle 1941).

After 43 years of Heberle's work, in a timethatalready exists several Brazilian caving groups, the pioneer SEE – Sociedade Excursionista Espeleológica (Speleological and Excursionist Society) performed a new mapping of the cave (Fig. 5).

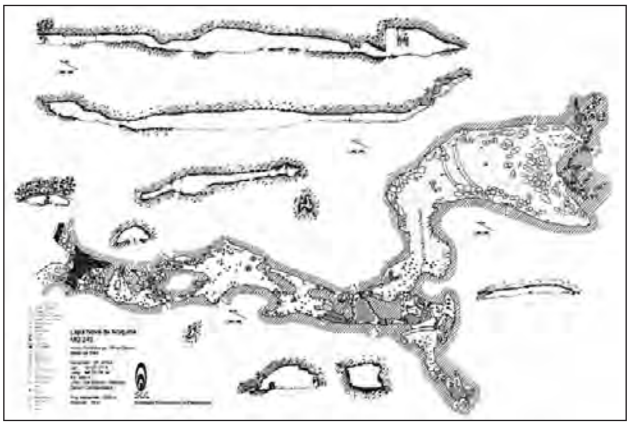

Figure 5. Maquiné Cave map (SEE,1983) by SEE-Sociedade Excursionista e Espeleológica (Speleological and Excursionist Society).

Also using theodolite, for more accurate measurements, the cavers have developed a methodology based in the modern cartographic documentation, where we highlight the following characteristics: (I) contour accuracy of passages and rooms; (II) the use of standardsymbology of clastic sediments, chemicals deposits and variations of internal relief, (III) three-dimensional representation of space with the use of cross sections and longitudinal profiles.

It is possible that other campaigns have been carried topography in Maquiné Cave, since there are marks which suggest such activities (Fig. 6). However, no references were found of such maps.

4.2. Actual map

For the current management studies and procedures was essential a reliable cartographic documentation with accurate representation of all speleological features. This was used as a fundamental basis for all work stages, as field surveys, analyses, diagnoses and planning. This mapping

Figure 6. Topographic mark of 1904, drawn in pencil over a flowstone.

was conducted in June / July 2009, by a team of cavers coordinated by L. Alt.

The 2009 map shows good precision in conduits and rooms contours, combined with a faithful representation of chemical deposits, clastic deposits, occurrences of water and internal relief fetures of the cave (Fig. 7). This detailed mapping allowed also the accurate representation of the current existing infraestrutue, as the lighting system equipments and walkways. The new topographic map was the basis for development of various thematic maps such as impacts, attractions, weaknesses, risk to visitors, zoning and others. It was impossible to use the previous existent maps to produce these thematic maps, which were the basis of the management studies.

The new map also incudes the detailed cross sections and a longitudinal profile represented the most important parts of the cave, showing the main sets of speleothems and other deposits (Fig. 8). This set of cartographic documentation allowed the proper development of the Management Plan and generated an important and accurate record of the current situation of the cave.

4.3. Ratio between number of topographic bases and cave area

We believe that to determine the accuracy of a mapping is not only important to measure parameters related to of precision equipment and team characteristics, but also the ratio between the number of bases and topographic area of the cave. With this relation it is possible to establish the detail level of one map, especially compared to other maps. To measure this ratio we propose using the formula below.

$$\mathbf{C_{det} = N_{bases} / Area}$$

C_{det} – detail coefficient

N_{bases} – number of topographic bases used

Area – cave area

Applying this formula to the 1940 map we have C_{det} = 0.0048, but using the 2009 map since we have C_{det} = 0.1175. Thus the coefficient of detail of the 2009 map is 24 times higher than that of the 1940 map. Comparing the two maps is visible this detail differences. This coefficient can be used as an additional criterion for measurement and qualification of one mapping work. Obviously this does not qualify the map itself, but must be combined with other analytical instruments.

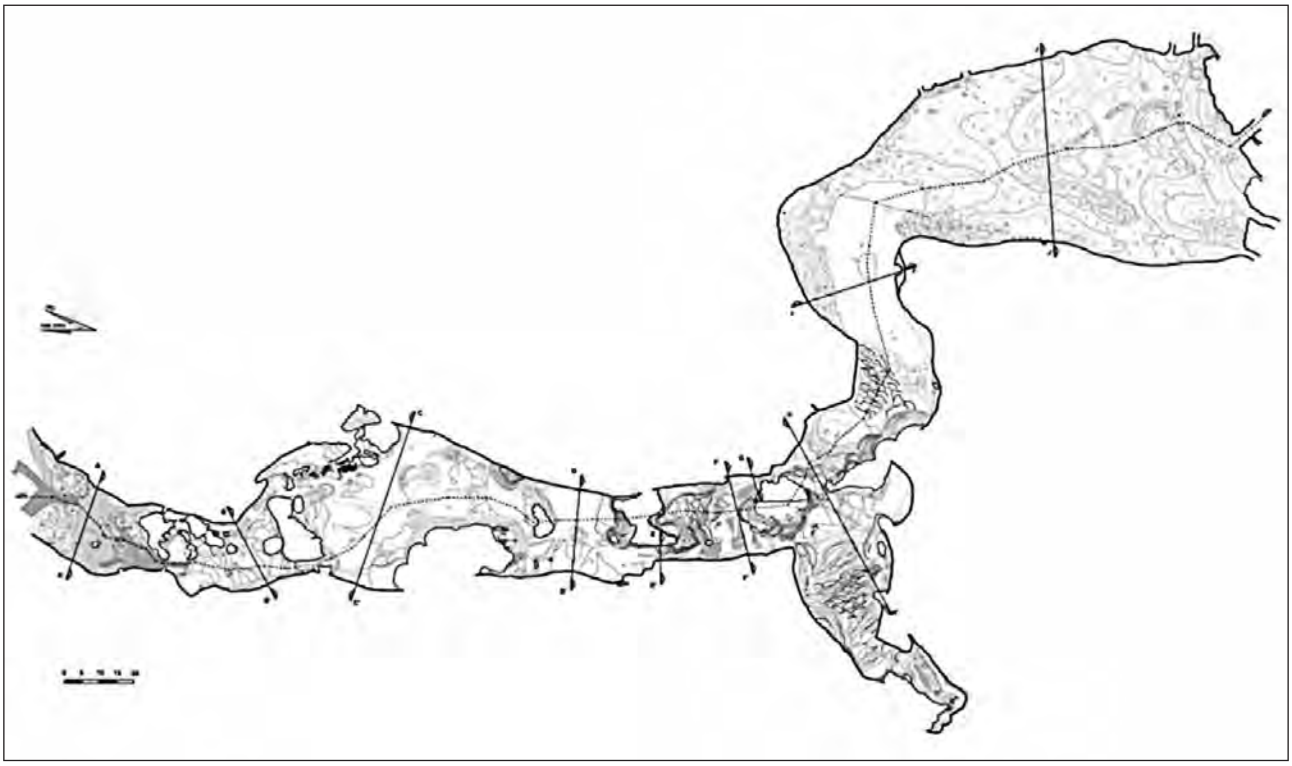

Figure 7. Maquiné Cave map of 2009 (IEF 2010).

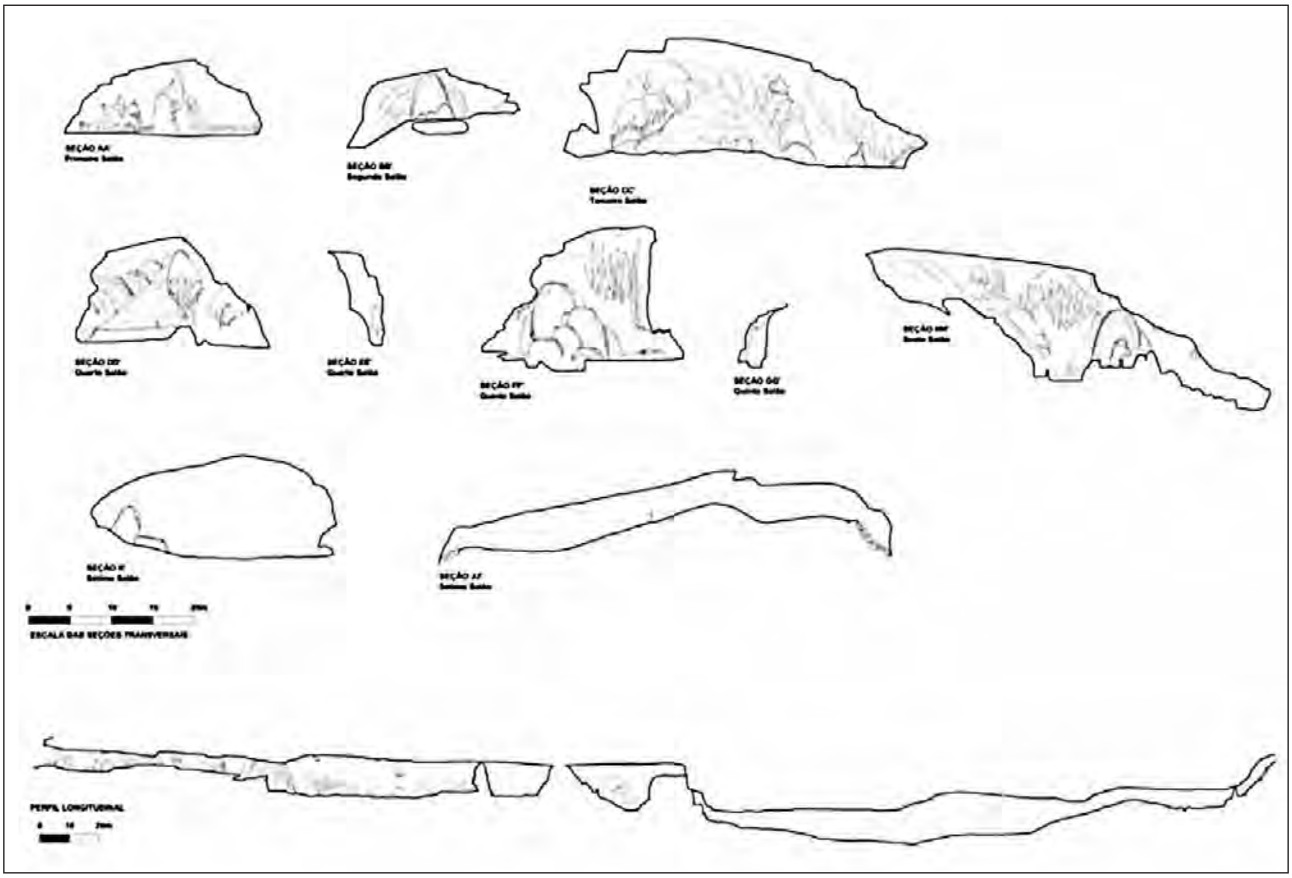

Figure 8. Maquiné Cave map of 2009, cross sections and longitudinal profile (IEF 2010).

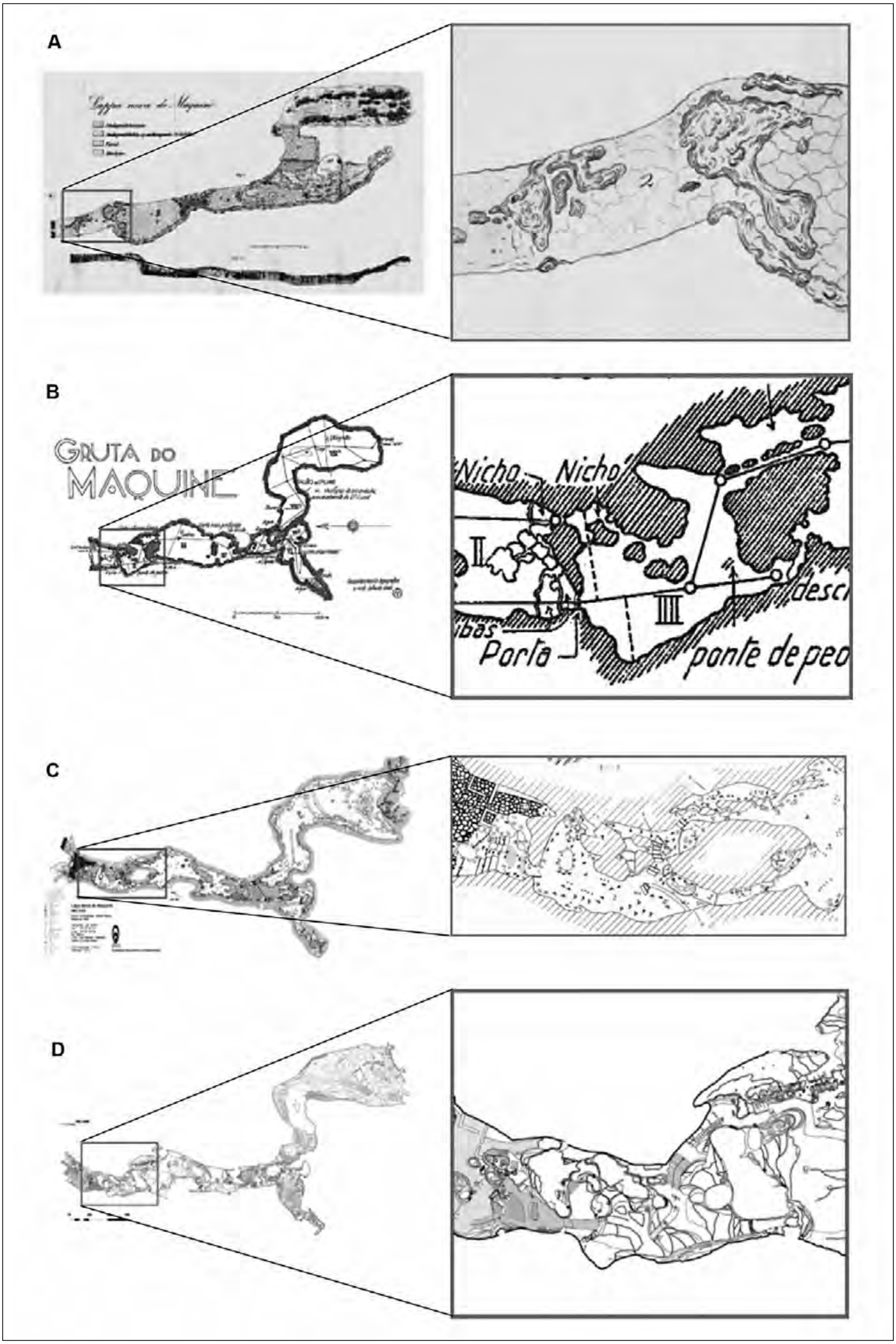

Figure 9. Comparison between the three historic maps and actual map, considering the same area of the cave (second room). On left column: (A) 1835, (B) 1940, (C) 1983 and (D) 2009 map with enlarged areas marked; on right column: respective enlarged areas.

5. Conclusions

The 1835 map shows a good representation of speleothems and enables a fine understanding of how these deposits fill the main conduit, dividing it into distinct rooms. However, due to technological and methodological limitations of the time, this map shows large deviations in speleothems and dimensional distortions in the walls of the passages and rooms. The 1940 map shows more realoutline, however, possess small detailing in chemical and clastic deposits, and does not present a clear differentiation between the sets of speleothems and the limestone shapesin the passage walls. The 1983 map shows inaccuracies in the walls and speleothems shapes. Overall, its accuracy is between the 1940 map and the actual map. This 1983 map has significant deviations in topography, especially between rooms, as can be seen in the enlargement of this map (Fig. 9). This area shows a remarkable elongation in the N–S direction, in the mass of speleothems that divides the Second and Third Rooms. This map also shows the disconnect between excerpts from the First and Second Rooms, in the eastern portion of the same.

We can conclude that the historical mapping of Maquiné Cave has not yet reached its end; new mappings can be made even more precise, with the use of new technologies and methodologies. But the level of fidelity of the 2009 map represents an important step in the management and and is a good basis for conducting future research in diverse fields such as bioespeleology, management studies, paleontology, geospeleology, climatology, and archeology.

In the study it was possible to evaluate each of the four mapping, analyzing the evolution of speleological mapping techniques in Brazil and the different uses of cartography produced.

Acknowledgments

Thanks to everyone who participated and contributed to this work, especially the guides and administrators Maquiné Cave.

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STATISTICAL EVALUATION OF CAVE LOCATION PRECISION BASED ON CARTOGRAPHIC SOURCES

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The applicability of cave documentation depends on the accuracy of the cave entrance coordinates. In the early years of cave exploration, the determination of the cave location was often inaccurate (even for several kilometers), while using better techniques such as GPS, the locations determined today are generally reliable. For many caves, the cavers have improved the entrance location coordinates in recent decades. The accuracy of the determined location primarily depends on the cartographic source used (map scale or GPS). In the Slovenian Cave registry, five major cartographic sources are applied. Among the 10,400 caves currently registered, almost 1,800 unique corrections of cave entrance locations were extracted in this work from the period of 1995–2012. Out of this set a statistical evaluation was performed based on the question, how much did the cave locations "change" at the corrections. In this way an estimation was made regarding the average precision of cave location based on the applied cartographic source. Using these data it was possible to calculate, how much has the average precision of cave location improved in recent years, and what is the trendline for the future.

1. Introduction

The coordinates of the cave entrance are one of the most important data in any cave database. As most caves are discovered by amateur cavers using amateur equipment, coordinates acquired at the discovery are influenced by a non-trivial measurement error. Using more advanced equipment, more precise cartographic background and better training, these locations have surely improved a lot. Nevertheless, the locations of less-visited and little-known caves discovered decades ago are likely to be known only by the coordinates measured at their first (and possibly last) visit. They may have been searched upon by the cavers, however, in the caving community there is often much more interest in discovering new caves than seeking the poorly-documented if not forgotten old caves.

In Slovenia, upon which this paper limits, there are two additional points to consider. Being a small and a relatively densely populated country with a strong caving tradition, the caves are generally well-known among cavers familiar with the neighborhood. On the other hand, being on the Eastern side of the iron curtain during the cold war, good maps were very difficult to come by. Anything better than the 1:50,000 scale was a state secret, though this regime eased a lot in the final years of communist rule.

The accuracy of a cave entrance location can be verified only on spot. However, using older versions of cave databases, one can track, how did the cave entrance coordinates "change" in time. Many have not changed at all. But many coordinates were corrected, from a poor cartographic source to a better one, in some cases more than once. Even a change using the same cartographic source as the original should be regarded as a legitimate improvement – a caver corrected his older colleague's mistake, though they may have used the same map. Using a large number of caves – in Slovenia there are about 10,400 registered today – provides a statistically significant sample to do an analysis.

There are numerous manuals, how to determine the cave entrance coordinates, see e.g., Ellis (1998) or for Slovenian cavers Gams (1964). However, little attention has been paid on the question, how precise these measurements are. The studies either discuss specific methods such as radio location (Gibson 1996), or surveying the caves themselves rather than the entrances (Canevese et al. 2011). Statistical methods have been used for studying morphology of cave systems (Piccini 2011) or distribution of karst phenomena in general (Plan and Deckar 2006).

The work in this paper is based on the databases of the Cave registry, which is jointly operated by the Speleological association of Slovenia and the Karst research institute of the Scientific research centre of the Slovenian academy of sciences and arts. The period of 1995–2012 was taken into account (Cave Registry 1995–2012).

2. Methods

From the Cave registry databases only two items were taken per cave per year: the Gauss-Krüger coordinates of the cave entrance and the cartographic source upon which these coordinates had been determined. This pair of data was taken for each year and checked if any change occurred between two consecutive years in any time from 1995 on.

In Slovenia there are three nation-wide topographic map sets (Central Evidence of Spatial Metadata 2012). The topographic map 1:50,000 is the most coarse of the three, substantially generalized and as such inadequately suited for cave documentation. However, it was the only map set widely available in communist times. The topographic map 1:25,000 has many more details and was partly available from late 1960's on. The topographic map 1:5,000 covers about 3/4 of the country area, while the remainder (mountains and thinly populated areas) is published in the 1:10,000 scale. Despite the scale difference these two sets are very similar thus in this paper they are regarded as one set. They are extremely detailed, showing even the most obscure footpaths, individual dolines, large rocks, etc, which makes them ideal for caving. Unfortunately, they were off-limits to the cavers before late 1980's. (In the following text, the designation "topo-50" is used for the 1:50,000, and in the same manner for the other scales.)

Two more cartographic sources have to be taken into account. One is the “not available”, where the caver did not write at all which map he had used to determine the location. These coordinates are notoriously unreliable. On the other side there is the GPS which can be regarded as the most precise of all the amateur-based methods (though this may be debatable).

Since 1995, our oldest accessible database issue, there have been about 2,100 cave location changes (either coordinate change or cartographic source change, or both). From this number several manual exclusions had to be made: excessively large change (above 5 km), non-standard cartographic sources (other than the five above), typographic error corrections (e.g., only one coordinate change for precisely 1 km), cave identity ambiguous cases and similar. This brings us down to 1,770 unique cave location changes, still a statistically large number. From here on the analysis actually started.

3. Results and discussion

3.1. Precision of cartographic sources

These 1,770 location changes were divided into pairs: (old cartographic source, new cartographic source), where the new source may be identical or more precise than the old source. Out of five source types this gives $n(n+1)/2 = 15$ pairs of changes, however, two pairs from the “not available” source have only a very small number of cases therefore they were omitted from further analysis. The location changes in each pair were divided in nine classes, ordered in geometrical series from 10 to 5,000 meters. Then a Gaussian least-square fit was applied to each of them. Essentially, a log-normal distribution was calculated on each of the 13 location change pairs.

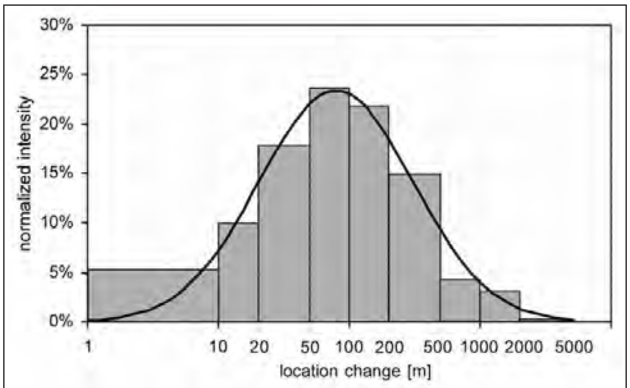

Figure 1. Distribution of location changes in the pair from topo-25 to GPS; the log-normal fit is added.

Such a distribution can be interpreted as follows. Let us take the example of the caves, where the old coordinates were determined by the topo-25 map, while the new ones by GPS (Fig. 1). There are 310 such cases. The peak of the Gaussian, i.e. the average location change is 79 meters. This means that in average the cave entrance coordinates were shifted by 79 meters. We do not know if they are more accurate than the original ones but since GPS can be considered a more precise method than the topo-25 map, a tentative conclusion is that the GPS locations are 79 meters better than the topo-25 locations. Strictly speaking, this applies only for the 310 changes evaluated and cannot be automatically expanded to the whole corpus of caves; see the end of this section for a discussion.

Similar conclusions can be made on other pairs. Of special interest are corrections using the same source. Out of 103 cases where the coordinates were corrected using the same topo-25 maps, the average shift is 147 meters. For the GPS-to-GPS corrections (nevertheless with a relatively low number of 35 cases) the average shift is only 16 meters.

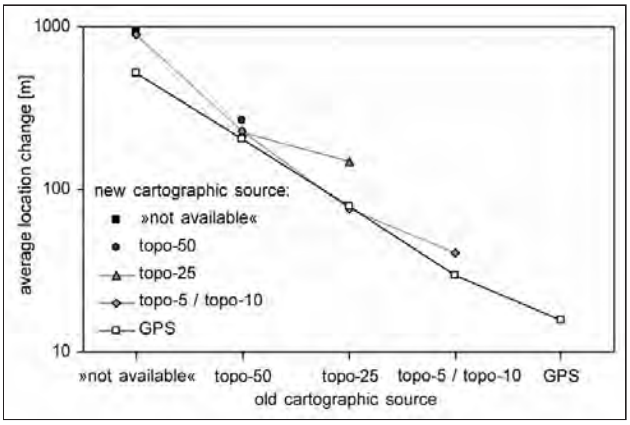

Figure 2. Average location change for the 13 pairs (old cartographic source, new cartographic source).

It turns out that the average location change hardly depends on the new source at all. Figure 2 shows the average location changes for all the 13 pairs studied. It proves that the average location change primarily depends on the old source. Therefore it is justified to calculate a grand average for all the location changes using the same new source. This finally gives as the average precisions as shown in Table 1. In addition to the average, the spread of the distribution is notable too, particularly how far do the Gaussian tails extend (Fig. 3). However, it has to be emphasized that these curves are fits on the whole distribution so these tails may be somewhat artificial. For each group of caves of interest (such as a designated geographic area) their precision distribution can be calculated using a weighted sum of the five partial distributions from Figure 3. This is further applied in the next section and shown in Figures 4 and 5.

Table 1. Calculated average precision of the five cartographic sources.

cartographic source	average precision [m]	distance on the printed map [mm]
“not available”	677	–
topo-50	222	4.4
topo-25	90	3.6
topo-5 / topo-10	35	4.7
GPS	16	–

The values for the more coarse maps appear huge. Finding a small cave entrance in the radius of 222 meters in a dense bush is almost impossible. But these numbers do make sense if they are translated into the distance on the printed map. For all the three map types these distances are around 4 millimeters which is comparable to the size of a typical pencil-drawn circle (Table 1).

The “not available” source justifies its notorious imprecision mentioned in the previous section. These caves

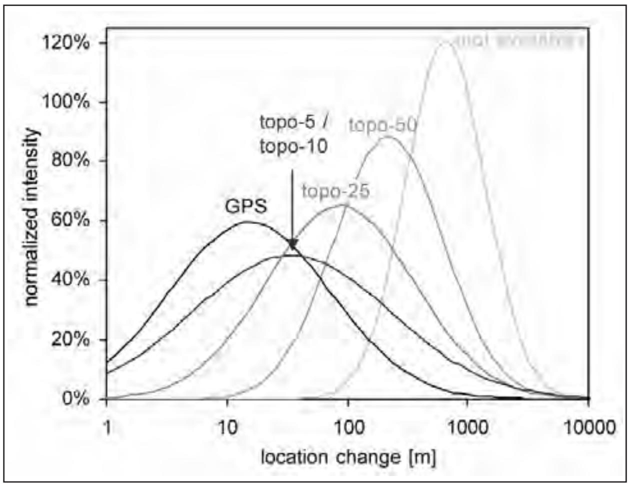

Figure 3. Location change distributions for the five cartographic sources.

can be considered as lost unless a reliable textual access description is available. On the other hand, the precision of GPS at 16 meters is worth discussing. The value itself may appear quite a success, but the Gaussian tail is far from negligible. There are GPS-to-GPS corrections of 100 meters and above. This can be attributed to cases of poor knowledge of the device, such as using wrong datum, taking the very first reading and the like.

The distributions deduced in this section suffer from another unknown. If a caver verifies the location of a cave and finds the existing location is wrong, he will report the correction to the Cave registry. On the other hand, if he finds the old location is accurate, he will probably not write any report at all. What is the minimum location change which merits writing a report depends on the caver. And even if he does report a location change for a few meters only, it is questionable whether the Cave registry database manager will bother about this negligible "change" at all. Therefore for all the distributions discussed above, there is probably a secondary unreported peak at far left of the diagram. From the data available its size cannot be guessed. We can only assume that the real precisions are probably somewhat better than the ones calculated, but not how much better.

3.2. Annual improvements of precision

In 1995, where this analysis starts, there were 6,637 caves registered in Slovenia. Since then there has been a steady increase of about 230 new caves per year. In this section the precision of this corpus is discussed using the location change distributions from Fig. 3. Again, it has to be emphsised that the statistics calculated on the set of the 1,700 location changes cannot be automatically expanded to the whole corpus of all the known caves, however, this is by far the best estimate at hand.

For each year of study, three groups of caves were considered. The first are the "old caves", registered before 1995. They are useful to get the idea, how much did the cavers improve the coordinates of the caves which had been known for many years. The second group are the newly discovered caves (or simply "new caves"), i.e. the caves discovered in that particular year. The third is the total of all the caves known up to that year.

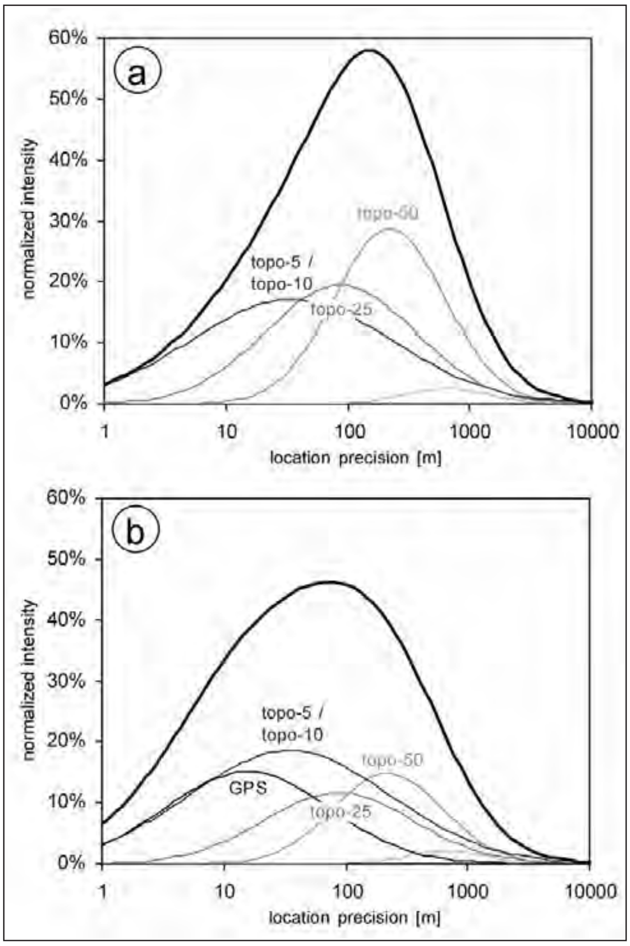

Figure 4. Precision distributions for all caves known in the years: (a) 1995, (b) 2012.

In Figs. 4 and 5 there are weighted precision distributions of five selected cases as predicted from Figure 3. Fig. 4a shows the old caves at 1995. The distribution is dominated by the topo-50 peak, followed by topo-25 and topo-5/topo-10.

In the new caves registered in the 1995–1997 period (three years were taken to get a larger sample) the topo-5/topo-10 already dominates (Fig. 5a). Less than a quarter of locations were determined by topo-25, and less than 10 % by topo-50. Compared to the old caves known by 1995 (Fig. 4a), there is a clear improvement towards more precise cartographic sources. Even two decades ago, the cavers determined the locations of new caves considerably better than used to be the case for older caves at the time. Eight years later (2003–2005, Fig. 5b) the "not available" and topo-50 essentially disappeared from current use. At the same time the GPS became prominent, already surpassing the topo-25. For the last three years (2010–2012, Fig. 5c) the cave locations have almost exclusively been determined by GPS, with only traces of other sources.

The total of all the caves known today is shown in Fig. 4b. All the four true cartographic sources (i.e. apart from the "not available" source) show roughly even shares.

The final question is how much has the average cave location precision improved in time. Again, we should look at this result using the already discussed three groups: the 6,637 old caves, annually new caves and all caves. The strongly improving trend in new caves has already been presented in Figure 5. Therefore the bottom trendline in Figure 6 is not surprising. The precision of newly discovered caves has been

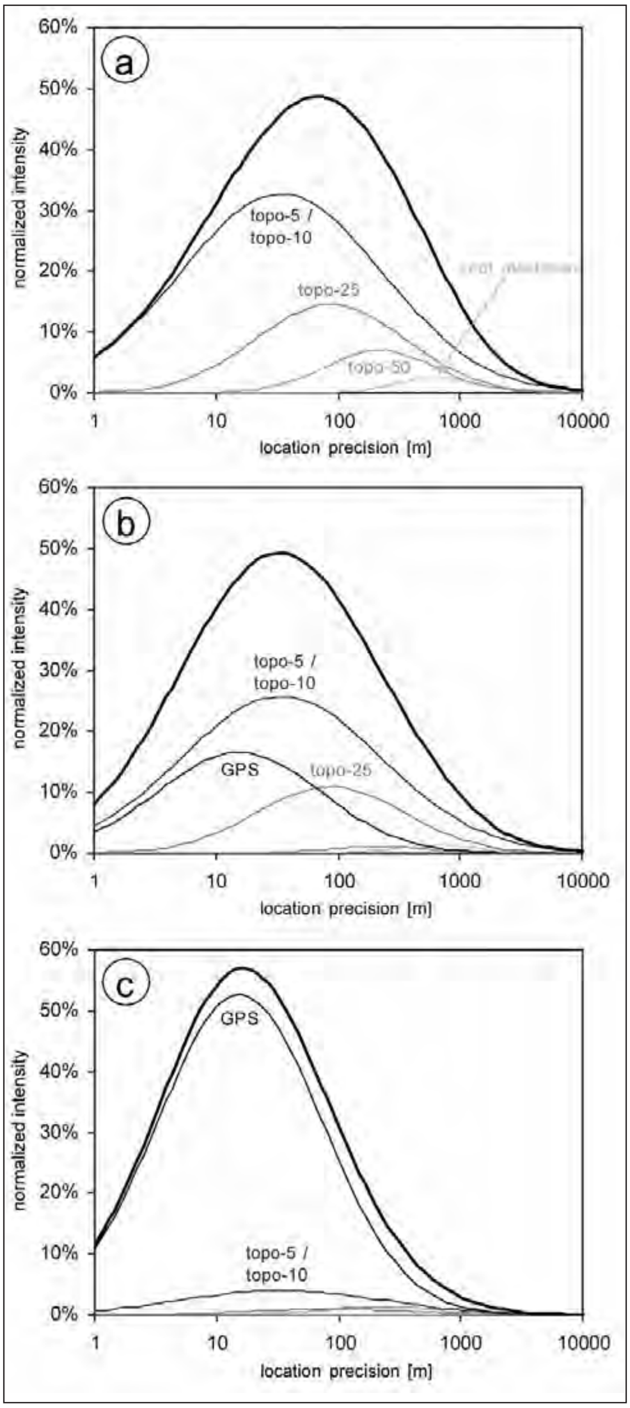

Figure 5. Precision distributions for new caves discovered in the years: (a) 1995–1997, (b) 2003–2005, (c) 2010–2012.

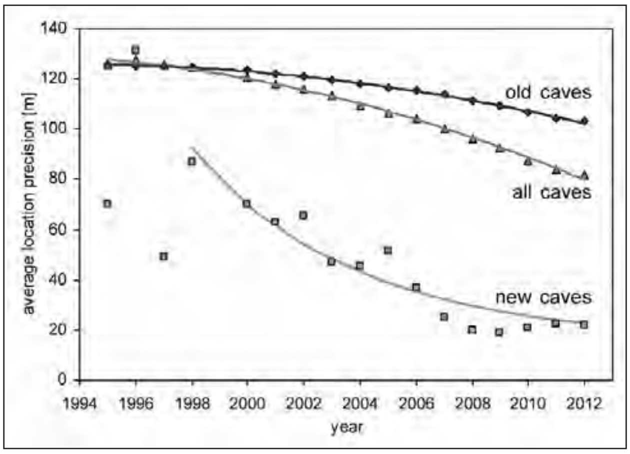

Figure 6. Average location precision for old, new and all caves in the analyzed years.

steadily improving from almost 100 meters down to about 20 meters. Mathematically, this can only improve to 16 meters (the average precision of GPS) when all the remaining map users swap to GPS. In real terms, of course, this is an oversimplification, but this is beyond the scope of this study.

The old caves on the other hand show a much more modest improvement in time, from 126 m to 103 m in 17 years. The annual improvement was below 1 meter per year in the late 1990's but somewhat accelerated to 2.5 m/year. If the trend of the last 10 years is extrapolated, the all-GPS precision of 16 meters will be reached in 46 years. Indeed, extrapolations in decade-scale in the future are vague at best, but it does stress the immense work ahead to be done for several generations of cavers.

The curve for all the caves known in a given year is somewhat more optimistic. But its more intense improvement is primarily due to the steadily increasing number of GPS-determined new caves. The burden of the poorly documented and very slowly decreasing old caves will keep the average precision down for many years to come.

4. Conclusions

Though this work is based on Slovenian caves exclusively, the large size of the sample allows us to draw conclusions which are applicable in general:

(1) As the amateur cavers improve the accuracy of existing cave entrance locations, these location changes (in meters) have a log-normal distribution. There is a non-negligible tail of very large changes, where the original location was substantially inaccurate.

(2) The peak of this distribution, i.e. the average precision, strongly depends on the cartographic source of the original location. For maps, this generally means around 4 mm on a printed map. For GPS, the average precision is 16 m.

(3) In the last 15 years, the location precision of newly discovered caves has improved for a factor of four. However, for old caves discovered before 1995, this improvement is only 20 %. Today the average precision for new caves is around 20 m, while for old caves it is just above 100 m.

(4) This analysis has one serious drawback, because re-evaluations of accurate locations are not reported in the Cave registry and thus remain unaccounted for. Nevertheless the main trendlines probably remain valid, though the precisions are likely somewhat better than the ones calculated in this paper.

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RESURVEY AND RESOURCE INVENTORY OF THREE FINGERS CAVE, NEW MEXICO, USA

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Named for three finger-like rock pinnacles jetting out of a nearby limestone fin, Three Fingers Cave has drawn cavers to its rifts and cavernous breakdown rooms for almost 50 years. This complex three-dimensional cave in the Guadalupe Mountains of in New Mexico has seen several survey efforts in those years. The cave is physically difficult, as well as being semi-remote and almost impossible to diagram in a 2-D map. The latest incarnation of the Three Fingers Cave Project is putting together a digital map and resource/mineralogical inventory to understand the cave and hopefully provide clues for further exploration in the area. The current project is in its fifth year of resurvey and inventory. The initial focus was on getting complete sketches of main rooms and travel routes and the current focus is to capture an area of the cave called the North Maze. After using old survey to lay a backbone through this labyrinth of breakdown, the project is now putting a survey line through every opening to make sure that all spaces between rocks were checked. Previously, the distribution of noteworthy cave features and resources was only captured in sketches of the cave and in trip reports. The current project, started in 2007, designates a separate person to record resources. Survey stations are points of reference for noting the location of features in the cave including: airflow, water, floor, ceiling, conservation, obstacles, bedrock geology, formations (lots of detail here), fossils, biology, and cultural artifacts. Of particular interest are mineralogical features, since it is hoped their distribution in the cave will aid in interpreting the morphology, genesis and possible continuation of the cave. To process and archive the data collected, line plots are generated from the sketcher's hand notes that are entered in Fountainware's Compass software. Digital map drafting makes it easy to combine inventory data with the cave map since the inventory information is entered into digital spreadsheets which are then imported to a Geographical Information System (GIS). Social networking is being used to maintain member information, organize and backup data, and disseminate information. Advances in technology have proved useful in the resurvey and new inventory of Three Fingers Cave, but the difficulties of remote location, inclement weather, steep terrain, complex breakdown passages, and delicate formations have challenged the latest attempt to document the cave. Caver perseverance is required and it is hoped we will be rewarded with a better understanding of the cave and knowledge that the resource is being adequately conserved for the enjoyment of future cavers.

1. Introduction

Three Fingers Cave stands out as a spectacular cave in the Lincoln National Forest of New Mexico, USA. Located in the high Guadalupe Mountains, the cave is known for its complex, 3-dimensional maze with a vertical span of over 150 meters. A variety of speleothems, unusual mineralogies, and paleontological resources abound throughout the cave system. Three Fingers Cave got its name from a distinctive rock formation on the top of a nearby limestone fin that resembles three boney fingers when viewed from the streambed below.

The entrance to Three Fingers Cave, located near the bottom of a rugged and remote canyon, was first reported in the early sixties by cavers who sighted it with a high powered rifle scope from Pinks Ridge. Viewed from that distance the cave entrance appeared to be just a terminal cleft in a limestone wall. That very obscure entrance was finally located, in the late sixties, by Jim Peck and Bob Sarabia while they looked for a known cave in the general vicinity. The cleft turned out to be a narrow entrance that led to the top of a 27-meter deep broken fissure requiring rope and dropping into a decorated and massive breakdown chamber.

2. Geology

Caves are difficult to find in the Guadalupe Mountains because their genesis and development are not directly related to surface processes and thus don't leave the characteristic features that cavers typically use to locate potential entrances. With a few exceptions, Guadalupe Mountain caves (at least most in the high Guadalupe Mountains) do not carry underground streams or rivers. The caves are hypogene in nature, which means that they owe their origin to processes beneath the surface. Hypogene caves form without surface entrances and are only exposed due to surface erosion that happens to intersect the existing void. They form by bacterially-moderated mixing zone dissolution so the caves that exist today are actually relict mixing chambers. Breakdown and secondary mineralization oftentimes obscure the structure and layout of the original void.

Three Fingers Cave is located on the southeast flank of the Guadalupe Ridge Anticline at an elevation of approximately 1820 meters above sea level. Stratigraphically it is formed in the Artesia Group that is composed of shallow shelf deposits associated with the Permian-age Capitan Reef complex. The cave entrance is situated within the Seven

Rivers Formation and descends into the Queen and possibly the Grayburg Formation with the southeast side of the cave possibly extending into the Capitan Limestone.

The cave morphology (passage layout) can be described as a boneyard maze complicated by breakdown. True walls are difficult to locate because of the breakdown, but in the lower levels of the cave, joint-control is evident. Major joint trends reflect the dominant joint trend noted in other caves of the high Guadalupe Mountains (330/150 degrees and 60/240 degrees). The joint trends run parallel and perpendicular to the reef escarpment.

Speleothem development has occurred throughout all areas of the cave. The entrance chamber contains columns 3–5 meters tall. Walls and ceilings throughout the cave are festooned with stalactites and stalagmites. Shields, helictites, soda straws, drapery, bacon rinds, and cave pearls are common throughout the cave. Popcorn usually abounds in those areas that display a lot of air movement. Unusual mineralogy includes gypsum (both as crust and as massive needles), celestite patches, goethite stalagmites and lots of rock flour (condensation corrosion). Many of the unusual speleothems and mineralogies from world famous Lechuguilla Cave also occur in Three Fingers Cave but at small scale in terms of size and distribution.

Figure 1. Large calcite spar crystals coat many pieces of breakdown and their distribution could provide clues to the speleogenesis of Three Fingers Cave. Survey book for scale. Photo by David Ochel.

3. Methods

3.1. Resurvey

Initial survey efforts in Three-Fingers Cave started in the late 1960's through the late seventies when cave survey standards were very different than they are today. Survey work continued in the late eighties through early nineties using more modern standards but did not include resource inventories. The current survey effort does include resource inventory, but in order to integrate the resource inventory with newer survey standards and to better accommodate digital cartography some resurvey is necessary.

As with any modern cave survey, in-cave data collected includes the distance, azimuth, vertical readings, and passage dimensions that are input into the COMPASS software, which converts the data to XYZ coordinates. The result is a preliminary line plot showing the horizontal and vertical extent of the cave and its passages. Cave data is georeferenced to a surface datum in order to relate cave features to topography. The software uses passage dimensions along with the XYZ coordinates to make volumetric plots of the cave passages, making it possible to rotate cave and volumetric plots in three dimensions. This is a valuable aid for envisioning the layout of a cave system and for detecting geologic and/or hydrologic patterns which are not obvious otherwise.

Line plots, sketches and associated geographic data are then used to generate detailed cartographic representations of the cave. One of the primary reasons for collecting cave survey data is to produce cave maps. The cave plot, passage dimensions, and sketches are the necessary components of making a good map. The cartographer integrates these data into a map of the cave in plan and profile. Cross sections are added to the plan view making for a more complete three-dimensional representation of the cave.

A cave map, in any stage of completion, serves as an underground base map from which all future work can be referenced. A map integrating cave and surface features makes for a powerful tool for exploration and from which to conduct work for resource inventories, restoration, and rescue planning. Cave resources are defined as all of the secondary attributes and features, both natural and man-made, which reside within the confines of the cave or cave system. Natural features include the biota, paleontology, mineralogy, speleothems, and sediments. Man-made features can be of archeological, historic, or cultural origin.

3.2. Inventory

Resource inventories are descriptive lists of the cave resources referenced to survey stations. Most resource inventories are done in conjunction with the cave survey and collect only very basic information on the resources such as location or simple descriptions. Basic training and the use of field guides can supply enough expertise for data collectors to provide more descriptive surveys. The resource inventory for Three Fingers Cave has been preformed during the resurvey. Detailed sketches and notations from the survey notes provide a generalized list. The resource inventory team follows up on the generalized list and provides detailed descriptions of the resources and the general cave conditions. Inventories are recorded on pre-printed checklist sheets that show a list of possible resources. The person inventorying simply checks the list and each item is referenced to a survey station.

As resource inventory data is collected, the descriptive information is entered into a database and exported to a geographic information system (GIS). Data in this format can then be searched and queried quickly and efficiently.

Photography is an important component of the resource inventory and augments the geographic baseline. As with resource inventory data, scanned photographs and digital images are catalogued, archived into a database, and referenced to surface or underground locations.

4. Results and Conclusions

Since September of 2007, this project has had 10 trips (22 survey teams) out to the high Guadalupe Mountains to resurvey and inventory Three Fingers Cave. These trips have focused on resketching the Bell Room and an area of the cave called the North Maze. The North Maze area of the cave follows the ceiling of the Bell Room as it slopes down to the north into the spaces between the bedrock ceiling/wall and the rock pile that fills the floor of the room. See Figure 2 for a sample comparison between a previous sketch of the Bell Room and the current digital map. As of August 2012, 1.9 km of approximately 5.9 km of known cave has been resketched with the addition of detail, cross-sections and profiles to the drawings. Not all of the 4 km difference between known cave and resurveyed rooms and passages will need to be redone since the project has been able to include some of the work from previous projects. By using previous surveys and notes, the impact on the cave will be reduced since cavers sent back to these areas will only need to collect inventory data and not resurvey.

The teams have inventoried over 300 survey stations since starting to gather this data in 2007. This is the first time inventory has accompanied survey in this cave and so far it only includes areas that have been resurveyed or resketched. As the project continues, additional inventories will be done for the parts of the cave that have an adequate survey but lack this information. These inventories will provide a baseline dataset of the features in Three Fingers Cave. The intention is that these efforts will expand our understanding of the speleogenesis of Three Fingers Cave and its resources and that this knowledge will enable the cave to be adequately conserved for the enjoyment of future cavers.

Acknowledgments

We would like to acknowledge the previous cave explorers and surveyors who initially discovered and began documenting the cave. We would also like to acknowledge the Lincoln National Forest of the US National Forest Service for providing permits to do this work. Finally, our gratitude goes out to the many volunteers that have given their time and money to help with this project.

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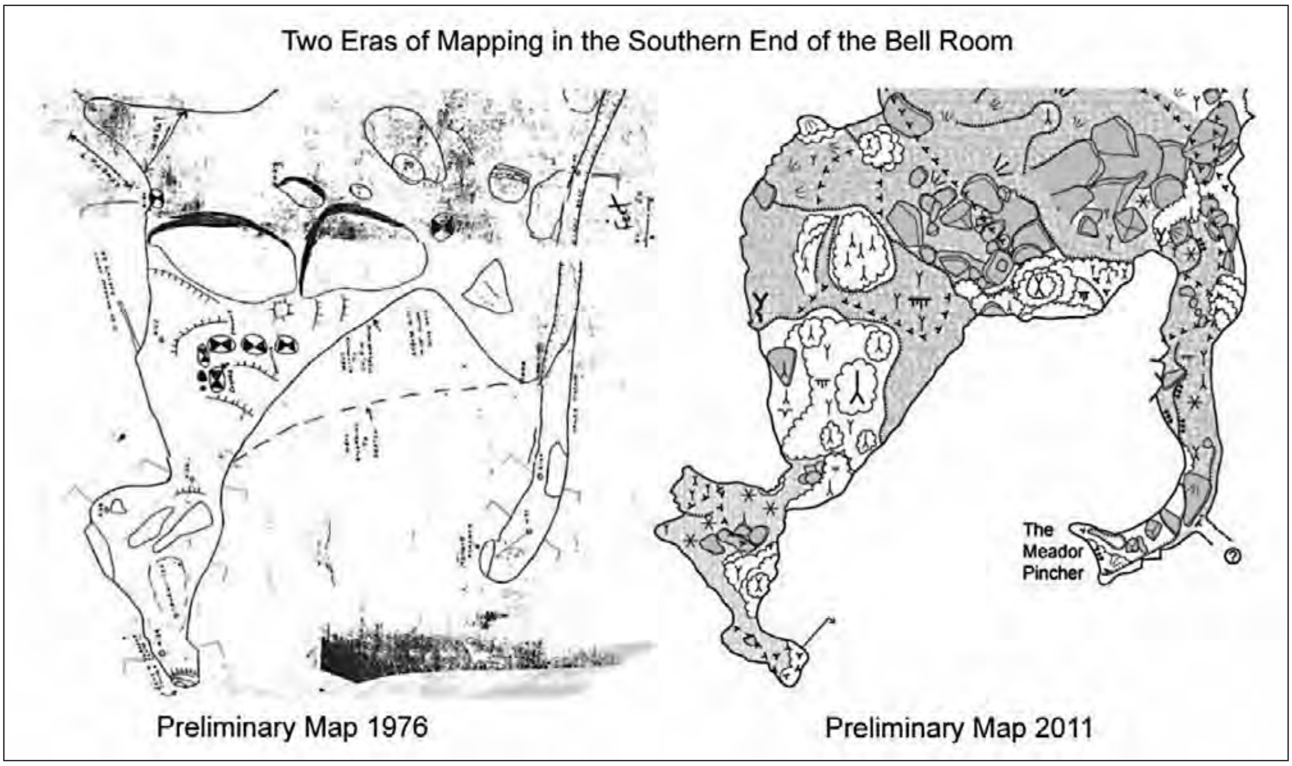

Figure 2. A comparison of samples taken from the current digital map and a previsious survey project in 1976.

VIRGINIA SPELEOLOGICAL SURVEY (VSS) GEOSPATIAL DATABASE

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The Virginia Speleological Survey (VSS) is a private organization that maintains comprehensive records on 2,500 to 4,500 caves and cave features (depending on your definition of cave) for all the caves in Virginia. A few years ago the VSS transitioned from a legacy database to Microsoft Access and ESRI ArcGIS. This software was chosen due to their ubiquity, vastness of resources, and the ability to readily translate into similar formats thus standing the tests of usability and time. Restrictive access and distribution policies still prompt a cautious view toward cloud platforms.

The database structure has about 24 related tables holding cave and entrance information such as maps, publications, owners, report events, legends, significant list classifications, and a growing list of queries, reports, and forms. GIS base data contains nearly every publically available map layer in Virginia as well as access to various web map services. This allows populating or verifying fixed attributes such as geology and elevation, or populating variable attributes such as ownership information. Subsequently these values broaden the ability of targeted data queries or complex geospatial queries.

Recent and current tasks include: rescanning the large cave maps (about a thousand) at higher pixel resolution as well as full color or gray scale; scanning and photographing the thousands of small maps and of pages information in the individual cave archive folders; archiving digital data files of all types; and developing a mailing list for all the state's caves for a Cave Owner's Newsletter.

A new goal is to acquire historic notes and digital data behind the traditional paper maps already held before this data is lost to time. Several individuals have donated their life compilation of cave survey notes from the 60's and 70's. These have been photographed, archived, and several caves will soon be entered in the computer for the first time to support current projects. For digital data the VSS policy is not to require a standard format because it would hinder submissions, thus we accept Compass, Walls, Survex, whatever one has.

The VSS's primary goal is preserve Virginia's cave information as individuals fade out of the caving community taking that "I'll get to it someday" data with them. Our call to cavers everywhere is to help preserve this information via your state cave survey or similar organization.

LESSONS FROM DRAFTING PROJECT STARTUP AND SUMMARY OF EXPLORATION ADVANCES IN FISHER RIDGE CAVE SYSTEM, HART COUNTY, KENTUCKY, UNITED STATES OF AMERICA

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Fisher Ridge Cave System (FRCS) was discovered in 1981 and has a current total length of 191.9 km (119.25 miles) and a vertical extent of 127.2 m (417.3 feet). Its discovery led to the inception of the Detroit Urban Grotto of the National Speleological Society which has conducted all survey of the system. In 2009, a project was begun to digitally draft the entire system using Scalable Vector Graphics (SVG) based file formats. This required significant changes to data storage and access systems. Tools provided by this project are used as resources for exploration and have resulted in quantifiable advances in exploration via tangible and intangible mechanisms. Current extent of exploration and statistical summary are given; exploration potential and objectives are described in historical context.

1. Introduction

Fisher Ridge Cave System (FRCS) is the 9th longest cave in the world at 191.9 km (119.25 miles) total current surveyed length (Gulden 2012). It has four known entrances of which only one is natural. It is developed in Fisher Ridge and Northtown Ridge, both located in Hart County, Kentucky. All four entrances are privately owned, which is unusual among the world's longest caves. The Detroit Urban Grotto of the National Speleological Society was created shortly after its discovery with the mission to survey the system. Caves that are a part of park systems benefit from increased organization and access to Information Technology (IT) resources. In the later stages of exploration, data management can fall behind the current best practice unless there is official oversight.

Focus primarily on exploration can result in a motivational barrier to drafting because of the backlog of surveys to be drafted. The longer this situation persists the larger the motivational barrier becomes; the rate of exploration benefits from up to date IT resources and drafted maps.

2. Historical project structure

FRCS was never formally drafted in any large part. From time to time there have been small focus areas that have been drafted by individual trip leaders in an effort to better understand those regions of the cave. Survey notes were sent to a single project member for archiving and copies were sent to another member for data entry. Project members could request copies of survey notes, but the process required the custodian to locate the originals, make photocopies, and physically mail them to the project member. This system proved to be prohibitively irksome in most cases.

Numerical and text survey data was entered into a computer program custom written by the project member entering data. This computer program was capable of preserving the data as entered in addition to closing loops and creating plots; it was flexible in forms of output. It functioned on a text based command system.

For three decades the line plot outputs from this program were the major tools used for exploration. Plots could be created with colors based on passage depth or date of survey, and various data could be appended to the station labels. Output was via postscript format.

FRCS is a long cave and has been historically surveyed by a relatively small group of people; the top 5 surveyors have all been on at least 10 % of the total survey trips each. One project member has surveyed over 43 % of the total cave length. Because of the large amount of passage, trip leaders necessarily tended to specialize in specific regions of the system. Due to the small number of project members often there would be only one trip leader familiar with each region. Leads were recorded in the raw text based computer file and were not easily accessible to project members. When trip leaders became less active in exploration or retired completely the navigational knowledge and qualified lead data for their focus regions were lost.

As the project aged and the quality of leads diminished the rate of survey slowed as seen in Figure 1, although occasionally there were breakouts. Areas where exploration had remained active continuously had a lower quality of remaining leads than areas that had not been pushed in several years due to the inactivity of trip leaders focusing there. With less access to quality leads, and navigational information the ease of recruiting new project members diminished – this was furthered by the historically small size of the group, its decentralization, lack of regular meetings or newsletters and introductory caving activities.

3. Restructuring challenges

A decision was taken in 2009 to pursue creation of a digital drafted map for posterity as well as to be an exploration resource. This startup faced several material as well as political challenges. As in many informal projects, new

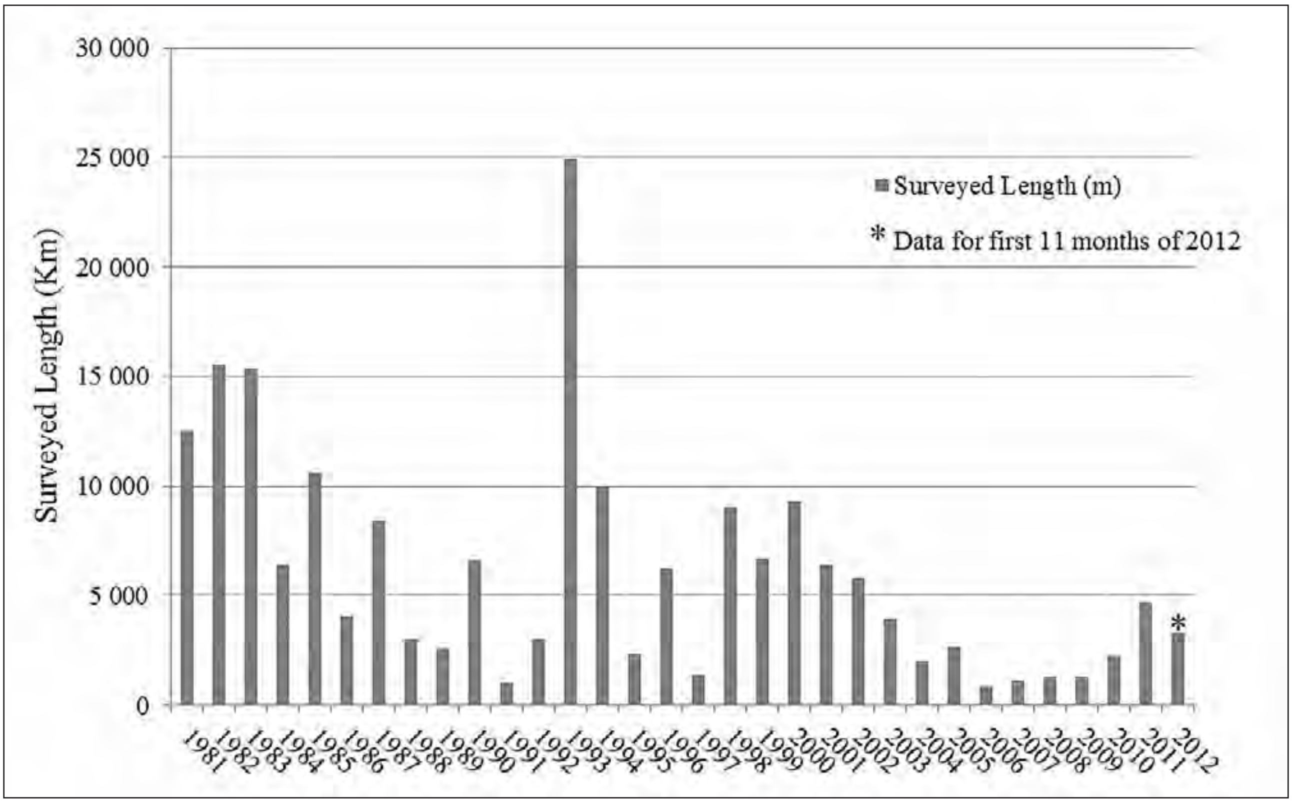

Figure 1. New survey in meters per year since discovery of the system.

developments are often begun by those who take the initiative. This can lead to political strife with project members with many years of involvement. An idealized drafting project was outlined and challenges were undertaken incrementally. A significant effort was made to engage all project members and to accommodate different aptitudes for technology and different finances.

The computer data set needed to be accessible to all cartographers in a file format/editor that they could manipulate. This was perhaps the largest political challenge of the restructuring because of the development time and longevity of the software program in use. Facility of user interface concerns, program functions, and preservability of data requirements dictated that a major overhaul of the program be required. Since the driving force behind the drafting initiative came from a different segment of project membership this was unlikely to happen. After the computer dataset was acquired and converted to a widely used format both dataset were used simultaneously and updated side by side. Compass cave mapping software was selected as the best widely used platform. It has compatibility with other widely used platforms.

Compass is used worldwide and has an active developer (Fish 2012). It has an easy to use graphical user interface. The widespread use guarantees a reasonable communicativeness of data, and likelihood of new project members already being familiar with it. Having an active developer is essential to software flexibility as new challenges unique to long cave systems are encountered. It is one of the few software packages which is capable of round-tripping Scalable Vector Graphics (SVG) files. This was a key detail in its selection. The Compass Sketch Editor also provides a utility to manipulate scanned survey sketches. While best practice is to create a scaled "clean" copy of sketches immediately after surveying, the realities of drafting a cave with close to 200 km of previously surveyed passage require working with non-ideal sketches, sketches drawn to out of date (i.e. poor) standards, and sketches by cavers who are no longer active in the project. The Sketch Editor allows morphing and scaling of sketches to fit the survey plot as well as general image editing customized for making images readable. It also facilitates merging of numerous images to allow easier drafting. Some of the steps of the image manipulation process are shown in Figure 2. The process starts with a raw scanned image in JPEG format. The image is then generally edited which includes: rotating north to up, bleaching, cropping, and scaling. The image is then morphed so that it matched the closed line plot perfectly. At this point multiple morphed images are assembled and merged in to a single image. The functional limit for the size of a merged image is 5,000 pixels × 5,000 pixels but may grow as personal computing power increases. The merged images are then morphed a second time (not shown) to ensure that no errors were introduces by the merging process. The re-morphed image is then made 50 % transparent and overlaid via linking (not embedding) onto an SVG plot with blocky approximated passages. These blocky passages provide a fast check to see if the manipulated image looks reasonable. The blocky passage approximations are then removed for easier tracing. Finally, the image is made invisible so that they are available for future use but do not clutter the screen.

Original survey notes needed to be made accessible and preserved for members' use. This necessitated consensus on a file format, method, and scanning resolution as well as a means of distribution. It was decided that original sketches would be scanned in full color at 300 dots per inch (DPI) resolution and a title page with survey summary information included as the first page.

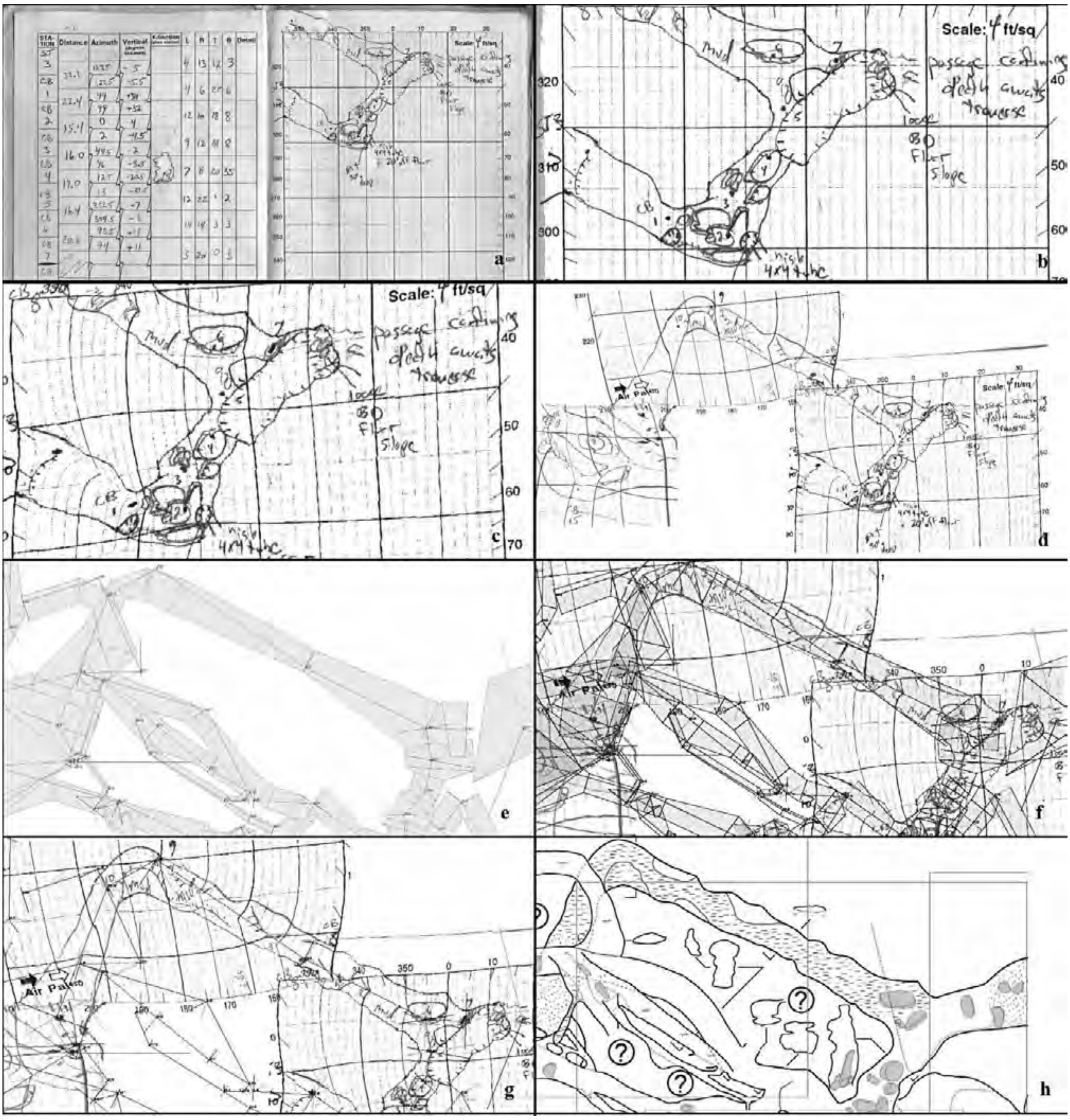

Figure 2. Images at various stages of manipulation during the drafting process: a) raw scanned image; b) edited image; c) morphed image; d) multiple merged images; e) SVG plot output; f) merged/morphed image overlaid onto SVG plot with blocky passages for general check; g) merged/morphed image overlaid onto SVG plot without blocky passage for tracing; h) rough draft of SVG map.

Storage and access of digital information is a major concern; security of data is sometimes a concern as well. FRCS data is hosted on a server administered by a long standing project member. There are two hard drives which mirror once each day and a UPS backup. It is possible to host data on Source Forge (Source Forge 2012) or other free online hosting services if it is acceptable that the data becomes public domain, but for reasons of data security the above mentioned hosting solution was used. Data is hosted on a Subversion (SVN) repository which members access via an SVN client, primarily Tortoise which is open source software for Windows and Linux. Using Tortoise, project members can continually upload changes to the data set and manipulations of images as well as maps in progress. It is even possible for multiple project members to work on the same data at the same time and save both changes. Tortoise tracks the changes in the files and only uploads/downloads information relevant to those changes and not complete files with each update. This minimizes the data transferred and allows slower internet connection speeds to be used. Tortoise facilitates all cartographers staying on the same page while simultaneously protecting the data and allowing recursion to previous versions of the dataset.

Due to printing limits and the desire to utilize multiple cartographers, it was necessary to divide the cave into Cartographic Sections. The divisions for the north half of the cave are shown in Figure 3. This was also a contentious topic as many opinions existed on the best practice. FRCS has been divided into 37 regions for drafting. The terminology of “Cartographic Sections” was utilized as regions were not divided based on a regular grid but rather in irregular footprints to minimize transected passages. Additionally, it was looked on as favorable to create

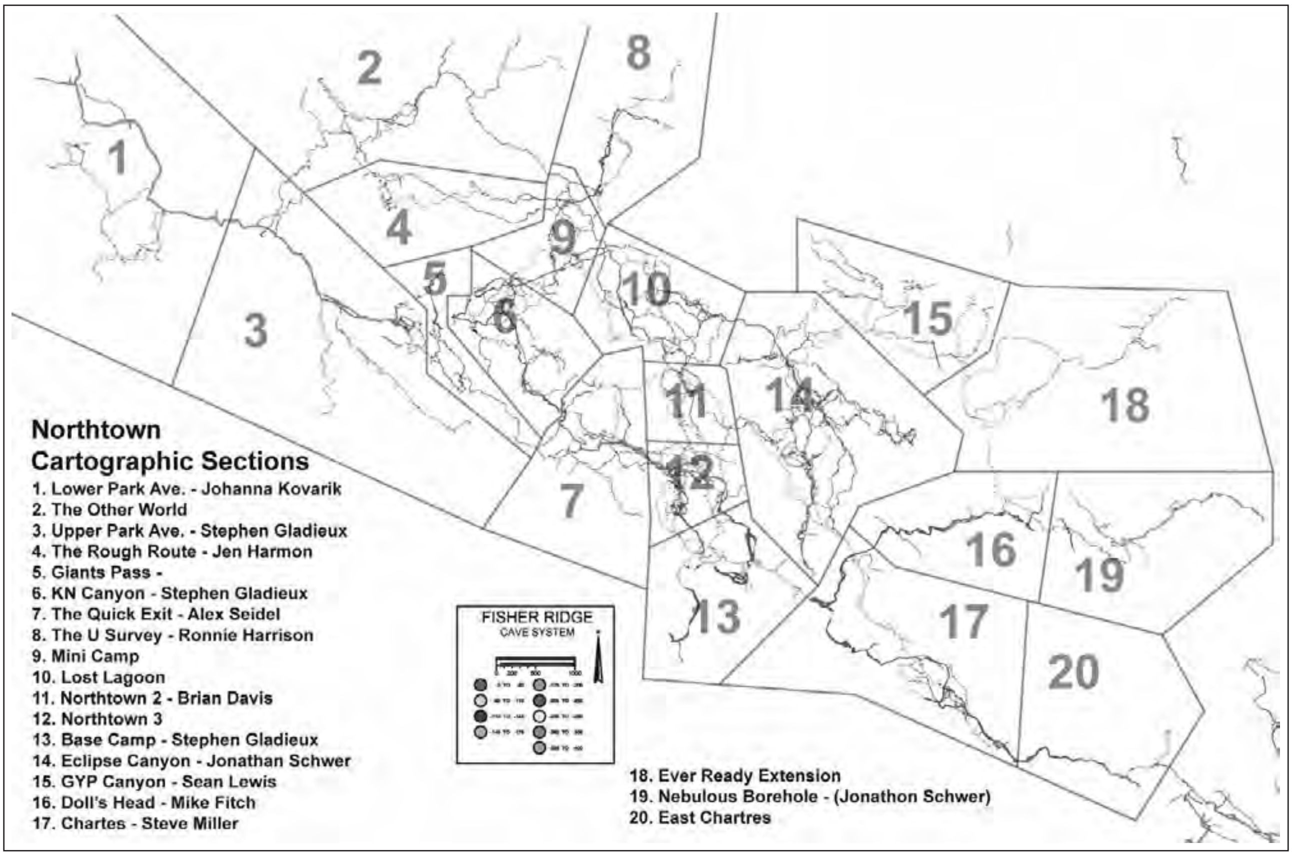

Figure 3. Plot tool defining Cartographic Section for the northern half of the cave.

numerous Sections that would be ideal in size and complexity for beginning cartographers as most project members were new to digital cartography.

Drafting standards and a common computer platform are required to realize a map. Variations in project member finances and previous experience exist. Consequently, two semi-interchangeable software platforms are currently used: Adobe Illustrator and Inkscape. These two programs are compatible with the generic SVG file format which allows unlimited scaling and lossless data storage. They facilitate changes to drafting style with minimal effort. Drafting standards were pioneered by the first project member to undertake a Section (the current author) and evolve with the special requirements of each new Section such as vertical complexity, etc.

The amount of time required to initialize a digital drafting project is large. Many hours of effort are required. The current author spent over 700 hours in 2011 working on converting data, setting up IT resources, developing drafting standards and tools, and drafting the first Cartographic Section. It is likely that it will take 300–1,000 hours to draft each of the 37 Cartographic Sections as well as ongoing effort to help new cartographers get setup and learn the process. The data must additionally be kept current.

4. Exploration resource utilization

Pioneering of the resources necessary for the drafting project resulted in an immediate increase in new survey footage. This is seen in Figure 1. The yearly survey had dropped to an average of 1,146 meters per year for 2006–2009. This was the longest period without 2,000 meters of new survey per year in the project's history. The digital drafting project was functionally begun in 2010 despite conceptualization in July of 2009 and a clear increase in survey is seen. The length of survey in 2011 (4,685.47 m) and 2012 (based on 3,284.97 m in the first 11 months and additional know, but not yet entered survey data) are each over four times the low point of 2006 (833.96 m). One of the biggest advances in exploration has been a breakout toward a neighboring cave system with a length of over 15 km passages from FRCS have been found to extend under this cave based on reasonable cave geo-fixing and calculated survey uncertainty for both systems.

Giving all project members easy access to the scanned survey notes was of immense value to the project. It gave project members access to sketch data and thus a morphological understanding of passages. Original lead information recorded on the survey notes allowed trip leaders to canvas regions of the cave for leads and identify the most promising ones.

Access to the computer dataset in a user-friendly format allows for manipulation of a 3-d plot and concrete understanding of how newly surveyed passages interact with known passages without the need to contact anyone else to get an updated 2-d plot. This is useful for extended serials of day trips into the cave as it allows for informed decision making about daily objectives based on recently surveyed passages.

During review of survey notes, and subsequent drafting, cartographers note leads. They are recorded with full information spatially on the SVG map as well as in a searchable, table-formatted Excel file which is accessible by all project members. Leads are classified according to the quality scale in Table 1. This is a new system for the project and has allowed easier communication and prioritization of objectives. The Unified Lead List records the following data for each entry: survey label, station number, Cartographic Section, lead grade, survey date, survey trip leader, and rigging requirements.

Table 1. Lead grading scale used in unified lead list.

Lead Grade	Passage Characteristics
A	Very good lead, going walking passage or pit with visible walking passage below
B	Good lead, hands and knees crawling or stooping sinuous canyon, has draft
C	Mediocre lead, less than hands and knees crawl, may have chest compressors, has not been scooped far, no draft
D	Digging lead, requires digging or microshaving

In addition to the above stated exploration resources, the startup of the drafting project has revitalized the grotto. Grotto membership is up and new members have stepped into the role of President, Webmaster, and Newsletter Editor. This momentum has contributed to increased new survey.

5. Conclusions

There are significant challenges to the startup of a digitally drafted map for cave systems with large amounts of surveyed passage but poor IT infrastructure – this describes many large cave projects without a drafted map. Some of these challenges, such as transitioning of leadership roles, are regular and inevitable. However, the process can revitalize the project; it can result in the creation of primary and secondary exploration resources. These resources, and additionally the enthusiasm generated, result in more new survey per year.

The effort to initialize a digital drafting project is immense, but possible and can be shared by multiple project members. The total cost of IT resources for such a startup is relatively low due to open source software solutions and the minimal cost of cave mapping software.

Despite the challenges, a digitally drafted map is a worthwhile endeavor for long caves.

Acknowledgements

31 years of cavers eagerly suffering through far-out, and challenging caving has made it possible to begin drafting this map. Without all of the project participants there would be no cave data; most notably: Peter Quick, Keith Ortiz, Chip Hopper, Suzanne Deblois, Mike Fitch, Larry Bean, Dan Crowl, Brian Davis, Joe Saunders, Steve Miller, and Jonathan Scwher. Chip Hopper has been custodian of the numerical survey data for 31 years and still is – his efforts, fastidiousness, and willingness to help have allowed this drafting project to work. Huge thanks go out to Mike Fitch and Peter Quick for their efforts in scanning original notes. Thanks to Geof and Dan Crowl for setting up the servers and hosting the repository. The conversion of data would not have been possible without the invaluable assistance of Larry Fish who wrote a custom conversion script and has updated Compass numerous times to address the specific challenges this cave offers. Thanks to Alex Seidel for pioneering this project with the present author and putting in many hours. Thanks to Mike and Andrea Futrell, Erin Lynch, Duncan Collis, Mike Ficco, and Paul Burger for their help in making the maps look nice and developing the style standards. Finally, Thanks to Ronnie Harrison and Sean Lewis for generating and maintaining huge enthusiasm for actually getting in the cave, which sometimes suffers during such large computer projects. A word of acknowledgement is due to the Cartography Salon at the 2009 ICS for providing the motivation to start this project.

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HUMPLEU CAVE (ROMANIA): WHAT'S UP?

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Humpleu Cave is the second longest cave of Romania. Because most of the original data was 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. Due to its length (around 40 km), the remapping is done in the scale 1:1,000, both in plan and in longitudinal section. In the last 11 years, some 30 km have been remapped, and an end of the work is in sight, if not in the immediate future. The present genetic hypothesis of Humpleu Cave is that it is more an enlargened gigantic paragenetic canyon than two distinct levels of large phreatic passages and an active canyon level.

1. The cave

Humpleu Cave is the second longest cave in Romania. It is situated in the Humpleu Hill, in the Bihor Mountains (Fig. 1). Discovered in 1984, it contains about 40 km of mapped passages. The cave is mainly horizontal, but has another entrance on top of the hill, that joins the main passages after a series of shafts. Humpleu is famous for two reasons: the first one is the size of its rooms, which are amongst the biggest in Europe. Moreover, they are often richly concretioned and thus very splendid. The other reason is the beauty of the 5.2 km long underground river, which runs quietly in a huge meander. The river passage has to be negotiated with a diving suit, since there are several ducks and semisumps to pass, before reaching the final sump in a distance of about seven hours from the entrance. The final sump could not been conquered: it gets too tight some 30 m further.

The first mappings after the discovery of the cave were done rapidly by several caving groups. Sadly, most of the mapping data has been lost subsequently due to various reasons. To date, only data of parts of the active river could be found again. The lack of data and of a beautifully drawn cave plan (and longitudinal section) effectively prevents any scientific work. So, the decision was made to remap the cave in those parts where there are no data, and to use the present data where possible.

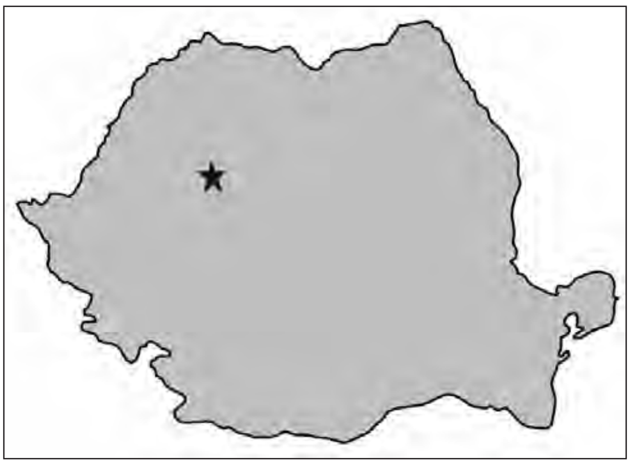

Figure 1. Location of Humpleu Cave in Romania.

2. The remapping project

The remapping is done in a Romanian-Swiss collaboration. Due to its size and length, we decided to remap the cave in the scale 1:1,000. This has the advantage that more than one room can be shown on one plan sheet, and the time used for drawing inside the cave is reduced to an acceptable amount.

The cave is remapped conventionally with tape, compass and clinometer. A plan view, a longitudinal section and gallery profiles are taken. Caves belonging to the same hydrogeological system are also remapped and integrated into the general overview of the area. The data is introduced into Toporobot. Remapping was originally done during cave camps of 6 to 10 days duration. If possible, several groups were formed per day, some of them remapping, others equipping shaft passages or climbing chimneys in order to make mapping more effective. For the last 2–3 years, the distance from the entrance grew too big to reach the mapping sites in reasonable time. Therefore, the international mapping camps that had been very successful, were abandoned and replaced with small groups (3–4 people) that camp 2 to 4 nights inside the cave.

Bad weather in some years (especially around 2010) effectively hindered good progress: the bivuac can only be reached by passing several semisumps with only 5–15 cm of air above the waterline. In cases of flood, the semisumps close completely, and because of their length (up to 90 m long), they cannot be dived freely. Still, about 30 kilometers of passage have been mapped so far, including a redrawing and correction of the shaft zone which was rigged for a possible case of flood emergency. The remapped parts of the cave are shown in Figure 2, in grey, the parts that have to be controlled or completely remapped.

As a whole, the project made good progress. There are, however, some flaws: In the large rooms behind the semisumps, an incredible number of blind shafts were visited and drawn during the first mapping efforts, but they were not mapped. Due to the difficulty rigging them (often the walls consist only of pebbly sediment and not of hard limestone), they are left behind for the moment. We consider it more important to set the straight lines first, before going into detail. Work to do for the future…

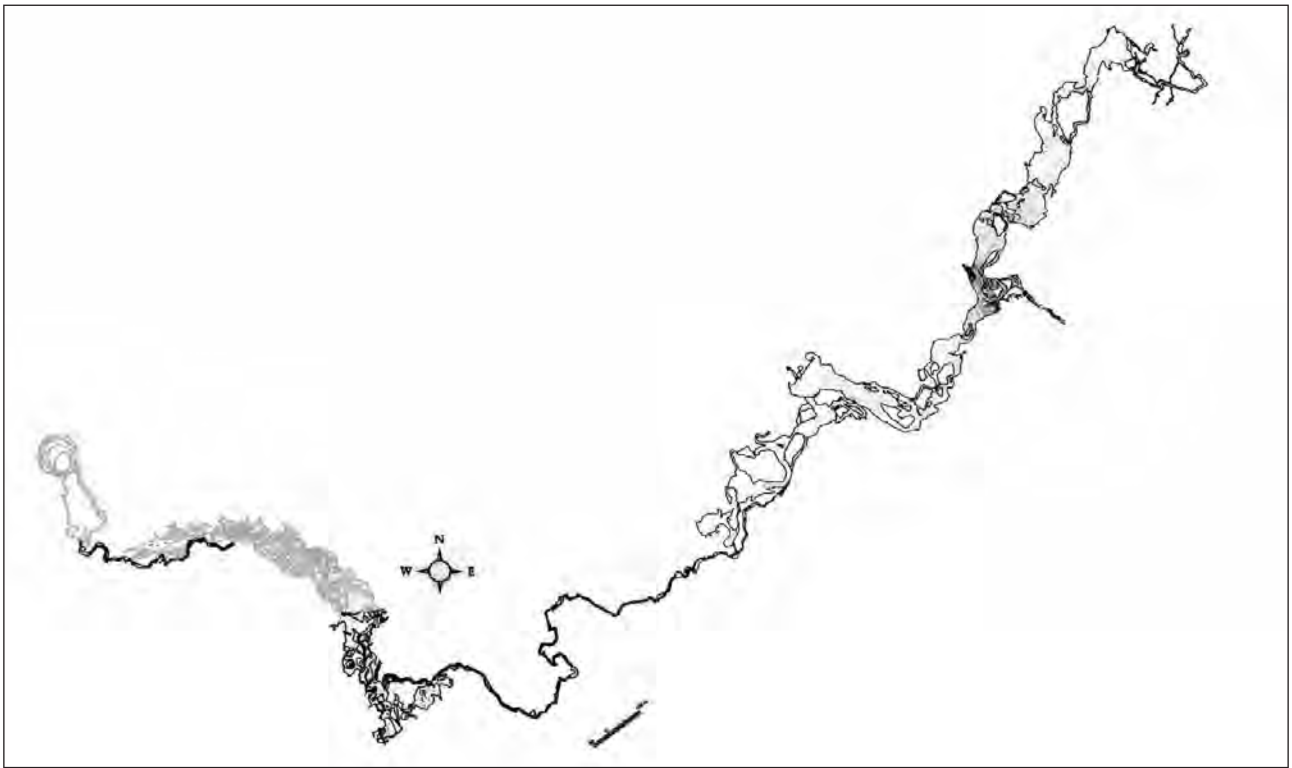

Figure 2. The original map of Humpleu Cave. In black: parts where data and drawings can mostly be used, grey: the remapped or verified parts or parts that have still to be remapped.

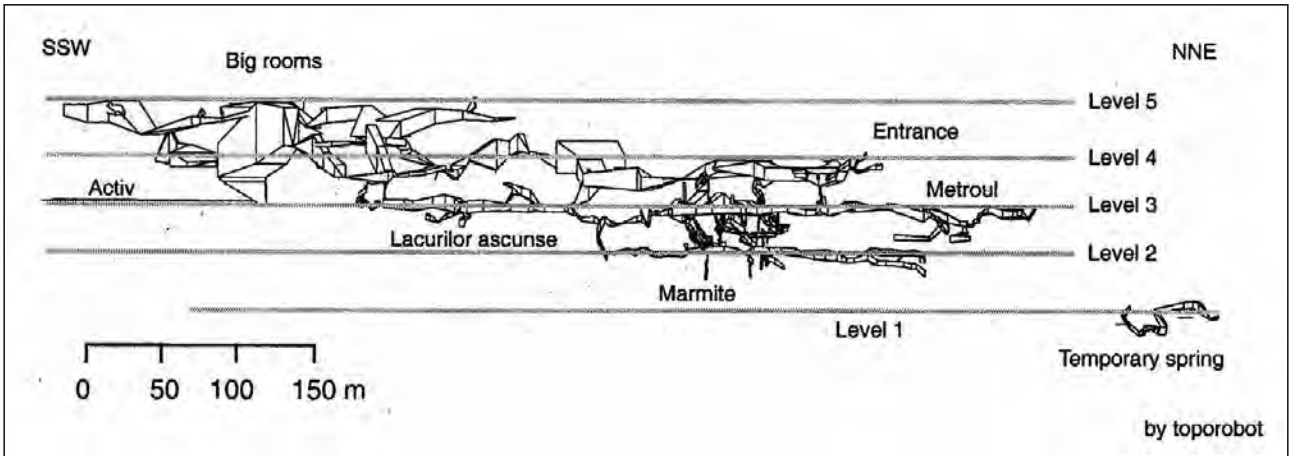

Figure 3. Projection of the entrance part of Humpleu Cave. The five levels are represented by the grey lines.

3. Some Results: Passage levels and passage size

At the UIS congress in Greece 2005, already some results have been presented. While the morphology of the cave did not change since then, so did the interpretation of its genesis. Therefore, it is good enough to review the present-day morphology and to re-publish the newer ideas. There is still a lot of science to do in the cave. Since our primary goal was the remapping, we didn't bother a lot with scientific progress. Still, a diploma thesis was done (Soit 2009), and some preliminary notes were taken.

The 3D representation of the cave (Fig. 3) makes it easy to recognize that the cave is organized in five levels, of which the lowest one is the temporary spring. The next lower level is active only during floods, and presents shafts going down to the water table. The next level is fossil in its downstream part, may get flooded in the middle part, and is perennially active in the upstream part. The entrance level comprises the huge rooms and big, fossil passages. They are sometimes connected with the uppermost level which also is represented by huge rooms. From the access to the river and further upstream, only levels 3–5 are present.

In 2005, the upper passages have been interpreted as being phreatic passages, due to the corrosion forms of the walls and the sometimes rounded passage size. The conclusion was that the river, impressive in flood, (estimated discharge of 5–10 m^3/s), could not be responsible for the creation of the large voids.

However, continued mapping revealed and scientific studies revealed the following:

- paragenetic signs are abound almost everywhere in the large rooms;

- lateral incision of a river into the walls was observed not only in the active meander, but almost everywhere in the large rooms;
- in some large rooms, the ceiling is leveled flat, and pebbly sediments close up to 50 cm from the ceiling;
- and last but not least, the separation of the three levels that remain upstream from the river, is hardly ever bedrock, but most of the time, it consists of breakdown, pebbles, flowstone and the like.

As a consequence, the genetic model of the cave presented in a rough sketch in 2005, must be revised. The present-day hypothesis (note the word hypothesis!) hints that the cave is, for the most part, a huge, more or less vadose canyon, that has been modified by paragenesis to create the large rooms, before incising again into sediment and bedrock, eventually creating another level. A summarized idea is presented in Fig. 4.

The hydrothermal influence that was evoked as a possibility in 2005, has been revoked. As a matter of fact, the cave seems to be affected by paragenesis only, and the observed large calcite spars that may be seen in some places, represent chambers that were accidentally cut by the present-day cave.

4. Future work

Remapping of the remaining passages will be the main goal of the years to come. The final and first result should be a usable map of this very interesting cave system that can then be used for further scientific studies. Very recently, caving in Romania seems to get more and more controlled by a joint effort of the State, the Speological Institute, and the Speleological Federation. I do hope with all my heart that this control is for the good of the caves and not for the detriment of all the interested cavers that still exist in this beautiful country. I also hope very much that the remapping project can be brought to a good end without bureaucratic hassle.

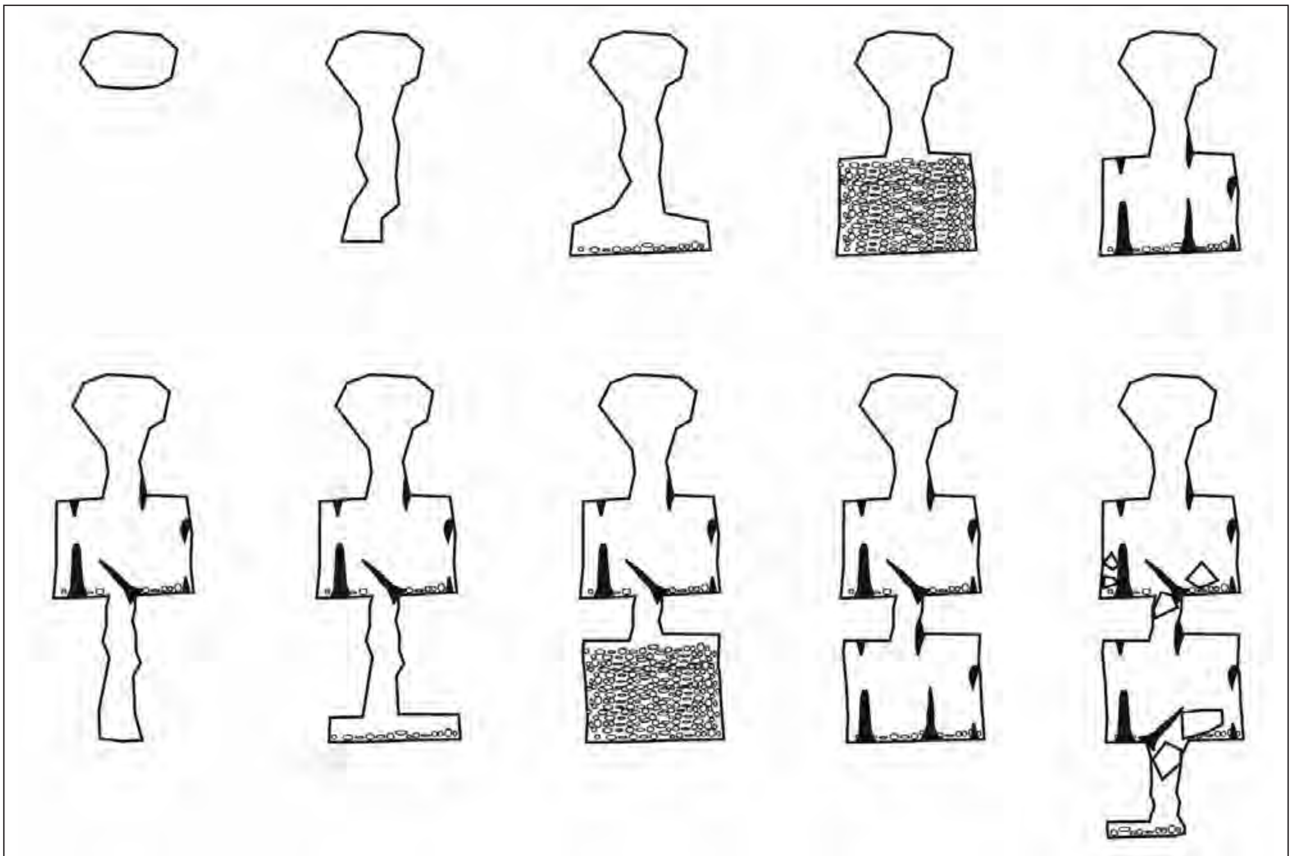

Figure 4. The presently favoured model for the genesis of Humpleu Cave. A relatively small phreatic passage (rarely seen) is entrenched by a meander; sediment filling of the meander induces paragenesis and an uplift and flattening of the ceiling of the river that undercut the rocks. Subsequent erosion of the sediment fill and bedrock was then followed by another paragenetic event responsible for the genesis of the 4th level. Later incision and some sediments led to the picture seen today (lower right). Note that the upper keyhole is hardly ever seen, there is the possibility that paragenesis effectively annihilated the original phreatic passages.

Acknowledgments

To all the cavers of various nationalities which helped in the remapping project, and the motivated students that got infected by the caving bacillus. To Felix Papiu, Gheorghe Fratila, Ovidiu Pop for assistance with the old mapping data. To Ovi for continous support of the remapping project. To Bogdan Onac for having me introduced to Humpleu…

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THE AURIGA PDA FREEWARE THE ELECTRONIC SWISS KNIFE OF CAVE SURVEYORS

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Ten years after its first public inception, the Auriga cave survey freeware for PDAs is a mature tool providing a wealth of features to a wide range of users, from international expedition teams to Sunday cavers. Far from being a gadget, Auriga brings the true benefits of a pocket computer to the underground: speed, confidence and convenience. Speed in note-taking and sketching, confidence that this data accurately matches the cave and convenience of a feature-rich tool. Not a port from existing software but designed from scratch, its interface is well adapted to a small PDA screen. A simple waterproof write-through case is enough to make it suitable for underground duty.

1. Introduction

The original goal behind the development of Auriga was merely to replace a power-hungry laptop used to compute survey shots into XYZ coordinates when at camp in the wild. But ten years after its first public inception, the freeware boasts a range of features seldom found in a single desktop cave survey program. Combined with an in-cave-oriented interface and an uncommon level of flexibility in measurement units, options and preferences, it has become a tool of choice for modern surveyors. Not only has it improved the way we input numeric data and sketch, it has also opened new possibilities to the survey process.

This presentation will cover the various aspects of using Auriga, both underground and on the surface karst.

2. Features, features, features

Fast input

Numeric input in Auriga is best done through its smart keypad (Fig. 1). Keys are big enough to be typed with gloves, and only context-relevant numbers, letters or symbols are made available.

Figure 1. The Auriga Keypad.

On-the-fly validations are applied (bound checking, likeliness of precision or distance, foresight-backsight comparison, etc.) to ensure the most reliable data. Each survey shot can hold a lengthy comment, and being in electronic form, everything remains well ordered and readable, no matter how muddy the cave (Fig. 2).

Figure 2. The Survey Shot form.

Let's connect!

For those who prefer acquiring data from Bluetooth-connected instruments, Auriga supports the DistoX, Disto A6, SAP and TruPulse devices as well as GPSes (Fig. 3). With 3-in-1 devices like the DistoX, passage widths and heights are automatically recognized from the main survey shot.

A companion standalone freeware calibrates the DistoX with the PDA. Users find it the most user-friendly program for that purpose.

Figure 3. The Link tab of the Preferences dialog.

Splay measures anyone?

When LRUD (left, right, up and down) passage dimensions don't provide enough guidelines for assisting in sketching, Auriga can store and show splay measures (Fig. 4), taken from either station, towards walls or random features. After that, sketching becomes akin to drawing by numbers!

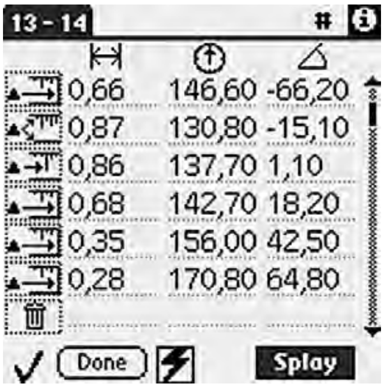

Figure 4. The Measures form.

Validation as you go

By replacing notebook columns of numeric data and a "hopefully" matching sketch by an immediate graphic rendition of the line plot and sketch, the PDA shows the surveyor his work so far. Slope inversions, heading errors and other survey blunders become much more apparent and can be fixed at once.

Easy sketching

Contrary to initial fears, sketching on a PDA is very easy. Cave walls and features can be sketched at any scale and Auriga allows editing parts of a sketch element, as we do with a pencil, but with an automatic eraser that removes the part that was just replaced. Lines can be given patterns (no more sketching of individual drop lines) and shapes can be filled (water, sand), just by selecting an option. And for more clarity, sketching is done in color and on togglable layers (Fig. 5).

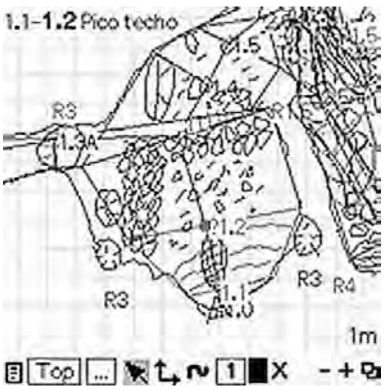

Figure 5. Map with hand-drawn sketches.

For die-hard paper sketchers, Auriga still offers tools like projected length and survey shot coordinates expressed in paper grid squares.

Loop closure

A survey loop suddenly happens? Auriga automatically computes the absolute and relative errors (based on loop length) and tells how good the loop closure is, given the survey instruments used. A loop closure algorithm can be applied to keep a closed line plot. Don't worry about sketches: they're self-adjusting to survey shot length and heading.

Blunder detection

Loop closure exceeds the expected error of the current instrument set? Auriga can perform a loop analysis to help find the faulty survey shot, if any, by proposing blunder hypotheses that can be immediately verified while still in the cave (Fig. 6).

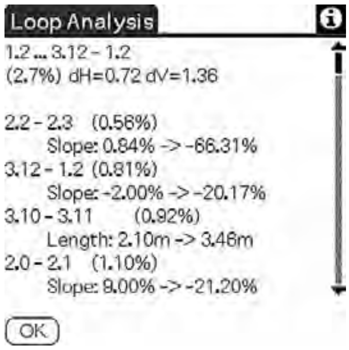

Figure 6. The list of loop analysis hypotheses.

Data mining

The cave data is now searchable and pokeable (Fig. 7). What's the distance between those two stations? What's the shortest path between those two areas? What's the main orientation of those fractures? Where is this station? How deep are we? Where is a permanent station to link to? Survey shots can be displayed in list fashion, sorted in any order and searched by various criteria

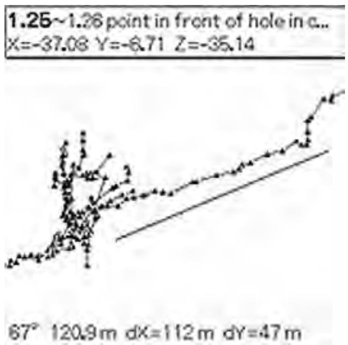

Figure 7. Getting distance and angles from map.

Pit sounder

When a new pit is found, it is common to bottom it before surveying it (Fig. 8). But how long a rope is needed? Dropping a stone can be very approximate, unless you proceed with care and let Auriga do the depth computation. A 1% margin is just too cool!

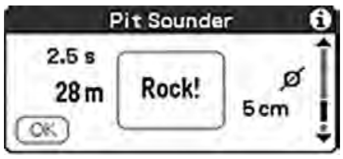

Figure 8. The Pit Sounder dialog.

Data management tool

Let two survey teams loose in a given area, and it's likely they end up with overlapping station names. That's not a problem until they connect their caves… Auriga offers various maintenance features (Fig. 9) to rename stations in bulk, correct input units after a mishap, inverse survey shot direction, etc.

Figure 9. Managing data in bulk through the Maintenance dialog.

Network management

If nearby caves don't connect but still gain from being displayed together, Auriga makes it easy to view the network, just list the caves to be shown together linked by GPS coordinates or a surface survey between entrances. (Fig. 10) And the same search or poke features used with individual caves are available to networks.

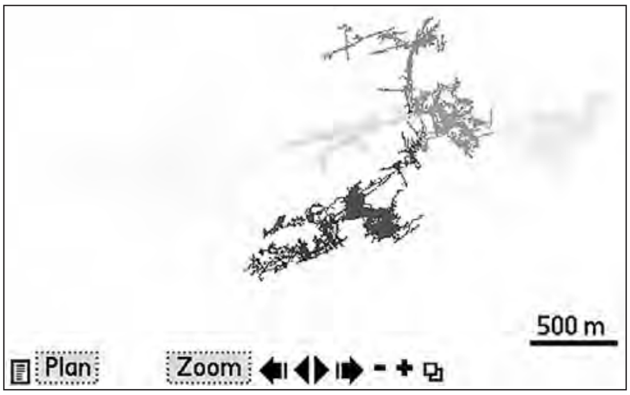

Figure 10. The whole 200-km Lechuguilla Cave on a PDA screen.

Getting the data out (or in)

Auriga can "beam" its caves and networks to other PDAs through its standard infrared or optional Bluetooth link (Fig. 11). Survey teams that meet underground can exchange their respective work in a few seconds, while relying on automatic data merge to handle overlapping changes.

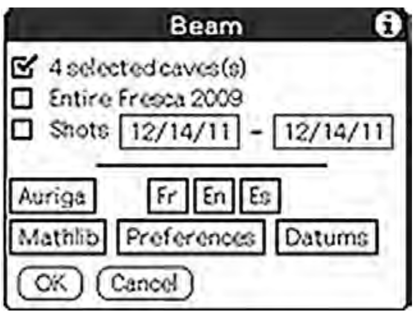

Figure 11. Beaming cave data or Auriga components to another PDA.

The binary raw survey data in Auriga can be exported in CSV files as well as Compass, GH Topo/Toporobot, Survex, Therion, Visual Topo and Walls text formats (Fig. 12). Computed data can be exported in CSV, DXF, GPX (GPS Exchange), KML (GoogleEarth) and SVG formats. Conversely, existing survey data can be imported from text files in Compass, GH Topo/Toporobot and Visual Topo formats.

Figure 12. Exporting cave data to sketching or surveying PC programs.

Take a walk on the surface side

By taking a surface walk with a GPS to locate karst features before starting to survey, these features can later be viewed in relation to underground passages as the survey goes. Are we getting close to that sinkhole? …to that other cave? It's right there, visible on screen.

Walk the cave from above

When looking for alternate entrances (such as fissures, collapses or sinkholes), connect a Bluetooth GPS to the PDA and let Auriga guide you over the cave in moving map fashion. Auriga supports a few grid formats in hundreds of geodesic datum.

3. Lessons learned from field experience

Auriga has now been used in many expeditions worldwide. Each of them constituting a new field test bringing new ideas, promptly implemented. Exploration teams have found the software speeds up the survey process and makes it more reliable. In some cases, the ability to see where passages trend to as the survey goes has permitted groups to take better exploration decisions and make connections. The software has also been successfully used to fix poorly-surveyed cave passages, allowing the surveyors to readily know when a survey loop is properly corrected (Fig. 13).

As with any electronic instrument, care must be taken to keep the data safe. It is now customary to keep a PDA at camp to act as a data repository, along with backups on memory cards.

Figure 13. Fixing bad survey loops in Lechuguilla Cave.

4. Summary

Auriga runs on a battery-powered PalmOS PDA or on Android, Windows Mobile or iOS devices thanks to the StyleTap emulator. It takes advantage of color, high-resolution, serial, infrared and Bluetooth links. The software is free, available in French, English and Spanish, ever-evolving and fully documented with a reference manual, embedded help and tutorial videos.

Acknowledgments

Christian Chénier for coding the exchange conduit.

Antonio Alcala Ortiz, Jeff Bartlett, Jean Bottazzi, Michel Cadieux, Daniel Chailloux, Christian Chénier, Éric David, Larry Fish, Paul Fretwell, Brandon Kowallis, John Lyles, Martin Melzer, Elena Navarro, Guillaume Pelletier, Gaëtan Perrier, Andrés Roz, Brauli Torres, Al Warild and the many cavers whom I forget who provided much appreciated input (design ideas, suggestions, bug reports or beta testing) and help with translation.

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www.speleo.qc.ca/Auriga for software download, history of changes, documentation, articles and testimonials.

QUICK 3D CAVE MAPS USING CAVEWHERE

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Cavewhere can create quick 3D working maps through a process called carpeting. Cavewhere implements carpeting with a 3D warping algorithm. It allows users to morph their two-dimensional cave sketches with line plot data. This paper presents the editors needed for the carpeting process: the Survey Editor and the Notes Editor. The Survey Editor allows users to enter shot data in a similar way to other survey packages like Survex, Compass, and Walls. The Notes Editor provides digitizing tools for cave sketches. After the user enters all the necessary information for carpeting, the warping algorithm morphs cave sketches in 3D. Cavewhere can display the results in interactive frame rates on standard desktop hardware. It can then export the results as a high-resolution image to aid with drafting a final map.

1. Introduction

Working cave maps are an important tool at the heart of every exploration project. Not only do they allow surveyors to orient themselves and keep track of known passage, they also show tempting leads that motivate cavers to return to systems again and again.

The complex nature of caves makes developing a working map that includes all the relevant details difficult.

Many cave systems have multiple overlapping levels. Furthermore, good cave maps have floor detail, profiles, passage offsets, cross-sections, and annotations (1). For large cave systems, hundreds of hours of drafting can be required by multiple people to complete a map (2).

Generally on extended expeditions, cavers have little time to draft a working map. Instead, they rely on line plotting software such as: Compass, Walls, or Survex. Cavers can quickly enter data into these software packages to create three dimensional (3D) models of survey shot data.

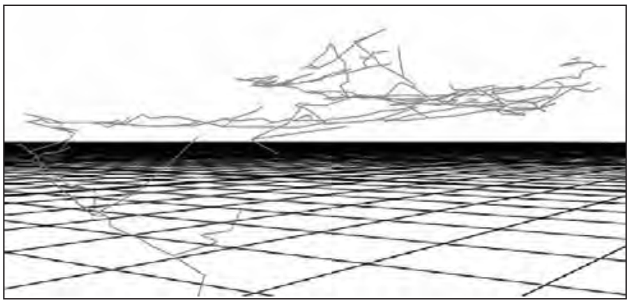

Figure 1. A perspective view, looking north-west, of the line plot of Quankou.

While 3D line plots expedite data visualization, they forgo several desirable map aspects. First, passages lack dimensions. Since all passages are visualized as lines, a large passage has the same visual impact as a small passage. Second, passages have none of the floor detail that is represented on the hand drawn map. Floor detail is extremely useful for locating survey stations, route finding, and resource inventory. Third, line plots are unable to show side leads. Finally, 3D line plot models can become indecipherable when presented in a format that doesn't allow viewers to manipulate them, as in Figure 1.

Cavers have mitigated the problem of misrepresentation of passage size in pure line plots by collecting Left, Right, Up, Down (LRUD) measurements while surveying and developing software that uses this data to generate models that show passage walls like Compass and Survex. LRUD measurements are made up of four distance measurements from the station: to the left wall, to the right wall, to the ceiling (up), and to the floor (down). Unlike when collecting length, clinometer, and compass measurements, there is no standard for collecting LRUD measurements. They can become arbitrary, especially at intersections, in irregularly shaped passages, and when surveying down vertical shafts. LRUD generated models ignore floor detail, as well as wall detail between shots as shown in Figure 2. LRUD modeling tends to under or overestimate passage dimensions. This is exacerbated when shot length increases.

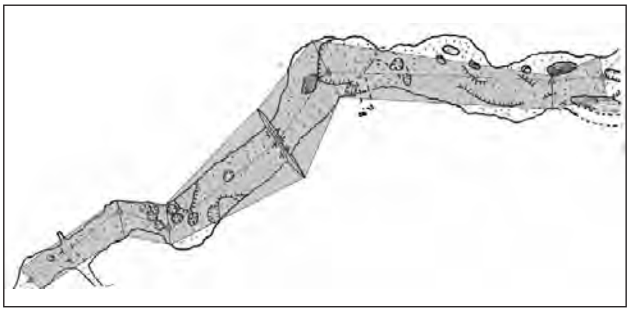

Figure 2. The deficiencies of 2D LRUD modeling (in blue) in comparison to a plan-view sketch.

Cavewhere combines the sketch with a 3D line plot through a method called carpeting, Figure 3. Carpeting allows surveyors to understand the spatial complexity of the cave without sacrificing the passage detail from the hand-drawn map.

2. Data Entry

2.1. Overview

Cavewhere makes entering data and developing a working map an easy process. The process starts by scanning from the survey notes. Then users enter their line plot data using Cavewhere's Survey Editor. Finally, users cut out map sections for carpeting, using the Notes Editor.

2.2. Survey Editor

Once survey book pages have been scanned the Survey Editor interfaces allows users to enter normal cave survey data: station name, length, compass, clinometer, and LRUD for each station. It features an offset format similar to that of survey book pages as seen in Figure 4. Just like in a survey book, Cavewhere's survey editor keeps continuous blocks of shot data together. Users need to create new blocks when entering data for divergent passage, such as a splay or a side passage.

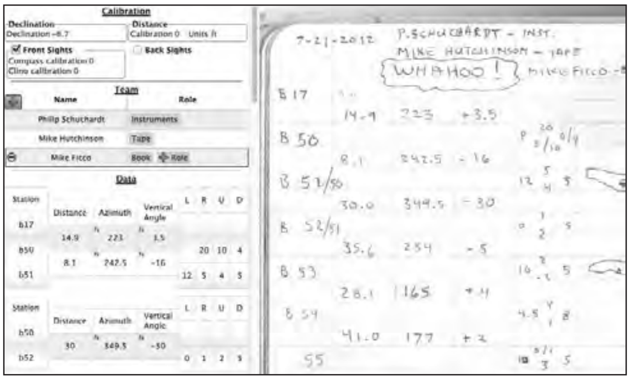

Figure 4. Cavewhere's Survey Editor. The Survey Editor is made up of two parts: the Editor (left column) and the Notes Viewer (right column). The Editor shown 2 survey blocks with shots: B17 → B50 → B51, and B50 → B52.

Cavewhere automatically processes and updates the line plot as survey data is entered. It also updates the total distance surveyed, displayed at the bottom of the editor.

Cavewhere has smart error handling that prevents users from entering erroneous data, as well as automatic station name incrementing. For example, if the user enters a1→ a2 for the first shot, for the next shot the user only has to press "Enter" for a2→ a3.

Cavewhere's editor doesn't lock users into its format. It can import and export survey data from and to Compass and Survex (Walls is in the works). Once data has been entered or imported users can create a model that unites the haste of line plot models with the detail of a hand drawn map in the Notes Editor.

2.3. Notes Editor

In the Notes Editor users can combine the hand-drawn map with a line plot in a process called carpeting. Carpeting is a two-step process that involves firstly, cropping the sketch with a polygon and secondly, digitizing all the station locations, shown in Figure 5.

Cutting out the passage (hereafter referred to as the sketch) from the hand drawn map isn't an exact process. Users can quickly and roughly draw a polygon around the sketch using a custom shape cutting tool. The polygon should include the passage walls for best results. After creating the polygon, users digitize the stations on the sketch using the station marking tool.

Users can add station markers simply by choosing the station marking tool and clicking on the stations. After naming the first station marker, Cavewhere will automatically name all consecutive station markers by

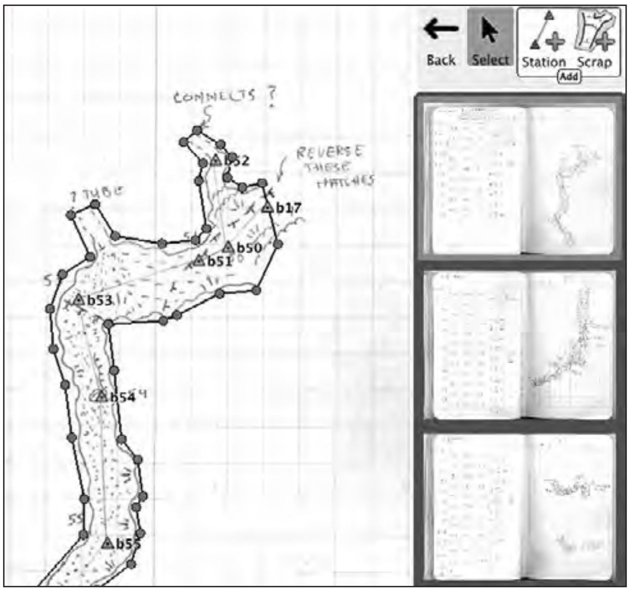

Figure 5. Cavewhere's Notes Editor. This screenshot shows the polygon around the sketched plan, as well as the digitized stations.

estimating the scale and rotation of the sketch, and analysing the survey data provided in the Survey Editor. Users can enter scale, rotation, and image resolution data to improve results.

These two steps are repeated for each sketch. Once the process is complete, Cavewhere will automatically carpet the sketch to the line plot data using sketch warping.

3. Sketch Warping

Sketch warping is a useful method for distributing the error in hand-drawn sketches. Sketch warping simplifies the map drafting process. When surveyors draw maps by hand there is error between the data and the sketch created. In Cavewhere, once stations have been digitized with the station marking tool, the polygon is deformed to make it fit the shot data using a warping algorithm. Unlike other 2D sketch warping software, such as Compass, Walls/Illustrator, or Therion, Cavewhere warps the sketches in 3D. Cartographers can easily draft a map using the results of the sketch warping algorithm.

4. Sketch Warping Algorithm

The warping algorithm uses station positions, as well as the cropped sketch, to create a 3D map in 4 steps:

1. The algorithm compresses the cropped sketch's image using a DXT1 compression algorithm. DXT1 is an OpenGL compression routine that provides 6:1 lossy image compression. This allows Cavewhere to store 6 times as many sketches on a graphics card and also improves rendering performance.
2. The algorithm triangulates the digitized polygon for the Notes Editor. The triangulation algorithm meshes the polygon using a regular grid in the interior and an irregular grid to fill the space between the regular grid and the boundaries of the polygon. Users can adjust the grid resolution to produce smoother or coarser warp results.

3. Cavewhere warps the grid in 3D using station data. The warping algorithm uses a weighed averaging method to adjust the position of each point in a triangulated mesh. Cavewhere calculates the weight between each mesh point's and every station in the sketch using a distance function. The closer a mesh point is to a station the higher weight. Then the warping algorithm calculates the position of the mesh point in respect to each station. The sum of all the weighted positions produces the final mesh position, shown in Figure 6.

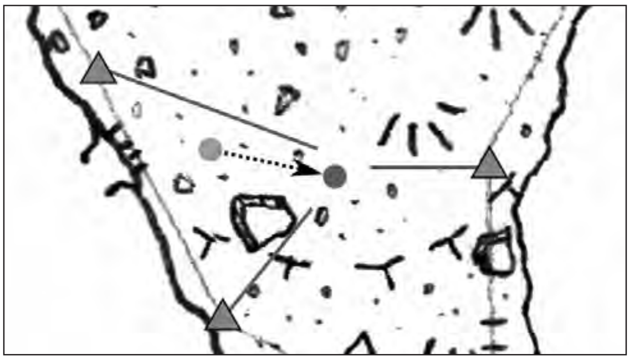

Figure 6. Shows the stations (red triangles) projecting (green lines) where a mesh position (orange dot) should be located. The resulting warped mesh position is represented by the green dot.

4. The algorithm textures the warped triangulated mesh, created in step 3, with the compressed sketch image from step 1. Cavewhere can render the resulting 3D map at interactive frame rates (see results and performance).

Sketches scanned at 200 DPI have a nice balance between quality and storage requirement.

The performance results, Table 1, were generated on a 2.2 GHz AMD Athlon(tm) 64 X2 Dual Core 4400+ with 4 GB of 333 MHz DDR2 RAM and a Nvidia GeForce GTS 250, 1024 MB video ram. This system is capable of rendering each model at real-time frame rates at 60 frame-per-second.

After creating a carpeted cave map, the results can be exported as a high-resolution image and drawn in a vector graphics program. Not only can the results be exported in plan view, they can be exported in any three-dimensional orientation.

Table 1. Cavewhere Results.

Cave	Length	Scan Resultion (DPI)	Percent Carpeted	Sketch Scale	System RAM Used	Disk Usage	Generation Time
Beer Can	883 m	400	100 %	1:480	72 MB	152 MB	21.3 s
Chasm							
Wahoo Cave	1,463 m	200	100 %	1:480	163 MB	70 MB	23.4 s
Quankou	12,991 m	200	75 %	1:500, 1:1,000, 1:2,000	154 MB	36 MB	39.5 s

5. Results and Performance

This section is a demonstration of Cavewhere using three different data sets, shown in Table 1 and Figure 3. The shot data from the Quankou and Beer Can Chasm data sets were entered in Survex and imported into Cavewhere. Wahoo Cave's shot data were entered using Cavewhere's Survey Editor. All three data sets were created using the Notes Editor.

Although Quankou is the largest cave of the three, 12,991 m, it uses the least amount of disk space. Unlike the other caves, Quankou was sketched at large scales and the sketches are free of mud and crisp, which improves the image compression, and only 75 % of cave was modeled using carpeting. The other 25 % was modeled as a line plot. On the other hand, Beer Can Chasm, the smallest cave in the data set, uses far more disk space because the sketches are scanned at 400 dots per inch (DPI.) As the scan resolution and number of sketches increase, computation requirements also increase. Sketches from Beer Can Chasm, a muddy and wet cave, are noisy, thus preventing Cavewhere from compressing them as much as Quankou.

6. Improvements

6.1. Notes Editor Improvements

Although versatile, Cavewhere does not support cross-sections and running-profiles. These could be added to the Notes Editor in future versions.

6.2. Warping Algorithm Improvements

Currently, when the warping algorithm positions a point in the mesh, it uses the weighted distance average from all the survey stations in the sketch. This can be problematic because if one shot is drawn incorrectly, then the error is distributed over the whole sketch, instead of being localized to that shot.

6.3. Import/Export improvements

Moving data between software packages is important**.** Although Cavewhere supports import and export with Compass and Survex, there are many other software packages that Cavewhere could interact with. Future versions of Cavewhere will probably support Walls, another popular line plotting software program. Cavewhere also lacks support for exporting to GIS formats such as ERSI shapefile and Google Earth KML.

7. Conclusion

Cavewhere gives users the ability to combine the speed of line plot software with the detail of hand drawn survey maps using carpeting. This provides a better representation of a cave than either a line plot or LRUD model. After the warping algorithm has fitted the sketches to the line plot, Cavewhere can export the result as a high-resolution image at any perspective. These resulting images can assist cartographers with drafting a map. Cavewhere can also render the carpeted 3D maps in interactive frame rates on standard desktop computer hardware. It gives cavers the ability to create 3D working maps that can better help them understand cave systems. Indeed, Cavewhere is easy-to-use, quick, and versatile.

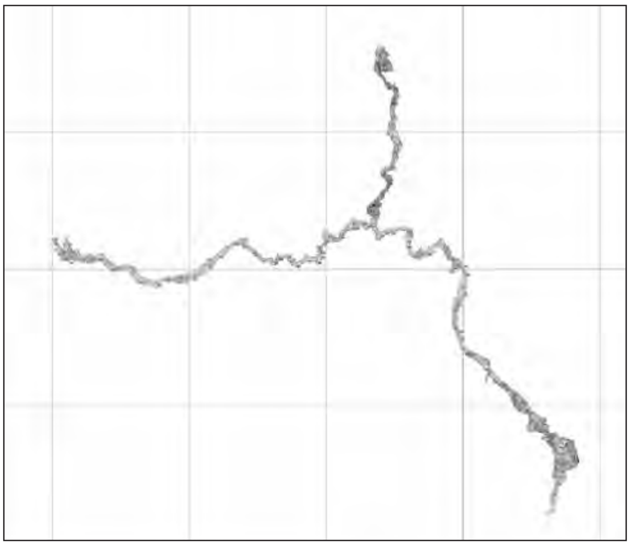

Figure 3a. Beer Can Chasm.

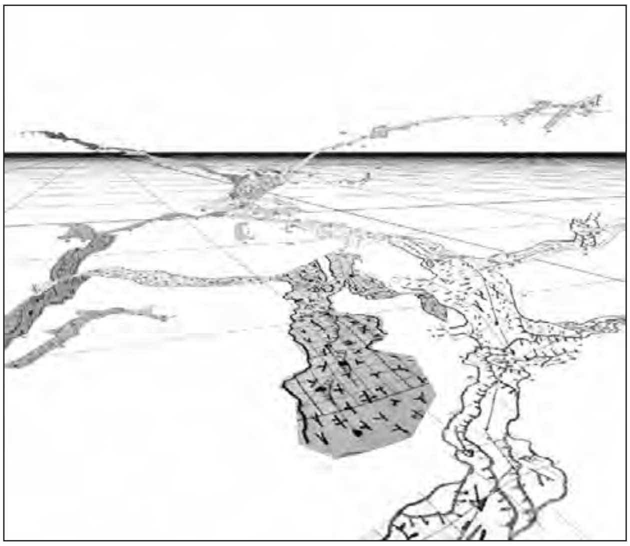

Figure 3c. Wahoo Cave.

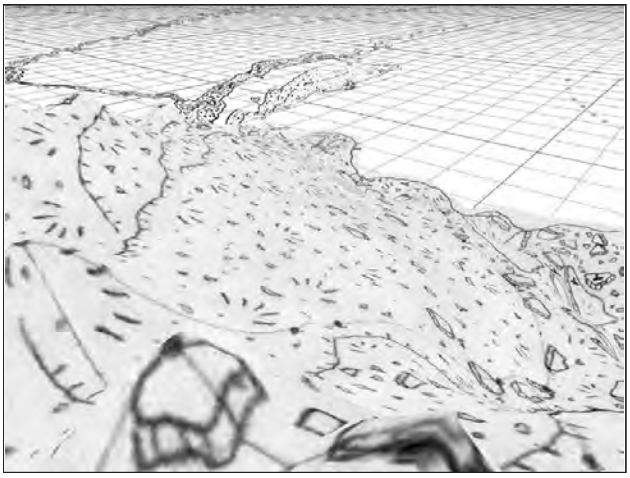

Figure 3e. Quankou, Plan view of Cloud Ladder Hall, the 6th largest room in the world, with 100 m grid in the background.

Acknowledgements

Thank you Matt Skowronski for your editing assistance.

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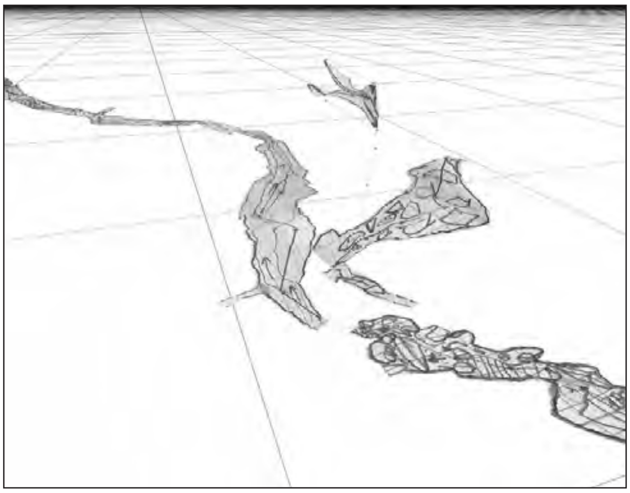

Figure 3b. Beer Can Chasm.

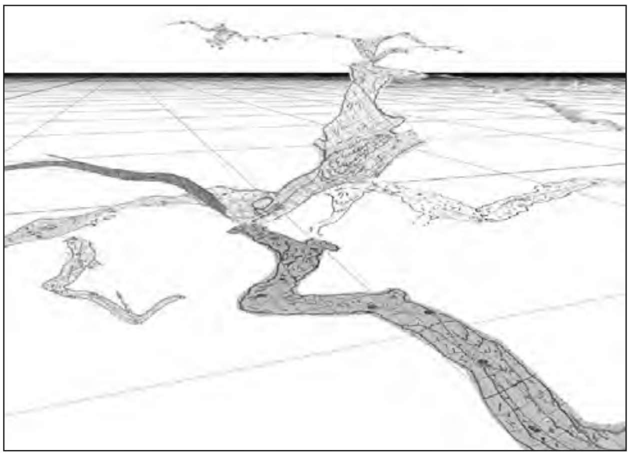

Figure 3d. Wahoo Cave.

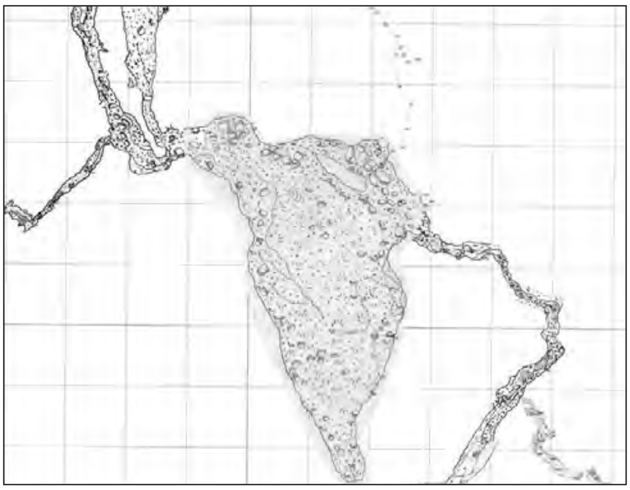

Figure 3f. A perspective view from a hill in Cloud Ladder Hall in Quankou.

THE UNIFIED DATABASE OF SPELEOLOGICAL OBJECTS OF THE CZECH REPUBLIC AS PART OF NATURE CONSERVANCY INFORMATION SYSTEM

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Abstract. The **Unified Database of Speleological Objects** (called JESO) represents the integral information system of karst and pseudokarst phenomenons (such as natural underground cavities – caves, and their relative forms of relief – swallow holes and hydrological objects – resurgences and sinks) in the territory of the Czech Republic.

JESO collects basic information about speleological objects, such as localization, dimension, description. There are also registered special supplementary information, e. g. condition, importance, utilization, enangering, research. It is possible to enclose electronic documents (photos, maps, reports) there.

Protection of caves is provided by the law on the Conservation of Nature and Landscape of the Czech Republic. JESO is also intended for ensuring the realization of purpose of Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora. The protection is possible only with quality and permanent documentation. Aim of JESO is centralization of information and data of speleological objects for the purpose of knowledge and their preservation for future generations.

Абстрактная. Единая база данных спелеологических объектов (называемая JESO) представляет собой цельную информационную систему карстовых и псевдокарстовых явлений (таких как природные подземные полости – пещеры и их вторичные формы ландшафта – воронки и гидрологические объекты – поноры и источники) на территории Чешской республики.

JESO сосредотачивает основную информацию о спелеологических объектах, таких как локализация, размеры, описание. Также регистрирует специальную дополнительную информацию, как например, сохранность объекта, его значение, использование, возможная угроза, исследование. В JESO можно укладывать цифровые документы (фотографии, карты, сообщения).

Охрана пещер реализуется на основе закона «Об охране природы и ландшафта ЧР». JESO также предназначена для реализации цели Директивы Совета об охране естественных сред обитания и дикой флоры и фауны. Охрана возможна только при наличии качественной и систематической документации. JESO сосредотачивает информацию и данные о спелеологических объектах с целью их познания и сохранения для будущих поколений.

1. Introduction

The Unified Database of Speleological Objects (JESO) is administrated as a public register and is used by the public administration authorities, specialized organisations and public. Data collection, visualization and administration of JESO system is provided by the web application on the URL address http://jeso.nature.cz.

JESO is administrated by Nature Conservation Agency of the Czech Republic (NCA CR), which cooperates with Cave Administration of the Czech Republic and Czech Speleological Society on the filling the data to database and data evaluation.

Nature Conservation Agency of the Czech Republic (NCA CR) is a governmental body established by the Ministry of the Environment as a successor of the former Czech Institute for Nature Conservation. The main aim of NCA CR is to protect and conserve nature and landscape on the whole territory of the Czech Republic. Link is http://www.nature.cz.

2. Nature Conservancy Information System (ISOP)

Nature Conservancy Information System (called ISOP) manage and make special data of nature conservation open to public. It is one of information systems of the public administration of the Czech Republic. It consists of central database and web applications with tools for editing, browsing and searching data. ISOP is provided by the web application on the URL address http://isop.nature.cz.

ISOP gives basic information about protected areas, Natura 2000 network and monument trees. There are also previews of some documents and photo evidence in the archive of the Nature Conservancy Central Register.

Current version of information system provides set of applications for everyday work of employees of nature conservancy and landscape protection. Data are effectively collected, managed and also provided for use. Applications communicate with each other and enable mutual data sharing.

3. JESO as part of ISOP

JESO use some components of ISOP. One of basic parts of ISOP is **Data Depository,** where the spatial and table data of nature and landscape of the Czech Republic are saved. Data Depository is central ArcSDE geodatabase, Enterprise version, ORACLE RDBMS, ArcGIS for Server Technology.

Other of components using by JESO is Database of Photos (called **FOTOARCHIV –** individually at link http://fotoarchiv.nature.cz). There are archived digital photos and scans of slides, negatives and photographs with information about their author, title, date of taking.

JESO also uses Database of Bibliogpraphy Register (called **BIBLIOGRAFIE** – its individual link is http://bibliografie.nature.cz). It serves for central registration, searching and export of bibliographic references of books, periodicals and special documents published in both printed and electronic version and of unpublished documents, too. This application is connected to external databases of libraries through international ISBN and ISSN codes. Bibliography entries are saved by standards of bibliographic references.

Another linked up component is **Digital Register of the Nature Conservancy Central Register** (called DRUSOP). It gives basic information about protected areas, Natura 2000 network and monument trees. Link is http://drusop.nature.cz.

4. Description of JESO system

Parts of JESO system are database web application, GIS map service and GIS map application.

4.1. Database JESO

JESO is used on platform SQL – ORACLE in architecture SERVER – CLIENT. Database is segmented into sections which are described bellow.

4.1.1. Section of JESO

JESO collects data of karst and pseudokarst phenomena in the Czech Republic. Some information is not visible for public. Data are classified into sections:

Basic information contains name, karstological division, type (cave, hydrological object or swallow hole).

JESO code keeps files of actual code, which is made on the basis of karstological division of the Czech Republic. There are also registered historical codes used before.

Dimensions notify length, depth, height, denivelation of caves (denivelation is calculated from depth and height automatically).

Entrances describe cave entrances, their localization, dimensions, type of barrier and its condition. They are and the like.

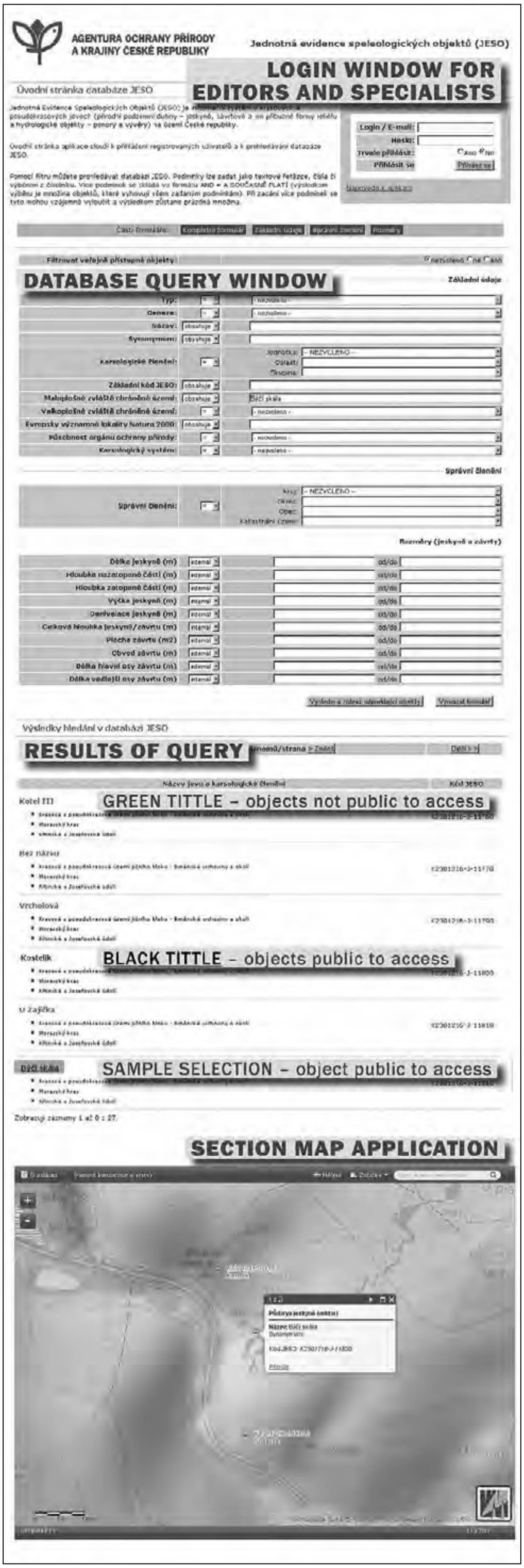

Figure 1. Home page JESO with login window, query window and results of query.

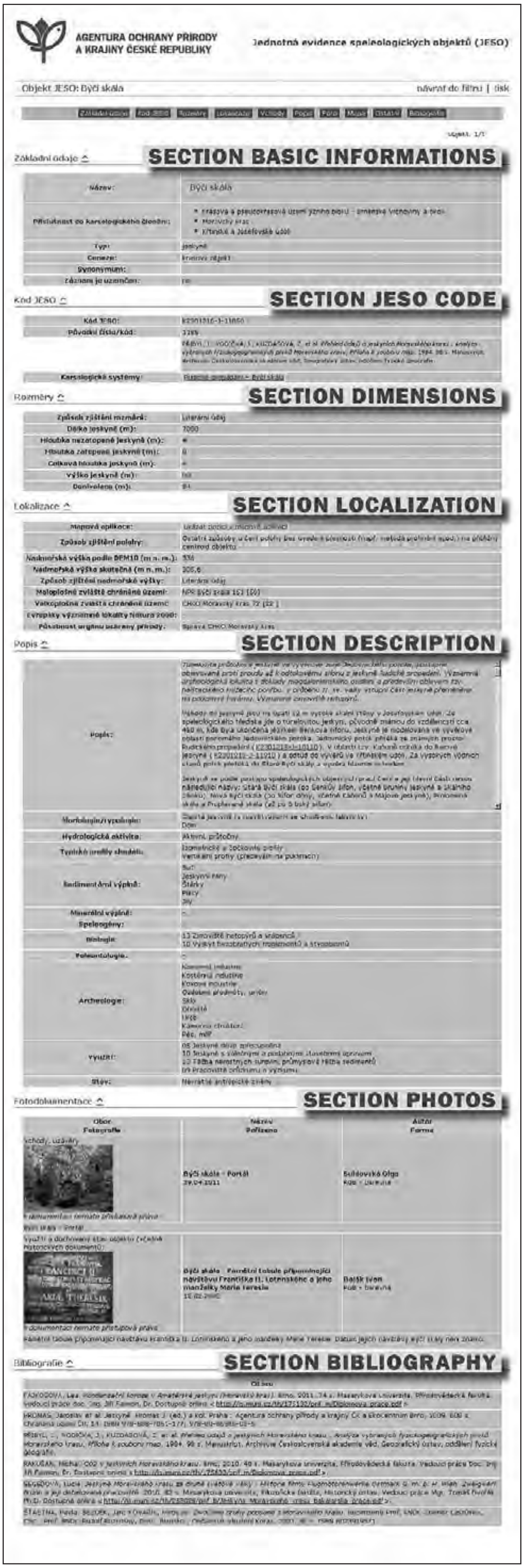

Figure 2. Detail of found object JESO.

Localization of speleological objects define coordinates (in case of caves it is coordinates of entrance). From these coordinates, further information is generated from GIS layers, such as altitude, protected areas, Natura 2000 network, geographical region.

Description consists of text part and nomenclature part (e. g. morphology, hydrology, sediments, speloethems, speleogens, biota, paleontology, archeology…).

Photos are linked up with ISOP section called FOTOARCHIV. It enables to add and describe photos of speleological objects. Users can see photos with information about date of taking, their author and description of photography object.

Maps collect electronic map documentations (as plan views, cross-sectional views of caves, 3D models of cave systems and other special maps) supplemented by information about author, title, date of drawing.

Other documentation collects electronic documents about karst and pseudokarst supplemented by information about author, title, place of depository.

Bibliography use component of ISOP called BIBLIOGRAFIE. This section inform about books, articles or other documents where you can find more information about speleological object. There are showed bibliography entries in standards of bibliographic references.

Events are database of important events, e. g. finds, open for public, building adjustment, damage, destroy.

4.1.2. Levels of data view

Users entering into JESO have different levels of data view. JESO gives access based on user's level of authorization.

Editor – can edit, update, view and download data in database.

Specialist – can view and download all data in database.

Public – has access to chosen data in database only.

4.2. Maps and Map Service

The geographic part of application uses GIS technology. JESO Map Service is presented by technology ArcGIS for Server. It is public accessible, therefore there are only show caves and other commonly known objects. The password-protected service for professional users will be added to the public one.

JESO Map service contains polygonal and point layers of entrance and converted plan views of caves, hydrological objects, karst relief and other special and base maps. Plan views of significant caves are transformed to GIS layers and displayed as a part of JESO Map Service.

4.3. Map application

Map Services is showed in web map application called JESOVIEW. This application uses technology ArcGIS

Online and Arc GIS API for Java Script. This application is integrate into JESO system. This technology enables making direct links to other database applications (e. g. DR USOP). Links of this application are situated at the web page http://jeso.nature.cz or direct URL http://webgis.nature.cz/jesoview.

Map application uses public map services (for example base maps of the Czech Republic, cadastral maps, geographical data of digital elevation model, maps of protected areas and Nature 2000 network, geographical names, waters) from servers of Czech Office for Surveying, Mapping and Cadastre, Czech Environmental Information Agency, Nature Conservation Agency of the Czech Republic, Czech Geological Survey and others institutions. JESOVIEW makes thematic compositions from those services and their layers. It is possible to make a query on a chosen object or use an information from other public databases (Cadastre, geological data, data of protected areas and of course data of JESO).

5. Data and cooperation with other organizations

There are many organizations in the Czech Republic, whose share in some activities connected with caves. They can use information from JESO. They also can fill in result from their researches or other specialities. There are e.g., the Academy of Sciences of the Czech Republic, Czech Geological Survey, museums, universities, high schools and last but not least two organization occupying with caves – Czech Speleological Society (CSS) and Cave Administration of the Czech Republic.

Every information system must contain quality and verified data. This is the reason for connection those organizations and others research workers to editing activities in JESO system. Authors and administrators of JESO systems (authors of this article) present this system and its possibilities, inform about news in JESO and also make training courses for JESO editors.

5.1. JESO and Czech Speleological Society (CSS)

Czech Speleological Society is a national caving association of Czech cavers. Members of CSS have cooperated on filling database since beginning.

Tradition of speleological research by Czech Speleological Society has started approximately in the middle of the twentieth century. Since that time, many documents and data have been collected in the central CSS archive and local and private archives that are mutually isolated. Because of the non-conceptuality and fractionalism, evaluation of these data is very problematic. JESO can collect and process those data without losing their historical value.

Actual speleological researches are another source of data of CSS. Speleological research is allowed only by a permission according to the Conservation of Nature and Landscape Law. One of the permission conditions is delivery of the copies of a text report, photos and map documentation to the nature conservations authorities. These institutions are also informed about possibilities of JESO system and progressively they give a requirement of filling data of research to JESO.

Archive materials of CSS (reports, maps, photos from historical and present researches) thus became one of the data pillars of JESO system.

5.2. JESO and Cave Administration of the Czech Republic

The Cave Administration of the Czech Republic manages in total 14 show cave systems and its Department of Cave

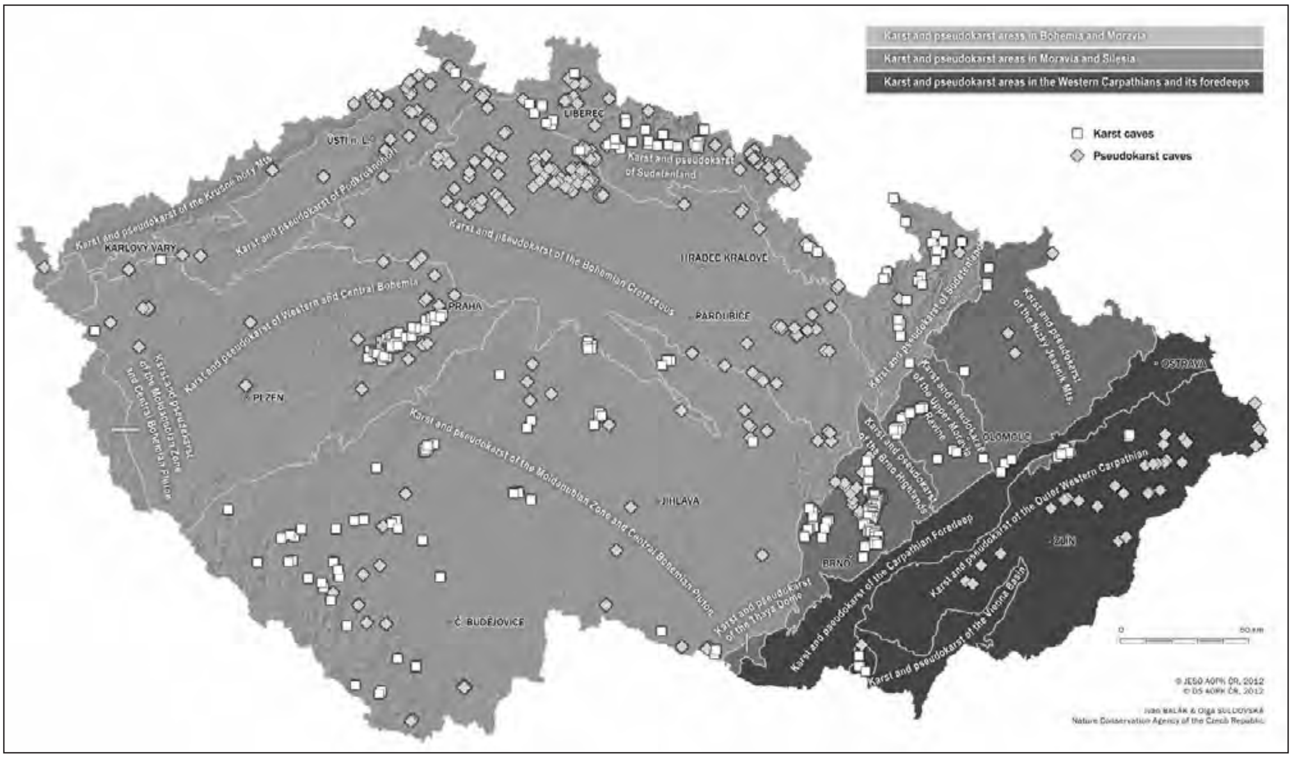

Figure 3. Karstological division of the Czech Republic.

Management carries out technical and expert activities in research, survey and registration including special projects and provides special services to other departments and external institutions. The Cave Administration of the Czech Republic has been not only continuing the implementation of the abovementioned tasks, but has also defined its aim to expand its research, survey and documentation activities in the karst and caves on the whole country.

Cave Administration of the Czech Republic has been involved in JESO since its formation. It gives first data about caves into JESO (information about location and description of show caves and other caves).

Database JESO was filled with primary data (about 3 500 objects) in cooperation with Cave Administration of the Czech Republic. These data are from publication JESKYNĚ issued in edition Protected areas in the Czech Republic in 2009. Many documentations of archive of Cave Administration of the Czech Republic were utilized in this publication. Its archive is next important source information about karst and pseudokarst of the Czech Republic, not only about 14 show caves, but also about protected research, monitoring, maping and so on. Archive materials of Cave Administration of the Czech Republic therefore are another pillars of the FESO system.

5.3. Other source of data

The important source of information for JESO are regional monographies specialized in karst and pseudokarst, also articles in special journals (e.g., Kras v Československu, Československý kras, Speleo) and anthologies. These data are continuously collected, scanned, evaluated and prepared for elaboration into BIBLIOGRAFIE and subsequently into JESO.

Much information are in archive of NCA CR. There are data from reports of inventory researches of specially protected areas, care plans for protected areas, maps, photographic and other documentation. Materials are scanned into PDF format and input into JESO (into the sections Photos, Maps, Other documentation, Bibliography).

6. Conclusions

The Unified Database of Speleological objects represents elaborated and comprehensive information system of karst and pseudokarst phenomenons in the territory of the Czech Republic. It is part of Nature Conservancy Information System administrated by Nature Conservancy Agency of the Czech Republic. Filling up this system with data is realized in cooperation with many organizations and subjects including Czech Speleological Society.

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SPELEOLOGICAL MAP OF THE KANIN MASSIF

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In 2011 a speleological map of the Kanin Massif (Slovenia) in the scale 1:10,000 was published in order to provide the cavers with a map which contains all valuable information for preparation of their expeditions and orientation in the field. The map consists of three maps of the Kanin, Rombon and Srnica areas. On the map all available toponyms are presented, hydrological features and infrastructure. Concerning the symbology of the caves three data sets are presented: cave depth, cave type and data quality. Ground plans of larger caves are added to the map as well. In a supplement to the speleological map a list of all caves with their basic characteristics is presented.

1. Introduction

The Kanin Massif is located in the Western part of the Julian Alps (Slovenia). It is a high mountain karst terrain most famous for the high density of deep caves. At the Kanin and nearby Rombon area there are five pits deeper than 1,000 m, the deepest one being Čehi 2 with a depth of 1,502 m.

As the Kanin massif is still believed to be one of the most perspective areas in terms of finding new deep caves many international caving expeditions are organised in the area on a regular basis. So far the cavers had to depend on cartographic data from various sources. In 2011 the *Speleological map of the Kanin massif* was published in order to provide the cavers with a map which contains all the valuable information for preparation of their expeditions and orientation in the field. Moreover, a supplement to the speleological map was prepared; in the supplement a list of all caves with their basic characteristics is presented.

2. Map characteristics

The map of the Kanin Massif consists of three maps in the scale 1:10,000 – maps of the Kanin, Rombon and Srnica areas. A map with an overview of the broader area was added for a better orientation. The maps are presented in Gauss-Krüger projection.

The cartographic basis for the map is the topographic map in the scale 1:10,000, overlain with a layer of the forested areas and a shaded relief map. All available toponyms are placed on the map as well as the hydrological features, such as permanent and intermittent waterflows, waterfalls, lakes and springs. The following infrastructure is presented on the map: marked Alpine paths (with defined difficulty), paths and roads (the path towards the cave bivouac is highlighted), cableways and their stops, mountain hut, cave bivouac, locations of summer camps, auxiliary heliport, etc.

Concerning the symbology of the caves three data sets are presented: cave depth, cave type and data quality. The size of the symbol is defined by the cave depth, and the shape of the symbol by the cave type defined in the Cave registry.The quality of the data for the caves in the Cave registry (overall quality) is presented with a colour of the symbol. Each cave is marked with a registry number from the Cave registry; the names of larger caves are added too. The plan views of larger caves are added on the map as well.

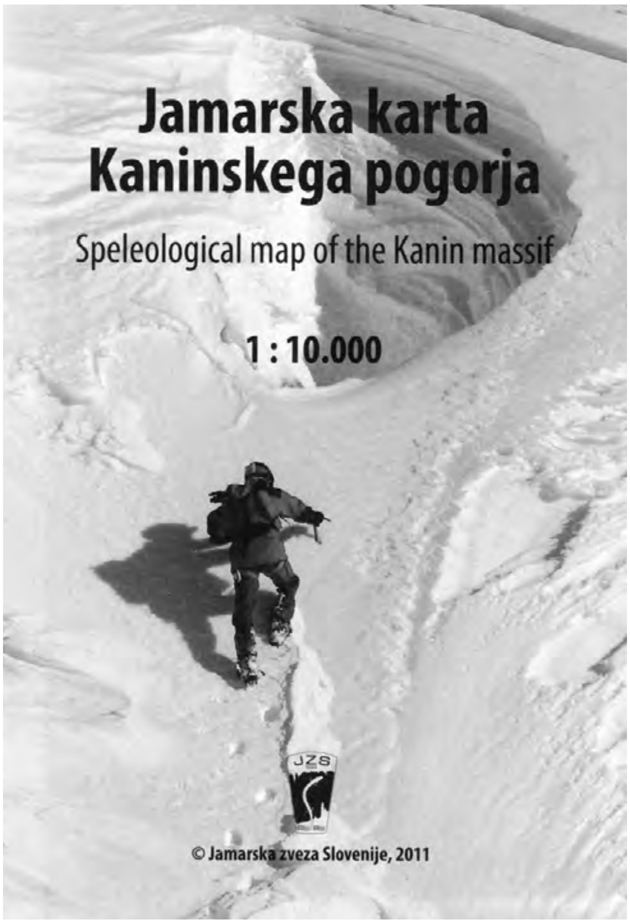

Figure 1. Front page of the Speleological map of the Kanin Massif.

3. Supplement to the map

A *Supplement to the map of the Kanin Massif* is added to the map in a form of a small booklet. In the supplement there is a list of all caves with their characteristics. For the preparation of the map all records in the Cave registry for the local caves were examined. The quality of the documentation was evaluated. On the map, the overall data quality is presented.

In the first part of the supplement the caves are sorted according to their cave registration number in the Cave

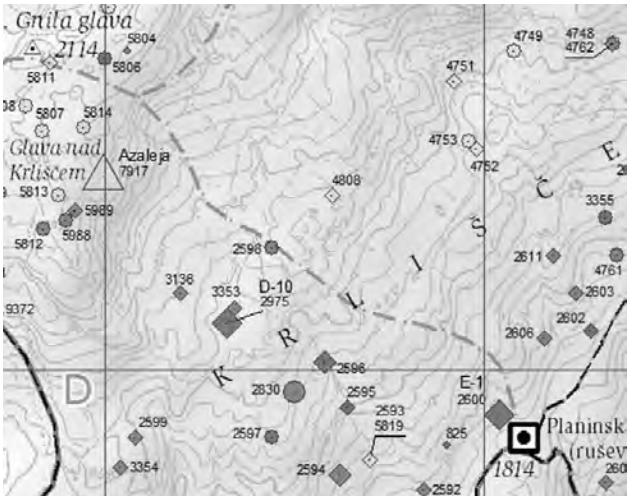

Figure 2. A section of the map.

registry, and in the second part the caves are presented in the alphabetical order. For each cave the following groups of attributes are presented:

- Identification: cave registration number, official name and eventual synonyms;
- Location: coordinates, altitude, source of cave location determination, estimated location precision;
- Entrance morphology: cave entrance dimensions, depth of the entrance pit;
- Cave morphology: cave depth, cave length, primary type;
- Exploration information;
- Documentation: quality of the documentation;
- Cave types.

9. Conclusion

The *Speleological map of the Kanin massif* and the *Supplement to the map* present a valuable tool, an instrument for more efficient research planning and exploration, especially with the implemented evaluation of the data quality provided by the Cave registry.

The map is not for sale – it is handed out free of charge at the Cave registry of the Speleological Association of Slovenia in Ljubljana (kataster@jamarska-zveza.si).

INTEGRATED THREE-DIMENSIONAL LASER SCANNING AND AUTONOMOUS DRONE SURFACE-HOTOGRAMMETRY AT GOMANTONG CAVES, SABAH, MALAYSIA

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The famous "bird's nest caves" of Gomantong Hill, Sabah, are believed to have been extensively modified by zoogenic erosion. We have mapped the caves and the overlying land surface with unprecedented precision, by integrating aerial photogrammetry using an autonomous drone, three-dimensional cave laser scanning at millimeter resolution, differentially-corrected geodetic GPS, and conventional compass-based cave surveying techniques. These data provide exceptional insights into the interplay of biology and geomorphology, with direct benefits for sustainable management planning.

1. Introduction

In recent years, the increasing availability and decreasing size of three-dimensional laser scanners, sometimes called "terrestrial LiDAR" (T-LiDAR, or TLS) scanners, has spawned numerous examples of their use underground. Early examples include Marais (2005), and Fryer et al. (2005). Until recently, these projects have been largely of a proof-of-principle, or of a simple imaging nature, and have been generally limited to geometrically simple cave passage morphologies (e.g., Gonzalez-Aguilera et al. 2009). Current trends are towards the use of 3D laser scanning technology to address specific scientific questions, such as passage stability analyses (Lyons-Baral 2012), bat counting (Azmy et al. 2012) and ice volume studies (Milius and Petters 2012, Buchroithner et al. 2011, 2012; Petters et al. 2011). There has also been an increase in the scanning of progressively more technically difficult and complex caves (e.g., Buchroithner and Gaisecker 2009; Addison 2010). Here we present a study that integrates high-resolution 3D scanning of complex cave morphologies with high-precision photogrammetric modeling of land surface topography, with the goal of investigating the speleogenesis of distinctive large cave passages in tropical karst structures.

2. Methods

Simud Hitam and Simud Puteh are two large volume limestone caves known for their culturally and historically important bird's nest harvesting industry (e.g., Burder 1961; Wilford 1964; Price 1996; Lim and Cranbrook 2002) that are located in Gomantong Hill, Sabah, Malaysia (5.52986° N, 118.07164° E). The best publicly available digital elevation model data for Gomantong Hill is the 30 m resolution ASTER dataset (http://asterweb.jpl.nasa.gov/gdem.asp), which is two orders of magnitude too coarse for our purposes. Hence, we obtained high-resolution imagery over the site using a Gatewing X100 autonomous drone (http://www.gatewing.com/X100), an aerial vehicle with a wingspan of 100 cm and thus well-suited to transport to remote locations. The vehicle was flown at 400 m elevation, obtaining a dataset of 240 overlapping images with ~6 cm geometric resolution and covering 2.1 km^2 (Figure 1a). Control points were taken using a Trimble GeoXH 600 geodetic GPS receiver (which provided ~25 cm real-time precision under tropical forest canopy) and a Trimble NetR9 base station providing centimeter-level post-processing precision. Photogrammetric processing of the Gatewing imagery was

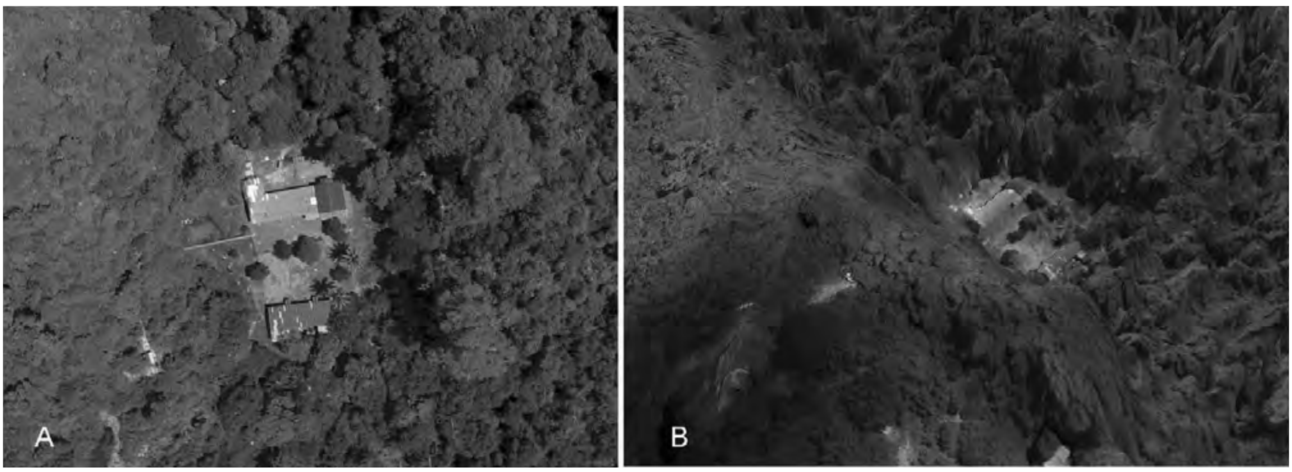

Figure 1 (a) Gatewing imagery, nest collectors longhouse, Gomantong. (b) Gatewing imagery draped over reconstructed digital surface model, Gomantong Hill.

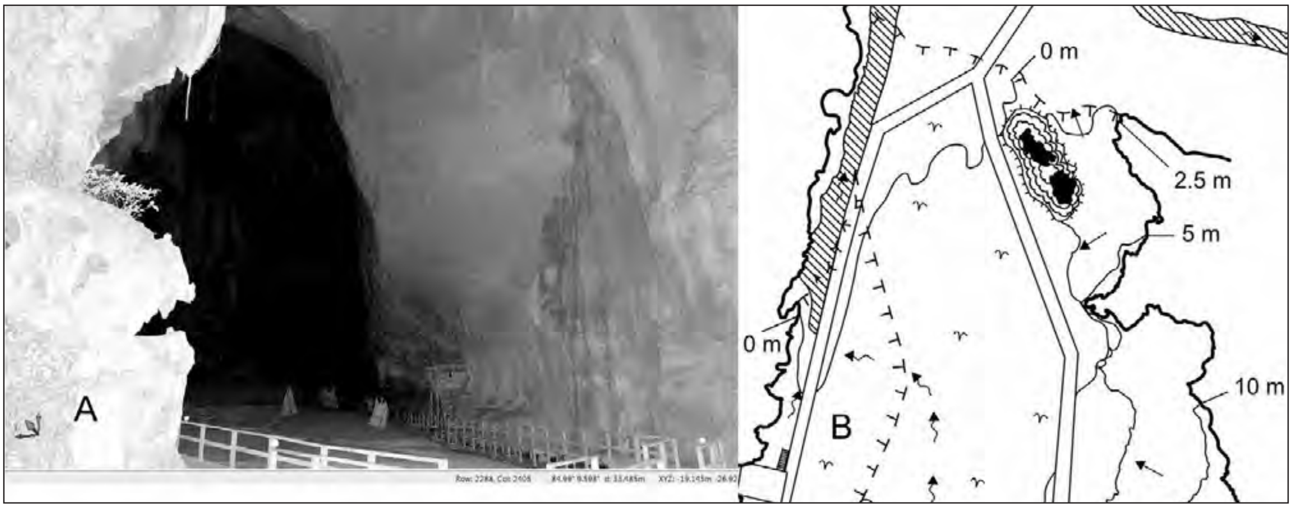

Figure 2. (a) 3D point cloud in FaroScan, Simud Hitam entrance. (b) Plan of Simud Hitam based on LiDAR data, with centimeter-precision wall detail.

performed using "Stretchout" software (http://www.gatewing.com/stretchout), employing a mean of 3080 keypoint observations per image. The final digital surface model has x/y and z axis means of 0.198 ±0.12, and 0.109 ±0.08 and one sigma errors of 1.095 ±1.07 meters respectively (Figure 1b).

Three-dimensional cave scanning was performed using a FARO Focus3D instrument, generally at ¼ resolution mode (= 244,000 points/seconds, yielding x-y point cloud spacing of 12.5 mm, ±2 mm ranging error, at typical wall/roof distances of 20 m), with additional scans at full resolution (x-y-z point cloud spacing of 3.1 mm, ±2 mm at 20 m) where required for specific geomorphological analyses. Data processing was done with FaroScene software (Figure 2a).

The cave was also surveyed using conventional compass-based survey techniques with a SuuntoKB-14/360R compass, a Bosch DNM6 digital inclinometer custom-fitted with a laser pointer (±0.1 degree precision), and a Leica Disto.

Lite 5 laser rangefinder (±3 mm precision). Data were processed in COMPASS software, version 5.06 (http://fountainware.com/compass/). Passage walls were drawn by integrating a "slice" of the T-LiDAR data with the COMPASS baseline, providing an exceptional degree of wall detail (Figure 2b).

3. Results

Survey statistics for the two caves appear in Table 1. A total of 69 scans, comprising in excess of 5 billion data points, were obtained in the lower "Black Cave" (Simud Hitam), and merged and processed with Faro Scene 5.0 software (http://www.faro.com/focus/us/software). A further 55 scans were made in the upper "White Cave", Simud Puteh.

4. Discussion and Conclusions

A standard statistic produced by COMPASS cave survey processing software is "volume density", a rough estimate of the proportion of the rectangular block bounded by the x, y, and z extremities of the cave occupied by cave passage (the later generally derived from simple polygon estimates of cave volume).

Table 1. Survey statistics for the Gomantong Caves.

	Simud Hitam	**Simud Puteh**
Surface length (m)	190.5	388.7
Surface width (m)	230.2	537.4
Depth (m)	88	188.5
Enclosed rock volume (m^3)	3,498,547	39,379,506
Surface area (m^2)	43,842	208,884
cave floor area (m^2)	15,549	38,640
Cave volume (m^3)	1,083,664	963,000

Volume density for Simud Hitam is 30.9 %, and for Simud Puteh it is 2.4 %. The volume density of Simud Hitam (the Lower Cave) is much greater than would be anticipated by modern hydrological conditions. It is believed that it is the result of extensive biogenic erosion driven by physiological processes associated with the large bat and swift populations, and by guano decomposition (Lundberg and McFarlane, 2012). These processes generate distinctive small-to-medium scale geomorphological features which we have termed "apse flutes". The integration of terrestrial LiDAR scanning with conventional cave cartography has enabled us to generate cave plans with centimeter precision and which allow these biogenic features to be quantified for the first time. Simud Puteh has been much less modified by these processes, apparently because of its proportionally smaller bat and swift population sizes. Thus, Simud Puteh better preserves the passage morphologies of the original "hydrological" speleogenetic processes.

Cave T-LiDAR scanning provides additional data that can be of value in biological inventory and management studies. Azmy et al. (2012) have shown that T-LiDAR can resolve individual bats on cave roofs with sufficient resolution to distinguish species identifications in some cases. At Gomantong, we have shown that T-LiDARdat can easily discriminate swift nests on cave roofs, and we are currently developing automated counting algorithms based on nest versus limestone laser reflectance values. This technique may prove to be useful in long-term swift population monitoring, which is a prerequisite to effective management of a sustainable nest collection industry.

Acknowledgments

We thank Dr. Charles Leh Moi Ung (Sarawak Museum) for his generous assistance. We are grateful to Datuk Sam Mannan, Director, Sabah Forestry Department, for granting us permission to work in the Gomantong Forest Reserve. Mr. Simon Pius Ital, Lands and Surveys Department, facilitated the aerial survey work. Mr. Soan Than Kay (Tskay Technologies SdnBhd) was unstintingly generous in providing the Gatewing X100 vehicle together with his expertise in operating it, with additional support from Mr. André Jadot of the Gatewing company, Belgium. FARO International Singapore kindly provided the Focus3D TLS device and shipping to Sabah. The Trimble Corporation and Electronic Data Solutions provided the Trimble GPS equipment at discounted lease rates, the later funded by the Libraries of the Claremont Colleges. Prof. Biswajeet Pradhan kindly provided assistance with the cave scanning. Field work was funded by a Global Exploration Fund grant from the National Geographic Society.

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NATURAL AND ANTHROPOGENIC FACTORS INFLUENCING THE KARST DEVELOPMENT IN THE NE ATHENS AREA, GREECE

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Several factors such as physical process factors and human activities influence the karst development. The aim of the present study is to identify the influence of natural and anthropogenic factors in karst development using a GIS approach. The case study area was the north-eastern part of Athens area in central Greece. Karst-related factors such as geological (lithology and tectonics), hydrological-hydrogeological (hydrographic network, springs), climatological (precipitation), geomorphological (slope, aspect elevation), and anthropogenic (road network and land use) along with the existing karst features were statistical evaluated. Each factor was separated into various classes and the density distribution of the karst formations in each class of the adopted factors was calculated. Concerning the natural factors, the statistical analysis suggested that the extensive development of marble formations, in the study area, have led to the creation of karst features. The karst of the study area is "directed" from the tectonic, and the caves are mostly "fissure caves" so the nearby areas to the tectonic elements are susceptible to karstification processes. Smooth slopes favor the karstification processes, while the majority of the karst formations are manifested in north quadrant facing slopes. The increasing of the elevation is not directly related with the karst landform density. On the contrary, the increase of karst feature density values associated with a rise in amount of precipitation. Regarding, the influence of anthropogenic factors, it was found that the proximity to road network related with an increase in occurrences of karst landforms. The polje and the dolines are cultivated because of their existing fertile soil that is "type of polje". The permanent karstification processes caused the development of many caves in the forest.

1. Introduction

Karst features developed on the surface and subsurface, are frequently used for several activities such as agriculture, mining and tourism (Papadopoulou-Vrynioti 1999). In many cases karst formations are a geological hazard and can cause serious engineering problems such as subsidence (Paris and Gunn 2007).

Several factors such as physical process factors and human activities influence the karst formations. Geomorpholocical, geological hydrogeological and climatological are physical process factors affecting to karst feature creation (Gillieson 1996, Papadopoulou-Vrynioti 2004). Although natural factors have a high influence to the karst development, they are often exacerbated by human activities. Anthropogenic factors such as urban development, quarrying, and road constructions in many cases cause karst collapse (Brezinski 2007). On the contrary many caves were found and protected during human constructions (Slabe, 1997).

During the last two decades Geographical Information Systems (GIS) and remote sensing have become integral tools for the evaluation of natural phenomena (Bathrellos et al. 2009). Moreover, GIS is a valuable tool for the spatial analysis of a multi-dimensional phenomenon such as karst development.

The aim of the study is to recognize the influence of natural and anthropogenic factors in karst development using a GIS approach. For this reason geological (lithology and tectonics), hydrological-hydrogeological (hydrographic network, springs), climate (precipitation), geomorphological (slope, aspect elevation), and anthropogenic (road network and land use) factors were used. In order to accomplish this scope the above mentioned factors along with the existing karst landforms were evaluated. The case study area was the NE Athens region in central Greece. The processing and the evaluation of the various thematic layers of the adopted factors and karst features were performed in a GIS.

2. Geological and geomorhological settings

The study area is located in north-eastern part of Athens and especially in northern place of Stamata that is a suburb of Athens Area (Fig. 1). The Marathon artificial lake is extending at the northern part of the study area.

Figure 1. The location map of the study area.

The study area covers 6.1 km^2 and characterized by a low hilly relief with altitudes varying from 100 to 380 m a.s.l and its hydrographic network has a seasonal flow.

According to the hydrometeorological data, for a time-period of 20 years (1980–2000), the mean annual precipitation of the broader study area that has occurred over the past 20 years is from 740 mm to 567 mm.

The geological formations that can be identified in the study area are schists and marbles of Almyropotamos-Attiki autochthonous unit and Neogene deposits. Schists have age Lower-Middle Triassic while marbles are of Mesozoic to Middle Eocene age. The Upper Miocene sediments comprise of coarse-grained fluvio-lacustrine with intercalations of marly-travertinoid limestones and fine-grained lacustrine-terrestrial formations (Katsikatsos 2002). The dominant directions of the fault system of the study area are NNW-SSE and NE-SW (Lozios 1993).

3. Methods

The data used in this study consist of:

1. Extended field investigation,
2. The topographic maps (maps scale 1:25,000 and 50,000),
3. The geological map (map scale 1:50,000) (Katsikatsos, 2002),
4. Air photos (scales 1:30,000 and 1:15,000)
5. Precipitation records from seven (7) hydrometeorological stations, belonging to the Ministry for the Environment, Physical Planning and Public Works. These records referred to mean annual precipitation for the period of 1980–2000 and
6. Orthoimages for the period 2007–09 from the Ministry for the Environment, Physical Planning and Public Works.

A spatial database was created, and ArcGIS 10 software was used to process the collected data. The karst occurrences in the study area and the seven influencing factors have been recorded and saved as separate layers in the database.

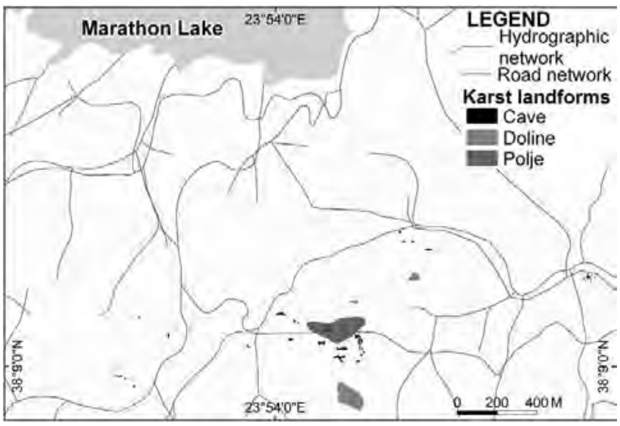

Figure 2. The spatial distribution of karst landforms.

A karst feature inventory map (Fig. 2) of the study area was created based on the karst landforms, recorded during the fieldwork of this study, but also those recorded from previous works (Petrochilos 1952). 39 sites of karst appearance were examined throughout the study area, having affected an area up to 39,684 m^2. The recorded karst features were separated as 36 small caves, 2 dolines and 1 polje. It should be mentioned that the polje and the dolines are cultivated.

Extended field observations, personal knowledge and experiences as well as the literature (i.e. Gunn 2004; Papadopoulou et al. 2012) were the basis for the selection of the appropriate factors and the determination of the classes' number as well as their boundary values. The lithology, the distance from tectonic elements, the distance from hydrographic network, the distance from springs, the slope angle, the slope aspect, the elevation, the mean annual precipitation, the distance from road network and land use of the study area were the selected factors. Each factor was then separated into various classes.

Degree of karstification is connected to karst formations occurrences (Milanovic 2000) so lithology is the principal decisive factors regarding the karst landforms manifestation. The geological settings of the study area based on literature (Katsikatsos 2002) and fieldwork were used for the classification of lithology. The distinctive geological formations were digitized and were classified into four categories, namely: marbles, schists, coarse-grained and fine-grained sediments (Fig. 4A).

In the study area an important role in the karst landforms occurrences plays the active tectonics. The observations during the fieldwork and the literature (Katsikatsos 2002) were used for the collection of the various tectonic features. The joints and the main axes of he karstic forms of the area was recorded and processed based on their linear characteristics and especially their strike. The software Rockware was used for the creation of the rose diagrams. Two coincined directions were identified for both joints and karst features with the following principal strikes: N50°–60° and N170°–180° (Fig. 3). The statistical processing of the joints was performed with the use of 107 linear features.

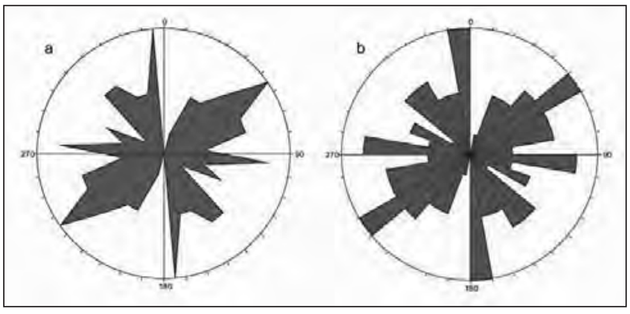

Figure 3. The directions of the joints (a) and the main axes of karst feature (b) in the study area.

Moreover, buffer zones were formulated around the digitized tectonic features (faults, overthrusts, etc.) at distances of 50 m, 100 m, 150 m and 200 m (Fig. 4B). Thus, the classes of the buffer zones are five, namely: (i) the nearest (0–50 m), (ii) the very near (51–100 m), (iii) the near (101–150 m), (iv) the moderate distant (151–200 m) and (v) the distant (>200 m).

The hydrographic network was derived from the topographic sheet and digitized as line layer in the GIS database. Buffer zones were generated around the streams of the area, at distances of 50 m, 100 m, 150 m and 200 m

(Fig. 4C). The classes of the buffer zones are also five, like for tectonic elements: (i) the nearest (0–50 m), (ii) the very near (51–100 m), (iii) the near (101–150 m), (iv) the moderate distant (151–200 m) and (v) the distant (> 200 m).

The existence of a phreatic aquifer or groundwater table is proved by the presence of surface springs in a region. The springs indicate the existence of groundwater table in the study area, since the soluble formations (marbles) overlie insoluble formations (schists). As in the previous case buffer zones were generated around the springs at distances of 50 m, 100 m, 150 m and 200 m and the same numerical classes were created (Fig. 4D).

As it is well known, precipitation is among the most usual influencing factors for karst development. The hydrometeorological stations used are well distributed in the study area both hypsometrically and territorially, giving very good results regarding the distribution of the precipitation. The mean annual rainfall of the area is between 584.3 mm to 640.4 mm. For the necessities of this study, the rainfall map was produced, using the data of the main hydrometeorological stations in the area and applying the Inverse distance weighted (IDW) interpolation method. This map was separated into 4 classes, i.e.: (i) < 590 mm, (ii) 591–610 mm, (iii) 611–630 mm, and (iv) > 630 mm. (Fig. 5D).

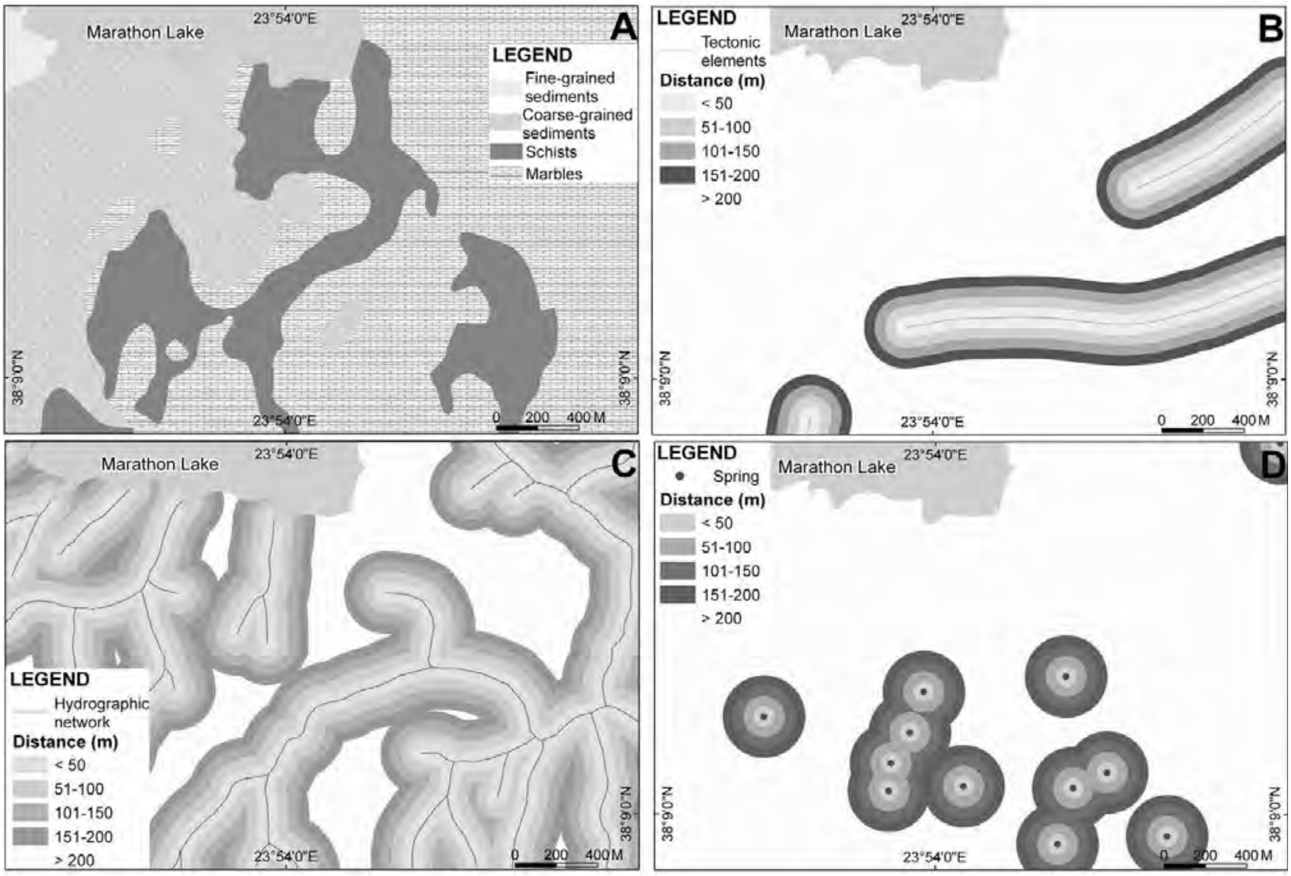

Figure 4. (A) The lithological map of the study area, (B) Distance from tectonic elements, (C) Distance from hydrographic network and (D) Distance from springs.

The karst development is affected by the angle and the aspect of the slopes. The topographic sheet was used as data source to obtain the contours with 20 m intervals that were digitized and saved as line layer. The digitized elevation data were utilized for the creation of a Digital Elevation Model (DEM) using 3D Analyst extension of ArcGIS, and the slope layer was extracted from it. The grid map of the slope angle was classified into 5 classes, as follows: (i) <5°, (ii) 5–10°, (iii) 11–15°, (iv) 16–20°, and (v) > 20° (Fig. 5A).

The slope aspect map was generated based on the slope angle map. The slope aspect map was classified into four categories, that is N 315–45°, E 45–135°, S 135–225°, W 225–315°(Fig. 5B).

Regarding the elevation a grid map of it was produced from the Digital Elevation Model. The division of the elevation was done into six classes: (i) < 150 m a.s.l., (ii) 150–200 m a.s.l., (iii) 201–250 m a.s.l., (iv) 251–300 m a.s.l., (v) 301–350 m a.s.l. and (vi) > 350 m a.s.l. (Fig. 5C).

In many cases human activities effect karst development (Millanovic 2000). Therefore, the road network and land use were chosen as a principal factors. The road network was digitized, using the topographic sheet as data source. Buffer zones were created around the roads of the area at distances of 50 m, 100 m, 150 m and 200 m. The classes of the buffer zones are five, similar to tectonic elements and hydrographic network: (i) the nearest (0–50 m), (ii) the very near (51–100 m), (iii) the near (101–150 m), (iv) the moderate distant (151–200 m) and (v) the distant (> 200 m) (Fig. 6A).

The variations of the vegetation in an area in many cases affect the karst feature creation (Pfeffer 2010). For the necessities of this study the data for the land use were taken from orthoimages and the land use, which reflects the vegetation covering, was classified into 5 categories as follows: (i) agricultural land, (ii) coniferous forest, (iii) grassland, (iv) shrubland, and (v) transitional woodland/shrubland (Fig. 6B).

The area of karst formations involved in each class of the parameters was calculated in order to establish the density of karst incidences. Thus the density distribution of karst events in each class of each parameter was computed. This statistical analysis was used in various studies (Bathrellos et al. 2009; Rozos et al. 2011) for the landslide hazard evaluation using GIS.

4. Results and discussion

The adopted factors and their classes are presented in Table 1, together with the density of the karst development. The density of karst formations is the ratio between the areas covered by the pixels of karst formations, which represent a class of a factor and the total karst formation area. This density, expressed in percentages, was considered to be the basic parameter for the determination of the influence of every principal factor class in karst development.

Table 1. Classes of adopted factors, with karst landform density distribution for each class.

Natural factors			
Lithology	Density (%)	Distance from tectonic elements (m)	Density (%)
Marbles	74.48	0–50	1.76
Schists	0.32	51–100	25.02
Coarse-grained sediments	25.20	101–150	27.73
Fine-grained sediments	0.00	151–200	12.10
		>200	33.40
Distance from hydrographic network (m)		Distance from springs (m)	
0–50	0.44	0–50	0.32
51–100	1.95	51–100	8.51
101–150	2.46	101–150	12.22
151–200	8.25	151–200	24.26
>200	86.89	>200	54.69
Slope angle		Slope aspect	
<5°	62.32	N 315°–45°	73.28
6°–10°,	21.99	E 45°–135°	11.09
11°–15°,	7.31	S 135°–225°	5.29
16°–20°	2.90	W 225°–315°	10.33
>20°	5.48		
Elevation (m)		Rainfall (mm)	
<150	0.88	<590	0.00
15–200	1.01	591–610	5.48
201–250	3.40	611–630	93.76
251–300	62.26	>630	0.76
301–350	31.70		
>350	0.76		
Anthropogenic factors			
Distance from roads (m)		Land Use	
0–50	31.25	Agricult. land	79.84
51–100	51.98	Conif. forest	18.27
101–150	13.42	Grassland	0.13
151–200	2.58	Shrubland	1.64
>200	0.76	Transitional woodland/shrubland	0.13

The lithology of the study area controls the occurrences of karst formations. The maximum density value of karst events was observed in the area underlain by marbles (74.5 %) as it is demonstrated in Table 1. The percentages of the lithological formations, in relation to the entire extent of the study area, are the following: 51.3 % for marbles, 21.7 % for schists, 25.6 % for coarse-grained sediments, and 1.4 % for fine-grained sediments. In the carbonate rocks such as marbles that has the largest development among the other formations of the study area, karstification is high, resulted the existence of many karst landforms. The coarse-grained sediments have a medium value of karst formation density while in the fine-grained sediments the value is zero. The appearance of limestone intercalations in the Neogene coarse-grained sediments explains the medium value of karst formation density in contrary to the fine-grained sediments that due to their lithology the density value is zero. The percentage (0.32 %) of karst formation density within schists is due to the fact that pseudo-karst features produced along with lithological discontinuity such as schistocity.

Regarding the tectonics, the near distance approximately (101–150 m) to the tectonic elements had the maximum percentage value of karst development density (27.73 %). The next higher proportion value of density (25.02 %) was noticed within the very near distance (51–100 m) (Table 1). Consequently in the study area, areas close to the tectonic elements are prone to the karst landform development. As it was observed from fieldwork the studied cave belongs mostly to the type of "fissure caves". The directions of the rose diagrams of joints and karst features (Fig. 3) show that there are two main coincident strikes. The main strikes of joints and karst features are parallel to NNW-SSE and NE-SW striking fault system. This fact means that the karst of the study area is "directed" from the tectonic.

About the hydrographic network, the maximum density value of the karst landforms (86.89 %) was observed within a distance of approximately higher than 200 m from any given stream. Additionally the density values of the karst features (54.69 %) reaches its maximum value within the distance class (> 200 m) for any given spring. Therefore, the percentage of karst landforms density accretes as the distance from the hydrographic axes and springs increases. The presence of unsaturated water favors the karstification processes so as the distance from streams and springs increase, it becomes more intense.

The smooth slopes (< 5°) of the study area included the maximum density of the karst development (62.3 %) and were followed by moderate slopes (6–10°). The value of the density of the karst landforms potentially decreases with increasing of slope angle value as shown in Table 1. Flat areas with a slope angle less than 3° favor the karst formations development, since the planation surfaces prone to karstification, so the karst density has the highest value among the others within the smooth slopes (< 5°).

The highest value of karst landform density (73.3 %) was commutated within slope aspect refers to "N 315–45°" class. As it was revealed from the fieldwork, most of the karst formations are manifested in the slopes with orientation from northwest to northeast so this class has the highest value of the karst density. The northern facing

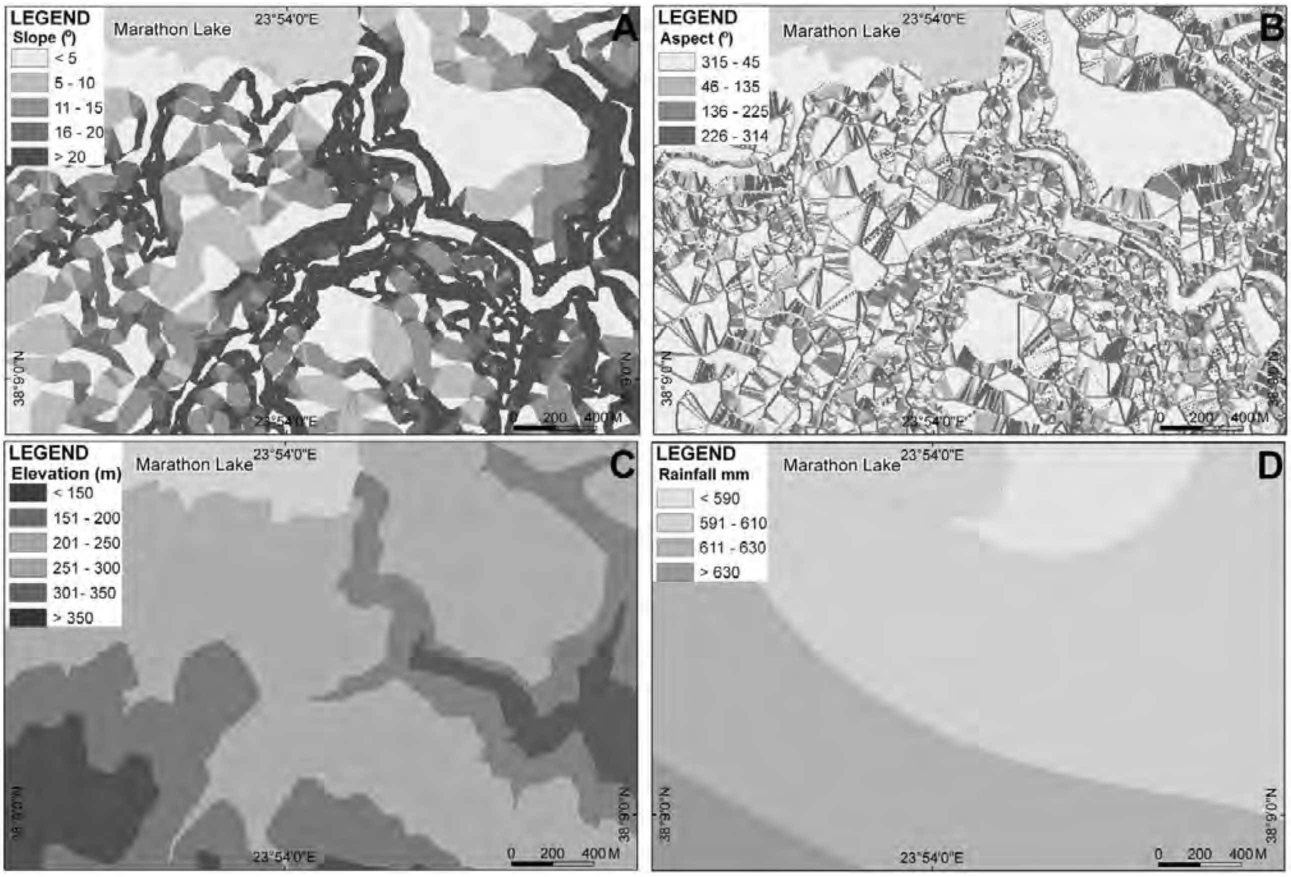

Figure 5. The spatial distribution of: (A) the slope angle, (B) the slope aspect, (C) the elevation and (D) the mean annual rainfall.

slopes are exposed to lower amounts of sunlight and heat during the winter compared to those with southern orientations. As a consequence, in these areas favor the karstification processes.

Concerning the elevation, the fourth class (251–300 m a.s.l.) had the highest value of density percentage of the karst landforms (62.26 %). The next higher value (31.7 %) of density among the others was calculated within the fifth class (301–350 m). Thus, the increasing of the elevation is not in a direct relation to the karst landform density. In the study area, the elevation contributes to karst formations, in relation to the other factors, such as lithology, tectonics, surface run off, and precipitation.

Finally, concerning the natural factors, the highest value of the karst feature density (93.76 %) was observed within the third class (611–630 mm) of the rainfall. Karst development density percentage is higher as the precipitation increases. Climate is an important factor directly related with karstification processes. In terms of precipitation, the rate of karstification is quick in humid and hot areas (Bogli 1980). Consequently, in the study area as the precipitation became higher so much favor the karstification processes.

Relating to the anthropogenic factors and especially the road network the highest percentage of karst development density (51.98 %) refers to the "very near" class. The results of the table 1 show that the percentage of karst development density reduces as the distance from the roads increases. The stability of existing subsurface karst features are disturbed from the road network constructions resulting, the acceleration of their surface appearance (Slabe 1997). Therefore, the proximity to road network related with an increase in occurrences of karst landforms.

The maximum value of karst density percentage (79.84 %) was is attributed to agricultural areas. The polje and the dolines of the study area are cultivated because of the type of their soils, so this high density value is justified. Moreover, a high percentage value of karst feature density (18.27 %) was observed in forest, since there is infiltration of the rainfall water thereby creating favorable conditions for karstification. The high density value of karst features and especially caves in forest caused by the fact that in soil covered karst the karstification processes is intense and continuous all over the year. As a result many caves are developed.

5. Conclusions

In the present work the factors control the development of surface and subsurface karst features were examined. For this purpose, a statistical analysis was performed by the calculation of the density distribution of the karst features in each class of every one of the adopted natural and anthropogenic factors using GIS. The north-eastern part of Athens in central Greece was the case study area. Concerning the natural factors the lithology greatly influences the occurrences of karst formations and the extensive appearance of marbles has the highest value of karst feature density. The karst of the study area is "directed" from the tectonic, as the studied caves are mostly "fissure caves" so the areas close to the tectonic elements favor the karst development. The percentage of karst feature density accretes as the distance from the hydrographic axes and springs increases. Smooth slopes favor the karstification processes, since the karst landform density has the highest value among the others within these slopes.

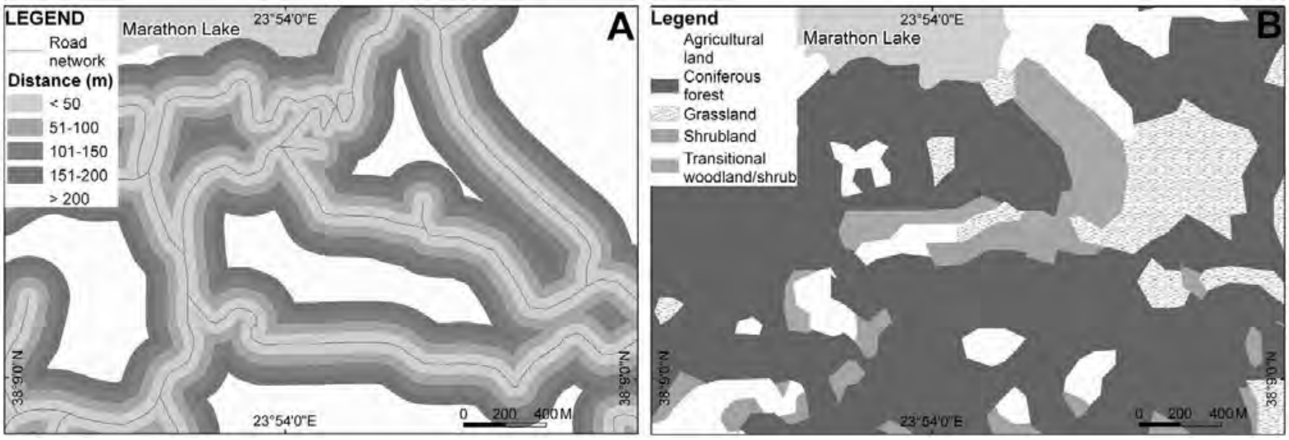

Figure 6. (A) Distance from road network, and (B) the land use of the study area.

The majority of the karst formations are manifested in north quadrant facing slopes. The increasing of the elevation is not directly related with the karst landform density. Climate affects the karst development, since the increase of karst feature density values associated with a rise in amount of precipitation. Finally, the influence of anthropogenic factors, in karst development was identified. The proximity to road network related with an increase in occurrences of karst landforms. The cultivation of polje and dolines is caused by the fertile soil which fills them and that is of the "type of polje". The permanent karstification in the forest led to the creation of many caves.

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THE SPATIAL DISTRIBUTION OF KARST ECOSYSTEM USING GIS IN ATTICA, GREECE

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Karst ecosystem is defined as the environment with its living elements and the factors that affect it. The presence of karst rocks affects directly in karst ecosystem. In Greece the most common karst rock outcrop is carbonate and especially limestone that supplies the soil with necessary materials to improve its quality. For these reasons, the karst rocks are frequently used for cultivation but in many cases, the intensive human actions have negative effects on a fragile karst ecosystem.

In the present study the spatial distribution of the carbonate rocks of Attica area were combined with human actions influencing to karst ecosystem. Although several karst landforms (surface and underground) are developed in Attica, the human activities have caused changes in the physical environment. Especially, during the last decade massive wildfires took place in the area leading to further degradation of natural environment. Moreover the area of karst ecosystem that may be at hazard due to rocky desertification was estimated. To accomplish this goal, the carbonate rocks, and the land uses along with the mapped burned areas during the period 2000–2012 of the study area were evaluated. The processing, the evaluation and the statistical analysis of the thematic map data were performed with GIS capabilities.

According to the applied statistical analysis 3.3 % of the total area of the carbonate rocks is covered by urban, 13.1 % by agricultural, 17 % by forest and 66.5 % by shrubby and sparsely vegetated land up to the year 2000. From the antiquity until present the several massive wildfires fires had occurred in the area destroying the pinus forests resulting the majority of the area of carbonate rocks to be covered by shrubs and sparsely vegetation. Nevertheless, a high percentage of the area of carbonate rocks is covered by forests while the percentage of the agricultural area of carbonate rock is relative high. For the same time period the majority (40.1 %) of the study area was covered by shrubs and sparsely vegetation, 33.3 % by cultivations, 14.7 % by urban areas, and only 11.9 % by forests. The percentage of urban area is high because it includes the urban fabric of the city of Athens which is the capital of Greece. During the last decade the percentages of the area that is covered by agricultural, forest and shrubby and sparsely vegetated land were decreased. The highest decrease was observed in the shrubby and sparsely vegetated areas. The fires that took place during the last decade have caused the considerable reduce of the natural vegetation leading to rock desertification. The burned land covers 11.6 % of the total area of the carbonate rocks and this part of karst ecosystem was considered to be at hazard. The deforestation of the natural vegetation has negative effects in the karstification processes, in the soil quality, water, plant and animal growth, people, consequently to the karst ecosystem.

1. Introduction

Karst ecosystem is defined as the environment with its living elements and the factors that affect it (Gary et al. 1973). According Yuan (2001) karst ecosystem is restrained by karst environment and may reflects how the karst environment affects life and the opposite one.

Natural factors such as geomorphology, geology, hydrogeology, and climate control the karst feature creation (Papadopoulou-Vrynioti 2004). Especially lithology is among the most decisive factors in the development of karst. The karstification in carbonate rocks is important, causing the appearance of many karst formations. Consequently the presence of karst rocks affects directly in karst ecosystem (Tepsongkroh 2000).

The most common karst rock outcrops are the carbonate ones and especially limestones. Limestones consist of calcite and other impurities such as clay, silicon dioxide and iron compounds (Bogli 1980). In the most regions of Greece, soils include large contents of calcite and consequently calcium that it reaches up to 70 %, because of the large spatial extend of limestones (Papadopoulou-Vrynioti 1999). The karst rocks supply soils with necessary materials to improve their quality. Soils are a significant link in the food chain as they transport trace elements and compounds not only to the plants but to water, animals and people directly or indirectly (Urushibara-Yoshino 1993; Kabata-Pendias and Pendias 2001).

For these reasons, the karst landforms are frequently used for several activities such as agriculture, mining and tourism (Papadopoulou-Vrynioti 1999). In many cases, the intensive human activities on a fragile karst ecosystem causes the karst rocky desertification involving serious soil erosion, drastic decrease in soil productivity, and the appearance of a lithologic desert almost devoid of soil and vegetation (Wang et al. 2004)

Geographical Information Systems (GIS) and remote sensing have become integral tools for the evaluation of natural phenomena (Bathrellos et al. 2009). Moreover, GIS is a valuable tool for the karst mapping (Hollingsworth et al. 2008).

Several karst landforms are developed in Attica region (Papadopoulou et al. 2012). On the contrary human activities in the area cause changes in its physical environment (Skilodimou et al. 2002; 2006). Especially, during the last decade massive fires took place in the area leading to the further degradation of the natural environment.

In the present study the spatial distribution of the carbonate rocks of Attica area were combined with human actions influencing to karst ecosystem. Moreover the area of karst ecosystem that may be in hazard due the rocky desertification was estimated. To accomplish this goal, the carbonate rocks, and the land uses along with the mapped burned areas during the period 2000–2012 of the study area were evaluated. The processing and the evaluation of the thematic map data were performed with GIS capabilities.

2. Geomorhological and geological settings

The Attica region is the north-eastern part of continental Greece. The north-western part of the area is surrounded by the Corinthian Gulf, while it's north-eastern and eastern ones from North Euboean Gulf and by Saronic Gulf at western and south-western part (Fig. 1). The study region covers a total surface area of 3,125.75 km^2 with altitudes varying from 0 to 1,413 m above mean sea level (m.s.l.). 6 % of the area of the Attica region is covered by mountains, 30 % by plains and 64 % by hills (Bathrellos et al. 2008).

The mountains of Gerania, Pateras, Kitheron, Parnis, Penteli, Ymmitos and Egaleo, form the relief of the area. The drainage network is poorly developed; its type is mainly denditic drainage pattern and comprises streams with seasonal flow. The main rivers that flows through the study area are: Kifisos which end up to Saronikos Gulf and Biotikos Asopos that ends up to Eubean Gulf (Fig. 1).

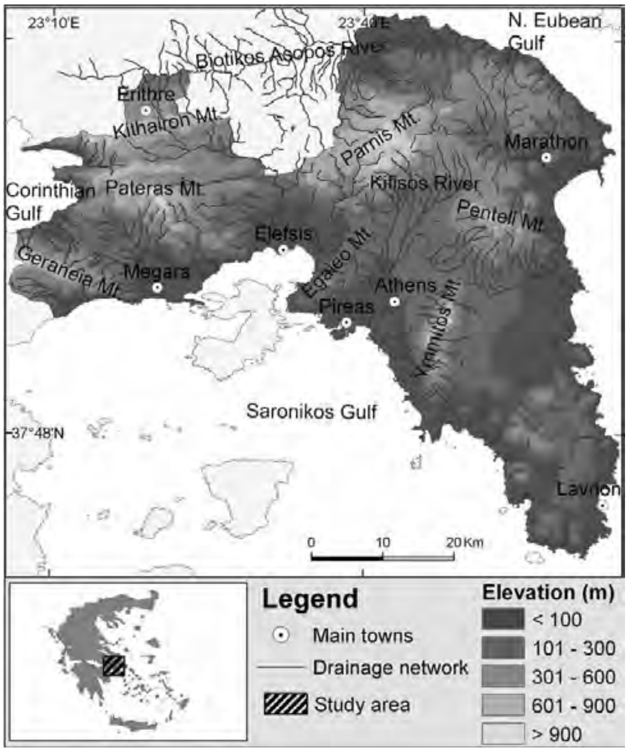

Figure 1. The location map of the study area with the classees of elevetion and drainage network.

The type of climate of the study area is Mediterranean with a rainy period which strarts in October and ends in April.The mean annual precipitation of the study area is low and fluctuates from 286.4 mm to 483.1 mm (Skilodimou 2002).

In the antiquity, the Attica region used to be a famous cultural centre of Greece. Nowadays, the study area has been affected by strong human interventions that have altered its morphology and natural environment during the last decade of 20th century. The intensive urbanization and the uncontrolled building construction have been caused many environmental problems not only in the city of Athens but in the whole of Attica region (Bathrellos et al. 2008).

The geological structure of the area under study comprises alpine and post alpine formations. The alpine formations belong to three main stratigraphic units, which are: the Pelagonian unit, the autochthonous unit of Attica and the nappe of Lavrio-Attica (Fig. 2). The Pelagonian unit consists of clastic formations, limestones, dolomites ophiolithic formations, transgression limestone, iron manganese ores and flysch. The autochthonous unit of Attica comprises mainly schists, marbles and limestones, while the nappe of Lavrio-Attica consists of phyllite, schist and metalliferous ores. The post alpine formations from the older to the more recent are: Neogene deposits, Pleistocene continental deposits and Holocene, alluvial sediments (Katsikatsos et al. 1986).

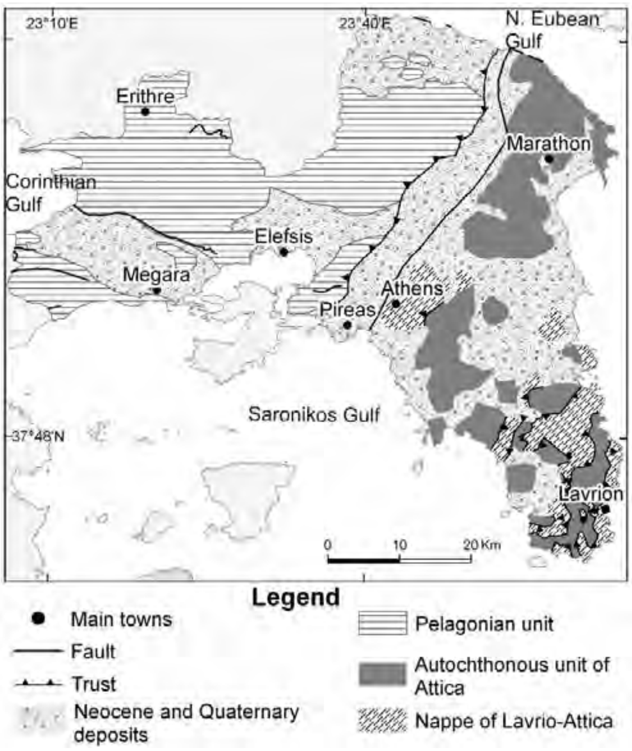

Figure 2. The simplified geological map of the study area.

The tectonic of Attica is characterized by alpine structures which is mainly thrusts (Fig. 2) and post alpine fault system (from Miocene up today). The alpine thrust tectonic is represented by the thrusts of Pelagonian unit over the autochthonous unit of Attica and nappe of Lavrio-Attica over the autochthonous unit as well as by frequent upthrusts with NE–SW directions. The western Attica is controlled by a main fault system with NW–SE direction, while the eastern part of the area is ruled by NE–SW-striking faults (Bathrellos et al. 2008).

3. Methods

The data used in this study consist of:

1. extended field investigation,
2. the topographic maps (maps scale 1:50,000),
3. the geological map (map scale 1:500,000) (IGME 1983),
4. land use data from the CORINE land cover programm (Bossard et al. 2000),
5. burned area data during the period 2000–2012 from the program Oikoskopio (WWF Hellas 2012).

A spatial database was created, and ArcGIS 10 software was used to process the collected data. The lithology, the land uses and the burned areas of the study area have been recorded and saved as separate layers in the database.

Extended field observations, personal knowledge and experiences as well as the literature (Bárány-Kevei 2000; Wang et al. 2004; Jianhua et al. 2007; Brezinski 2007; Papadopoulou et al. 2012) were the basis for the selection of the appropriate thematic maps and the their spatial correlation.

The lithology is the principal decisive factors regarding the karst landforms manifestation. The lithology of the study area was derived from the geological map (IGME 1983).

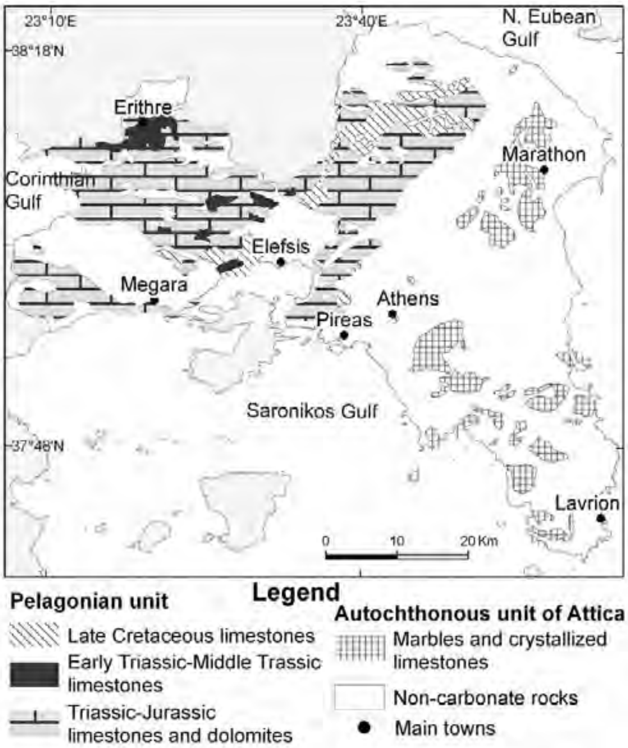

Figure 3. The spatial distribution of the carbonate rock types.

Firstly the geological formations were categorized into carbonate rocks and other lithological formations. Fieldwork observations were used for the further classification of carbonate rocks. The carbonate rocks were divided according to their stratigraphic unit and their age. They were categorized to into tree classes: Early-Middle Triassic limestones, Triassic-Jurassic limestones and dolomites, Late Cretaceous limestones belonging to Pelagonian unit and marbles and crystallized limestones of autochthonous unit of Attica (Fig. 3).

The karst ecosystem favors the plant and animal growth and human activities. So the vegetation cover of a region affects directly to it (Pfeffer 2010). The land use of the study area was taken from the CORINE Land Cover Program. The program contains land cover data for Europe including land cover class description for mapping at scale 1:100,000 published by the European Commission (Bossard et al. 2000).The land cover represent the land uses of the study area up to the year 2000. The land use was classified into several types as follows: urban areas (including continuous urban fabric, industrial, commercial and transport activities, construction sites), agricultural areas (including non-irrigated arable land, permanent crops and heterogeneous agricultural areas) forest areas, and shrubby and sparsely vegetated areas (Fig. 4).

Since the land degradation involves the karst ecosystem, the burned areas during the period 2000–2012 were used for the study area. The areas were mapped using as source the Oikoskopio program (WWF Hellas 2012). The program contains data with mapped burned land data for a period of over ten years (2000–2012). The burned areas were digitized and a map of the recent burned land of the study area was produced (Fig. 5).

The area of every carbonate rock type laid on every land use was calculated using the zonal statistics tool of ArcGIS. The land uses were spatially combined with the burnt areas and the changes in the area of every land use were defined.

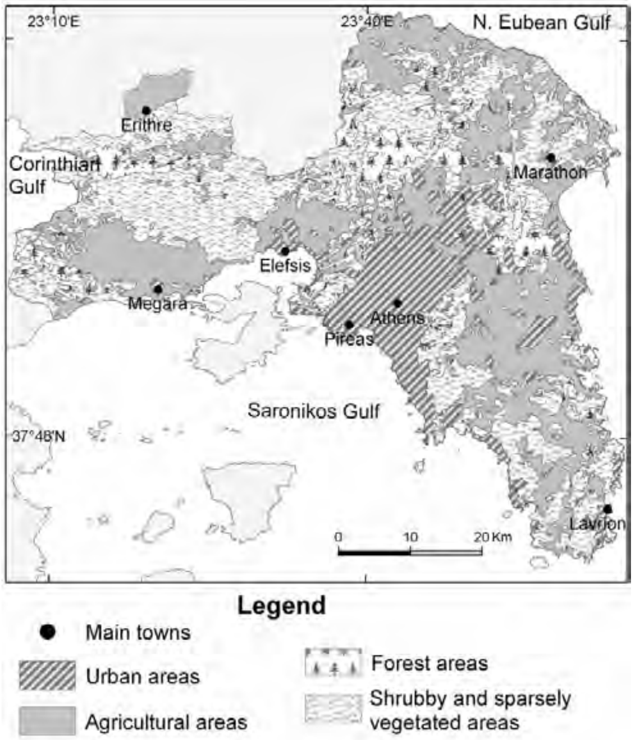

Figure 4. The spatial distribution of the land uses of Attica.

Moreover the areas of carbonate rocks involved in burned land were computed. Thus the spatial distribution of karst ecosystem that may be at hazard because of rock desertification was computed. This statistical analysis was used in various studies for environmental (Bathrellos et al. 2008) and landslide (Bathrellos et al. 2009; Rozos et al. 2011) hazard evaluation using GIS.

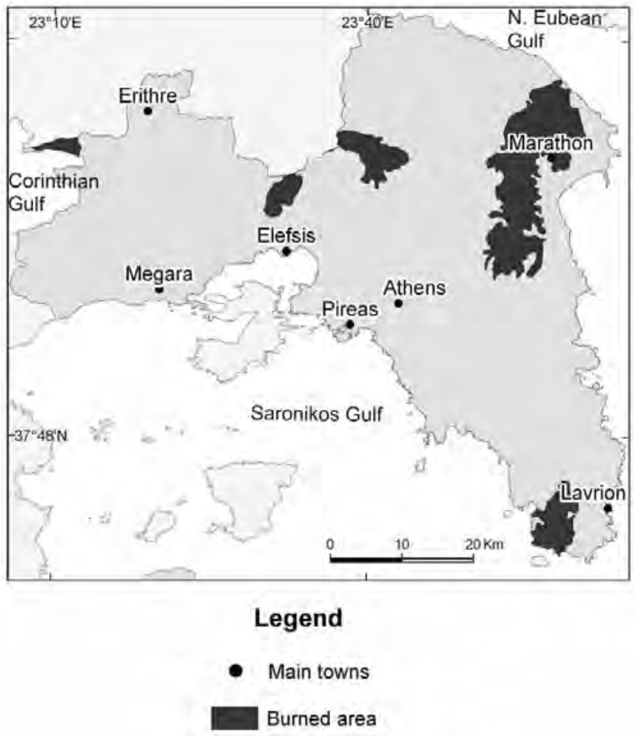

Figure 5. The spatial distribution of the burned areas.

4. Results and discussion

The area of the carbonate rocks, expressed in percentages, was calculated. This area was considered to be the basic parameter for the determination of the influence of land uses and burned areas in karst ecosystem development.

The carbonate rocks cover 34.7% of the total study area. In fact their extent is high such as they cover the 1/3 of the total the study area. The percentages of the carbonate rocks of Pelagonian unit, in relation to the entire extent of the study area, are the following: 1.9% for the Early-Middle Triassic limestones, 21.5% for the Triassic-Jurassic limestones and dolomites and, 4% for the Late Cretaceous limestones. The marbles and crystallized limestones of autochthonous unit of Attica cover 7.3% of the total study area. The Triassic-Jurassic limestones have the largest development among the other carbonate rocks.

The percentages of the area of each carbonate rock type within each land use are presented in Table 1. Moreover the percentage of the total area of the area for carbonate rocks involved in each land use was calculated and illustrated in the table.

The results demonstrate that nowadays the majority of the carbonate rock area is covered by shrubs and sparsely vegetation. In the antiquity, Attica was covered by Pinus Halepensis forests (Pausanias 1992). From the antiquity until present several massive wildfires fires took place in the area destroying the pinus forest land. Forests assist the mechanical and chemical processes and create favorable conditions for karstification. The catastrophe of forest area causes the rock desertification and reacts to karst ecosystem. Nevertheless, as it is resulted from Table 1, at the present time a high percentage of carbonate rocks is covered by forests.

As, carbonate rocks supply soils with necessary materials to improve their quality, the percentage of the area of carbonate rocks which is cultivated is relative high. The existence of polje and dolines in the study area favor the cultivations because of their fertile soil. In several places of Greece, polje (e.g., Kopais) underlying by carbonate rocks constitutes the unique cultivated land of the area (Papadopoulou-Vrynioti 1990).

Table 1. Land uses of the study area, with carbonate rock area distribution for each land use (TL = Early-Middle Triassic limestones, TJLD = Triassic-Jurassic limestones and dolomites, CL = Late Cretaceous limestones, MLA = marbles and crystallized limestones of autochthonous unit of Attica, TC = total area of carbonate rocks, UA = Urban area, AA = Agricultural area, FA = Forest area, SSVA = Shrubby and sparsely vegetated area).

Land uses	TL %	TJLD %	CL %	MLA %	TC %
UA	6.6	1.1	6.5	1.8	3.3
AA	20.4	9.5	14.5	10.7	13.1
FA	7.5	3.3	13.3	22.2	17.0
SSVA	65.5	86.1	65.7	65.3	66.5

Table 2 shows the percentages of the surface for each land use in relation to the total study area up to the year 2000. Furthermore the percentages of the area for each land use and their changes during the period 2000–2012 are presented.

Table 2. Land use area distribution for the years 2000 and 2012 and their changes (UA = Urban area, AA = Agricultural area, FA = Forest area, SSVA = Shrubby and sparsely vegetated area).

Land uses	UA %	AA %	FA %	SSVA %
2000	14.7	33.3	11.9	40.1
2012	14.7	31.4	9.4	35.0
Changes	–	1.9	2.5	5.1

The percentage of the area for each land use was calculated as follows: 14.7% of the total area of Attica is covered by urban land, 33.3% by agricultural land, 11.9% by forest land and 40.1% by shrubby and sparsely vegetated land. The shrubby and sparsely vegetated areas have the highest percentage among the other land uses until the year 2000. Given that the urban areas include the urban fabric of the city of Athens which is the capital of Greece, the percentage of urban areas is relative high.

During the decade 2000–2012 the percentages of the land uses apart from urban areas have changed (Table 2). The percentages of the area covered by cultivations, forests, shrubs and sparsely vegetation have been decreased. A series of massive wildfires that had broken out across Attica during the summers of the years 2007, 2009, 2010 and 2012 burned areas of cultivations, pine forests and shrub land. Thus, the wildfires caused reduction in the area of these land uses. The highest decrease in land cover (5.1%) is observed in the shrubby and sparsely vegetated areas and followed by the forests. Therefore the fires that took place during the last decade have resulted in considerable decrease of the natural vegetation of the study area leading to rock desertification and further land degradation.

The results of the statistical analysis of the spatial distribution of the carbonate rock area within the burned areas are presented in Table 3. A high percentage of the marbles and crystallized limestone of autochthonous unit of Attica is found within the burned areas. The fire had occurred since summer of 2012 in the northern part of Attica, burned thousands of hectares of forest land. Moreover, the marble and crystallized limestone outcrop is extensive in this area. Thus, the high percentage of this carbonate rock within burned area is fully justified.

Table 3. The burned land within carbonate rock area distribution (TL = Early-Middle Triassic limestones, TJLD = Triassic-Jurassic limestones and dolomites, CL = Late Cretaceous limestones, MLA = marbles and crystallized limestones of autochthonous unit of Attica, TC = total area of carbonate rocks).

Land uses	TL %	TJLD %	CL %	MLA %	TC %
Burned area	8.6	5.9	3.6	32.9	11.6

The total surface of the burnt area underlain by carbonate rocks was calculated. The burned land covers 11.6% of the total area of the carbonate rocks. Since karst ecosystem is related with carbonate rocks and vegetation cover this part of the study area may be considered to be at hazard. The deforestation of the nature vegetation have a negative effect in the karstification processes, in soil quality, water, plant and animal growth, along with human life quality, consequently to the karst ecosystem.

5. Conclusions

In the present work a statistical analysis was performed using the spatial distribution of carbonate rocks, land uses and burnt areas of Attica along with GIS capabilities.

The statistical analysis revealed that 3.3% of the total area of the carbonate rocks is covered by urban, 13.1% by agriculture, 17% by forest and 66.5% by shrubby and sparsely vegetated land. Since, Attica was suffered in the past by massive wildfires; the majority of the area of carbonate rocks was covered by shrubs and sparsely vegetation until the year 2000.

Regarding the land uses of the Attica in the same period, the majority (40.1%) of the total area was covered by shrubs and sparsely vegetation, while 33.3% by cultivations, 14.7% by urban areas and only 11.9% by forests. The percentage of urban area is high because it contains the urban fabric of the city of Athens. During the last decade a series of massive wildfires had broken out across in the study area and resulted in considerable reduce of the natural vegetation leading to rock desertification.

The burned area covers 11.6% of the total area of the carbonate rocks and it was considered to be at hazard. The deforestation of the nature vegetation has negative effects in the karstification processes, in soil quality, water, plant and animal growth, along with human life quality, consequently to the karst ecosystem.

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CLAUDE CHABERT AND THE MAPPING OF AYVAINI CAVE – TURKEY

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In this poster presentation a detailed explanation will be made about the long years' caving activities and explorations of Claude Chabert in Turkey, in addition to his famous Ayvaini Cave map, which he began measuring at 1988 and finalized by 1993. Measurement and drawing stages of this huge map will be explained in details. Upon an invitation of Dr. Temuçin Aygen, Claude Chabert visited Turkey at 1966 for the first time and explored, documented and mapped more than 200 caves till 2001, mostly around Taurus Mountains. Some caves that he explored are among the longest in Turkey, namely Pınargozu and Tilkiler. In this poster presentation, a short summary of all his works including his articles will be given. Meanwhile, in the same poster, in addition to his other works, Claude Chabert's efforts about drawing a 1/500 scale map of Ayvaini Cave will be explained. This map, which was never published due to its error, is the longest cave map of Turkey with a total length of 10 meters and covers incredible details of that 4,866 m cave. As a part of that poster presentation, this map will be distributed as an atlas.

1. Claude Chabert

Claude Chabert began his caving career in 1960, as a member of Speleo Club de Paris. His first arrival to Turkey was during 1966 with the invitation of Dr. Temucin Aygen. That year, SCP first began to study the northern basin of Manavgat River at southern Turkey. Next year, studies spread to the proximities of Dedegol Massive and Egridir area. By the end of 1968, more than 65 caves, including Dudensuyu, Tinaztepe Ponor and Cave, Zindan Cave, Dudencik, which would be the depth record of Turkey with its depth of -330 meters, were explored, surveyed and mapped. In 1970, 4 siphons were passed in Pinargozu and the cave had already been reached to +190 meters. SCP cavers were searching for dolines that would make a connection to this cave over Mount Dedegol.

In 1972; the sixth year of Claude Chabert's first arrival to Turkey, Pinargozu had already reached a length of 4,685 meters and a height of +244 meters. That year's annual report suggests that the enumeration of the caves that were found and explored in six years were more than 100.

In a derivation tunnel that is dug during the construction of Oymapinar Dam in 1976, Tilkiler Cave found. Though the idea of closing the mouth of the cave with concrete is considered at first, cavers were decided to be called. SCP began their studies about the cave that year. The next year the 4,845 meters and in 1979, the whole cave was scaled.

In 1976, Claude Chabert and four other cavers from SCP make their first trip to North Anatolia; Zonguldak. In this trip Kizilelma and Gokgol caves were studied and Cumayani Cave was mapped.

Besides his constant work and studies, Chabert was also a caver that publishes his works: He had 54 published articles about the caves of Turkey. In 1988, he published his "Bibliography of Speleology of Turkey" which had been a first until a recent time.

For those who think that he is only interested in caves of Turkey, it should be emphasized that he joined explorations from Lebanon to Indonesia in 16 different countries and has 66 other articles about the caves of those countries. He is the author of "Atlas des Grandes Gouffres du Monde" which is the first work that includes the most important caves of the world, and he is one of the two authors of the extended second edition of it; "Great Caves of the World".

Chabert visited Turkey in 2001 for the last time, for the re-survey of Kocain. After that, he mapped Gruta do Janelao in Brazil for several years. Subsequent to a long period of sickness, he deceased in 2009.

Figure 1. Location of Ayvaini Cave.

2. Ayvaini Cave

2.1. Location

Ayvaini Cave is at Ayvakoy, near to Bursa, northwest Turkey. In order to reach the entrance of the cave which is also called Cankuyu, one should follow the Ayvakoy-Doganalan road. The left turn that will be seen after approximately 3 kilometers is headed to the mouth of the ponor. There is roughly 4 kilometers of distance between the ponor and the spring.

2.2. Geology

Ayvaini Cave is located in Sogutalan Plateau which surrounds Lake Uluabat from south. The cave is formed within Upper Jurassic – Lower Cretaceous aged limestones. With a thickness of 100–150 meters, these limestones are the main factor of the karstification of the region. That beige and light grey crystalized formation is often massive and there are stratifications in patches. There are also calcite veins formed in different directions. According to the *Pleuromya alduini*, *Bryozoa*, *Quinqueloculina*, *Spiroloculina*, *Trocholina sp.* fossils that are found, this transgressive structure that begins with conglomerate and marl at the bottom and ends with crystalized limestones at top is dated as Upper Jurassic-Lower Cretaceous.

The impermeable denominations just below this limestone reef, which is relatively thinner, form a floor for the caves of the region and most of the caves that are located in Sogutalan Plateau are formed within the contact zone between those two units. Sogutalan Plateau, with all its different abrasion surfaces, fragmented foljes, karstic valleys, caves and ponors, has a surface that largely eroded and took its shape in Pliocene Period. The surface waters flow north, to Lake Uluabat or south, to Kocasu Brook valley, and some of the surface water is, because of the massive limestone on the ground, drained to underground.

One of North Anatolian Fault's two branches that strides through the south side of the Sea of Marmara strolls along the north side of Lake Uluabat and the other fault passes by the north side of Sogutalan Plateau, almost over Ayvaini Cave. With the effects of these two faultlines that has a great importance in the tectonics of the region, the depression surface around the lake that was begun to be formed in Early Pliocene have been covered with alluvion since Quaternary, and the faultline that is located in farther south caused the Sogutalan Plateau to raise.

Ayvaini Cave, located in this plateau's north edge, is a huge cave system covering the undergound and surface waters of a large area. Being formed at the edge of a sizable polje, the cave is headed to north east and opens to a surface again in the left slope of Yesildere, near Ayvakoy.

Except for few small branches, Ayvaini has only one main gallery in northwest-southeast direction and is shaped completely horizontally after the ponor entrance. The main gallery has a width of 3–15 meters and a height of 2–8 meters. There are many lakes with a changing number depending on the amount of water that flows in, with lengths of 10–200 meters. Formed within limestones that are extremely suitable to karstification, Ayvaini Cave also hosts stalactites, wall dripstones and travertine pools in patches. As a cave that gathers both underground and surface waters of a huge region, it is also active hydrologically. Even in dry seasons, the cave has a water flowing in from the ponor mouth. Besides, there are several different springs inside the cave. Within the limestone that formed the cave there is a dense karst consisting of doline and ponors. Waters that are drained by many nearby ponors are also gathered at Ayvaini and certain parts of these springs can be seen within the cave by their chimney forms.

Both from underground and surface, all these waters are drained from a rift near to the spring mouth, not from the spring mouth itself. The waters rise to the surface once more from the side of Ayva Brook, which is located below. However, in rainy seasons this rift fails to drain all the water and most of this water is spewed out. This phenomenon is called "The eruption of the cave" by Ayvaini locals.

2.3. History of the Explorations

Ayvaini's first study was made by Swedish biospeleologist Knut Lindberg in 1952. After the Spanish cavers' exploration during 1970, Ayvaini Cave identified as one of the longest caves of Turkey. BUMAK (Bogazici Univ. Caving Club) began surveying the cave in 1986 and 1987, but only 1,947 meters of cave, starting from Doganalan entrance were mapped.

3. Mapping of Ayvaini Cave by Claude Chabert

Claude Chabert, began to prepare his 1/500 scaled map of Ayvaini in 27 August 1988. He visited the cave many times during 1992 and 1993. In his surveys many Turkish cavers accompanied him. During those surveys his longest topo station was 20 meters. Hundreds of measurements were made and all of them were double checked. Still because of the differences between the measurements that are made from surface and the cave map, Claude Chabert did not publish this map and did not state how much difference there were.

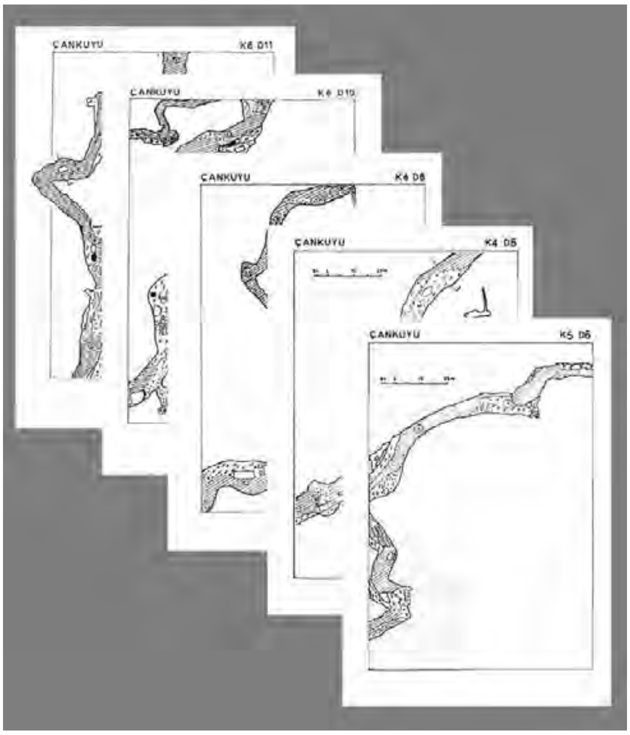

Figure 2. Some pages of Claude Chabert's Ayvaini Cave Atlas.

When we bring all these 40 unpublished map sections of his survey together in an atlas today, we can calculate that the difference between his survey and the GPS references of the both entrances of Ayvaini Cave is only 105 meters. Considering that the cave is 4,866 meters, the error rate was just 2 %, which is inevitable in a cave with more than 260 topo stations.

Even computer softwares that are made for cave mapping have a “fix”. You may push and shove the map. Yet, Claude Chabert was a man that saw caving beyond being a lifestyle; he dedicated all his energy, time and labour to caving, doing his best and never giving up being scientific. Consequently, the word “To fix” was not a part of his dictionary.

He and his dedicated, scientific caving will always be missed by Turkish cavers.

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RE-MAPPING OF INSUYU CAVE (BURDUR – WESTERN TURKEY)

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Despite the fact that Insuyu Cave which is in the neighbourhood of the city Burdur – Turkey and long been known by the residents of the area, the scientific exploration of the cave took place in 1952. Its research had begun in 1964 and opened to tourism as the first touristic cave of Turkey in 1966, the scientific studies in the cave has lasted hitherto.

In Insuyu Cave which was mapped a few times by different experts during the first period studies, the exploration of a new gallery in 1993 led the cave beyond estimations and surveys had been accelerated from that day forward.

OBRUK Cave Research Group who realised the deficiencies in the previous maps of the cave, launched a project in 2011 in order to perform an accurate mapping of this long and important cave of Turkey as much as possible. Several visits were performed in Insuyu Cave during the this project and the new map of the cave with 8,100 meters lenght was drawn.

In this poster presentation; in addition to previous scientific works and older maps of Insuyu Cave, this new mapping project of the cave will be explained in detail.

1. Introduction

The scientific exploration of İnsuyu Cave, 13 km from Burdur, near the main road, on the outskirts of Sarpguney Hill (1,606 m), occurred in 1952 when Dr. Temuçin Aygen was informed. Aygen; having realised the importance of the cave after his first investigation, excited attention of the authorities, and performed a second and comprehensive research in Insuyu Cave in 1953.

Aygen wrote in his book “Turkiye Magaralari” (Caves of Turkey) that, before opening of the artificial tunnel which provides touristic entry now, it was rather hard to enter the cave from the natural entrance. Besides, the natural opening was completely submerged during spring when the amount of water increased. Insuyu Cave was opened as the first touristic cave of Turkey in 1966. (Fig. 1)

Biospeleologic research by Paolo Marcello Brignoli in the years 1968, 1971, 1972, 1973 and 1978 and a research for bat species by Friederike Spitzenberger in 1973 were also carried on in the cave.

2. Maps of Insuyu Cave

The first detailed map of Insuyu Cave was drawn in 1968. Only main galleries and some major branches were stated on this 1/1000 scaled map and neither of the small galleries were shown. But the narrow passage, which provides a pass towards the non-touristic part and located in the northeast of “Buyuk Gol” (Big Lake), was shown on this map. Nevertheless, this passage, which had not been studied for long years, was first passed in 1993. In the report by the the research team who investigated this part first, the cave was said to continue with several galleries from that part on and to have many lakes behind. “Umut Lake” (Lake of Hope) which was their first lake to find and to give its name. The first map of this part of the cave drawn in 1993 was rather insufficient. After some years following this first exploration, MADAG (ODTU Cave Diving and Research Group) and BUMAK (Bogazici Univ. Cave Research Club) began to research and map those newly discovered galleries underwater and surface via common activities. A detailed map of this, non-touristic part was completed in 2006.

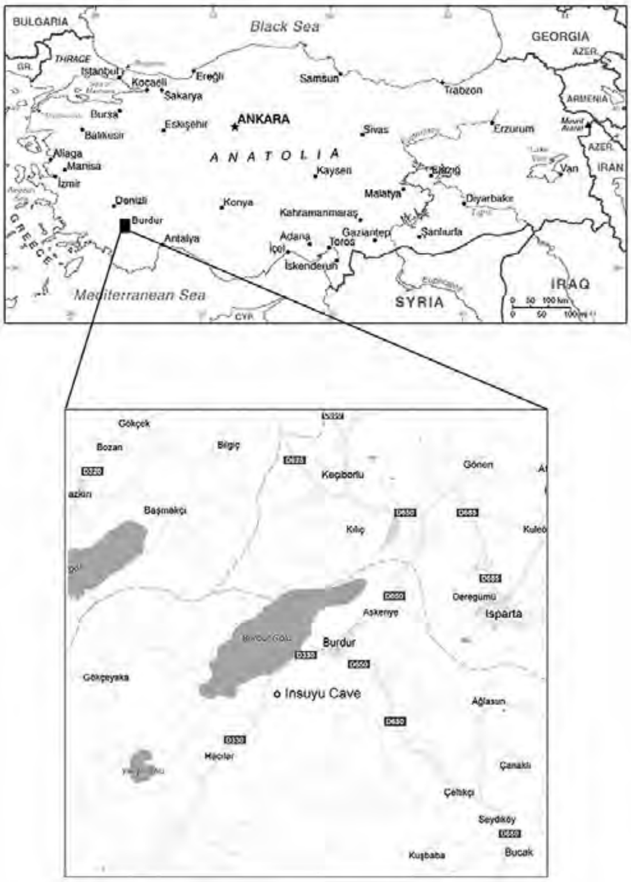

Figure 1. Location of Insuyu Cave.

On the other hand; the modification map for the touristic part which was prepared in 1997 and the maps re-drawn in 2007 of the same part were also rather insufficient.

OBRUK Cave Research Group who realised the deficiencies in those 5 maps started a project in 2011 in order to provide an accurate mapping of Insuyu Cave as much as possible. 7 survey trips were performed during this project and a new map of the cave with 8,089 meters lenght was drawn. That length nearly doubles all the previous surveys.

During these researches, all galleries in touristic parts of Insuyu Cave were measured, and three new lakes were discovered which had not been known before.

Additionally, a new water gallery and a huge chamber following that gallery were also found in the second part of the cave. OBRUK's research and measurements still continues in the cave (Fig. 2).

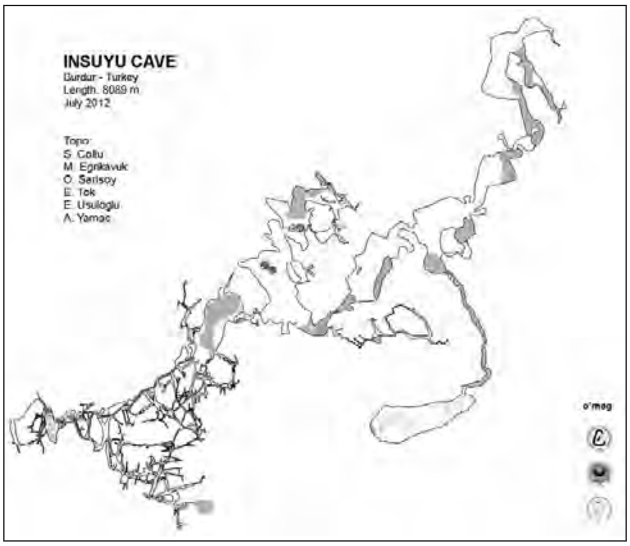

Figure 2. Map of Insuyu Cave (July 2012).

3. Geology and Hydrogeology of Insuyu Cave

It is clear that the formation of Insuyu Cave is multiphase. Distribution of dry galleries to the sub-branches and erosion formations which could be observed on ceilings and walls in these parts can caused only by high flow water indicates that these galleries which are dry for today have been developed under submerged conditions.

The cave probably transformed from saturated into half-saturated conditions in the process of time. During this process, subterranean streams and branches, which had a high flow speed and turbulance, were also effective in erosion. Insuyu Cave was probably discharging much more amount of water than observed now.

Facing the morphology of "key hole" in some narrowing parts of the tributaries, being semi-saturated following the primary waterlogged development period and stream erosions are other evidences of the secondary development phase. In these parts, spoon formations on the high parts of the walls and ceilings show that the stream rises from time to time providing the galleries completely filling with water. The presence of the formations such as soda tube, stalactites are sufficient evidences that the erosion by subsurface stream loses its effect within the time by reducing in time. These deposits are the products of the latest development phase which has been influential up to now.

It is inferred from all those visual data that the development process of İnsuyu Cave has at least 5 different phases:

i) "The primary gallery formation period" in submerged conditions.

ii) "Active stream period" when semi-saturated conditions and subsurface stream system are influential together with the decline in subsurface water level.

iii) "Passive dry period" when the secondary deposits are developed on spoon formations.

iv) "Water-level rise period" which causes the mentioned deposits to be in drawn condition in some parts of the cave.

v) "Water-level subsidence period" which also continues today.

The blocks falling from the ceiling that is faced intensively in most parts of the cave show that tectonic movements are not only influential in development of the cave but, also in destruction through natural processes. The parent rock, forming the walls in some parts, is extremely diffusable due to the fact that the corresponding blocks are intensively influenced by the shear through the fault scarp which is notable in development.

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Session:

Modelling in Karst and Cave Environments

MICROMETEOROLOGY OF MT CRONIO CAVES, SICILY

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1. Introduction

Mt. Cronio 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 gave rise to the Ferdinandea island (Graham Bench) in 1831. Afterwards the island quickly disappeared.

Since classical antiquity due to the presence many cave entrances (Stufe di San Calogero – now Antro di Dedalo – and others) with strong, exiting hot airflow (37 °C, RH = 100 %), have been known at the summit of Mt. Cronio (370 m a.s.l.). These caves have represented an interest as *calidaria* (hot rooms in Roman baths) since ancient times. In the past centuries, these caves were explored several times, but the hot atmosphere and the presence of a pit not far from the entrance allowed only very limited visits (Guidi and Verde 2001).

Cavers from Trieste (CGEB) have explored this cave system since 1953, discovering important archaeological deposits in the deeper parts, which have not yet been studied (Guidi 2000) in detail; however, a quick survey showed that they belong to pre-greek civilisations, some 4,000 years ago. Before these times the caves were probably used for cultual purposes (religious rites and burials), but then abandoned due to the sudden arrive of hot vapour flux.

2. Caves and micro-meteorology

At the end of the 1990s, a total of 1,500 m of conduits and 20 caves were known; the most important being Cucchiara cave (length 560 m, depth 127 m) and Antro di Dedalo (length 580 m, depth 56 m).

The Antro di Dedalo and other smaller entrances show a flux of outflowing air, seasonally constant at about 3–4 m^3/s, whilst the flux in Cucchiara is inflowing, so that the cave temperature is well below the temperature in Dedalo.

CGEB and the La Venta association are now collaborating for a multi-disciplinary project, named “Progetto Kronio”, to study this cave system, one of the most interesting worldwide from the historical and speleological point of view.

The environmental conditions are really harsh for people and instruments (high temperature, high carbon dioxide level, presence of sulphur, RH > 100 % with stationary clouds…) and do not allow continuous environmental monitoring.

Nevertheless during 5 years of study many micro-meteorological data series have been acquired. We have especially focused our attention to:

1) Micro-variations of internal temperature and its correlation with external meteorology;

2) Correlation of air fluxes at different entrances;

3) Correlation between airflow and external meteorological conditions;

4) Search for infrasounds;

5) Chemical composition of internal atmosphere;

6) Internal thermal sedimentations.

In particular, the Cucchiara cave shows an astonishing micro-meteorological variety of processes, with thermal sedimentation which reaches up to 15 °C/m, probably the widest known, and has probably an enormous variety of ecological niches and minero-genetic processes.

Our main aim is to create a model of cave structure in the most internal, unexplored parts. In particular it looks possible to estimate the cave volume from airflow data.

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NEW ACQUISITION, 3D MODELLING, AND DATA USE METHODS: THE LASER SCANNING SURVEY OF RE TIBERIO CAVE

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Precise surveying in underground contexts with traditional systems is a challenge due to the complexity of natural forms, the extent of the caves, and the work conditions. Laser scanning is a solution that can be applied to many cave surveys to get a complete high-precision three-dimensional database, from which the end user can select the information on the basis of his technical and operational, or research objectives. Laser scanning is a multidisciplinary tool for knowledge and information management concerning the cave.

This paper illustrates the three-dimensional laser scanning survey, data processing, and representation of the so-called "Gothic Hall" of Re Tiberio Cave (Riolo Terme, Italy), carried out by Virtualgeo in September 2010. The three-dimensional digital model, which was obtained from processing the acquired laser data, allowed us to define in detail the shape of the surveyed object, which was represented in a series of graphic representations. Another advantage of laser scanning technology is the possibility to use the acquired data (and, in particular, the 3D model) for educational and dissemination purposes, with the same standards of precision and scientific rigor.

1. Introduction

The Re Tiberio karst system is located in Mount Tondo, in the right bank of the river Senio. The karst system, which is developed in the Messinian gypsum, is certainly the most important and most studied karst phenomenon of the Vena del Gesso Romagnola, at least in relation to some of its particular aspects (De Waele et al. 2011; Lucci and Rossi 2011). It's the second longest epigenetic gypsum cave in Italy and among the top five in Europe for development and complexity (more than 6,000 m long with a depth of nearly 200 m). Today the Re Tiberio karst system is in the territory of Riolo Terme (Ravenna, Italy), is part of the Vena del Gesso Romagnola Regional Park (established in 2005), and was designated as a Site of Community Importance and Special Protection Area (code IT4070011). Nevertheless it continues to be partly demolished by a large, still active, gypsum quarry.

From the speleogenetic point of view, the morphologies present in the cave are basically due to joints and tectonic discontinuities (faults and diaclases). The former had a key role in the genesis of large galleries, which formed along them. The latter favoured gravitational morphologies such as pits and canyons, since such disjunctive lines were the preferential centers of the movement of groundwater that, gradually lowering, reached their current base level.

The general direction of the Re Tiberio Cave is NW-SE although there are many maze bodies and some galleries with SW-NW direction. The cave mostly develops horizontally, with five levels of superposed galleries connected by small vertical pits. However, many parts of the cave were partially destroyed by the quarry, thus their sedimentological and morphological characteristics are difficult to read.

From the hydrogeological point of view, the karst area of Mount Tondo remained totally unknown for a long time; only recently were targeted studies carried out (Ercolani et al. 2003). Today it's a known fact that the area of Mount Tondo is divided into two distinct karst systems:

a) In the first one, the waters of the Abisso Mezzano reach the Re Tiberio Cave, as well as the waters from the Abisso dei Tre Anelli, Abisso Cinquanta and Inghiottitoio del Re Tiberio. Some of these underground rivers were intercepted by the quarry galleries.The spring of the system is just on the quarry plain, a few meters above the Senio riverbed.

b) The second karst system starts from the Buca Romagna and reaches the spring located N-W of Ca' Boschetti, crossing the Grotta Grande dei Crivellari and the two caves of Ca' Boschetti. Moreover, a tributary from the Enrica Cave directly flows into the main catchment of the Grande Grotta dei Crivellari.

Actively frequented from the Copper Age (probably as a burial area) until the 15th century (when it possibly was a clandestine mint), the cavity is famous for the archaeological finds, so that it has been the object of scientific excavations since the mid-nineteenth century (Pacciarelli 1996).

Finally the most recent speleological explorations discovered archaeological remains in other cavities of the Vena del Gesso, thus proving that the area of archaeological interest is much wider than the entrance of Re Tiberio Cave (Forti et al. 1997; Ercolani et al. 2003).

The three-dimensional laser scanning survey of caves and rocky habitats is widely discussed in the specialist literature. As in the case of the Re Tiberio, the caves often incorporate a set of values. They aren't "only" unique geological archives, natural beauties and geological rarities, but they also have historical, archaeological, artistic, and ethno-anthropological value. Therefore, it's necessary to apply a method that meets different needs:a method that, with a multidisciplinary approach, provides the key tool for exhaustive knowledge and complete management of all the information regarding the cave.

Concerning geology and engineering geology, the literature produced in recent years proves the potential of laser scanning techniques for geomorphic studies, for monitoring, and supervising (quantitative control) both in managing natural events (for routine and/or exceptional ones), and managing activities of territory "transformation" (geo-resource exploitation, infrastructure works, etc.) (Alba et al. 2005, 2009; Clerici et al. 2005, Francioni et al. 2010; Riccucci et al. 2010).

Interesting applications of laser scanning involve cases where geology and cultural values merge, such as in mines (Hanke et al. 2009; Tucci et al. 2009b).

Over the years, the use of laser scanning as a valid tool to survey hypogean contexts has increased (Beraldin et al. 2006; Baiocchi et al. 2011), particularly for works related to archeology and paleontology (Caprioli et al. 2003; Fryer et al. 2005; Chandelier and Roche, 2009; González-Aguilera et al. 2009; Pucci and Marambio, 2009; Tucci et al. 2009a).

The key tool is the three-dimensional qualitative high-precision database delivered by laser scanner. The laser scanning database integrates existing speleological surveys carried out with traditional topographic instruments. Moreover, it becomes a platform for merging and categorizing the data and documents from in-place sampling, analysis, and specialist research. That allows productive sharing between scholars, professionals, institutions, etc. fostering interdisciplinary exchanges. Such sharing can be extended to public enjoyment, without risks for safety of tourists and of the cave itself, especially for closed or not easily accessible sites.

2. Laser Scanning Survey in Caves

The survey of one of the most significant (from the archaeological point of view) natural caves of the Vena del Gesso Romagnola is the last of a series of important cave surveys (with three-dimensional digital data processing) performed by Virtualgeo in Italy and abroad. The company provides 3D laser scanning and reverse modelling services, and develops dedicated software technologies and work processes (Canevese et al. 2008, 2009, 2011).

Precision surveying in caves with traditional methods (total station or unsophisticated instruments used in underground topograpy) is a challenge due to the natural shape irregularity and complexity, cave extension, and (not negligible) work conditions. Laser scanning can be an alternative resource to apply to many cave surveys in order to obtain complete quantitative and qualitative high-precision databases.

Laser scanning survey instruments combine the functions of a distance measuring device and a theodolite, which measure respectively distances, and horizontal and vertical angles. Laser scanners systematically acquire x, y, z spatial coordinates of surveyed surfaces, as high density "point clouds", by analyzing the inbound signal of the emitted laser pulse. In addition to spatial coordinates, for each point the laser scanner acquires the intensity of the pulse reflected back, according to the material characteristics of the surfaces. Moreover, it allows linking of each surveyed point with a RGB colour value, thanks to an associated camera.

Terrestrial laser scanners available on the market have different functioning principles, inbound signal reception, processing systems (time-of-flight, phase shift, triangulation), range (maximum ranges vary from a few dozen centimetres up to some thousand meters), accuracy and precision. The choice of laser scanner has to be evaluated on the basis of the peculiarities of the object/area to be surveyed, and of its technical specifications: accuracy, field of view, range, measurement speed, wavelength of the pulse, material reflectivity, environmental factors (e.g., sunlight, humidity), portable format (weight, dimensions, toughness), power supply, user interface, data storage and transfer, peak operating temperature and humidity levels.

The fast rate measurement, amount and quality of acquired data (point clouds), non-contact with the surveyed surfaces, and adaptability of use allow laser scanning to perform precision surveys also for morphological complexity and large surfaces, keeping the work continuity in place. Moreover, thanks to process rapidity and automation, it assures high survey productivity even in difficult or dangerous working conditions (as it allows remote work in safe conditions), even with a single technician.

Laser scanning survey is independent of topographer's discretion and lets the various users (scientific, institutional, etc.) read and select the significant and useful data of the point clouds and/or 3D model obtained from point clouds, even after some time or while comparing scans acquired in separate time periods.

Once aligned in a single Cartesian coordinate system through known reference points by appropriate software, the point clouds reconstruct the three-dimensional shape of the surveyed object or area. The final result of the scans post-processing is a global point cloud, which is a metrically accurate three-dimensional point model of the surveyed object containing also chromatic information. The latter information, which can be grey scale reflectance data or RGB values, visually helps the final users to interpret the surveyed object and extract geometrical data from the point model.

Among their most important works in the underground, in the years 2006–08 Virtualgeo surveyed with laser scanner and 3D modeled: the Grave in the karst complex of Castellana, the mine caves of Naica, and the Santa Barbara karst system in Sardinia.

In the caves of Castellana, hosted in the Altamura limestone, Virtualgeo carried out the laser scanning survey of the Grave: the widest and most complex shaft of Apulia region (100 m long, more than 40 m wide, and about 60 m high), and among the most important of southern Italy (Canevese et al. 2009).

As a part of the multidisciplinary project, in Mexico the laser scanning work related to the survey of the Cueva de las Espadas and Cueva de los Cristales. They are extraordinary cavities, developed in the Albian age carbonate formations of the Sierra de Naica, hosting gigantic gypsum crystals (in Cueva de los Cristales they reach up to 12 m in length, and almost 2 m in diameter) (Canevese et al. 2008, 2009).

In Sardinia, near Iglesias, a part of the mine caves of Santa Barbara was surveyed. This system consists of two large subvertical cavities that are considered among the oldest limestone caves of the world. Moreover, the upper cavity (Santa Barbara 1) is one of the most famous mine caves worldwide for the beautiful euhedral baryte crystals covering its walls (Canevese et al. 2009, 2011).

In all those cases, the use of laser scanner allowed the fast acquisition of a large amount of data, required to describe the complexity of the cavities. It also allowed overcoming specific problems, such as the extreme climate in Naica (temperature of 48 °C and humidity around 100 % in the Cueva del los Cristales), and prevented interference with the flow of tourists in Castellana and Iglesias.

Figure 1. Survey with total station for the cartographic setting of the Re Tiberio cave (left), and laser scanning test with FARO LS PHOTON 20-120 model (right). The survey was carried out with laser scanner Leica HDS6100 (Table 1).

3. 3D Laser Scanning of the Re Tiberio Cave

In September 2010, the three-dimensional laser scanning survey was performed on the first 60 m of Re Tiberio Cave (from the cave entrance to the Gothic Hall, a circular hall with a diameter of about 15 m, and an ogive vault) (Figure 1). This includes the small portion of the Re Tiberio Cave (total length over 4 km) that everybody can easily walk along.

This paper focuses on the survey, data processing, and 3D modelling of the Gothic Hall, and of a portion of gallery giving access to it.

The purpose of the survey work was to accurately document the shape of the cavity, with a system that allows surveying and georeferencing the position and development of all significant morphological elements (including discontinuities, fractures, etc.), with the possibility to produce, in a flexible way, graphic representations to complement the existing maps.

A phase shift technology-based laser scanner, measuring the distance of an object by "comparing" the pulses of different wavelengths reflected back, was used to survey. It has a medium measurement range (suitable for limited distances), an almost spherical field of view (particularly suitable to survey inside closed spaces such as caves and galleries), and a high points-per-second measurement speed. Moreover, in comparison with other models, this laser scanner has a rather compact size and lower weight, and thus is more functional to carry and handle inside a cave (Table 1).

Table 1. Technical specifications of the Leica HDS6100 laser scanner used to survey the Gothic Hall in Re Tiberio Cave.

Range	up to 79 m
Measurement rate	up to 508,000 points/second
Accuracy	±1 mm at 25 m, ±2 mm at 50 m
Horizontal/vertical field of view	360/310°
Weight	14 kg
Dimensions	294 × 199 × 360 mm (W × L × H)
Operating conditions	from -10 °C to +45 °C, non-condensing, fully operational between bright sunlight and complete darkness
Camera model	Canon EOS 450 D – 12 MPixel

Before the laser scanner survey, an acquisition plan was prepared to locate the best positions (according to the development of the cave and the possibility to easily manage people and instrument mobility) for the scanner stations in order to reduce "shadows" in the scans, and to define the most appropriate scanning angles to obtain scans with a uniform resolution (by setting the average distance between scanner stations and surfaces to acquire, as well as the scanning point grid density) and a good overlapping area.

Before starting the cave laser scanning, 38 reference targets were placed (at significant visible points) and surveyed with total station to georeference and align the point clouds obtained from the various scans. The topographic works were executed to establish one open traverse (with 5 control points) to survey the reference targets, while 6 existing data points and a set of outside significant points were surveyed to establish the cartographic setting of the cave.

In about 8 working hours 2 technicians established the traverse, surveyed the targets and data points, and finally scanned the Re Tiberio Cave. The amount of acquired data is summarized in Table 2.

Table 2. Total data acquired by laser scanning and camera in Re Tiberio Cave and, in the right-hand column, the detail of data regarding the Gothic Hall.

	Re Tiberio Cave (total)	**Gothic Hall**
Acquired scans	14	6
Points	about 630,000,000	about 270,000,000
2D images	84	36
Laser data amount	7 GB	3.5 GB
2D images amount	378 MB	165 MB

The post-processing and representation of the data followed the laser scanning acquisition. These stages are crucial to optimize laser scanner characteristics; therefore the support of dedicated software is essential for the suitability of the acquired information, and for the production of an effective three-dimensional model that can satisfy the multidisciplinary purposes of the survey, and also unknown potential future objectives.

The post-processing of the acquired data started with alignment (to obtain a global point cloud from the various scans), cleaning, and filtering of the point clouds to remove "noise" and non-significant points with Leica Geosystems dedicated software.

The point cloud is a point model of the cave surface that documents exact dimensions, morphology, and, in particular, all the irregularities of the walls. Such information is by far better, in quantity and reliability, than the data obtained from traditional topographic surveys or on-site inspections. Point clouds allow visualization of the cave morphology (colours or grey scale make this reading phase easier), and extraction of dimensional data (linear and angular, slopes) (Figure 2).

Figure 2. Sectioned point model of the Gothic Hall: view from the south.

The three-dimensional modelling of point clouds to obtain a continuous surface 3D model was carried out with CloudCUBE, software on AutoCAD platform developed by Virtualgeo. The millions of points acquired were treated and arranged to produce a "smart" three-dimensional model of the cave: metrically exact (it sums the accuracy and precision of the laser scanner survey, topographical works and alignment of point clouds), corresponding to the surveyed morphometry, segmented, and innovative regarding the immediate and potential uses of the survey.

The cave was modelled with the most suitable among the techniques (2.5D and 3D triangular grid meshes, quadrangular "surfaces", "region" entities) for modelling its dimensions and complex uneven morphologies. The construction of 3D triangular meshes was carried out directly on point clouds by an automatic technique. In the process of point joining (triangulation) the 2.5D triangular mesh takes into account only the x, y coordinates (therefore, it's more suitable to model planar surfaces), while the 3D mesh considers all three x, y, z coordinates; thus it's more suitable to model complex three-dimensional surfaces.

The digital model of the Gothic Hall and entrance gallery, obtained by processing the point clouds, is a complete high precision three-dimensional database that allowed a detailed geometric definition. A series of graphic representations (plan with contour lines and elevation levels, significant sections with applied orthophotomaps) was elaborated from the model (Figure 3). They provided a clear graphic description of the cave (an example of the graphic representations is in Figure 4).

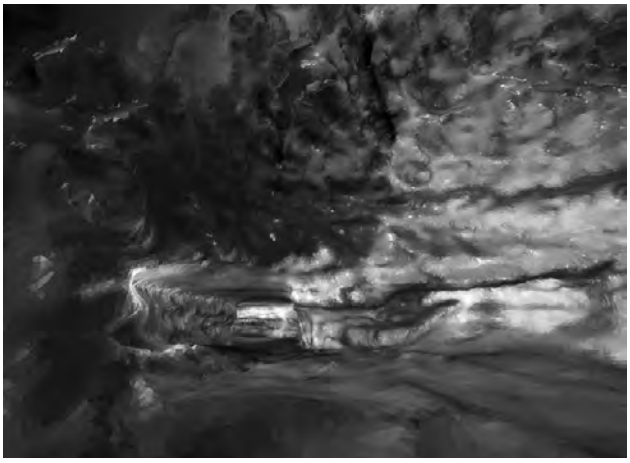

Figure 3. 3D model of the Gothic Hall: inside view from the west. On the lower side of the figure the 3D triangular grid mesh, obtained by triangulating the point cloud, is visible.

Anyway, it must be stressed that from the three-dimensional model it's possible to obtain unlimited representations of any type, with any scale, and plot plans at any elevation level and vertical sections along any section plan, without additional surveys on-site to acquire new data. That case would increase the costs and work time and, as in the case of Re Tiberio Cave, could conflict with access restrictions due to safety reasons.

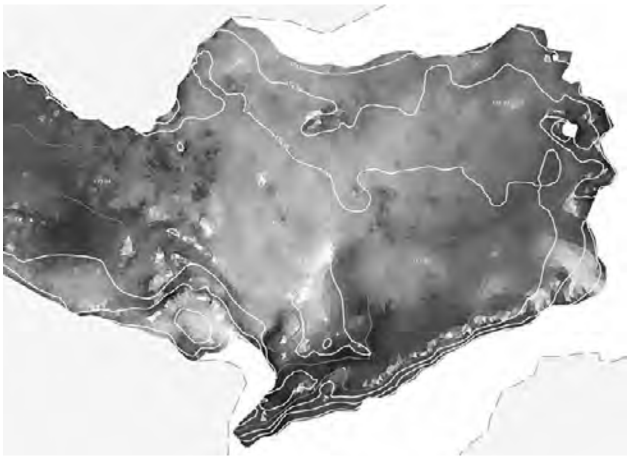

Figure 4. Plan with elevation levels and contour lines of the Gothic Hall.

Moreover, the model of Re Tiberio Cave can be "segmented", i.e. divided into parts associated with different layers (visually identified by different colors) according to specialized requirements and customized standards, e.g., geological units.

The segmented model is a particularly effective analytic tool (even for non-experts), thanks to the colors that makes the interpretation easier. It can be directly interrogated about dimension and information data.

The digital model, segmented or not, allows extracting any type of dimensional information (linear and angular, slopes) and computing contour lines, areas, and volumes. Moreover, it's possible to study and measure evolving phenomena (e.g., rock detachments, displacement, etc.) by "superimposing" digital models obtained in different monitoring surveys.

4. Conclusions

The speleological topographic survey and digital three-dimensional modelling systems presented here provide an accurate database that allows significant qualitative analyses and reliable computations for the morphological study of the current status, the analysis of rock mechanics and rock face stability, etc.

The possibility to use the survey data, and above all the 3D model, for multidisciplinary research in caves (without time and space restrictions) is a particularly interesting prospect.

The digital model and graphic representations can be used not only to study the current situation of the subject of interest, but also to verify a study hypotheses. For instance, in the geological field to retrospectively analyze collapses, or in a historical study to integrate the archaeological excavations carried out in the past, and materials exhibited in museums, etc.

Furthermore, the data acquired by laser scanning and, in particular, the 3D model can be used not only for technical-operative or research purposes, but even for educational and public dissemination purposes. In fact, from the acquired data (point clouds and pictures) and three-dimensional model it's possible to obtain "products" for scientific dissemination (e.g., regarding geology and archaeology for Re Tiberio Cave), or accessing the cave virtually, such as traditional and 3D pictures and videos, 360° panoramic images, point cloud animations, 3D models to explore, scale models, etc.

Acknowledgments

The authors thank the Soprintendenza per i Beni Archeologici dell'Emilia-Romagna (Italy) for allowing access to Re Tiberio Cave, and the company Wunderkammer s.n.c. (Bologna, Italy) for the opportunity to carry out the laser scanning survey.

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A THEORETICAL FRAMEWORK FOR UNDERSTANDING THE RELATIVE IMPORTANCE OF CHEMICAL AND MECHANICAL EROSION PROCESSES IN CAVE STREAMS

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The majority of quantitative models of speleogenesis focus on the early stages of cave formation when the dissolving fractures are water-filled and flow velocities are relatively low (see e.g., Dreybrodt et al. 2005). However, to understand the development and evolution of mature cave systems, and to elucidate connections between cave formation processes and observed morphologies, models must be pushed beyond these initial stages. One critical assumption of current speleogenetic models is that cave passages are enlarged solely by dissolution. This assumption is unlikely to hold in large cave streams that transport appreciable amounts of abrasive sediments. In these systems mechanical erosion should play an important role. In contrast, current models of stream incision in surface streams typically assume that dissolution can be ignored as a stream erosion process (Wohl 1993). This disconnect between the speleogenesis modeling community and the bedrock channel modeling community is indicative of a switch between the relative importance of chemical and mechanical processes as stream size grows. However, the factors that control this switch have not been identified. Here, we develop an initial framework for the exploration of this question.

Models and approximate relations have been developed for estimating dissolution rates given the saturation state with respect to calcite and the partial pressure of CO_2 (pCO_2) (Palmer 1991; Dreybrodt et al. 2005). Models for erosion in bedrock channels are often expressed in terms of a stream power or shear stress erosion law (Howard and Kerby 1983; Whipple and Tucker 1999). These models are a power law function of excess shear stress (or stream power) that can be expressed as a function of stream discharge. Comparing the scaling behavior of these common dissolutional and mechanical erosion laws provides initial hypotheses for the factors that control the relative importance of the two processes.

A complicating factor is that stream discharge and chemistry are variable over time, such that rates must be averaged over a wide range of conditions. Such averaging has been accomplished in the study of stream erosion models by employing probability distribution functions for discharge and driving the model stochastically over the expected distribution of discharges (Tucker and Bras 2000; Molnar et al. 2006). To enable a similar approach for stochastically driving the dissolution model, we must express chemical variation as a function of discharge. We use field data from a few example sites, and statistical analysis of stream chemistry from over 50 sites within the United States Geological Survey (USGS) Hydrologic Benchmark Network, to show that saturation state frequently varies as a power law of discharge, such that higher discharges carry less saturated water. While the relationship is not universal, it allows an initial means of stochastically driving dissolution models. The resulting mechanical and chemical erosion models, both driven by the same stochastic forcing functions, allow us to calculate average long-term erosion rates of each process in a variety of conditions and to thereby develop a framework for understanding the relative importance of the two types of processes. Future work will test this initial framework using field data from cave streams.

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EVOLUTION OF CONDUIT NETWORKS IN TRANSITION FROM PRESSURISED TO FREE SURFACE FLOW

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To get a better understanding of the general properties of solution conduits in karst aquifers, different numerical models have been developed to simulate speleogenesis based on the physical principles of flow, dissolution and transport (Palmer 1991; Siemers and Dreybrodt 1997; Kaufmann and Braun, 1999; Clemens et al. 1999). These models have given new ideas on the dynamics of the evolution of individual karst conduits and conduit networks. Modelling the evolution of a single conduit revealed a feedback mechanism between flow and dissolution rates, and the importance of a kinetic switch for the evolution of extended conduits. The feedback mechanism ends at the *breakthrough*, when flow and widening rate increase by several orders of magnitude in a short time (Dreybrodt and Gabrovšek 2000). Individual fractures have been assembled into fracture networks to model patterns of evolving karst networks. Modelling revealed the nature of competition between different pathways connecting inputs and outputs. During the initiation phase, the most successful pathway diminishes head gradients of other competing pathways, so that they practically cease to grow until the winning pathway breaks through. After the breakthrough of a first pathway, the pattern of hydraulic potential is redistributed, the gradients along other pathways build up again and the network integrates to a branchwork or maze pattern, depending on the availability of the recharge (Gabrovsek 2012**)**. Modelling of unconfined networks demonstrated the important role of changing water table in speleogenesis and the formation of base level conduits (Gabrovšek and Dreybrodt 2001; Kaufmann 2003). Many other scenarios of early speleogenesis have been modelled including the role of geochemical conditions and mixing corrosion, exchange flow between the matrix and conduit network, and the role of insoluble rocks in the evolution of conduits (see Dreybrodt et al. 2005). Numerical models have been also used to discuss an increasing leakage at dam sites or other hydraulic structures where unnaturally high hydraulic gradients cause a short breakthrough time. Although these models revealed many new mechanisms and profoundly deepened our understanding of the formation of karst aquifers, they are limited to stages of speleogenesis when all conduits are under pressurised flow.

There is a common agreement that early stages of speleogenesis determine the pathways which develop into caves. However, so far no model of conduit network evolution was extended to the latter stages, when conduits are not necessarily under pressurised flow. Therefore, the selective role of the mechanisms during and after the transition to open channel flow is poorly understood.

The hydraulic and geochemical boundary conditions for speleogenesis vary extremely. We cannot embrace the whole spectrum in a single model. This work extends the line of models presented by several authors (see Dreybrodt et al. 2005). We model networks of conduits on a 2D grid. The recharge is (spatially and quantitatively) randomly distributed to junctions (= conduit intersections). One side of the network allows outflow, and other three sides are no flow boundaries. Initially, the conduits are small enough that flow is fully pressurised everywhere.

The model undertakes the same basic steps as other models: 1) Calculate the flow in the network. 2) Calculate the dissolution rates along all conduits. 3) Change the conduit diameter. 4) Start a new cycle with 1.

We applied EPA Storm Water Management Model (SWMM) to calculate flow. SWMM efficiently solves 1D Saint Venant equations in a single channel or arbitrary network of channels. These equations are based on mass and momentum conservation along a channel with an open surface flow. To account for the pressurised flow and the transitions between both modes, a Preissmann slot is used. Dissolution rate in each conduit depends on the saturation state of solution with respect to the mineral being dissolved and to the thickness of a diffusion boundary layer (DBL), which limits the diffusion flux of dissolved ions away from the walls. Flow and dissolution are coupled through mass conservation, in our model realised through the pollutant tracing module in SWMM.

Most of the simulations have been done for the case of rock salt, where dissolution rates depend on the thickness of diffusion boundary layer, which depends on the flow velocity in a conduit. Generally, the dissolution rates increase with flow velocities. The results are qualitatively valid for also for gypsum, but only partially for limestone. There is an open question related to the role of diffusion boundary layer in limestone dissolution for relevant cases. If diffusion is rate limiting in limestone, the concepts inferred from the model are valid for also for speleogenesis in limestone.

Two conceptually different networks have been simulated. In a “low dip” case, the network is slightly inclined, with the gradient pointing towards the springs. Initially all conduits are pressurised. During the “phreatic” development, conduits carrying most of the flow evolve fastest. In a uniform case, where all conduits have the same initial diameters and the same invert elevation in a junction, the flow stays active only along conduits belonging to the shortest pathways connecting inputs to outputs. The model gives an important rule which is valid for the drainage of any junction: the conduit with the lowest invert at the moment when the junction becomes vadose, will on a long term remain the only active channel. Several different configurations of boundary conditions and network structure are presented, which result in various branchwork and maze patterns.

In a "high dip" scenario, a sub vertical network was modelled with recharge from the top and a seepage face on one of the sides. Again, the geometry of junctions plays an important role. The end result for the uniform network is a water table cave at the base level; similar results have been obtained by Gabrovšek and Dreybrodt (2001). In (an/the: depending on whether you mean in general or a specific simulation) inhomogeneous case, loops along the most permeable pathways develop, forming a complex conduit pattern in a vertical plane.

Prominent vertical fractures focus flow from the adjacent network. If a series of such vertical fractures (planes) exists, the one closest to the output boundary develops first; it becomes vadose and presents a new seepage boundary for the not yet developed planes in the interior. This mechanism proceeds from the rim of the massif inwards and results in a series of shafts.

The presented modelling approach suggests several new mechanisms for the development of conduit networks in karst systems. The model preliminarily focuses on the hydraulic control of network evolution via thickness of the diffusion boundary layer.

Details on the model and results are available in the dissertation of Perne (2012).

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ANALYTICAL MODELS TO DESCRIBE THE EFFECTS OF TRACER MIXING BEFORE AND AFTER ADVECTION AND DISPERSION

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Groundwater tracing is typically the preferred method to delineate flow paths and determine basin boundaries in karst aquifers. Tracer recovery data are also used in some karst studies to infer solute transport characteristics. Methods for quantitative determination of transport parameters such as the average groundwater velocity and the coefficient of dispersion from tracer data typically employ one dimensional transport models that ignore variations in hydraulic and mass transfer properties along the path taken by the tracer. However, such variations may significantly alter apparent dispersion and create asymmetric tracer recovery curves. Even when flow and transport in the conduits and channels of the aquifer are adequately characterized by average parameters, the effects resulting from the injection of tracer may be confounded with those resulting from transport. Analytical models are presented here for one-dimensional transport of tracer that undergoes mixing in a reservoir either before or after advective migration. Using the advection dispersion equation with constant coefficients to approximate tracer transport in the advective mode, equations for tracer recovery may be written explicitly in terms of dimensionless time and distance as well as a ratio of time constants. The models presented here are used to develop some crude but simple criteria to evaluate the impact of mixing on apparent dispersion both prior to or following transport by advection. Applications to tracer migration from a pooled source through conduits of a karst aquifer or from karst channels dominated by advective transport into a pool are considered.

1. Introduction

Tracer migration in conduits of karst aquifers is usually thought to be advection dominated, and modeling of tracer recovery with an advection-dispersion equation (ADE) has been used with some success to determine representative velocities and dispersion coefficients. In practice, tracer is sometimes injected in flooded excavations or sinkholes or in pools in cave streams where both tracer residence time and local hydraulics are such that significant mixing occurs prior to advective transport. Likewise, tracer may undergo significant mixing in a pool some distance downstream of the injection point. Theory and observations indicate that either losses of tracer from the primary channels to adjacent low velocity regions or migration of the main tracer mass into pooled areas will result in increased dispersion and tailing of tracer concentration in recovery curves (Jeannin and Marèchal 1997; Field and Pinsky 2000).

Despite the extensive use of both mixing and advection-dispersion models to approximate mass transfer in unit operations, analytical models of mass transfer dominated by mixing in series with mass transfer dominated by advection were not published in the process engineering literature. There are, however, a number of analytical solutions to the ADE that may be adapted from soil physics and hydrogeology applications to simulate a finite mixed source boundary condition. Considering a completely mixed source separately from the downstream transport is equivalent to prescribing exponential decay of the source concentration. Depending on the description of mass continuity at the transition to an advection-dispersion mode of transport, the result may be a condition that stipulates decay of tracer concentration at the boundary or a condition that requires decay of the mass flux at the boundary. Solutions to the one-dimensional advection-dispersion equation for exponential decay of both concentration and mass flux at the boundary of a semi-infinite domain have been published (Marino 1974; van Genucthen 1981). These models yield the evolution of solute concentration in terms of familiar special functions, but may violate a mass balance over the system as a whole or may be difficult to evaluate (Novakowski 1992). For some combinations of transport parameters and residence times in a mixed reservoir, function arguments lie in the complex plane.

Esling and Jones (1992) solved the one-dimensional advection-dispersion equation with a mixed reservoir source having a different media type to the downgradient dispersive medium. Rather than prescribe concentration or flux at the source boundary, the ADE was solved in conjunction with the ordinary differential equation (ODE) that results from a mass balance over the source. The model has been simplified and adapted here to transport of a conservative tracer initially restricted to the source. A similar mathematical approach was used by Freijer et al. (1998) for modeling pesticide transport in column tests, and the analytical solution they present can also be directly simplified to the model presented here.

Novakowski (1992) did not give formulae for the solution to the ADE with a mixed source at the domain boundary, but generated results by numerical inversion of the Laplace transformed solution. The goal of his work was to evaluate various boundary conditions used to interpret tracer tests against laboratory data and to use the results to better inform the choice of boundary conditions applied to field scale tracer tests from wells. This is similar to the motivation for this paper, which aims to identify some conditions where mixing before or after advective transport may confound the interpretation of tracer recovery. The ratio of time constants that we find to be a controlling parameter on the effects of mixing is generally equivalent to the "dispersion parameter" of Novakowski or the dimensionless source layer thickness in Freijer et al.

There is less in the way of prior work that may be readily adapted to the description of tracer mixing downstream of transport dominated by advection. Mixing of solute at the exit of columns of finite length has been described with analytical models, but with the assumption of insignificant storage so that concentration changes little between reservoir inlet and outlet. This yields a Danckwerts boundary condition at some finite distance from the source rather than a complete mass balance over the reservoir, as would be more appropriate for the purposes of this study.

Here, the upstream transport by advection and dispersion is modeled as evolving from an instantaneous injection of tracer into a one-dimensional uniform flow field in an infinite medium. This crude treatment of upstream transport is apt to be a more reasonable approximation in stream channels or master conduits of karst aquifers where large Peclet numbers may be anticipated. The differential mass balance over the downstream reservoir is solved to predict evolution of tracer concentration at the reservoir outlet given the resulting Gaussian distribution of concentration at the inlet. The ratio of dispersive to mixing time constants appears again as the controlling parameter in this model, and the resulting integral was evaluated either analytically or numerically, depending on the time constant ratio.

2. Equations

In both cases considered here, the ordinary differential equation describing the mass balance over a mixed reservoir (given by equation 1 below) and the one-dimensional partial differential equation to describe advection and dispersion (equation 2) are solved. For mixing prior to advection, the initial conditions are a reservoir filled with tracer at concentration C_{S0} and tracer absent in a semi-infinite domain (x = 0 to x = ∞) downstream. The concentration of tracer entering the reservoir, C_{SI}, is zero.

$$V_s\left(\frac{\partial C_s}{\partial t}\right) = Q(C_{SI} - C_S) \qquad \text{Equation 1}$$

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} - D\frac{\partial^2 C}{\partial x^2} = 0 \qquad \text{Equation 2}$$

Here V_S is the reservoir volume, and C_S is tracer concentration of the reservoir. Q is the discharge through the reservoir, while U is the average velocity, D the dispersion coefficient, and C the tracer concentration through the advection dominated karst channels. The analytical solution to equations 1 and 2 solved together with these initial conditions and a condition that tracer concentration goes to zero at large distances from the reservoir (as x → ∞) is, for $\theta \neq 1$:

$$\frac{C(x_D,t_D,\theta)}{C_{s0}} = \frac{1}{2(1-\theta)}\left\{ Exp[x_D]Erfc\left[\frac{1}{2}\left(\frac{x_D}{t_D}\right)^{\frac{1}{2}}(1+t_D)\right] + (1-2\theta)Exp[\theta x_D(1-t_D+\theta t_D)]Erfc\left[\frac{1}{2}\left(\frac{x_D}{t_D}\right)^{\frac{1}{2}}(1-t_D+2\theta t_D)\right]\right\}$$

Equation 3

When $\theta = 1$,

$$\frac{C(x_D,t_D)}{C_{s0}} = \left(1+\frac{x_D}{2}(1+t_D)\right)Exp[x_D]Erfc\left[\frac{1}{2}\left(\frac{x_D}{t_D}\right)^{\frac{1}{2}}(1+t_D)\right] + \left(\frac{x_D t_D}{\pi}\right)^{\frac{1}{2}}Exp\left[-\frac{x_D}{4t_D}(1-t_D)^2\right].$$

Equation 4

Here $x_D = \frac{Ux}{D}$ is dimensionless distance or Peclet number, and $t_D = \frac{t}{\tau_a}$ is dimensionless time. Exp(x) and erfc(x) are the exponential and complementary error function, respectively, and

$\tau_a = U/x$ a time constant equal to the residence time in advection dominated transport,

$\tau_d = D/U^2$ a time constant that is a measure of the strength of dispersive mechanisms,

$\tau_m = V_S/Q$ a time constant equal to the residence time in the mixed reservoir, and

$\theta = \tau_d/\tau_m$ the ratio of dispersion to mixing time constants.

The dispersion time constant may be thought of as the time taken for solute advecting at the average fluid velocity to reach a distance where the Peclet number is unity. The dispersion time constant is, in fact, related to the Peclet number and advection time constants by $\tau_d = \tau_a / x_D$. In the limit of small θ, when the residence time in the source is much larger than the dispersion time constant, Equation 3 takes the familiar form of Ogata and Banks (1961). As the ratio of time constants becomes very large, equation 3 converges to the solution of the ADE (equation 2) for an impulse source in a semi-infinite domain (Martinec et al. 1974).

For mixing after transport by advection, equation 2 is first solved for an impulse function source in an infinite domain yielding the Gaussian expression given in equation 5 below for the evolution of tracer concentration downstream. Here and in subsequent equations, the injected mass per unit cross sectional area of flow is expressed as the total tracer mass $C_{S0}V_S$ divided by Q/U, which is, in a steady one dimensional flow, equal to the cross sectional area of the field of flow.

$$\frac{C(x_D,t_D)}{C_{s0}} = \frac{Exp\left[-\frac{x_D}{4t_D}(1-t_D)^2\right]}{2\theta(\pi x_D t_D)^{1/2}}$$

Equation 5

When equation 5 is substituted for the inlet reservoir concentration $Cs_I(x_D,t_D)$ in equation 1, the solution to the resulting ordinary differential equation is:

$$\frac{C(x_D,t_D)}{C_{s0}} = \frac{Exp(-\theta x_D t_D)\sqrt{x_D}}{2\sqrt{\pi}} * \int_0^{t_D} \frac{Exp\left[\theta x_D t'_D - \frac{x_D}{4t_D}\left(1-t'_D\right)^2\right]}{\sqrt{t'_D}} dt'_D$$

Equation 6

Equation 6 can be integrated to arrive at the expression given below in equation 7, which can be readily evaluated for $\theta < 1/4$.

$$\frac{C(x_D,t_D)}{C_{s0}} = \frac{1}{2\mu} Exp\left[-\left(\theta x_D t_D + \frac{x_D}{2}(\mu-1)\right)\right] * \left(Erfc\left[\frac{1}{2}\left(\frac{x_D}{t_D}\right)^{\frac{1}{2}}(1-\mu t_D)\right] - Exp(\mu x_D) Erfc\left[\frac{1}{2}\left(\frac{x_D}{t_D}\right)^{\frac{1}{2}}(1+\mu t_D)\right]\right)$$

where $\mu = (1-4\theta)^{1/2}$. Equation 7

3. Applications

The conceptual models that are used to describe transport in this analysis are so simple that the equations presented above are not apt to be very useful for accurate prediction of transport in karst aquifers. Rather, the analytical expressions provide a means to evaluate bounding scenarios that may inform tracer test planning or interpretation of tracer recovery data. Tracer recovery at Big Spring, a spring used for municipal water supply near Elizabethton, Tennessee, is shown in Figure 1. The intent of the trace was to better determine travel times and mass attenuation from the site of a proposed wastewater discharge to the spring, so quantification of tracer recovery and dispersion were of interest. The tracer recovery curve exhibits some characteristics that might be due to either holdup of tracer during injection or variability in flow and transport process along the path taken by the tracer.

Uranine dye was introduced during recession of storm water runoff into a flooded composite sinkhole. In this case, dye was mixed with 100 and 200 cubic meters of runoff in three areas of the sinkhole where water was pooled. At the time of injection, the sinkhole was draining at the rate of a few litres per second. The sinkhole was almost entirely drained 24 hours later, and minimal residual dye was observed. Tracer recovery was only about 5 %, possibly due to storage in the epikarst as the discharge from the sinkhole to the conduits decreased. Unfortunately, loss of tracer into epikarst or bedrock storage that becomes inactive hydraulically as aquifer stage declines cannot be addressed with steady flow models such as those presented here.

The tracer is thought to follow geologic strike through Cambrian age limestones down the plunge of the Stony Creek syncline to Big Spring. The karst features of the area, which include a well-developed epikarst over an irregular bedrock surface and pits that penetrate a few tens of meters into bedrock, suggest complex conduit geometries for the path taken by the tracer. Consequently, the variability of hydraulic and transport characteristics in the karst aquifer might contribute significantly to an increase in the apparent dispersion coefficient and the asymmetry of the tracer recovery curve shown in Figure 1.

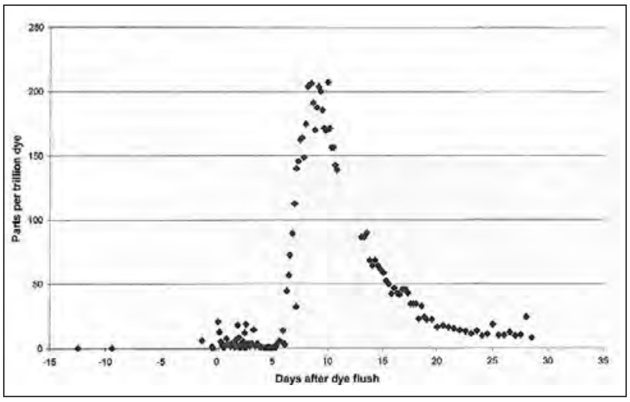

Figure 1. Tracer (uranine dye) recovery at Big Spring.

Figure 2 shows that as the time constant ratio approaches unity, the effects of the source diminish. For most Peclet numbers of interest, tracer recovery curves should appear similar to those generated by an impulse source when $\theta \geq 1$. Computing an approximate value of θ for the trace will then allow an estimate of the effects of the injection on the shape of the tracer recovery curve.

The mixing time constant, τ_m, or mean residence time of the tracer in the sinkhole, may be estimated to be on the order of 10^4 seconds and is, in any case, less than 10^5 seconds. The average dispersion coefficient and velocity can be estimated from the tracer recovery curve. Straight line distance from the point of injection to the spring is about 2.2 kilometres and a reasonable estimate for the travel time using the time to peak is about 8.5 days, so mean velocity is around 0.003 meters per second. Dispersion coefficients computed from tracer recovery data in karst aquifers vary over several orders of magnitude, and vary considerably even over the same path as a function of aquifer conditions (Mull et al. 1988). Dispersion coefficients have been estimated using the variance calculated from the recovery data (Smart 1988) and by fitting the rising limb of the recovery curve (Hauns et al. 2001). The latter method should result in a smaller coefficient of dispersion for the data shown above. A smaller dispersion coefficient would decrease θ but increase the Peclet number. The dispersion time constant thus obtained is between 10,000 and 20,000 seconds and θ is thus near unity. Since the Peclet number computed with these data is about 50, the injection probably had little effect on the shape of the recovery curve.

The author has recovered tracer at spring pools with mean residence time of at least several hours. The larger pools were typically due to constructed impoundments, created by the activities of either *Homo sapiens* or *Castor Canadensis.* However, better data to test the model of downstream mixing is available in Hauns et al. (2001), since they present tracer recovery data both before and after tracer traverses a cave pool. A Gaussian fits the upstream recovery curve. The authors report a dispersion coefficient of 0.0265 m^2/s and an average velocity of 0.047 m/s, yielding a dispersion time constant of 12 seconds. Information on discharge and pool dimensions indicates that discharge was a few tens of litres per second and the pool volume was a few tens of

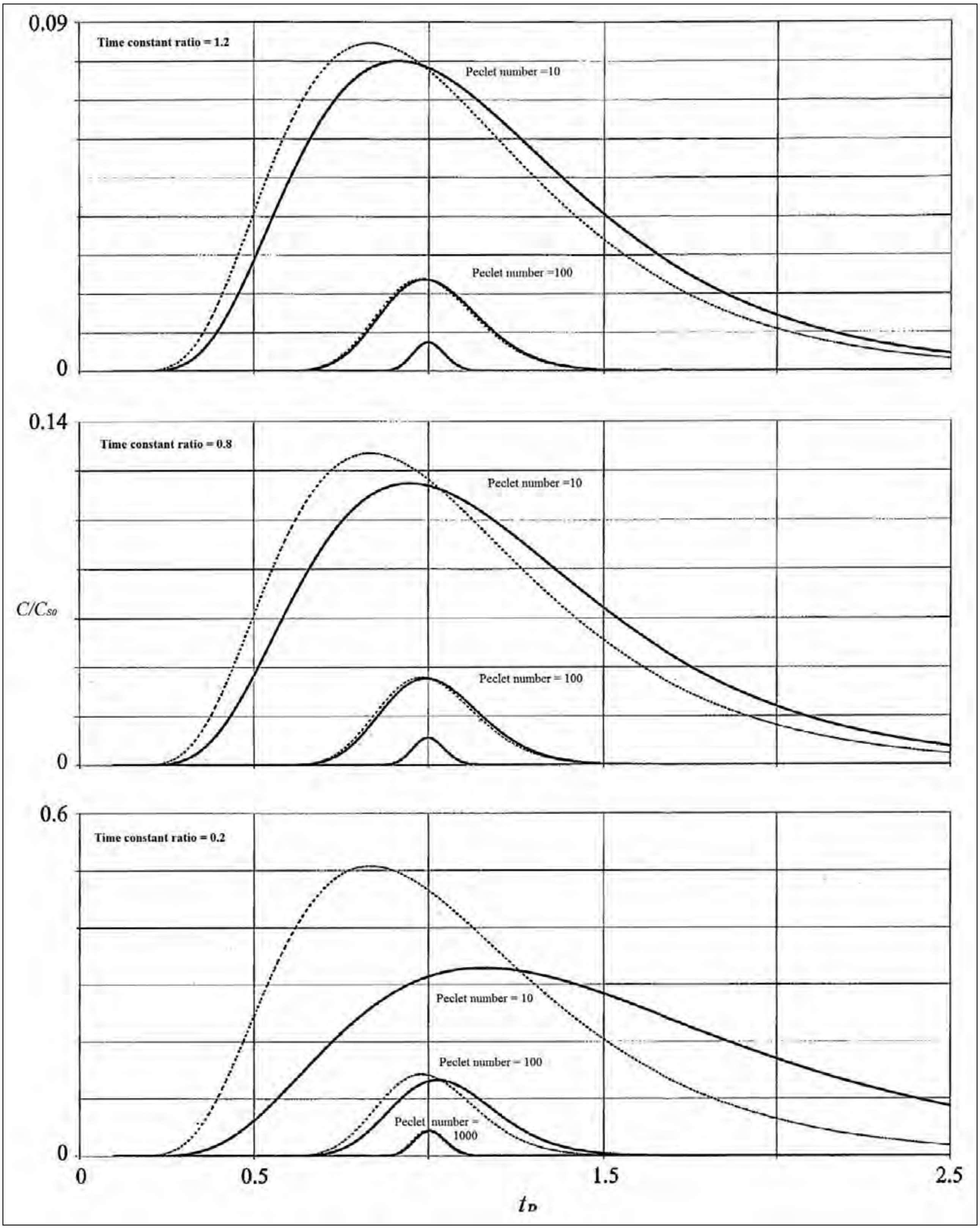

Figure 2. Dimensionless concentration as a function of dimensionless time from Equation 3 and from an impulse source in a semi-infinite domain for various Peclet numbers and time constant ratios. Solid lines were generated using a finite, mixed reservoir source (Equation 3) and dashed lines using the analytical solution for an impulse source.

cubic meters. Thus, the mixing time constant is on the order of 1,000, and θ is about 0.01.

Figure 3 shows the dimensionless tracer concentration entering and exiting the pool. Entering concentration is computed from equation 5 after 15 meters of travel from an impulse injection using the reported values of dispersion coefficient and mean velocity. Concentration exiting the pool was computed from equation 7 assuming a time constant ratio of 0.01. The equation predicts about a fivefold decrease in peak concentration as tracer crosses the pool, as reported by Hauns et al., but the recession following the peak of the theoretical recovery curve exiting the pool is much more gradual than the recession in the data.

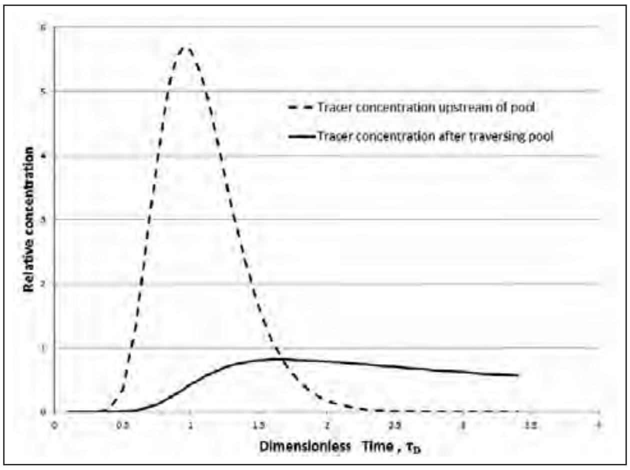

Figure 3. Effects of downstream pool on tracer recovery.

Poor agreement with the data is not unexpected, since the model requires that tracer be mixed to a uniform concentration over the entire pool. This represents a worst case for loss of tracer from flow paths that "short circuit" through the pool into "dead zones." The assumption of perfect mixing also implies that tracer stored in regions of a pool having long residence time can bleed instantaneously back into regions with shorter residence time to keep concentrations approximately equal over the entire pool. Tracer transfer throughout the pool should be greatest when concentration gradients in the pool are at a maximum, near the peak of influent tracer concentration. Tracer may be less efficiently transferred after passage of the peak. This discrepancy between the model assumptions and actual conditions in the pool may explain why the model does a reasonable job predicting the change in magnitude of the peak tracer concentration, while not accurately predicting the general shape of the tracer recovery curve.

4. Conclusions

Analytical models to describe tracer mixing before or after advective transport are developed by solving the advection dispersion equation in conjunction with the mass balance equation over a mixed reservoir. The models may be used to determine a range of parameters, specifically Peclet numbers and time constants, where upstream or downstream mixing is not likely to appreciably alter the apparent dispersion coefficient. The models also provide an estimate of the effects of pools on peak tracer concentration.

Acknowledgments

Figure 2 of this manuscript was adapted from a figure constructed with assistance from Dr. Steve Esling at Southern Illinois University at Carbondale.

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IS THE HELMHOLTZ RESONATOR A SUITABLE MODEL FOR PREDICTION OF THE VOLUMES OF HIDDEN CAVE SPACES?

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An assumption exists that the Helmholtz resonator could be used as a suitable model for estimating the volume of hidden cave spaces. This hypothesis was tested in the simple-shaped two-entranced Císařská Cave (Moravian Karst, Czech Republic). Data (airflow and exterior/cave temperature) were monitored at the lower entrance of the cave. The observed airflows oscillated at frequencies in the range from 1.7 to 16.1 mHz based on the temperature differences $\Delta T = T_{exterior} - T_{cave}$ from -9 to -1 °C. Furthemore, the oscillations varied with time. Both the multiple "fundamental" frequencies and the time-variability question the possibility that the oscillations (1) are a result of cave resonance and that (2) they can be described using Helmholtz resonator.

1. Introduction

The air exchange between the exterior and the cave (1) controls cave microclimate (temperature, humidity, and gas levels) and (2) influences various karst processes, such as speleothem growth (Fairchild et al. 2007) or speleothem corrosion by condensed water (Dublyansky and Dublyansky 1998; de Freitas and Schmekal 2006). We can distinguish (i) static caves and (ii) dynamic caves, based on number of cave entrances at different levels (Geiger 1966; Bögli 1978). The dynamic caves ventilate during the whole season by a chimney effect. The main driving forces of airflow are triggered off by the differences in air densities (de Freitas et al. 1982). The density is function of many variables, of which the temperature is the most significant (Faimon et al. 2012). Therefore, driving forces of airflows may be expressed as a function of $\Delta T = T_{exterior} - T_{cave}$ (de Freitas et al. 1982; Pflitsch and Piasecki 2003; Kowalczk and Froelich 2010). The cave airflow typically oscillates at relatively high frequency (Faimon et al. 2012). Cigna (1968) explains airflow oscillations by Helmholtz resonator, which is defined as an air reservoir of given volume with rigid walls, that is vented through a neck (its cross section area is smaller than the reservoir volume) (Fig. 1). Based on French (2005), the resonator fundamental frequency f [Hz], is given by

$$f = \frac{c}{2\pi}\sqrt{\frac{A}{tV}}, \qquad (1)$$

where c is speed of sound in air, A is the cross section area of the resonator neck [m^2], t is length of the resonator neck [m] and V is the resonator total volume [m^3].

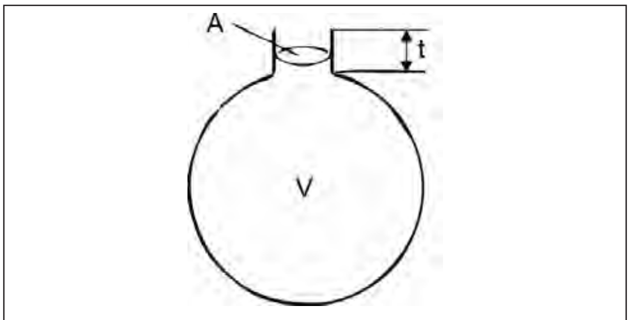

Figure 1. Helmholtz resonator (French 2005).

In last decades, some attempts have been made to use the Helmholtz resonator in speleology for predicting volume of hidden caverns (Rothman 1989). The goal of the presented work is to verify whether it is correct to use the Helmholtz resonator concept in such cases.

2. Methodology

2.1. Site characterization

The Císařská Cave was chosen as the site of this study. It is situated in the northern part of Moravian Karst (Czech, Republic) (Fig. 2a). The cave is formed in the Devonian limestone of the Macocha Formation. It is 250 m long and lays about 40 m under the surface. It consists of narrow passages and relatively small chambers. Total volume of the cave is about 11,500 m^3. Part of the cave is flooded by almost stagnant karst water. Concrete sidewalks pass through the cave. Morphology of the cave and two entrances at different altitudes, 460.7 and 470.7 m (Fig. 2b), a dynamic character. The both entrances are closed by steel doors, in which there are the windows 20 × 20 cm in size (total area of 0.04 m^2). Currently, the cave has been used for speleotherapy by an organization Children Sanatorium with Speleotherapy from Ostrov u Macochy.

2.2. Monitoring

Three time series of cave airflow and cave/external temperatures were obtained in the period from November 2010 to November 2012 depending on ΔT. The airflow and external/cave temperatures were monitored at a various measuring intervals from 5 seconds to 1 minute. Airflows were measured at the lower entrance in the door window by thermo-anemometer FVA935 TH4 (measuring range from 0.05 to 2 $m^3\ s^{-1}$ with precision ±0.04 $m^3\ s^{-1}$) linked with datalogger ALMENO 2590-4S (Ahlborn). The measured linear airflow velocity in m s^{-1} was converted to a volume velocity in $m^3\ s^{-1}$ based on the cross section area of the windows. The external and cave temperatures were measured by the datalogger COMET S3120 (measuring range from -30 to 70 °C with precision ±0.4 °C).

2.3. Data processing

Spectral analysis of the airflow time series were performed using the STATISTICA code (Statistica 2012).

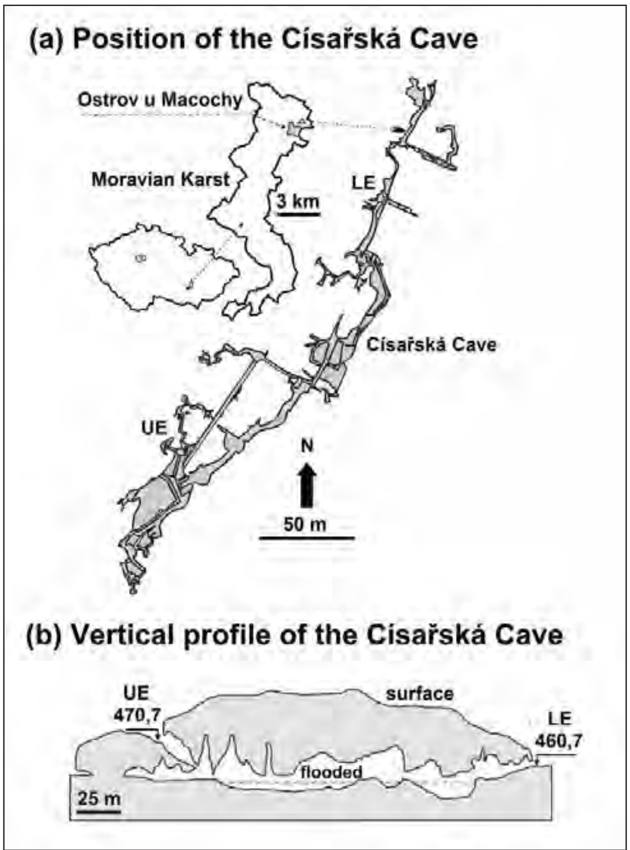

Figure 2. Sketch map (a) and cross section (b) of the Císařská Cave (LE means lower entrance, UE means upper entrance).

3. Results and their discussion

All data were obtained at upward airflow ventilation mode, i.e. when external air flowed into the cave by the lower entrance and blew by the upper entrance. The airflows oscillated with the amplitudes of 0.021–0.051 m^3s^{-1} (November 2010), 0.007–0.025 m^3s^{-1} (October 2011) and 0.003–0.02 m^3s^{-1} (November 2012). The temperature differences ΔT changed between -4.6 and -4.0 °C (November 2010), -9.1 and -9.0 °C (October 2011), and -1.0 and 0.6 °C (November 2012). One of the time series is shown in Fig. 3. It oscillates with amplitude up to 0.08 m^3s^{-1} and main period about 40 min. Shorter data segments long ~0.5 hour at ΔT ~ -1, -4 and -9 °C) were selected from the airflow time series for spectral analysis.

Fast Fourier Transformation (Brigham 1988) was applied on these segments and the most significant frequencies were identified (Tab. 1). The data in frequency domains are given in Fig. 4. As shown in Tab. 1, the significant frequencies ranged from 1.7 to 16.1 mHz. Similar values were measured by Plummer (1969) or Badino (2010).

Table 1. Significant airflow frenquencies at different temperature differences ΔT.

ΔT	Significant frequencies
-1 °C	2.2 mHz; 4.4 mHz; 6.11 mHz
-4 °C	1.7 mHz; 4.4 mHz; 6.7 mHz
-9 °C	8.3 mHz; 11.7 mHz; 16.1 mHz

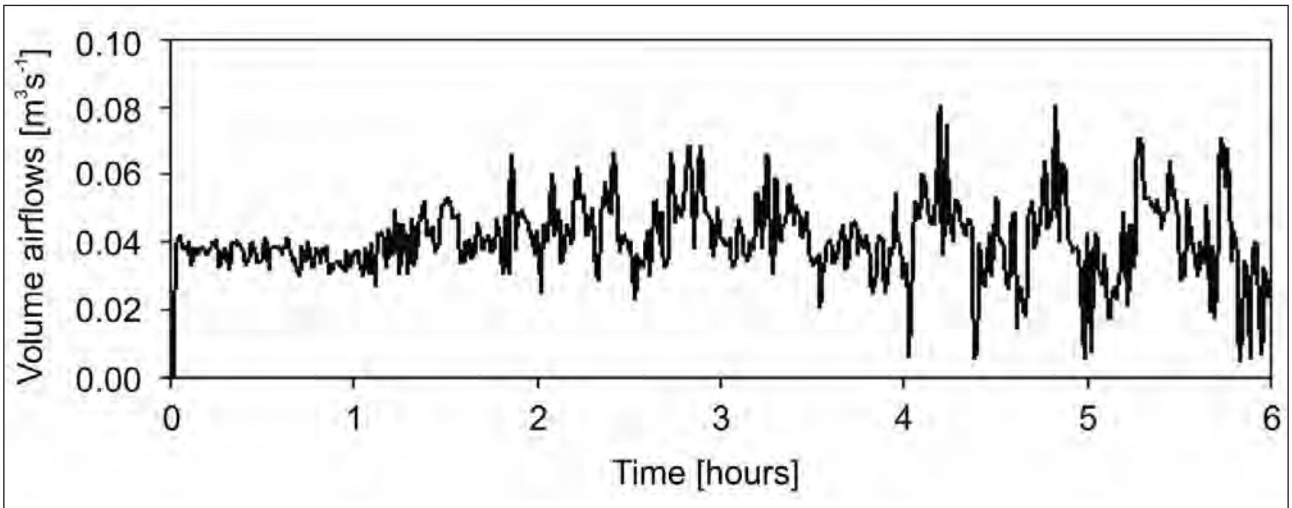

Figure 3. Selected time series of the airflows monitored at the lower entrance of Císařská Cave.

For application of the Helmholtz resonator model (Equation 1) to the Císařská Cave, many uncertainties exist. The windows cross section (0.04 m^2) and total volume of the cave (~ 11,500 m^3) are well defined.

However, problem is at definition of the resonator neck length. Cigna (1968) divided resonator neck into two parts, (1) one part before the entrance into exterior and (2) second part in cave. We applied two extreme values, 5 and 20 m, based on the narrow cave passage behind the lower entrance. The frequencies from Tab. 1 were used to test the Helmholtz resonator model. The calculation based on Equation (1) gives the cave volumes in the ranges of 70,430–6,317,056 m^3 and 17,607–1,579,266 m^3 for the resonator length of 5 and 20 m, respectively. These values are much higher than the actual volume of the cave.

If the airflow oscillations were the result of a cave resonance, just one frequency in the spectrum should be dominant. However, the spectrum is complex and shows different frequencies depending on the driving forces ΔT (Tab. 1). Moreover, the spectral analysis of two different

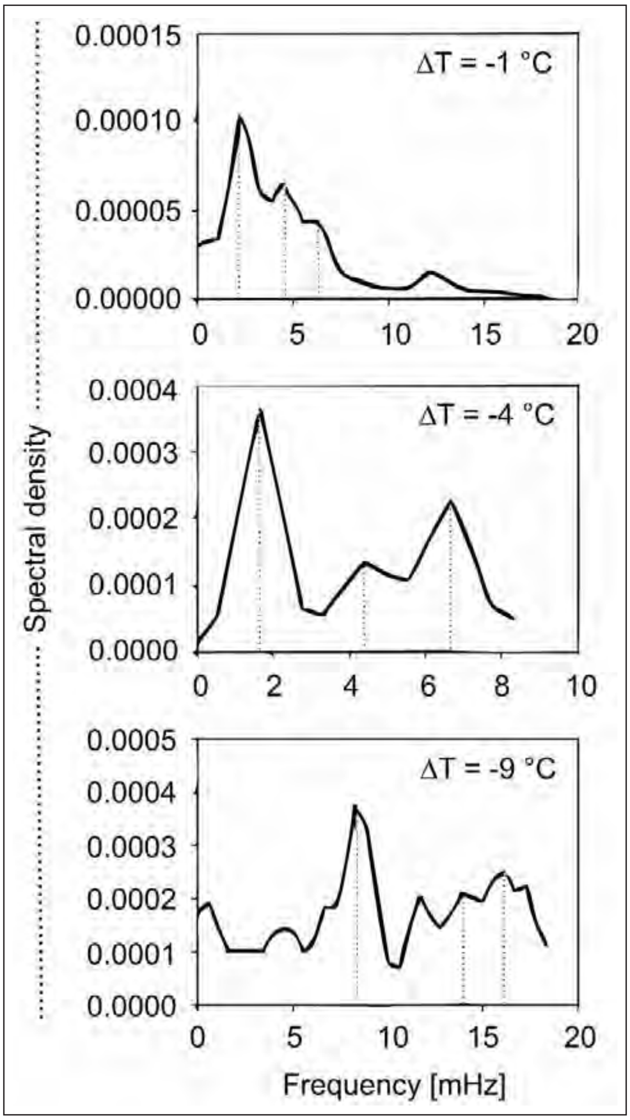

Figure 4. Spectral analysis of the selected 0.5-hour segments from airflow time series corresponding to three temperature differences ΔT (ΔT = $T_{exterior}$ - T_{cave}) (Císařská Cave, lower entrance).

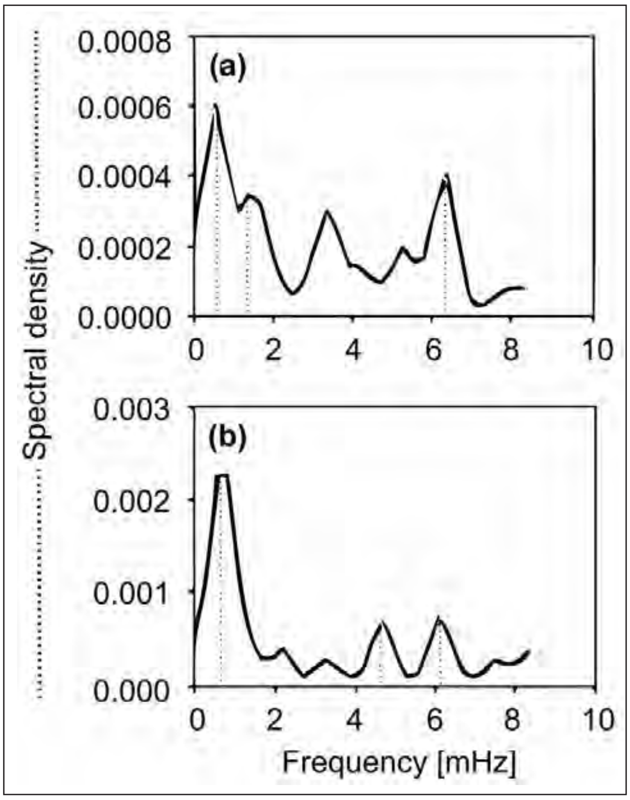

Figure 5. Spectral analysis of one-hours segments taken from six-hour airflow time serie: The initial segment (a) and final segment (b) (Císařská Cave, lower entrance).

one-hour segments selected from 6-hours airflow signal shows that the frequencies are shifted against each other (Fig. 5). The multiple "fundamental" frequencies, the dependence of frequencies on driving forces, and the frequency time-variability question the hypothesis that the oscillations are cave resonance phenomena and that they may be described in terms of Helmholtz resonator.

4. Conclusions

Oscillations in cave airflows were studied in the Císařská Cave (Moravian Karst) during the period between October 2010 and November 2012. The study showed that the cave airflows are unstable and oscillate. Based on spectral analysis, multiple "fundamental" frequencies were identified in the oscillations. In addition, the frequencies were found to change with the driving forces and time. These facts indicate that the airflow oscillations are not result of a cave resonance and cannot be described in term of the Helmholtz resonator. In order to achieve better understanding of cave airflow oscillations, further studies are required. We believe that the presented results could be helpful for many karstologists and speleologists.

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ANTHROPOGENIC BIAS ON POWER-LAW DISTRIBUTIONS OF CAVE LENGTHS

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It is well known that in any cave region, there are a large number of small caves and few large ones. The distributions of cave lengths often display hyperbolic, or power-law distributions witwh a negative exponent (Curl 1986; Badino 2001). A power-law distribution has no mean unless a lower boundary is defined, this is usually the lower limit for what is regarded as a "cave", or the shortest cave that will be mapped or registered. The scale-invariant properties imply that the distribution of cave length should have "fractal" behaviour, i.e. they have a fractional dimension, D. Various, geologically conceivable, physical processes, like fragmentation or exponential growth with random "kills", will result in fractal behaviour (Turcotte 1992). A cumulative power-law distribution (or its ordered statistic) will plot linearly in Log-Log space where the slope is – (D +1). Physically, a fractal dimension of cave lengths ($1 < D < 2$) would mean that the cave lengths (each of them one-dimensional) on the population level are partially area-filling. The determination of the slope in Log-Log space is normally done by curve-fitting. However, linear regression by the least squares estimate (LSQ) may give erroneous results, and the maximum likelihood estimate (MLE) is recommended (Newman, 2005). The least squares technique fails mainly because cave lengths are not normally distributed in the interval to be analysed, especially for long caves the statistics are poor (few caves), and the distribution is "fat-tailed" (the "King Effect"). If a limited interval is used, avoiding the longest caves, the two methods give consistent results. In practice, D varies from region to region and also seems sensitive to the size of the cave database in question. Here, we have investigated a number of national cave length databases, varying in number from several hundred to more than 10^4 caves, using both LSQ and MLE methods. A Matlab procedure published by (Clauset et al. 2009) was modified to analyze the same data sets by both methods and estimate errors through the jackknife method and by Monte-Carlo simulation of similar populations with the observed constants.

First, it was found that some regions display knick-points in the distributions at about. We think that this is an anthropogenic (psychological) bias towards "long" caves; when a cave exceeds a certain length, it becomes more attractive for exploration and surveying and hence it becomes ("grows") proportionally longer than shorter caves that get less attention from cavers.

Secondly, we have found that LSQ and MLE methods give consistent results within error when LSQ is done on subpopulations where the 5% upper and lower lengths are rejected, Figure 1.

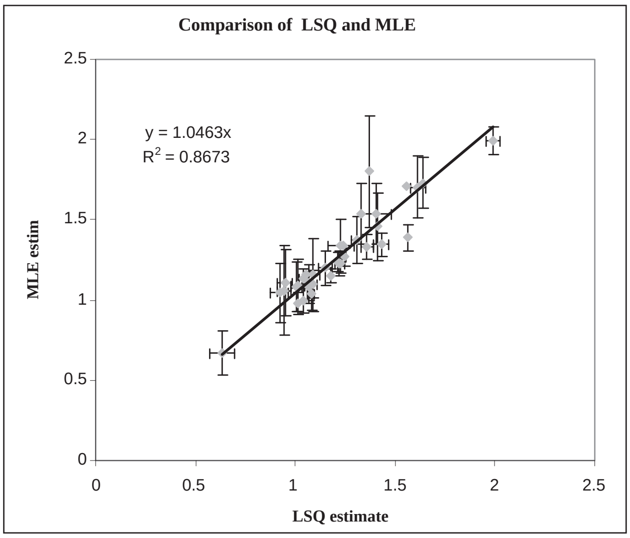

Figure 1. Comparison of the fractal dimension determined through least squares (LSQ) and maximum likelihood estimare (MLE). The regression line slope is unity and it has no y-intercept.

Thirdly, the MLE method and Matlab algorithm yields the minimum length (L_{min}) for which the distribution $L > L_{min}$ obeys the (log-log linear) power law. Assuming that the real cave population is "fractal" over the entire length range greater that some minimum cave length (say unity,), or L_1, The observed number of caves at L ³ L_{min}, $N(L_{min})$, divided with the estimated total number of caves longer than unity, L_l, $N(L_1)$ provide a measure of the "completeness" of the cave database, i.e. $R = N(L_{min}) / N(L_1)$. The index R may also be regarded as an (inverse) measure of the explorational bias or deficiency in the cave kadaster. In Figure 2, the observed D is plotted as a function of R. The closer R is to unity, the closer D is to -1, i.e. the distribution approach the simple hyperbola 1/x. Samples which display large R also tend to represent small countries with huge cave databases, like Slovenia and Great Britain. Here, the cave populations may be better known than in large countries with few known caves. The "world" list comprises an extreme member with highest D of them all. The "world" is also the largest possible region on Earth, where caves are also least well known, Figure 2.

Fourthly, we could not detect effects between regions like alpine and low-relief regions.

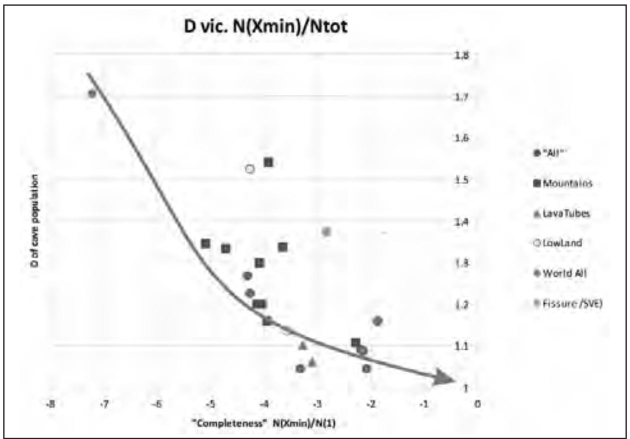

Figure 2. Fractal dimension of cave length populations as a function of the "completeness" (log R) of the observed power-law distributions. "Complete" distributions tend to have a low D, approaching unity.

In conclusion, most cave databases are immature and suffer from anthropogenic bias, only the very largest samples may approach a "true" distribution, if attainable.

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DOCUMENTING SWISS KARST AQUIFERS USING KARSYS APPROACH – EXAMPLES OF RECENT APPLICATIONS

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Karst hydrological systems are characterized by a highly heterogeneous structure including quick- and slow flow components (conduit network, phreatic and epikarstic storage). It induces an important hydrodynamic variability and complex flow dynamics. In Switzerland, regional characteristics of karsts aquifers are poorly documented and a synthetic overview of the karst water resources and reserves does not exist yet. This situation is not satisfactory and the management of these precious resources is far from being optimal. These are the reasons why SISKA (Swiss Institute for Speleology and Karst Studies) has developed a specific approach so-called "KARSYS" for (i) characterizing these particular media, (ii) understanding its hydrological functioning at a regional scale and (iii) improving a suitable and sustainable management of karst water. In the frame of the SWISSKARST Project – part of the 61th Swiss National Research Program – SISKA is progressively covering the Swiss territory by using the approach with the objective to provide a systematic, consistent, comparable and reproducible documentation of the karst aquifers. Three examples of recent application of the KARSYS approach are here presented: the first one is dedicated to the assessment of groundwater resources and reserves in the Bernese Jura (BE), the second one deals with the characterization of karst flood hazards in the Jura (JU) and the last one briefly exhibits the results of the hydroelectric potential characterization in karst systems in the Vaud canton (VD). Results are provided online through a specific www.swisskarst.ch website. In addition to these "home" applications, collaborations are ongoing with Slovenian partners in the Kanin and the Trnov regions of Slovenia and with Spanish partners in the Picos de Europa massif to test and improve the approach on their sites.

1. Introduction

Facing to the lack of documentation related to karst media and karst resources in Switzerland, SISKA (Swiss Institute for Speleology and Karst Studies) submitted a project in 2010 aiming to characterize karst aquifers by the use of a systematic and iterative approach. The objective of SISKA was to provide a relevant and comparable documentation of these particular media which may be understandable by the wider audience – leading to enhance the consideration of this media involved in various topics (groundwater supply, civil construction, geothermic, etc.). Thanks to the initial fund provided by the Swiss National Fund in the frame of the 61st National Research Program and additional funds provided by cantons and/or local authorities, SISKA expands progressively the documentation of these aquifers and improves the approach and its application for various topics in which the karst is usually involved.

2. Principles of the KARSYS approach

Fundamentals of the KARSYS approach have been recently published (Jeannin et al. 2012). It aims at building up a descriptive hydrogeological model of karst systems behavior. This synthetic approach is very effective in order to get a first picture of the karst aquifers distribution and their organization into systems. Kiraly 1973, Jeannin 1996, and Butscher and Huggenberger 2007 are the main background of the approach. Issue provides a 3D model of the system, as well as a map and hydrogeological profiles which are really useful documents to assist the management of these systems (groundwater resources assessment, definition of protection areas, flood hazards, hydroelectrical potential, and effects of civil constructions…).

The approach formally combines all existing data of the geology and hydrology into a 3D conceptual model of flows within the investigated karst system.

The approach is organized in 6 steps:

1) The first step is to define the lithological boundaries in which the investigated karst aquifer has developed (hydrostratigraphical units).

2) Then, a 3D model of the aquifer geometry is constructed (Figure 1). The model should cover an area sufficiently large to enclose the whole catchment area of the investigated spring(s). Ideally the area should also cover the catchment area of the neighboring springs.

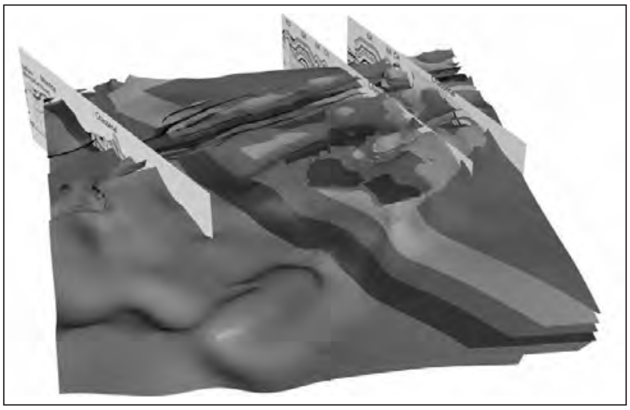


Figure 1. 3D geological model of the Brunnmuehle karst system (Jura, BE)*. Starting from the left low corner, the displayed surfaces are respectively the bottom of the Dogger* (Middle Jurassic) *and the bottom of the Malm* (Upper Jurassic) *aquifers.*

3) In this step all hydrological information are included in the 3D model. Usually only karst springs are well known. Their approximate discharge must be evaluated (even roughly) and their elevation must be established as

precisely as possible. Any piezometer, borehole, cave or point where the water has been (or could be) identified and measured have to be incorporated within the model with an indication of the water table elevation.

4) This step includes the modeling of the water table (Figure 2) flooding the aquifer. Knowing that karst networks are usually well drained, the elevation of the hydraulic gradient upstream of the main perennial springs is very low, at least less than 0,1 % (Bögli 1980, Worthington 1991). If no indication about the gradient of the water table is available, a flat water table can then be assumed upstream from the springs. It can be extrapolated throughout the aquifer volume (in 3D) to sketch the saturated part. This provides a first idea of the extension of the phreatic zone at low water stage. Slight gradients (usually between 0 and 0.5 % max) may be assumed and introduced in the model. If water levels data are available it is very important to assess their pertinence: values in caves usually indicate more directly heads in the karst conduit network. However they can be perched and disconnected from the main aquifer (as pictured in Figure 7). Values in boreholes are precisely measured, but may be meters above the water level in the karst conduit network. Using such information as exclusive to draw the elevation of the hydraulic gradient within the aquifer may reveal uncertain.

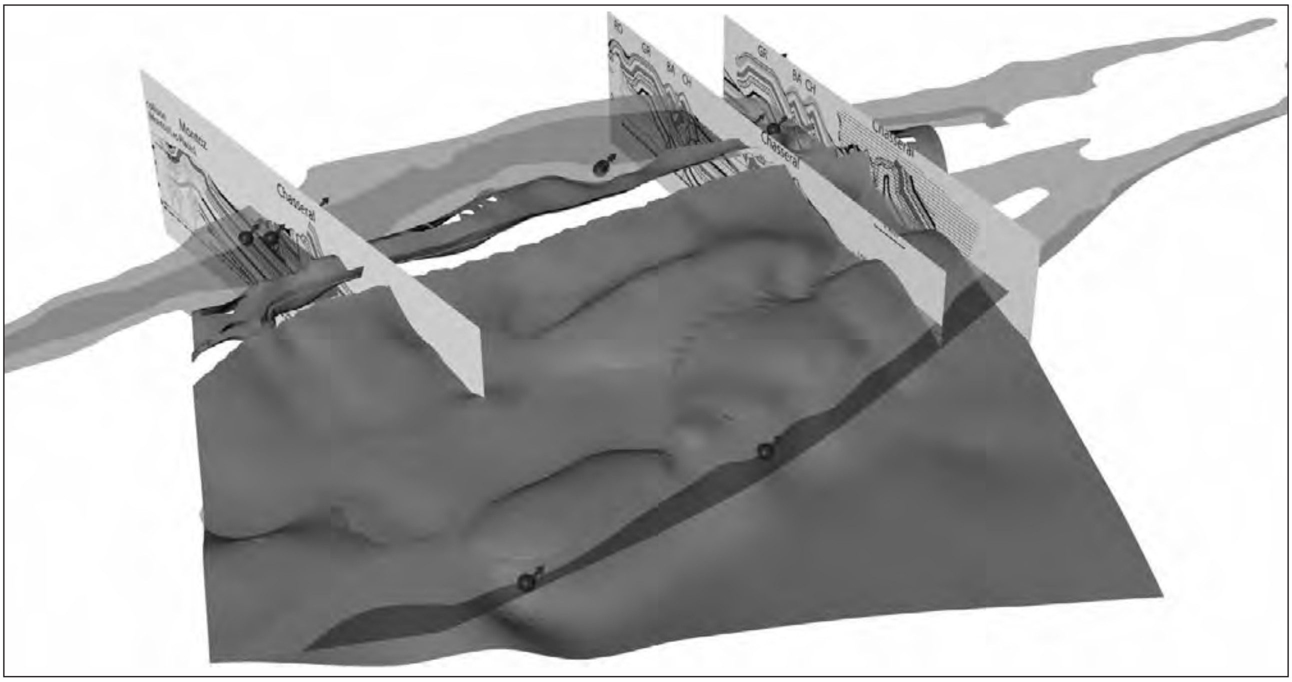


Figure 2. Extension of groundwater bodies (distinguished if they are unconfined or confined) and location of the main perennial springs integrated within the geological model.

5) Once the groundwater bodies are considered as reasonably consistent, the catchment area can be delineated by considering the organization of the flows. Flow paths or “drainage axes” are constructed assuming the following principles:

   i) A vertical flow path through the unsaturated zone;

   ii) A down-dip flow path on top of aquicludes;

   iii) A pseudo horizontal flow path towards the spring(s) in the phreatic zone, along the slope of the hydraulic gradient.

The schematic model for the flow paths construction is displayed Figure 3. Flow paths from various parts of the catchment can be constructed following these rules. The result for the Brunnmuehle karst system is displayed in Figure 4.

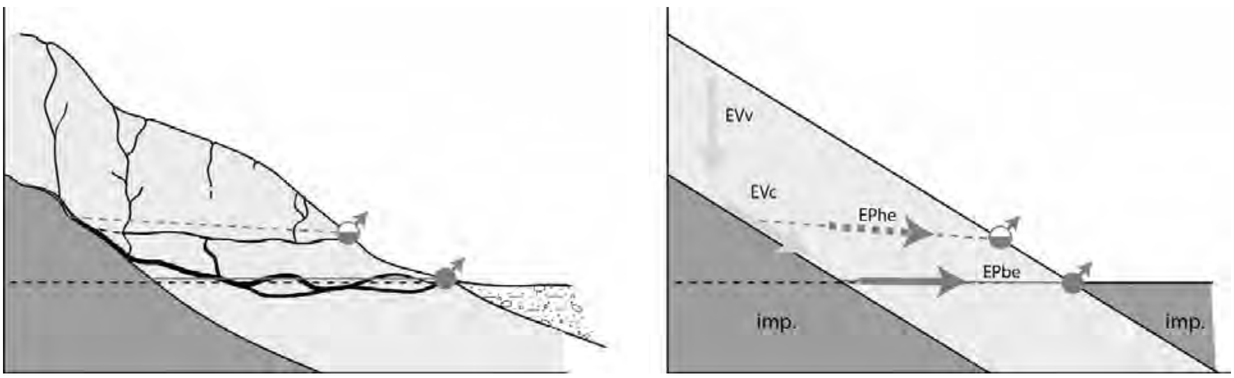


Figure 3. Schematisation of the flow paths or “drainage axes” in karst system: EVv = vertical vadose flow path, EVc =down-dip vadose flow path, EPbe = pseudo horizontal phreatic flow path, EPhe = high water phreatic flow path. imp. refers to impervious formation (= aquiclude).

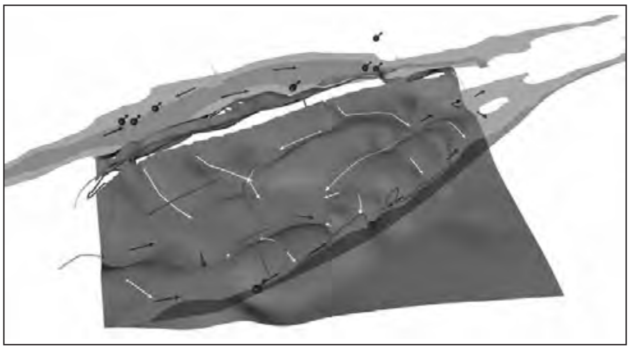


Figure 4. Hydrogeological model of the Brunnmuehle karst aquifer including the extension of the GW-body, the estimated catchment area and the main flow paths. Light arrows refer to vadose flow paths, dark ones to phreatic flow paths.

Up to now, only low water conditions have been considered. This model can be validated using all existing data concerning low water situation: (i) results of tracing experiments (if any at low water conditions), (ii) minimum and average discharge flowing out of the system compared to the estimated catchment area must be in the same range as those of nearby karst systems, (iii) all other data such as hydrographs, chemical or microbiological analyses, etc. must be checked to be consistent with the proposed model.

6) The next step of the approach is to consider data at high water conditions. The elevation of overflow springs as well as any data on heads in the karst network at high water should be implemented in the 3D model and used for inter/extrapolating the hydraulic gradient at high water conditions. The groundwater body usually enlarges significantly with the raise of water and the catchment area analysis can then be applied again. This usually leads to an enlargement of the catchment boundaries during high water conditions. Results of existing tracer tests (high water) can be compared for a validation.

The application of this approach to many systems clearly evidenced that parts of the catchment area feed one spring at low water conditions, and another, or several springs at high water conditions. A new definition of catchment areas in karst regions is therefore proposed to take this particularity into consideration. It can be implemented iteratively, starting with a very approximate model, which is refined along the investigations and with the collection of new data.

3. Outputs of the approach application

Results of this approach are presented as a set of various formats:

- An hydrogeological karst map based on a new mapping process focused on the system of interest as well as on smaller scale;
- An identification card for each main karst system which gathers the main characteristics of the systems (size of the catchments, discharge rates of the associated spring(s), lithological description of the aquifer, etc.). Details of the identification cards were presented in a separate paper (Demary et al. 2011);
- A 3D interactive and ready-to-use model which includes predefined views focusing on the significant aspects or specificities of the systems. The model is viewable using a simple and free .pdf viewer;
- A list of attachments (typically literature) which refer to the materials used for the model establishment (references of the geological maps, cross-sections, etc.)

Another extension of the SWISSKARST project is dedicated to the development of a pragmatic hydrological modeling tool for the simulation of karst spring discharge based on recharge simulation and conduits flow processes. This becomes possible once the first approach has been accomplished. This is not discussed in the following paper but a complete presentation of this tool is described by Weber et al. 2011.

4. Application to the Swiss territory (2012 statement)

The KARSYS approach is currently applied to the Swiss territory. Depending on the karst significance and the local interest from the canton or other administration, particular topics (groundwater resources assessment, karst flood hazards evaluation, etc.) have been in focus. These various applications are capitalized and contribute to expand coverage of the territory. Examples of such recent applications and related references are here succinctly discussed.

4.1. Characterization of regional karst aquifer organization and assessment of the karst groundwater resources and reserves (BE).

The application of the KARSYS approach (Malard et al. 2012) to the entire Bernese Jura (540 km^2) documented and delineated 17 main karst systems draining the Malm aquifer (Upper Jurassic) which are harvested by communities for supplying water. KARSYS made it possible to identify and delineate the extension of seven major groundwater bodies and (locate) their discharge outlets. The main underground flow paths have been sketched for all systems, as well as interactions occurring between the regional groundwater bodies (Figure 5).

The total capacity of karst groundwater reserves in the Bernese Jura was estimated about 2.2 km^3 assuming an average porosity value of 2% which refers to the total porosity (value of efficient is closer to 0,5%, Burger and Pasquier 1984, Kiraly 2003) and without considering the foothill aquifer. This suspected volume is twice the water volume of Lake Biel (“Bielersee”).

4.2. Karst flood hazard mapping using the KARSYS approach (JU)

Facing the risk of flooding in the city of Porrentruy (Ajoie, JU) the KARSYS approach was applied to the karst systems of the Beuchire-Creugenat, Creux des Prés and Bonnefontaine in order to (i) assess places where groundwater is expected to reach the surface first and (ii)

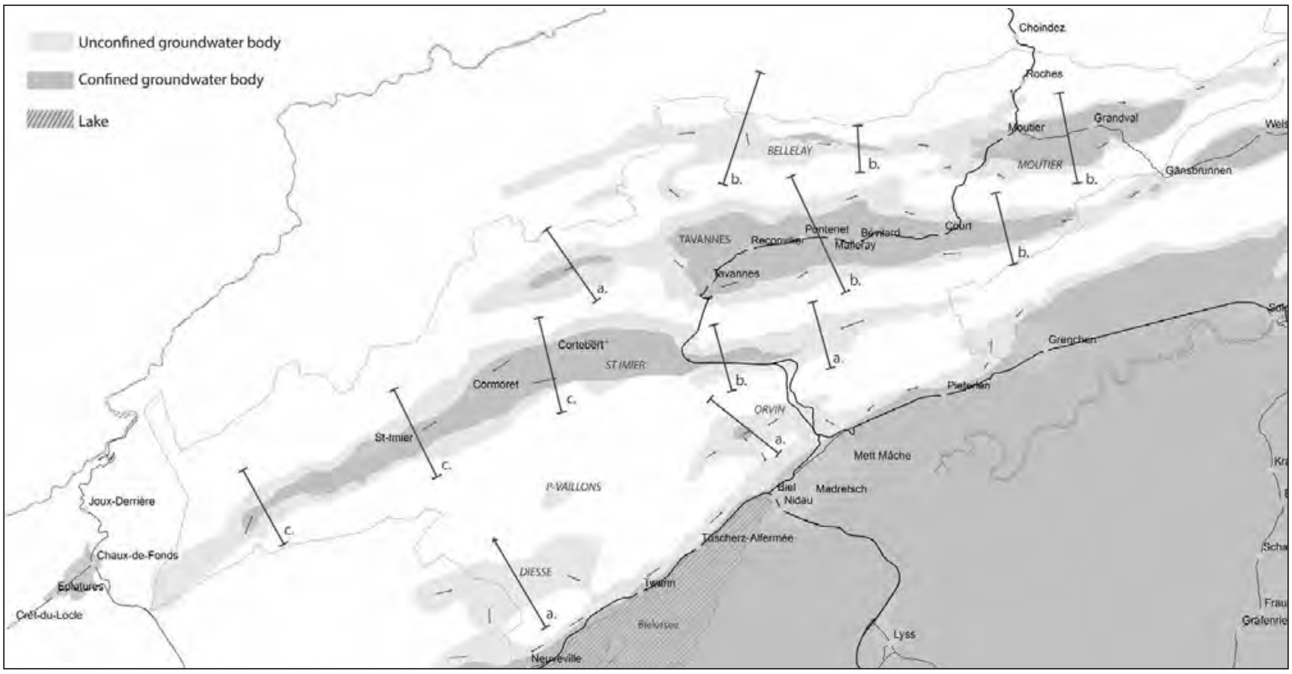
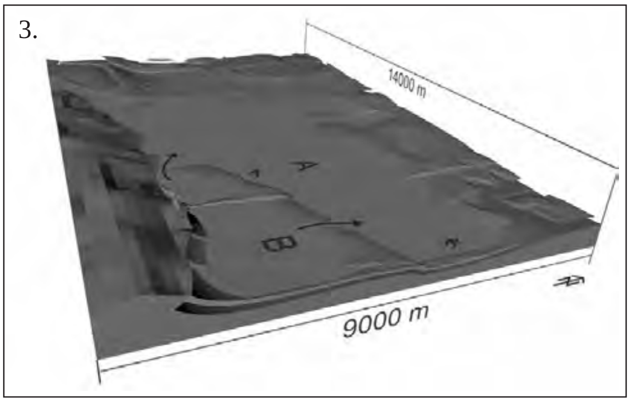
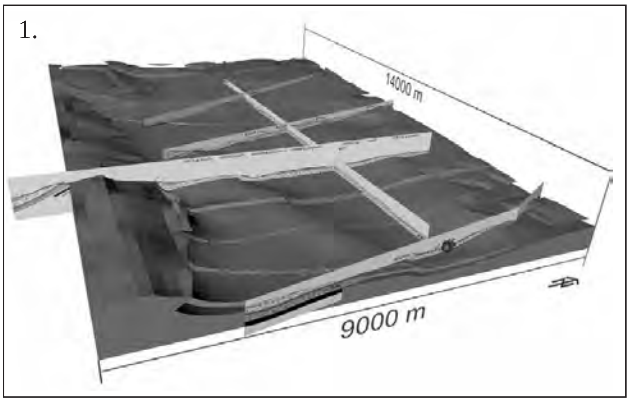
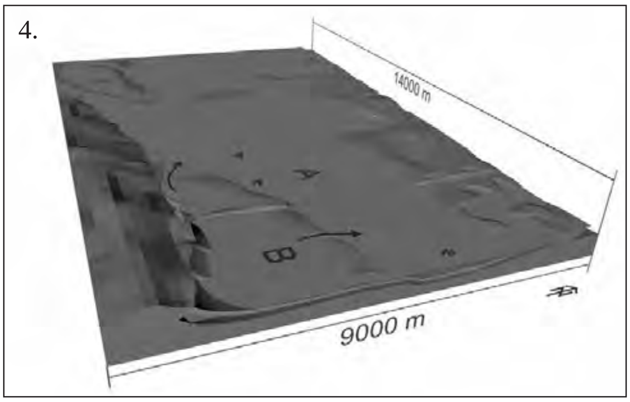


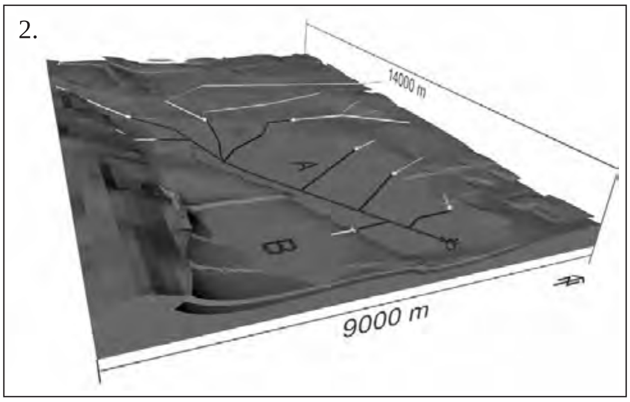
Figure 5. Organization of the regional groundwater bodies of the Malm karst aquifer in the Bernese Jura and their main water flows. Arrows ①, ② and ③ represents overflow of the TAVANNES groundwater body which over passes towards other downstream groundwater bodies. Segments refer to geometry of the aquifer in depth (a. synform, b. simple faulted, c. double faulted).

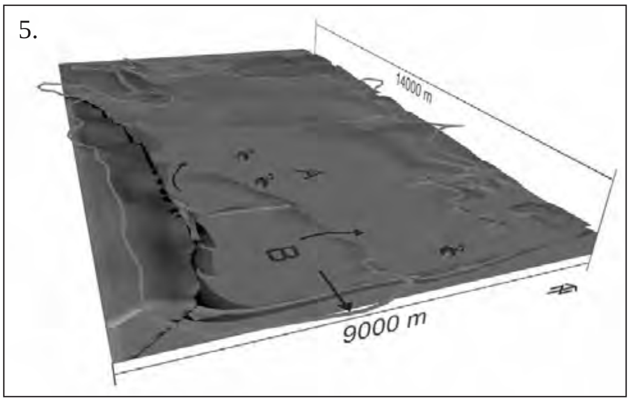
provide order of magnitude of potential discharge rates according to the considered return-period event, multiannual, 30 years and 300 years (Vouillamoz et al. In press). Although the situation is quite complex (due to changing hydraulic connections between two or more adjacent groundwater bodies depending on hydrological conditions), the step by step application of KARSYS (see Figure 5) provides a consistent conceptual model from which heads and discharge rates at high-water stage could be extrapolated. Mapping results (Figure 5) makes it possible to clearly show sectors which are sensitive to flooding depending on the considered event.











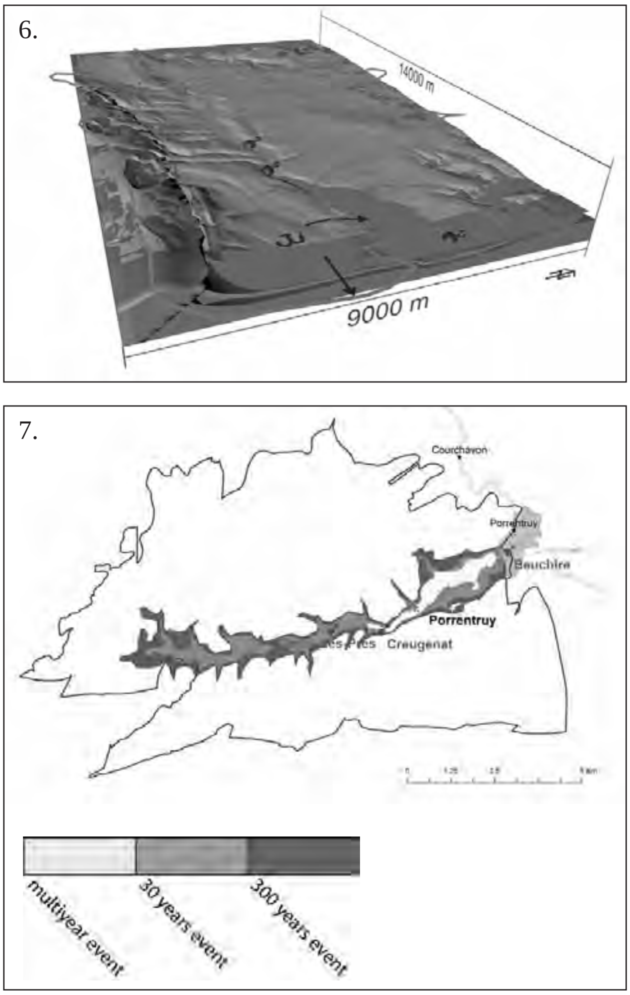


Figure 6. The hydrogeological functioning of the Beuchire-Creugenat Karst system: 1. Construction of the 3D geological model; 2. Implementation of the hydraulic features, sketch of the groundwater table at low water stage and the main suspected flow paths (vadose and phreatic ones); 3. Reconstitution of the hydraulic gradient for a multiannual flood event, exchanges do appear between the groundwater bodies A and B; 4. Reconstitution of the hydraulic gradient for a 30-year return event; 5. Delineation of the spring catchment; 6. Characterization of the flooded areas depending on the considered event (multinannual, etc.); 7. Mapping results.

The delineation of the main suspected flow paths allowed the estimation of the maximal discharge drained by the underground streams (Figure 6.2.). Such estimation provides locally the maximal expected discharges emerging at the overflow springs as indication of the risk.

Here, the KARSYS approach offers a consistent alternative in mapping the flood hazards in a region where the increasing hydraulic gradient within the karst network leads to a strong extension of the flooded area and the activation of successive overflow springs.

4.3. Assessment of the hydroelectric potential of karst systems (VD)

Some karst environments offer a structured conduit network and an interesting hydraulic potential which could be exploited for electric production. Improvements have been made in the field of micro turbine devices and such installations already exist in karst media (e.g., La Verna Chamber, FR, Viguier and Bertuola 2006). Principles of power plant feasibility in karst media and evaluation elements of the profitability of such projects have been synthetized for the Vaud canton (Jeannin et al. 2010).

The KARSYS approach was applied to karst systems of the Vaud Canton (~600 km^2) to assess their potential for hydropower production and to classify them according to various criteria: production, financial risks, profitability, etc. The first step of the study was to select the most favorable sites which present a significant annual discharge (up to 30 L/s) and a significant elevation difference from the highest locations of the flows in the systems and the outlets. The higher these factors are the more favorable the site. Around 39 sites were retained and – in a second step – a more detailed 3D model was established for each system showing the geometry of the aquifer and the location of the most likely flow path. Based on these models and various capture scenarios (perched spring capture, fetching an underground stream or water from a phreatic groundwater body, underground power plant, etc. see on Figure 7) a possible production value has been estimated for each of them. It appears that the potential of all investigated springs (means the combination of a significant discharge and elevation) is in the same order of magnitude as a typical dam (total potential of 40 Gwh compared to the 100 Gwh produced by the Chatelôt dam (NE)). In detail 7 sites have been recognized as economically feasible within the short term. Another series of 5 projects are more risky and would require more investigation.

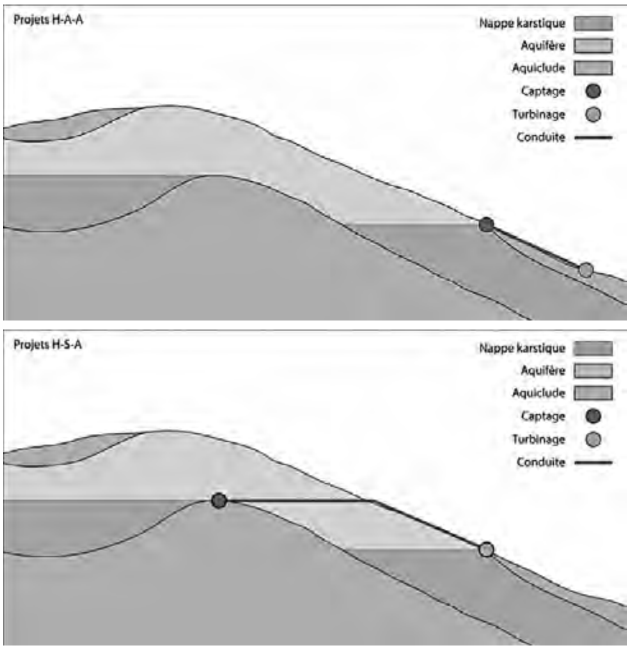


Figure 7. Scenarios of hydroelectric devices in karst media (red = capture point, green = turbine). In the second case a precise location of the perched ground water body is required.

5. Conclusions and perspectives

Since the SWISSKARST project started, real improvements have been made in the formulation and the process of the so-called "KARSYS" approach. These three examples show that KARSYS provides a pragmatic approach to a variety of applications such as resources-assessment, flood hazard mapping, evaluation of hydroelectric potential in karst media. Further applications are still in progress and will be presented in the future (waste deposits management in karst environment, prescription for geothermal probes, etc.). Collaborations with others countries on the topic (Slovenia and Spain) show the wide applicability of the approach and the interest from other practitioners in the field. The SWISSKARST project is still working in 2013 and all the references and papers related to the project are available through the website www.swisskarst.ch. Feedback is welcome regarding this work.

Acknowledgments

The team SWISSKARST wishes thank the SNF/PNR61 and the administrations involved within the project they offer additional funds to cover the Swiss territory (Vaud, Bern, etc.).

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CAN DRIPWATER HYDROGEOCHEMISTRY HELP US TO DISCOVER HIDDEN UPPER CAVE LEVELS?

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Hydrogeochemical parameters of cave dripwater contain information about the processes related to the water flow path. One of the processes that may occur is the prior calcite precipitation on hidden upper-lying cave levels. For prediction of such spaces, it was proposed a simplified criterion, UCL = 1/(EC_{norm} x ΔQ^n), where EC_{norm} is a dimensionless "normalised" water conductivity defined as EC/EC_{usual} and ΔQ is a dimensionless drip rate variation defined as σ_Q/Q. The symbol EC represents the mean conductivity of given drip [mS/m], EC_{usual} is the mean conductivity of ordinary dripwaters in the cave [mS/m], σ_Q is the standard deviation of given drip rate [drops/min], and Q is the mean drip rate of given drip [drops/min]. The empirical coefficient *n* is used to correct a "weight" of the ΔQ variable. The criterion was tested on a real data set collected in Punkva Caves (Moravian Karst, Czech Republic). The UCL values ranged from 1.06 to 1.42 in case of the "usual drips" without prior calcite precipitation and reached up to 2.74 in case of an "anomalous drip" that are demonstrably associated with a prior calcite precipitation at the upper cave level. The UCL behavior is consistent with further hydrogeochemical indices as saturation index or Mg/Ca and Sr/Ca ratios.

1. Introduction

Speleology focuses on scientific study of caves and other karst features. It is often connected with caving, physical exploration of caves in situ. In general, cave exploring is a tiring and demanding process. It usually involves tracking the known caverns and subsequent digging and extraction of sediments. Alternative approaches are based on indirect methods, e.g., water tracing or various geophysical methods. Any new method providing more guidance to the exploration is welcome.

It is well-known that dripwater hydrogeochemistry permits determination of the processes occurring on reaction/flow paths in karst systems such as dissolution, water dilution/mixing, CO_2 production, prior calcite precipitation, etc. (Tooth and Fairchild 2003). In this study, we focus on the possibility of using the indices resulting from drip water hydrogeochemistry in search for hidden upper cave levels.

Water path through a karst vertical profile may be simplified as follows: Atmospheric precipitations infiltrate soils and underlying rocks. The water is stored in soil or epikarst and continuously feeds the vadose zone by infiltrating water. This water appears in the cave as dripwater. Eventually, the water gets into phreatic zone and flows out of the karst. On its path, water interacts with the surrounding environment, atmosphere and rocks. The water usually achieves equilibrium with calcite and gaseous CO_2 before reaching the cave (Tooth and Fairchild 2003). However, another scenario is conceivable: Some waters might be drained through wide fissures so rapidly that they come to a cave without achieving equilibrium. Such flow paths are characterized by a tight contact with surface and by a high variability in drip rate. Calcite precipitation (speleothem growth) is conditioned by water supersaturation with respect to calcite. It is reached when the water is exposed to conditions different from the conditions, under which it was formed, usually at reduced $P_{CO2(g)}$. If CO_2 partial pressure in water, $P_{CO2(w)}$ (activity of aqueous CO_2 corresponding to ambient gaseous P_{CO2}) is less than that in the atmosphere, $P_{CO2(g)}$, the water degasses. As a result, pH of such water increases and water becomes supersaturated with respect to calcite (Fairchild et al. 2000). A crucial condition for degassing is a free atmosphere with gaseous CO_2 at $P_{CO2(g)}<P_{CO2(w)}$. The $P_{CO2(g)}$ in pores and small air pockets quickly reaches $P_{CO2(w)}$, stopping further degassing. Whereas most effective degassing occurs in voluminous and well-ventilated caverns – the spaces of speleological interest. In such spaces, prior calcite precipitation (PCP) is expected.

During PCP, the hydrogeochemical parameters of water change: Ca concentration decreases, whereas Mg/Ca ratio (or/and Sr/Ca ratio) increases (Fairchild et al. 2000). The saturation index with respect to calcite approaches zero. Overall mineralisation and electric conductivity (EC) decreases. To distinguish PCP waters from the waters of low mineralization/EC due to their extremely rapid passing karst profile, we will assume the waters associated with PCP to be of low variation in drip rate in contrast to more variable flow regime of the rapidly moving waters.

The aim of this study is (1) to propose hydrogeochemical parameters indicating hidden upper cave floors and (2) to test such parameters using both real and synthetic data.

2. Methods and situation

Dripwater hydrogeochemistry was studied in the Punkva Caves. These show caves have been formed in Devonian limestone of Macocha Group of strata in the central part of the Moravian Karst (Czech Republic). Water samples were collected twice per month in the period between February and November 2012 in the passage behind Přední Chamber (three drips labelled B) and in Tunnel Corridor (two drips labelled A). Dripwaters B come from small straw stalactites. The dripwater A1 comes from a drapery about 30 cm in length. Drip A2 falls from a straw stalactite. Whereas the waters B1-B3 and A2 represent ordinary dripwaters in the given cave, the water A1 represents an anomalous drip.

Immediately in the cave, pH, electrical conductivity, alkalinity (acidimetric microtitration), and calcium (complexometric microtitration) were determined. Complete chemical analyses were done subsequently in laboratory (ICP, AAS). Saturation indices for calcite (SI) were calculated by using PHREEQC modelling software (Appelo and Parkhurst 1999). Climatic variables (T, P_{CO2}) were measured by using data logger Almemo 2594-4S linked with the sensors FTA104PH (T) and FYA600CO2 or FYA600-CO2H (CO_2) (all the devices by Ahlborn).

Table 1. Data on dripwater hydrogeochemistry (mean values of 18 measurements for each drip).

Dripwater	usual				anomal	d.c.
	B1	B2	B3	A2	A1	
Q [drops/min]	38.8	17.7	19.5	6.1	32.1	
σ_Q [drops/min]	24.2	2.9	6.3	1.7	5.84	
$\Delta Q = \sigma_Q/Q$	0.62	0.16	0.32	0.28	**0.18**	us > an
EC [mS/m]	62.9	62.1	62	55.1	31.1	
EC_{usual} [mS/m]	60.5	60.5	60.5	60.5	60.5	
$EC_{norm} = EC/EC_{usual}$	1.04	1.03	1.02	0.91	**0.51**	us > an
(Sr/Ca)x1000	0.31	0.31	0.31	0.31	**0.65**	us < an
(Mg/Ca)x1000	16.5	15.8	16	19.1	**44.1**	us < an
$SI_{calcite}$	0.99	1.03	1.04	0.85	**0.14**	us > an
n	0.2	0.2	0.2	0.2	0.2	
UCF	1.06	1.40	1.22	1.42	2.74	

anomal – anomalous; d.c. – drip comparison; us – usual; an – anomalous; Q – mean rate of given drip; σ_Q – standard deviation of given drip rate; EC – mean conductivity of given drip; EC_{usual} – mean conductivity of ordinary dripwaters in the cave; *n* – empirical coefficient.

3. Results and data analysis

Hydrogeochemical parameters of five drips from Punkva Caves based on 18 monitoring campaigns are given in Table. 1. The anomalous drip A1 is almost at equilibrium with calcite, whereas the drips B1-3 and A2 show supersaturation to calcite. Electrical conductivity of A1 is 31.1 mS/m, whereas drips B1-3 and A2 have almost twice as high conductivity. The drip A2 shows slightly lower EC compared to drips B1-3. The mean EC for "usual drips" in cave system (B1-3 and A2) is 60.5 mS/m. The Mg/Ca ratio of A1 is more than two times higher than that of other drips. The Sr/Ca ratio of A1 is enhanced as well. Drips A1 and B2 show low drip rate variability, whereas drip B1 shows high drip rate variability and very wide drip rate range. The drip A2 shows low drip rate and medium variability and drip B3 shows medium drip rate and medium variability.

Considering somewhat limited geochemical capability of ordinary speleologist, we propose a simplistic empirical criterion for the distinguishing PCP and predicting upper-lying cave level. It is based on two well accessible variables, electrical conductivity EC (as a measure of mineralisation) and drip rate Q (as a measure of flow dynamics). The criterion labelled UCL is

$$UCL = \frac{1}{EC_{norm} \times \Delta Q^{n}}, \qquad (1)$$

where EC_{norm} is a "normalised" dripwater conductivity defined as $EC_{norm} = EC/EC_{usual}$ (EC is mean water conductivity of given drip [mS/m], EC_{usual} is mean conductivity of "usual dripwaters" in the cave [mS/m]) and ΔQ is a drip rate variability defined as $\Delta Q = \sigma_Q/Q$ (σ_Q is standard deviation of given drip rate [drops/minute], Q is mean rate of given drip [drops/minute]). The empirical coefficient *n* (chosen to be 0.2 for this study) takes into consideration lesser importance of the ΔQ variable for the prediction by introducing strong nonlinearity to the variable. The UCL criterion was derived in such manner so that the low values of both EC_{norm} and ΔQ contribute to the higher UCL, indicating the PCP and upper-lying hidden space possibility.

4. Discussion

The cave anomalous drip, notably drip A1, shows many atypical hydrogeochemical parameters. It shows (1) reduced mean conductivity indicating lower mineralization in comparison to drips B1-3 and A2, (2) low variability in drip rate, (3) almost equilibrium with calcite, and (4) enhanced Mg/Ca and Sr/Ca ratios. Low variations in Mg and Sr concentration indicate that the ratio is controlled by calcium concentration. High and stable flow of drip A1 indicates a voluminous water source and long residence times. This contradicts origin of the dripwater by mixing with influx of unsaturated water after rainfall. All the indices suggest prior calcite precipitation. This process signalizes a hidden cavity lying on water reaction/transport path. Indeed, such a cavity was confirmed by speleologists in the past. It is a spacious chimney about 25 meters long, partially filled with flowstone and clay (Glozar 1984).

Potential anomalous drips can be sought out by a simple method. Whereas regular drips are marked by white flowstone accumulations on the floor and/or by stalactite on the ceiling, low-saturation index drips leave no flowstone patches on the floor or in dripping holes. Such drips require further atention. Both conductivity and drip rate are easily measured and can be used in UCL criterion.

The results of the data analysis based on UCL are summarized in Table 1. The supersaturated, highly variable dripwater B1 shows UCL = 1.06. Wide drip rate range and variations in flow document its strongly seasonal regime. The dripwater B2 shows supersaturation with respect to calcite, very stable drip rate and UCL = 1.40. It is indicated to be a usual flow regime drip. The dripwater B3 is supersaturated with medium drip rate variability and shows UCL = 1.22. The dripwater A2 is quite similar with lower EC and medium drip rate variability and shows UCL value of 1.42. For the anomalous drip A1, the UCL value is 2.74. Such high value for A1 implies PCP occurrence and indicates hidden cavity. This conclusion is consistent with further hydrogeochemical parameters discussed before.

The UCL criterion is enhanced in case of anomalous drip, i.e. in case of prior calcite precipitation in upper-lying spaces. The UCL criterion does not give any sharp dividing line between the waters with and without PCP. Instead, it offers some indices for speleologists about a possibility of occurring hidden upper lying spaces – the higher UCL criterion the more likely is the space occurrence.

5. Conclusion

Based on hydrogeochemistry of the dripwaters in Punkva Caves (Moravian Karst), several variables indicating calcite prior precipitation (PCP) were tested. It was deduced that the massive prior precipitation should be connected with large cavities, in which water freely degasses. One anomalous drip that passes demonstrably through such cavities was found in Tunnel Corridor. In general, many parameters (such as $SI_{calcite}$ or Ca/Mg and Sr/Mg ratio) are necessary for the proper prediction of PCP and hidden upper-lying cave levels. As many of the parameters are inaccessible for ordinary speleologists, we proposed a simplified empirical criterion (UCL) based on electrical conductivity and drip rate variability. These variables are measured by simple methods and need no extensive laboratory equipment. Using the UCL criterion, anomalous drips with potential PCP occurring in upper cave levels can be revealed and subjected to further research.

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CAVE EXPLORATIONS AND APPLICATION OF HYDROLOGICAL MODEL IN RAŠPOR CAVE (ISTRIA, CROATIA)

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The paper describes exploration conducted in Rašpor Cave ("Jama kod Rašpora"), lying in the immediate vicinity of the village of Rašpor in the north-eastern part of the Istrian Peninsula in Croatia. The cave has during earlier exploration been known under the names of Žankana jama and Abisso Bertarelli. With its depth of 358 m and length of 4,996 m, it is the deepest and the longest cave explored in Istria. In over 90 years of exploration, the cave was first made famous by speleologists from Trieste, Italy, in the mid-1920s, when it held the record of being the world's deepest cave. The explorers of that time had in several large actions reached the then bottom of the cave and had drawn a map, stating a depth of 450 m, which was at the time the greatest depth ever reached worldwide. The paper addresses the results of more recent cave explorations carried out during 2008–2012, led by the Speleological Society Spelunka. During that period, many by that time unknown passages were explored and a new map with a 3D model of the cave was prepared. The explored length of the cave thus extended from the earlier known 1,106 m to 4,996 m, noting that there was no time to explore and survey many other passages. The so called Croatian sump had inhibited explorations for a long time. In 2011 the hydrological conditions allowed exploration of the whole cave without cave diving. On that occasion, data loggers were placed in the passage linked with the Croatian sump, with the purpose of monitoring the water level and temperature in the passage in order to obtain information about correlation between water oscillations in the passage and external hydrological conditions – rainfall and air temperatures in the wider impact area. A hydrological model was also prepared using the shell script of the machine learning software Weka, i.e. M5Base classifier (Implements base routines for generating M5 Model trees and rules). Very good results were obtained (with a correlation coefficient of 0.956), which makes it possible to assess whether passages are passable based on the monitoring of climatological conditions outside the cave, and largely facilitates decision-making about the timing of going down into the cave in order to continue with its exploration through the Croatian sump under dry conditions. The paper shows that when cave explorations are planned, the application of consistent monitoring is very useful, as well as the application of its results in mathematical modelling of hydrological conditions in the underground. This gives not only very valuable information about the characteristics of the function of karst aquifers in the underground, but also information based on which speleological activities in a certain period can be planned.

1. Introduction

Rašpor Cave ("Jama kod Rašpora" in Croatian) has been attracting speleologists' attention for a long time (Bertarelli and Boegan 1926; Pirnat 1970; Medeot 1974; Jalžić 1976; Šušterić 1981; Kuhta 1992; Lacković 1993; Glavaš 2011). Initial information about Rašpor Cave dates from 16 April 1922, when Italian speleologists from a Trieste society called "Commissione grotte della Societa alpina delle Giulie" (CGSAG) were on their way back from days-long exploration across Istria. When their van broke down in the neighbourhood of the village of Rašpor on Mount Ćićarija, they then learned from the locals that there was a sink with an entrance of large dimensions near the village. Once they passed the first horizontal part of the cave and stopped in front of a large-sized vertical drop, assuming that the geological composition of the terrain was not suitable for the formation of a deep cave, they decided on exploring other caves. Around the same time, in between different explorations in the Istria area, speleologists from another big Trieste society, Asocciazione XXX Ottobre (AXXXO), came across the entrance into Rašpor Cave on 20 July 1924. They visited its first horizontal part and, unlike the first team, came to the conclusion that the cave was very promising. Less than two months later, they came back and explored it down to 192 m depth. This led to a dispute between the two societies as to which one had priority in exploration. Competition among explorers and parallel exploration of the cave ensued, resulting in the members of CGSAG taking a five-year lease of the terrain around the cave in order to be able to freely explore the cave. During an action undertaken on 1st and 2nd November 1924, they reached a depth of 381 m, which was a world record at the time. The next, thoroughly planned and organized expedition was made on 24th August 1925. According to their measurements they reached a depth of 450 m. Later measurements revealed an error of over 100 m. In honour of their deserving member, they then named the cave Abisso Bertarelli. With the record set, a tragedy happened, as the storm that hit a considerable part of Europe that night didn't spare them either. Due to heavy rainfall, otherwise dry brooks that discharge into the cave suddenly gushed forth, surprising the explorers. Water rushed in suddenly, with a wave fatal for Karlo and Blaž Božić, who were part of a five-member team of Rašpor locals who were assisting the explorers in the upper parts of the cave. The remaining team, positioned in other parts of the cave, managed to survive, but they felt strong fear and witnessed the cave during a hydrological regime that has never been witnessed before or after that event.

After that the cave had been visited by many speleological teams, but mostly with the aim of conquering its bottom and with no exploration ambitions. In 1968 Slovenian speleologists from the speleological society Ljubljana Matica (later renamed into Društvo za raziskovanje jam Ljubljana) started re-exploring the cave. They discovered new secondary passages and drafted a new map of the cave all the way to the Italian sump, the place where Italian speleologists had previously set the world depth record. New and more precise measurements showed that the cave was "only" 345 m deep. Even though they then found continuation of the cave, they surveyed the newly explored parts only during an expedition in the following year. Approaching the sump, a strong draught promised that the passage would continue, but the draught suddenly ceased and the disappointed explorers realized that the sump was submerged. They named it "Slovenian sump". Their mood soon improved, as the map-based calculations showed that they were at 361 meters' depth, which was a new Yugoslav depth record (Pirnat 1970; Šušteršič 1981). According to their map, which was until recently considered the most complete and precise, the cave was 361 m deep and 1106 m long.

In 1974, organized by the Speleological Commission of the Croatian Mountaineering Association (KSPSH), speleologists from the Speleological Section of the Mountaineering Club Željezničar and speleologists from the Speleological Section of the Mountaineering Club (SO PDS) Velebit explored the cave and drafted a new version of the map according to which the cave was 365 m deep down to the Italian sump (Jalžić 1976). Following a later survey of the lower parts of the cave, the depth was revised to -355m (Kuhta 1992).

During a dry spell of 1993, the members of the SO PDS Velebit visited the cave and instead of the Slovenian sump come across a passage ending after some 15 m with a new low air space through which a narrow continuation was visible. A promising continuation of the passage was also indicated by an air draught (Lacković 1993).

The latest explorations of the cave started in early 2000. They were at first led by speleologists from the Speleological Society Had, later by the Speleological Society Spelunka, and by numerous speleologists from Croatia. Since then, the greatest attention has been given to exploration and technical climbing through incoming passages, and to air circulation monitoring (Glavaš 2011).

In 2008, the preparation of a new map of Rašpor Cave started, including resurvey of all earlier known passages. Members of the Speleological Society Estavela, of the Speleological Section of the Croatian Mountaineering Club Željezničar and many other speleologists joined in this exercise. A big step forward in exploring the cave was achieved by successfully passing through the Croatian sump, which turned into a small lake during a heavy drought in the summer of 2011 (Kukuljan and Glavaš 2012). A probe was then sited there to monitor the water level and water temperature. As the passages behind the sump widened, the progress and surveying were made much easier. In addition to the main part, explorations in several other, less attractive, narrower parts of the cave also continued. Over a short period, the length of surveyed passages in the cave increased to nearly 4 km and the depth was revised to -338 m. In 2012, there was another summer drought, which made it possible to explore the main passage further, resulting in the length of 4996 m explored so far and the depth of 358 m.

The paper presents the above-mentioned results of the latest survey of Rašpor Cave, the results of meteorological and hydrological monitoring collected during recent explorations of 2011–2012, as well as the results of the conducted mathematical modelling – assessment of water levels in the part of the cave near the Croatian sump based on the data obtained from the monitoring of rainfall and air temperature on the surface.

2. General characteristics of the studied area

The wider area of Rašpor Cave belongs to thrust structures of the Ćićarija massif. According to (Urumović and Rubinić 2000), this is a heavily faulted area characterized by a series of reverse faults thrusting. The basic characteristic of Ćićarija is step-like morphology of terrain and flake structure with alternating permeable limestone and confined impermeable flysch deposits, on which short surface water courses are formed which sink into closed depressions. There are also significant underground karst formations, particularly a number of very deep sinks and caves.

The cave is in the north-eastern, highest part of the Istrian Peninsula. Its entrance is at an elevation of 665 m above sea level (ASL). In the broader area there are mountain peaks reaching as high as 1,060 m ASL (Figure 1.). In the last 100 years, the Ćićarija area has belonged to the administration of four countries, and it is now crossed by a state border which was until 1991 only a border between federal republics. The cave has thus been explored by teams of speleologists and explorers from Croatia, Italy and neighbouring Slovenia.

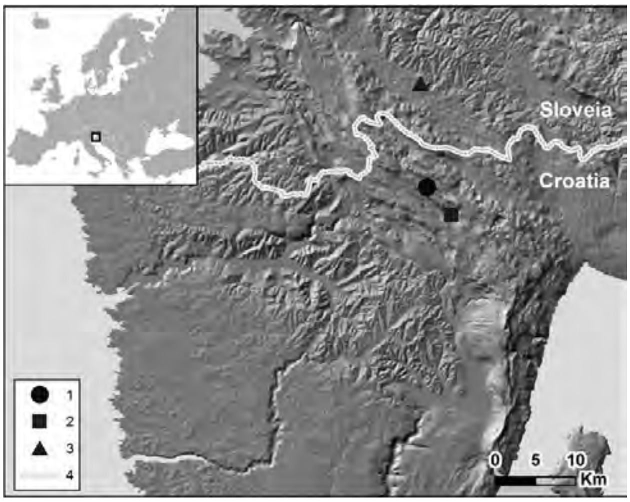

Figure 1. Location of Rašpor Cave, including the locations of measuring stations (1 – Rašpor Cave, 2 – Lanišće rain gauging station, 3 – Gradišče – Brkini weather station, 4 – State border).

The cave is an intermittent sink and it is only at time of heavy rainfall or immediately after such event that water discharges into the sink. The surface basin covers an area of only 0.24 km^2 and it is mostly composed of impermeable flysch deposits.

The average annual air temperature in the area ranges between 8 and 9 °C and the average rainfall ranges between 1750 and 2000 mm (Croatian Hydrological and Meteorological Service, 2008). The nearest rain gauging station is 4.5 km away from the cave entrance; it is situated in the settlement of Lanišće at an elevation of 560 m ASL and is managed by the Croatian Hydrological and Meteorological Service from Zagreb. The nearest weather station is Gradišče – Brkini at an elevation of 590 m ASL, 13 km away from the sink. It lies in Slovenia and belongs to the system of amateur automatic monitoring stations of the organization Vremensko društvo ZEVS.

3. Methods

The cave was surveyed using standard speleological instruments for measuring azimuth and inclination, a Suunto tandem, a Leica disto A3 distance meter and a DistoX instrument. Data from earlier surveys has not been used. There are 1,250 measuring points and the average length of a survey traverse is 3.98 m.

A 3D model of how the cave spreads was prepared with the help of Speleoliti software (Dular 2006) which is used for cave representations of that type.

Climatological measurements on the surface refer to the data collected at the standard rain gauging station Lanišće, with daily readings of rainfall at 7 a.m., and at the automatic weather station Gradišče with hourly readings of rainfall and water temperature. Data from the latter were, for comparison purposes, also reduced to daily readings at 7 a.m.

Hydrological measurements of the water level and temperature in the cave were taken at a depth of 327 m at a traverse distance of 1,111 m from the entrance (Figure 2 – location 2). A Micro-Diver-type data logger manufactured by Schlumberger Water Services, which records pressure and water temperature each 12 minutes with a reading precision of ±5 cm and 0.1 °C, was used. Another data logger of the same manufacturer, but of Baro-Diver type, was sited at a depth of 292 m and at a traverse distance of 613 m from the entrance (Figure 2 – location 1) for the purpose of compensating for air pressure changes. It recorded air pressure and temperature at 24-minute intervals, with a measuring precision of ± 0.5 cm H_2O and ± 0.1 °C. The measurement activities took place from 29th August 2011 to 8th September 2012, i.e. for 376 days.

The modelling/forecasting of the water level in the cave was done using a model from the domain of Data Mining (DM) models, i.e. a model in the development of which the artificial intelligence application methods are used. The basic objective of this modelling/forecasting is to learn whether the sump to which the modelling refers is submerged or whether it is passable. In that process a classifier approach was used; it generates decisions in the form of regression trees, with each generated leaf representing a numerical prediction defined by the regression equation in the function of analyzed impact factors. The model itself was formed with the help of machine learning software Weka 3.6 (Mark Hall et al. 2009). Classifier M5Base (Implements base routines for generating M5 Model trees and rules) was used. Input data was the following: daily rainfall at the Lanišće station and the average daily temperature at the Gradišče – Brkini station, and the data derived therefrom and which characterizes the earlier status: rainfall in the preceding day, average 3-day rainfall, average 3-day air temperature, average 9-day rainfall, average 9-day temperature, average rainfall in the preceding 21 days, average air temperature in the preceding 21 days, average rainfall in the preceding 42–21 days, average temperature in the preceding 42–21 days, and the number of days without rainfall of more than 3 mm. The model was trained on 66 % of available data, and tested on 33 %, using standard statistical tests which define deviations between the measured and modelled values – Correlation coefficient, Mean absolute error, Root mean squared error, as well as Relative absolute error (Hall 2001).

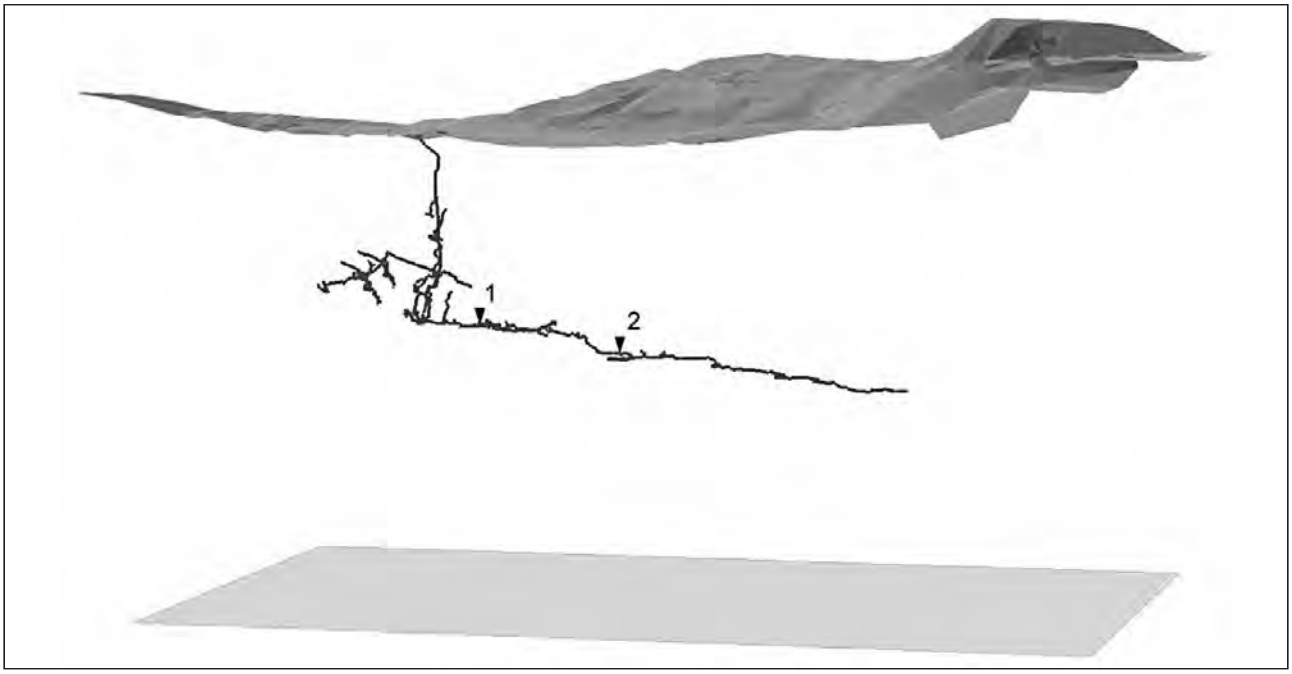

Figure 2. 3D model of Rašpor Cave with delineated positions of: 1 – Data logger for compensation of pressure and air temperature monitoring, 2 – Data logger monitoring water level and temperature.

4. Results and discussion

4.1. Survey results

The results of the cave survey are presented in the form of a 3D model that depicts the positions of the data loggers (Figure 2). At location 1, a data logger was placed in the air to monitor air temperature and barometric pressure. At location 2, a data logger was placed in the Croatian Sump, to monitor fluctuations in water level and temperature.

The cave is 4,996 meters long and 358 meters deep. A steep funnel-shaped entrance turns into a mostly horizontal passage 10 m wide and 7 m high. The passage slopes gently, with a small step down to 60 m depth, followed by a big vertical drop (Figure 3) of 125 m. From the bottom of the vertical drop in Božićeva Hall, the cave continues with another 45 m vertical drop and a narrow meander with no visible ceiling and bottom. The meander opens into a wider vertical drop, followed by several smaller steps leading to a modest-sized hall at a depth of 280 m. This hall is the starting point of the main meander-shaped passage which continues with a very mild slope down to the deepest parts of the cave. The dimensions of this passage or meander are mostly up to 1 m in width and most often over 10 m in height.

It is assumed that the majority of the water found along the horizontal part of the cave comes from the entrance. However many tributary channels and meanders contribute water as well (Figure 4.). Individual incoming meanders lead to bigger halls which branch out further into meandering passages. Many of these are left unexplored due to their small widths. The main water flow, intensified by water from the incoming flows, flows further through the main meander and discharges into the first, Italian sump. Not far away from this sump a dry link has been discovered to the passages behind the sump, thus making exploration of those parts of the cave much easier. The passages behind the sump become slightly larger and eventually lead to another two sumps, the Slovenian sump, and the Croatian sump close behind it (Figure 5). No dry bypass has been found above these two sumps. For that reason, exploration in the passages behind these sumps depends to a large extent on their water levels. Speleologists can easily pass through the sumps if the level of water in the sumps is below 75 cm in relation to the initial level defined upon the establishment of a measuring station at the site of the Croatian sump (location 2 in Figure 2). The passages behind the sumps become wider and their ends have not yet been found.

Figure 3. Big vertical drop, photo I. Glavaš.

Figure 4. Not easily passable incoming meander, photo D. Reš.

Figure 5. Location of the so called Croatian sump, measuring point 2, photo A. Rubinić.

4.2. Results of analysis of hydrometeorological data

The results of the monitoring of fluctuations in the water level and of water and air temperature in the cave are presented in Table 1 as well as in Figure 6. The results indicate that water in the sump has dropped below water level 0, i.e. that there is very little water and that it is below the measuring instrument.

Table 1. Basic characteristics of the results of hydrological monitoring undertaken in Rašpor Cave (29th August 2011 – 8th September 2012).

	Water level (cm)	Water temperature (°C)	Air temperature (°C)
Average	73.7	9.0	7.6
Max	176.3	9.2	7.8
Min	0.0	7.9	7.3
Stdev	41.1	0.2	0.1

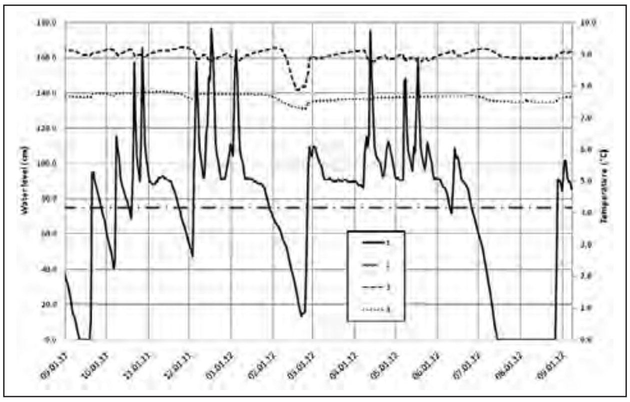

Figure 6. Presentation of data measured in Rašpor Cave (29th August 2011 – 8th September 2012): 1 – Water level in the Croatian sump (measuring point 2) (cm), 2 – Water level 75 cm, 3 – Water temperature in the sump (ºC), 4 – Air temperature in the hall at (measuring point 1) (ºC).

It was identified that during the analyzed monitoring period (29th August 2011 – 8th September 2012) the level of water in the Croatian sump was below 75 cm (i.e. the sump was passable) for 37 % of the time. This was a very dry period, which is best illustrated (Figure 7) by comparing the registered monthly rainfall during that period with the average rainfall for the preceding multi-annual period (1953–2011).

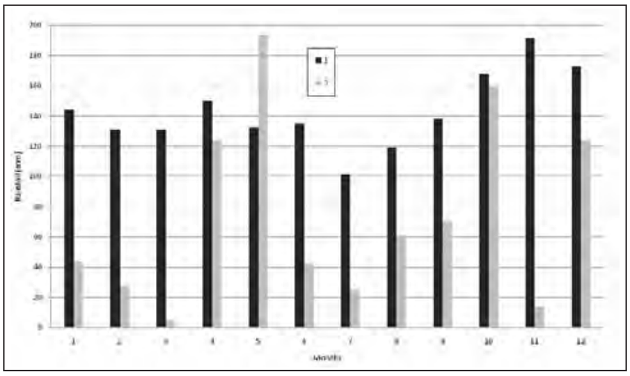

Figure 7. Monthly rainfall registered at the Lanišće rain gauging station: 1 – Average monthly rainfall for the 1952–2011 series; 2 – Rainfall registered in the period September 2011 – September 2012.

The results of monitoring of water and air temperatures in the cave show relatively stable temperature conditions with relatively low oscillations, with air temperature oscillating much less (a range of 0.5 °C) than water temperature (1.3 °C). It is evident that water temperature is under a stronger impact of external factors – inflow of water into the sink, which is manifested by short-term and weak drop in water temperature during increased levels of water in the cave. On the other hand, the higher average water temperature of 9.0 °C in relation to the average air temperature in the cave of 7.6 °C indicates potential longer retention of cooled air which intrudes from the surface into the underground.

Likewise, the obtained data, partly presented in Figure 5. showing daily rainfall at the Lanišće station, indicates that the water level in the underground responds very quickly to the rainfall – water level peaks generally occur with a lag time of only one day and less.

4.3. Modelling results

The modelling of water level in the Croatian sump, performed on the basis of hydrological data measured in the cave as well as on the basis of data on rainfall and temperatures in the wider impact area above the cave, has resulted in a regression tree prepared using WEKA software, as presented in Figure 8. The results are also presented in Figure 9.

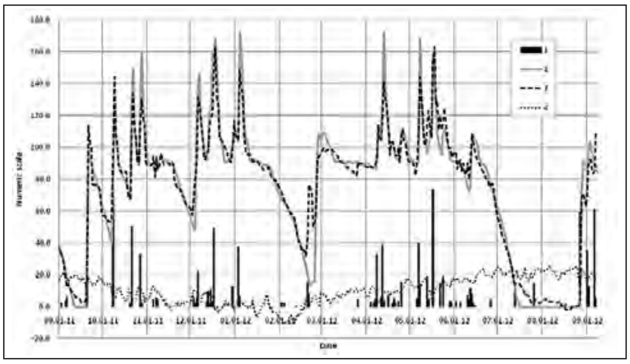

Figure 9. Comparison of measured and modelled data in Rašpor Cave: 1 – Rainfall at the Lanišće station (mm); 2 – Measured average daily water level (cm); 3 – Model-calculated average daily water level (cm); 4 – Average daily temperatures at the Gradišče-Brkini station (ºC).

It is evident that very good adjustment of the modelled data on water levels in the Croatian sump to the observed values has been achieved. Testing was also performed using an independent series – the model was generated at 66 % of available data, and testing was performed at the remaining 33 % of data series. Very good indicators of adjustment were obtained (Table 2). Of 139 days with registered water levels lower than 75 cm, the model predicted 130 days with this situation (2.4 % of false predictions in relation to the total period of observation), and only 6 days (1.6 %) had false predictions that the water level is lower than 75 cm, and it was slightly higher.

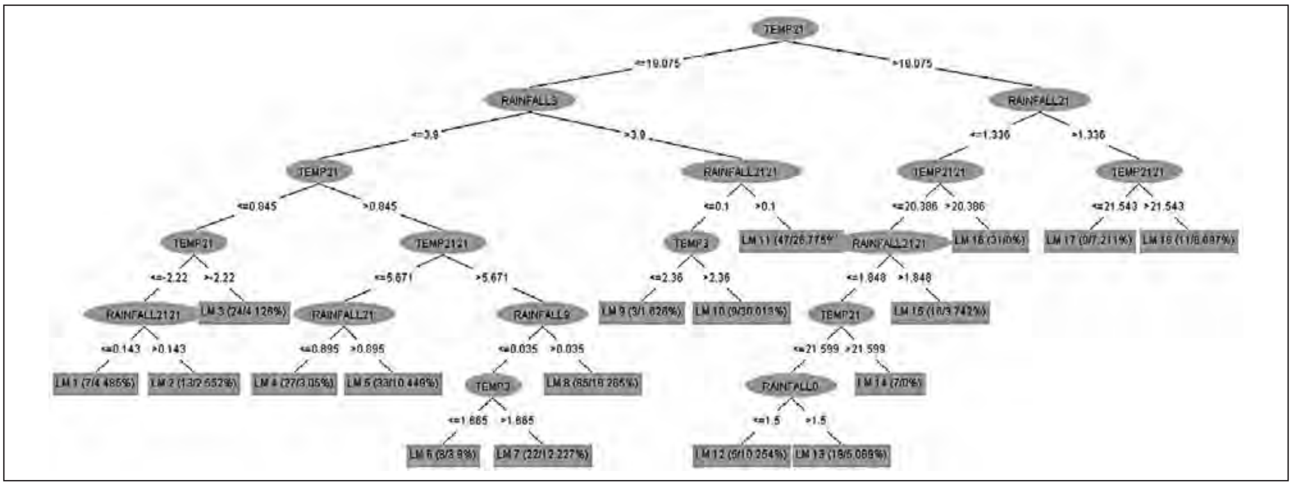

Figure 8. Regression tree of the model forecasting water levels in the Croatian Sump.

Table 2. Results of tests modelled in relation to observed water level values.

Evaluation method	Value
Correlation coefficient	0.956
Mean absolute error	7.456
Root mean squared error	11.334
Relative absolute error	25.118 %
Root relative squared error	30.031 %

Consequently, the forecasting of water levels in the Croatian sump as a critical spot for continued speleological exploration of the continuation of the main passage of Rašpor Cave has been exceptional. This provides an appropriate tool for planning the timing for going down into the cave in order to continue exploring the cave spaces lying behind that sump.

5. Conclusions

The results of cave explorations carried out in the period 2008–2012 and of hydrological measurements taken in the period 2011–2012, as presented in this paper, show that Rašpor Cave is still an extremely valuable speleological site offering great potential for continued exploration. By passing through the so called Croatian sump which was for the first time done in 2011, a very dry year, the explored length of the cave was extended by more than 1.5 km, thus proving that this is only a rather short suspended sump. A depth of 358 m or an elevation of 307 m ALS was reached. The 3D model of the cave made shows that after the initial predominantly vertical part of the cave it continues to spread in a gentle slope even after the Croatian sump is passed.

The results of climatological and hydrological monitoring showed very interesting interrelations both in terms of interrelations between air temperature on the surface and in the cave and water temperature, and in terms of reactions to rainfall. The results of this monitoring also provided very valuable supporting data for the preparation of a forecasting model for water levels in the Croatian sump depending on air temperatures and rainfall recorded in the wider impact area on the surface of the cave. A very well adapted model has been obtained based on a machine learning approach. The model can successfully predict the state of Croatian sump (dry/full) and thus help efficient exploration of the deepest part of the cave.

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TEMPERATURE AND KINETIC CONTROL OF CAVE GEOMETRY

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Network or maze geometry dominates among the longest caves in Norway, where karst caves are initiated or developed in a cold climate. Laboratory experiments of calcite kinetics demonstrate that under low temperature conditions the capacity of dissolution increases while the initial dissolution rate decreases. Through modeling experiments the influence of water temperature and kinetics on cave geometry is investigated suggesting that the cold setting may enhance network development.

1. Introduction

Karst caves in Norway are initiated or developed in a cold climate. Network or maze geometry (Skoglund and Lauritzen 2011) dominate among the longest caves in the country. The Norwegian stripe karst setting (Lauritzen 2001) (with marble interbedded with schist layers), and caves situated in a hanging position in glacially sculptured valleys, rule out intra-stratal diffuse recharge (Klimchouk 2009) and the flood water (Palmer 1975) as the maze developing mechanism. This presentation investigates the relation between temperature, kinetics and cave geometry.

Laboratory experiments of calcite kinetics demonstrate that under higher temperature conditions the initial dissolution rate increases while the capacity of dissolution decreases. Under low temperature conditions the opposite is true, the capacity at thermodynamic equilibrium increases, whilst the Arrhenius effect decrease the initial dissolution rate (Lauritzen and Skoglund 2013). High initial dissolution rates indicate a relatively high first order kinetic constant, and a rapid exhaustion of the low capacity of dissolution. Since the time for the solution to reach equilibrium is still long, the higher order kinetic constant must be reduced. In the opposite case, low temperature leads to slow initial dissolution rate and high solution capacity. We suggest that the second order kinetic constant in this case may be higher than in the first case. This initiates the question: Does water temperature influences cave geometry?

2. Methods

In order to evaluate the influence of water temperature and kinetic control on cave geometry we use the modeling program for evolution of karst aquifers from the Bremen group (Dreybrodt et al. 2005). To represent the marble karst setting, a confined, dual fracture network is applied where a coarse net of prominent fractures is embedded into a fine fracture network. Simulations run under constant head conditions and are stopped when the discharge exceeds 50 l/s. Breakthrough occurs when a feeder tube establishes an efficient flow path through the net between the recharge and discharge zone.

In accordance with the results from the laboratory experiments three simulation scenarios are applied.

A) A tropical climate scenario with temperature of 25 °C and the first order kinetic constant $k_1 = 8\times10^{-11}$ mol cm^{-2} s^{-1}, the second order kinetic constant $k_2 = 1\times10^{-8}$ mol cm^{-2} s^{-1} and n = 4 for higher order kinetics.
B) A cold climate scenario with temperature of 0 °C and the kinetic constants $k_1 = 1\times10^{11}$ mol cm^{-2} s^{-1} and $k_2 = 8\times10^{-8}$ mol cm^{-2} s^{-1}, and n = 4.
C) A temperate scenario with temperature of 10 °C and the kinetic constants $k_1 = 4\times10^{-11}$ mol cm^{-2} s^{-1} and $k_2 = 4\times10^{-8}$ mol cm^{-2} s^{-1}, and n = 4.

3. Results

When the feeder tube penetrates into the fracture net, the high head of the inflow boundary is shifted far into the net and a steep hydraulic gradient forms radially around the tip of the feeder tube towards the outflow boundary (Fig. 1). At breakthrough, the dissolution rate in the feeder tube (discharge segment) increases rapidly towards the rapid first order dissolution rate. Under the tropical scenario (A) the feeder tube widens rapidly and becomes a very efficient water conveyer and few other fractures dissolve and widen before the model is stoped at a discharge of 50 l/s (Fig. 1 upper). This contrasts the evolution in the cold climate scenario (B) where a network or maze develops in the outflow zone. This may be the result of the smaller difference between the first and second order dissolution rates or the longer penetration lengths at the tip of the main channel. The temperate scenario C shows an intermediate evolution with a smaller network (Fig. 1 lower).

4. Concluding remarks

As a concluding remark, these preliminary results indicate that slower first order kinetics with lower dissolution rates restrict the positive feedback at breakthrough which prevents accelerated flow rates in the feeder tube. If this is true, it may suggest that cold climate settings enhance network development. Although several other factors affect the speleogenetic conditions under the glacier ice-contact regime (Skoglund and Lauritzen 2011; Lauritzen and Skoglund 2013), the temperature effect in it self might be sufficient to affect cave geometry towards the network or maze cases. However, these are still tentaive ideas which need further elaboration.

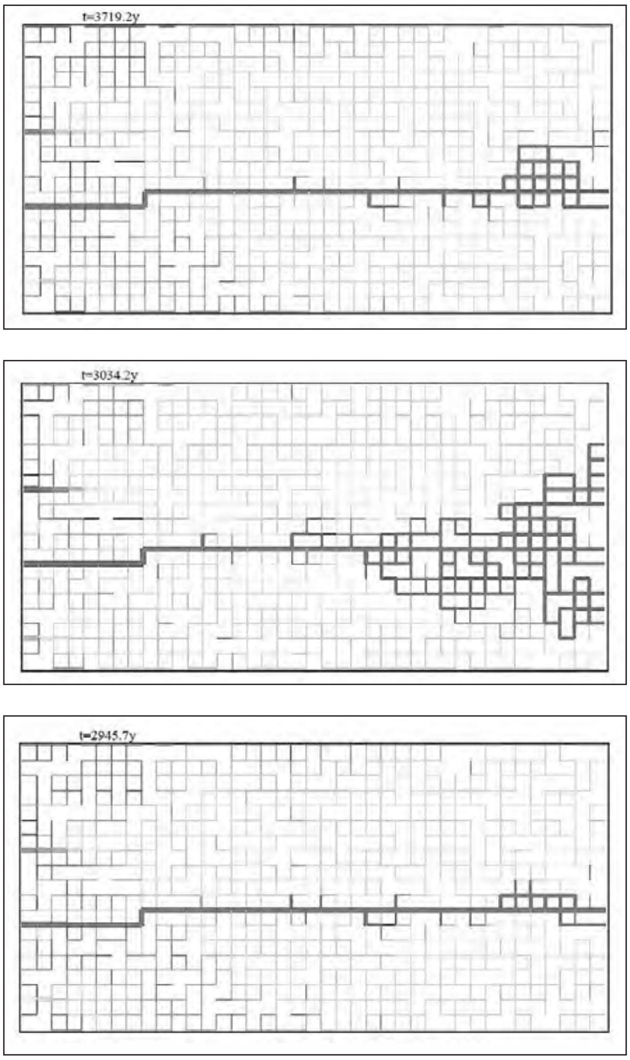

Figure 1. Network developed under the different scenarios. Upper: Tropical scenario A at T = 25 °C. Middle: Cold climate scenario B at T = 0 °C. Lower: Temperate scenario A at T = 10 °C. Line thickness shows aperture, while grey scale shows dissolution rate: dark grey is F_{max} decreasing towards light grey which is $10^{-4}F_{max}$ and black shows no dissolution.

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Session:

Cave Climate and Paleoclimate Record

AN EXTENDED LATE PLEISTOCENE RECORD OF WATER-TABLE FLUCTUATIONS IN DEVIL'S HOLE, NEVADA

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Calcite speleothem *folia* in Devil's Hole mark former positions of water table of the regional Ash Meadows groundwater flow system, southern Great Basin, USA. Previous studies identified fluctuations of the water table over the last 120,000 yr (Szabo et al. 1994). In this study we extend the record of water-table elevation back to 332,000 yr. Low water-table stands correlate with warm Marine Isotope Stages 5.5, 7.3, 7.5 and 9. Water table elevations at earlier times may have been controlled by the local extensional tectonic regime rather than by climate.

1. Introduction

The regional Ash Meadows groundwater flow system in southern Nevada is hosted in Paleozoic carbonate rocks (Winograd and Thordarson 1975). Discharge from this large (ca. 12,000 km^2) basin occurs along a prominent spring line at the Ash Meadows oasis. Adjacent to the central part of this lineament, there are two prominent tectonic caves, Devils Hole and Devils Hole II (Fig. 1). The caves are open extentional fractures which extend to a depth exceeding 130 m underwater. The water in the discharge area of this flow system is slightly supersaturated with respect to calcite. Along with the extensional tectonic regime, this led to the development of thick, dense mammillary calcite crusts (cave clouds) coating the walls of the fractures below the water table. Crusts were depositing continuously from 566,000 ±20,000 yr to as recently as 4,500 yr (Ludwig et al. 1992; Winograd et al. 2006).

Mammillary crusts were also reported from air-filled chambers of the caves up to 9 m above the present water level, implying that the latter occupied higher positions in the past (Szabo et al. 1994). In addition, calcite deposits indicative of paleo-phreatic water flow (veins) and former springs (tufa/travertine), respectively, were found in Quaternary alluvium and lakebeds. These deposits indicate that the Pleistocene water table in the area could have been tens to hundreds of meters higher than it is today (Winograd and Doty 1980).

On the basis of hydrogeologic, neotectonic, and paleoclimatologic information available at that time Winograd and Szabo (1988) concluded that "the water table in the south-central Great Basin progressively lowered throughout the Quaternary" and, on the basis of U-series dating calculated a rate of apparent watertable decline of 0.02 to 0.08 m/ka for the area of Ash Meadows during the middle and late Pleistocene.

This simple water table decline model has been revised in 1990s, after studies of the folia deposits in Browns Room – an air-filled chamber of Devil's Hole. There, a specific type of speleothem, *folia*, forming at the (fluctuating) water-air interface, was dated from different positions ranging up to 9 m above the present water level.

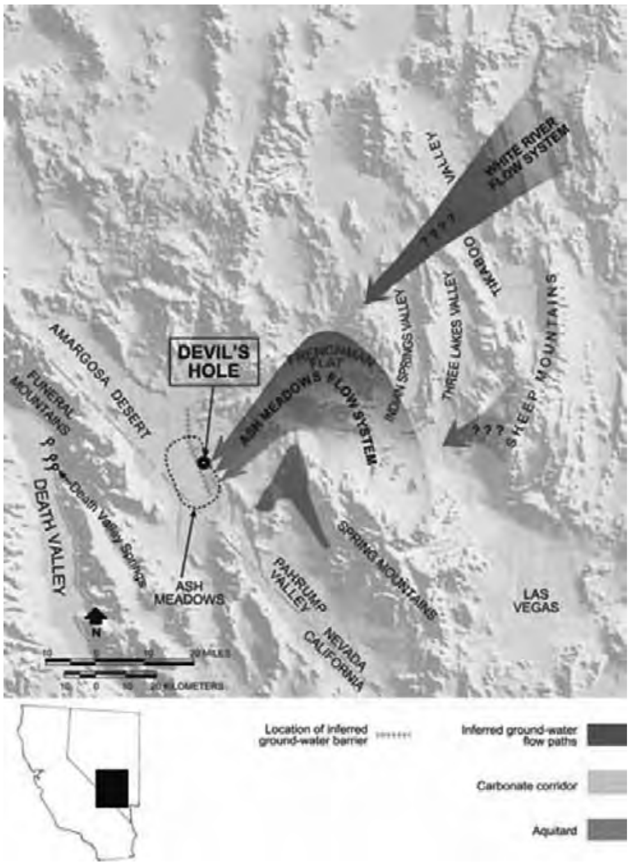

Figure 1. Location of Devils Hole at the discharge end of the Ash Meadows flow system (from Riggs and Deakon 2002).

2. Folia as an indicator of the paleo-water-table in Devils Hole

According to Davis (2012) "*Folia are relatively rare speleothems that manifest as fields of overlapping, downward-slanting, interleaved shelf-like structures that are best developed on overhanging cave walls. They are generally restricted to a limited vertical range in the host caves*". Folia have most commonly been interpreted to grow in association with fluctuating water tables of large subterranean water bodies. Although other mechanisms of folia growth have been proposed (e.g., Audra et al. 2009; Queen 2009) the fluctuating-water origin is clearly the most feasible explanation for this type of speleothem in Devil's Hole.

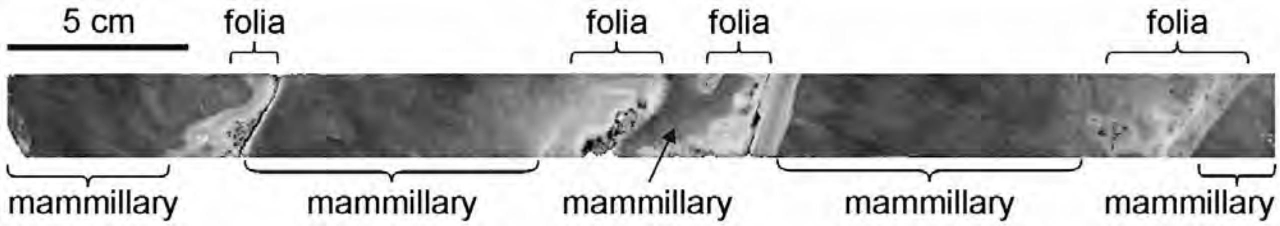

Figure 2. Core from hanging wall of Devils Hole II featuring mammillary calcite deposition (phreatic growth) interrupted by four episodes of folia deposition (water-table growth).

Figure 3. Dense folia on the hanging wall above the water table in Devils Hole II. The figure is c. 1.5 m across.

Szabo et al. (1994) observed that in Browns Room folia are ubiquitous from the ceiling (+9 m) to 1 m below the present-day water table, but disappear rapidly below this level. Only mammillary (i.e. phreatic) calcite is present in cores drilled to bedrock at depths of 12 and 30 m below the water table. These authors were the first to use this information along with U-series dating to reconstruct a history of past water-level fluctuations within this cave. They have found that the water table fluctuated around +6 m between 116,000 and 53,000 yr ago and did not drop below +5 m between about 98,000 and 53,000 yr ago. The water level rose to +9 m ca. 44,000 yr ago, and fluctuated from +9 to <+6 m from about 44,000 to 20,000 yr ago. After ca. 18,000 yr ago the water level experienced a rather rapid and uninterrupted drop at a rate of ca. 0.35 m/1,000 yr.

3. Episodes of low groundwater levels during the Pleistocene

In 2010–2011 we drilled several cores across calcite deposits +1.8 m above the water table in Devils Hole II (Figs. 2 and 3). The 66 cm-thick deposits from the hanging wall of the cave featured four episodes of folia growth, indicating that the water table fell to a level similar or only slightly higher than today at least four times during the last ca. 590 ka (Fig. 4).

By dating the mammillary calcite underlying and overlying folia using the U-Th disequilibrium method and interpolation using the previously established rather uniform average growth rate of the mammillary calcite in Browns Room (0.86 mm/1,000 yr; Szabo et al. 1994) these low groundwater levels are dated to ca. 332,000, 244,000, 214,000 and 121,000 yr before present (Fig. 4).

4. Possible causes of water-table fluctuations

The Ash Meadows groundwater flow system is ca. 12,000 km^2 in extent. The transmissivity of this fractured carbonate aquifer is very high, resulting in hydraulic gradients as low as 0.06 m/km (Winograd and Thordarson 1975). For this reason, the documented water-table fluctuations are likely to have been of regional significance (Szabo et al. 1994).

The idea that such large water-table fluctuations were related to climate was previously considered unlikely (e.g., Winograd and Doty 1980). Winograd and Szabo (1988) suggested that displacements of the paleo-water table reflect a combination of (1) tectonic uplift of the area, (2) lowering of water-table elevation in response to tectonic subsidence of an adjacent region, and (3) lowering of water-table altitude in response to increasing aridity, or to erosion.

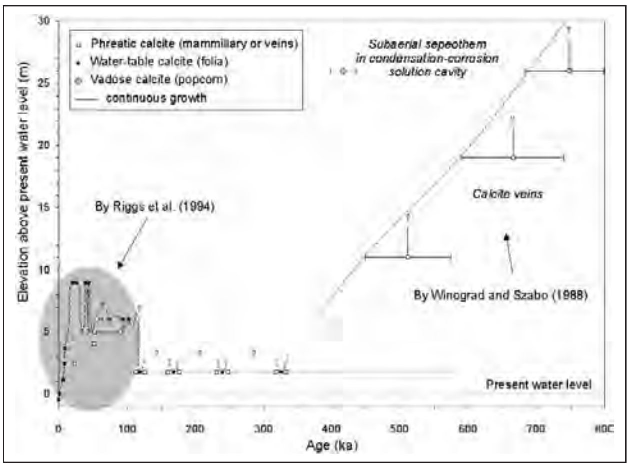

Figure 4. Summary of the data on the paleo-elevation of the groundwater table in the Devils Hole cave system during the Late Pleistocene (this study).

Szabo et al. (1994) compared the 120,000 yr-long history of water table fluctuations with paleoclimatic and paleoenvironmental data from the Great Basin and suggested that the Browns Room fluctuations were controlled primarily by changes in climate. Our new data provide further support for this model.

All four newly identified low stands correspond to warm, interglacial Marine Isotope Stages (MIS): 5.5, 7.3, 7.5 and 9, respectively.

During pre-MIS 9 times the water table elevation in the Ash Meadows groundwater flow system, as recorded by calcite deposits, appears to have been unrelated to climate. This may indicate a more prominent role of extensional tectonics in controlling the flow of the groundwater system.

Acknowledgments

The authors acknowledge the Death Valley National Park Service for permission to conduct field studies and take samples. Field and logistics support was kindly provided by personnel of the Park (K. Wilson, R. Friese, A. Snow, and J. Snow) and by the Southern Nevada Grotto (S. Deveny).

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REVIEW OF PALEOCLIMATE STUDIES IN TURKEY: THE ROLE OF SPELEOTHEM-BASED DATA

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Turkey is located on a north-south transect at the middle latitudes of the northern hemisphere where atmospheric pressure centers like the North Atlantic Oscillation at the west, eastern Atlantic-western Russia in the north and Indian monsoon and the eastern Mediterranean oscillation determine the climate. Turkey is also close to and apparently affected by changes in the Intertropical Convergence Zone (ITCZ). Hence, information on paleoclimate in Turkey may help to understand how ITCZ has changed temporally its position in this part of the earth. Turkey and surrounding seas are abound with paleoclimate archive records such as lake and marine sediments (e.g., pollen, foraminifera, diatoms etc.), tree rings and speleothems. Many of the previous paleoclimate studies in Turkey are based on lake or sea sediment records. Among them, those carried out in the two paleolakes of the central Anatolia closed basin (also called the Konya Closed Basin) are most remarkable. Those studies revealed the existence of two large fresh/brackish water lakes that formed during the late Quaternary as a result of cooler temperatures which resulted in a positive water balance. Lake studies also reveal that a warmer climate started to become dominant after the Last Glacial Maximum (LGM). The arid climate of early Holocene later on turned out to be today's more wetter climate. Speleothem-based paleoclimate studies in Turkey have increased remarkably during the last 5 years. The results of these studies are in agreement with the findings of previous work. However, the high temporal resolution of speleothem signals allowed for better characterization of the paleoclimate. The paleoclimate signals of the speleothems collected from northern and southern caves in Turkey have different trends before and after LGM. The Holocene paleoclimate in southern Turkey were found to resemble the concurrent eastern Mediterranean climate.

1. Introduction

Climate in Turkey, located on a north-south transect at the middle latitudes of northern hemisphere, is determined by the North Atlantic Oscillation in the west, eastern Atlantic-western Russia to the north and the Indian monsoon and eastern Mediterranean oscillation. Turkey is close to and apparently affected by shifts in the Intertropical Convergence Zone (ITCZ). Thus, paleoclimate changes in Turkey indicate also changes in the position of the ITCZ. Turkey has regionally varying temperature and precipitation regimes as most of the land is surrounded by the northern, western and southern seas and has a mountainous topography. These features make Turkey a remarkable region from the perspective of paleoclimate research.

Many of the previous paleoclimate studies conducted in Turkey have been based on core samples from lakes and surrounding seas and on tree rings (e.g., Reed et al. 1999; Marino et al 2009; Touchan et al. 2007). These studies resulted in low resolution past climate data mainly because of the poor age dating of samples. During the last decade, paleoclimate studies in Turkey have concentrated on cave sediments because of the vast extent of the karst areas that abound with numerous caves.

Cave sediments, stalagmites in particular, have gained a special role in paleoclimate studies as they can be dated precisely, be found in most of the caves and, their stable isotope contents better reflect the conditions of the paleoenvironment. Studies on cave sediments help to understand the paleoclimate, particularly during the late Quaternary when combined with other paleo archive data obtained from tree rings and lake/sea sediments.

This paper provides a list of the paleoclimate studies in and around the Turkey and gives a brief summary only of those limited to Holocene due to space limitation. Studies based on cosmogenic moraine ages (e.g., Zreda et al. 2011) have been kept outside the scope of this paper.

2. Paleoclimate studies in Turkey

2.1. Lake and sea sediments and tree ring studies

Many of paleoclimate and paleoenvironment studies in Turkey has been conducted on lake sediments collected from locations listed in Table 1 (Fig. 1). These studies are focused on the temporal variation of diatom and pollen species, stable isotope composition of fossils and/or carbonate precipitates, mineralogy and geochemistry as proxies of paleoclimate and paleoenvironment. The age of the lake sediments have been determined by varve counting between cores points dated by the radiocarbon technique. Paleolake studies in Turkey concentrates in the central Anatolia (i.e. Asia Minor) where the Konya Closed Basin (KCB) has hosted many lakes since the beginning of the Tertiary. Roberts et al. (1999) utilized the pollens, diatom, stable isotope data combined with radiocarbon ages to determine the late Quaternary paleoenvironmental conditions in the KCB. They revealed that two paleolakes (paleo Salt Lake at the north and paleo Konya Lake at the south) existed in the KCB during the last 60 ka BP (before present, 1950) and their extent has been controlled mostly by climatic oscillations. The Konya paleolake reached its maximum extent (4500 km^2) and depth (~20 m) during the Last Glacial Maximum (LGM) but shrank and dried out in the early Holocene. Another study aiming to explain the late Pleistocene climate in the KCB was done by Kuzucuoğlu

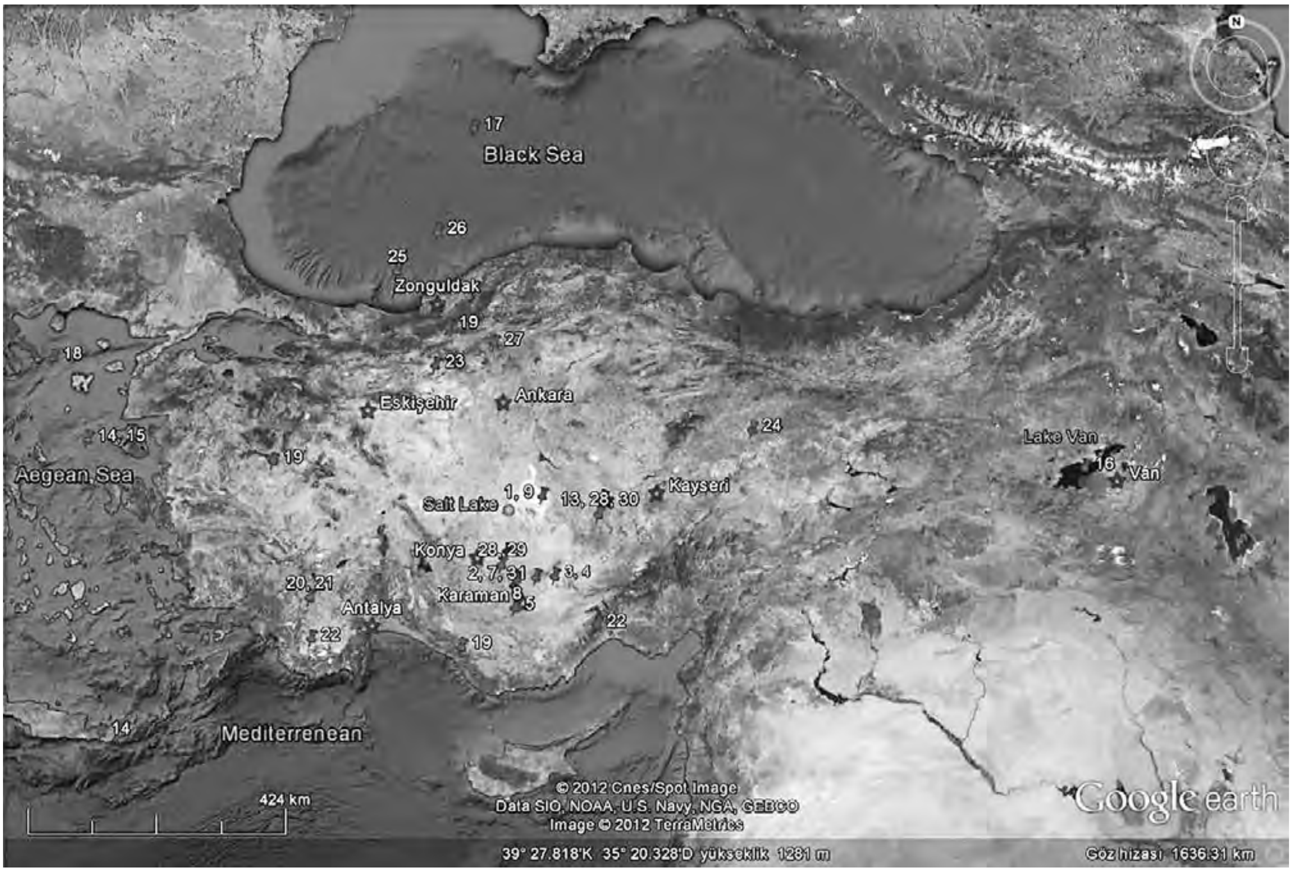

Figure 1. Locations of the sites of paleoclimate studies based on tree ring, lake and sea sediments in and around Turkey (numbers are keyed to Table 1).

Table 1. Paleoclimate studies based on lake-sea sediments and tree rings in Turkey.

Key No	Study Area	Location	Archive Type	Reference
1.	Konya and Salt Lake	Konya	Lake sediment core	Erol, 1985
2.	Konya Closed Basin	Konya	Lake sediment core	Roberts et al. 1999
3.	Akgöl	Ereğli, Konya	Lake sediment core	Kuzucuoglu et al. 1999
4.	Akgöl	Ereğli, Konya	Lake sediment core	Leng et al. 1999
5.	Pınarbaşı	Konya	Lake sediment core	Leng et al. 2001
6.	Konya Closed Basin	Konya	Lake sediment core	Roberts et al. 1979
7.	Konya Closed Basin	Konya	Lake sediment core	Katsuhiro et al. 1997
8.	Süleymanhacı	Karaman	Lake sediment core	Reed et al. 1999
9.	Salt Lake	Aksaray	Lake sediment core	Kashima 2002
10.	Göçü	Göçü, Konya	Lake sediment core	Karabıyıkoğlu et al. 1999
11.	Eski Acıgöl	Nevşehir	Lake sediment core	Roberts et al. 2001
12.	Eski Acıgöl	Nevşehir	Lake sediment core	Jones et al. 2007
13.	Eski Acıgöl, Nar Lake	Nevşehir	Lake sediment core	Turner et al. 2008
14.	Southern Aegean Sea	Aegean Sea	Sea core	Rohling et al. 2002
15.	Aegean Sea	Aegean Sea	Sea core	Marino et al, 2009
16.	Van Lake	Van	Lake sediment core	Wick et al. 2003
17.	Western Black Sea	Black Sea	Sea core	Bahr et al. 2006
18.	Northern Aegean Sea	Aegean Sea	Sea core	Kotthoff et al. 2008
19.	Mengen, Simavi Alanya	Bolu, Kütahya, Antalya	Tree rings	Mutlu et al. 2011
20.	Gölhisar Lake	Burdur	Lake sediment core	Eastwood et al. 1999
21.	Gölhisar Lake	Burdur	Lake sediment core	Jones et al. 2002
22.	Elmalı, Mersin around	Antalya, Mersin	Tree rings	Touchan et al. 2007
23.	Eskişehir, Ankara, Bolu	Eskişehir, Ankara, Bolu	Tree rings	Akkemik et al. 2008
24.	Tecer Lake	Sivas	Lake sediment core	Kuzucuoglu et al. 2011
25.	Black Sea	Black Sea	Sea core	Kweicen et al. 2009
26.	Black Sea	Black Sea	Sea core	Baderschter et al. 2011
27.	Güvem Basin	Ankara	Pollen	Yavuz 2008
28.	Çatalhöyük	Konya	Lake sediment core	Weninger et al. 2006
29.	Çatalhöyük	Konya	Lake sediment core	Bar-Yosef Mayer et al. 2012
30.	Nar Lake	Nevşehir	Lake sediment core	Woodbridge and Roberts 2011
31.	Konya Closed Basin	Konya	Lake sediment core	Inoue et al. 1998

et al. (1999). They found that a large sinkhole located along the flank of Taurus carbonate rock massif at the south acted as a spillway when the paleolake reached its maximum level.

In another important study based on analyses of micro charcoal samples from paleo Acıgöl and Nar crater lake (Turner et al. 2008), lower than modern precipitation and temperature values is inferred for the period just before that LGM. Besides, a wetter than early Holocene is inferred for the modern climate.

In a study conducted in Lake Van, (largest lake in Turkey, located in the east) it was determined that the aridity started to increase and the modern climate conditions started to develop after 4 ka BP (Wick et al. 2003). Kuzucuoğlu et al. (2011) determined the variation of Mediterranean climate and its effect on Anatolia during the last 6 ka based on records obtained from Tecer Lake.

Several paleoclimate studies based on marine sediment and tree ring records have also been conducted in and around Turkey. These studies concentrate mainly in the Black Sea and Aegean Sea regions where $\delta^{18}O$ content of planktonic foraminifera and ostracoda have been used to infer the temporal variation of sea surface temperature and hence the paleoclimate. Studies in the northern (Kothoff et al.,2008) and southern Aegean Sea (Rohling et al. 2002) suggested the Holocene climate in the Aegean Sea was determined by the low latitude monsoons and by the temporal variations of the solar insolation. Bahr et al. (2006) determined an isotopic depletion in Black Sea water after the LGM based on oxygen-18 data obtained from ostracoda.

Despite their limited temporal extent, dendrochronological studies conducted in Turkey helped to determine past environmental variations based on $\delta^{13}C$ and $\delta^{18}O$ signals obtained from tree rings. Mutlu et al. (2011) determined the effect of industrial development on precipitation and atmosphere chemistry during ca. last 200 years based on the tree ring $\delta^{13}C$ and $\delta^{18}O$ data obtained from black pine.

2.2. Speleothem-based studies

While paleoclimate studies based on the lake and marine sediments provide useful long-term paleoclimate data, they also suffer from the large age uncertainty. Data obtained from well-dated tree rings has limited spatio-temporal extent. Under these circumstances, speleothems which can be dated precisely appear to be indispensable archives of the late Quaternary paleoclimate. Hence, the number of paleoclimate studies based on speleothems has increased substantially during the last 5 years. Several caves developed in carbonate rocks along the northern, southern and central-west Turkey were studied for speleothem-based paleoclimate records during this period (Fig. 3, Table 2). Data obtained from caves in central-west and southern Turkey caves revealed a paleoclimate similar to that inferred for the eastern Mediterranean region. Moreover, the data obtained from these caves is found to be in agreement with those obtained from lake and sea sediments.

Fleitmann et al. (2009) evaluated the $\delta^{18}O$ and $\delta^{13}C$ signals of precisely ^{230}Th dated, 50 ka old stalagmite obtained from Sofular Cave. They found evidences of the rapid climate fluctuations during the Greenland interstadials of the last glacial period. In another study based on the same stalagmite sample from Sofular Cave Göktürk et al. (2011) compared the speleothem signal with the concurrent Black Sea core records (Bahr et al. 2006) (Fig. 2) and other cave (Soreq, Qunf, Jeita caves) records that reflects the late Quaternary paleoclimate in the eastern Mediterranean Sea. The effect of regional and global climate dynamics upon the paleoclimate of central Anatolia was studied by Özbakır (2010), Erkan (2012) on stalagmites obtained from Incesu Cave. The authors compared the temporal $\delta^{18}O$ and $\delta^{13}C$ signals obtained from Incesu Cave samples with those of obtained from lake-sea sediments and speleothems from locations in the eastern Mediterranean Sea, central Anatolia, Aegean Sea and Black Sea regions. They found that the isotopic signal of precipitation over the Black Sea and eastern Mediterranean Sea regions had different trends before and after the LGM. They found evidences of a cooler and more arid climate than the present between the LGM and early Holocene while after the early Holocene a warmer and more humid period existed. Moreover, they found also that the Younger Dryas, 8.2 ka event, 4.2. ka event and some of the Heinrich events affected the central Anatolia.

The paleoclimate records of Sofular Cave was also used by Baderschter et al. (2011) to explain the paleo precipitation regime and water mass flux in Black Sea and Mediterranean Sea during the late Quaternary. Kweicen et al. (2009) conducted a study for a similar purpose.

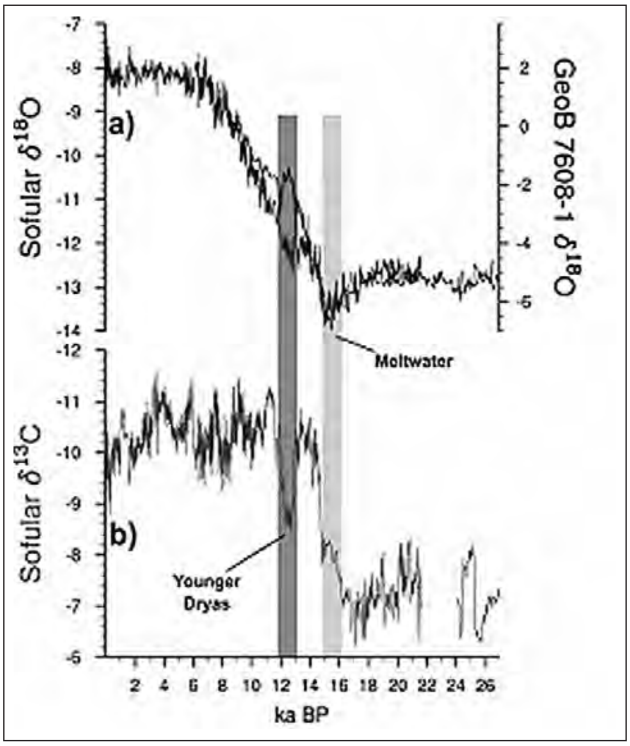

Figure 2. Comparison of isotope signals obtained from Sofular Cave and western Black Sea core (Göktürk et al. 2011).

In another study conducted by Şenoğlu (2006) in Yelini Cave, LA-ICP-MS technique was used to determine the temporal variation of trace element composition along the growth axis of a stalagmite that formed during the last 0.6 ka. She used trace element (Sr, B, Mg, Al) signal intensity variations, changes in laminae color and thickness, and the variations of stalagmite diameter from bottom to top as proxies of paleoclimate. The laminae were found to

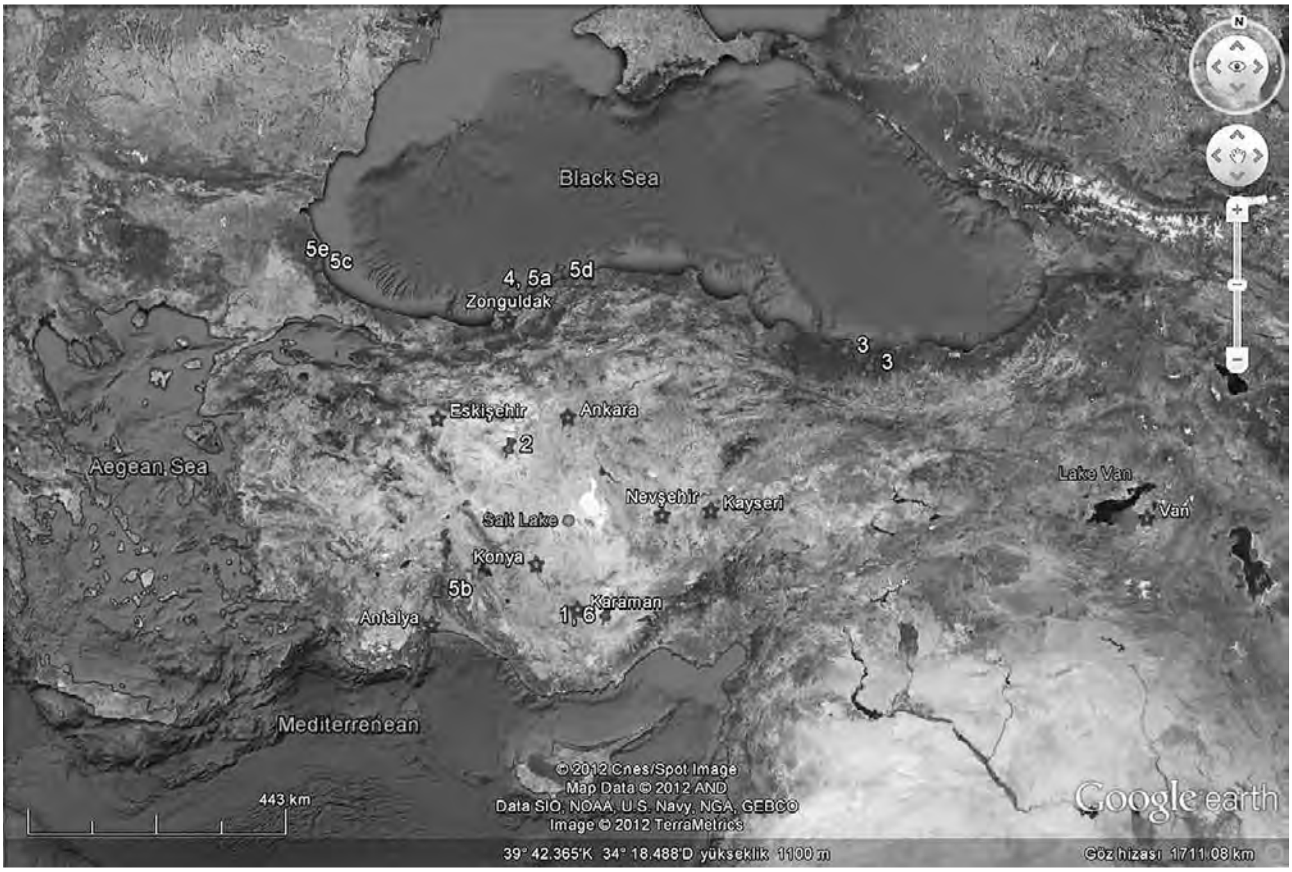

Figure 3. Locations of speleothem-based paleoclimate studies in Turkey (numbers are keyed to Table 2).

Table 2. Speleothem-based paleoclimate studies in Turkey.

Key No	Study Area	Location	Archive Type	Reference
1.	Incesu Cave	Karaman	Stalagmite	Özbakır Msc thesis 2010
2.	Yelini Cave	Eskişehir	Stalagmite	Şenoğlu Msc thesis 2006
3.	Karaca Cave	Gümüşhane	Stalagmite	Jex PhD thesis 2008
3.	Akçakale Cave	Gümüşhane	Stalagmite	Jex PhD thesis 2008
4.	Sofular Cave	Zonguldak	Stalagmite	Fleitmann et al. 2009
5a.	Sofular Cave	Zonguldak	Stalagmite	Göktürk PhD thesis 2011
5b.	Kocain Cave	Antalya	Stalagmite	Göktürk PhD thesis 2011
5c.	Uzuntarla Cave	Trakya	Stalagmite	Göktürk PhD thesis 2011
5d.	Ovacık Cave	Zonguldak	Stalagmite	Göktürk PhD thesis 2011
5e.	Yenesu Cave	Trakya	Stalagmite	Göktürk PhD thesis 2011
6.	Incesu Cave	Karaman	Stalagmite	Erkan PhD thesis 2012

be relatively thin and white in color and the diameter of stalagmite is relatively narrow during the relatively cool periods. It was also found that laminae color changes to brownish during the relatively warm-humid periods as a result of the increased biogenic activity in the soil zone. The signals obtained from this stalagmite were found to be in agreement with the historical records of famine, flood and cooling events in central Anatolia.

3. Conclusions and Outlook

Many studies have been conducted in Turkey to determine the paleoclimate/environment conditions during the late Quaternary based on data from lake and sea sediments, tree rings and speleothems. Studies based on speleothems have increased during the last 5 years. The data obtained indicate several important conclusions as summarized below. The paleoclimate of central Anatolia during the late Quaternary resembles that of the eastern Mediterranean. The isotopic signals of paleoprecipitation and paleobiogenic activity in the soil zone have different trends in the northern and southern parts of Turkey. In general, a cooler and drier climate is inferred for the period before LGM while a warmer and more humid climate is inferred for the late Holocene. Early Holocene is relatively drier and cooler. Global events like Younger Dryas, 8.2 ka event, 4.2 ka event and some of the Heinrich events have recorded also in speleothem samples in Turkey.

The studies conducted to determine the paleoclimate and paleoenvironment of Turkey concentrate mainly on the western part of the country. Studies in the eastern part are limited to Black Sea mountains at the northeast. Though central-eastern Anatolia suffers from a lack of cave-hosting carbonate rock formations, the geology of southeastern Turkey is very promising. Thus, part of the future studies can be carried out in this region. Another challenging study area is the coastal and submarine caves. Some of the submarine caves may host speleothems formed during the

LGM. Studying these samples would help to better understand the eastern Mediterranean climate during that period.

Acknowledgments

Field and laboratory studies associated with Incesu Cave was financially supported by the Scientific and Technological Research Council of Turkey (TUBITAK) under the grant CAYDAG 108Y004. Dr. D. Fleitmann (University of Bern), Dr. H. Cheng (University of Minnesota), Dr. K. Törk, Dr. N. Güner (Turkish Geological Survey, MTA), Dr. N.N. Ozyurt and Mr. M. Ozbakir (Hacettepe University) have collaborated in study of Incesu and Yelini Caves.

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ISOTOPES OF GYPSUM HYDRATION WATER IN SELENITE CRYSTALS FROM THE CAVES OF THE NAICA MINE (CHIHUAHUA, MEXICO)

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We examined the isotopic composition of gypsum hydration water ($\delta^{18}O$ and δD) in several selenite speleothems from the caves of the Naica Mine (Chihuahua, Mexico). The gypsum samples were collected from depths of -120 m ("Sword Cave") and -290 m below the surface ("Crystales Cave" and "Ojo de la Reina Cave"). $\delta^{18}O$ ranged between -4.66 and -3.26‰, whilst δD varied between -81.78 and -71.43‰, relative to V-SMOW. The isotopic composition of the Naica aquifer was calculated using known isotopic fractionation factors for δD and $\delta^{18}O$ during gypsum precipitation ($\alpha D_{gyp-H2O}$= 0.980 and $\alpha^{18}O_{gyp-H2O}$= 1.004), which are independent of temperature (at low values). Our results reveal that $\delta^{18}O$ of the Naica aquifer water ranged between -8.62 and -7.23‰, whilst δD was between -63.04 and -52.48‰ during the period in which the gypsum crystals precipitated under subaqueous conditions from a hydrothermal solution. The data are described by a line (δD= 7.97 $\delta^{18}O$ + 5.81) that is close to the current meteoric water line at the setting of Naica. Furthermore, the current water of the deep aquifer shows isotopic values that also fit with the inferred values of the aquifer palaeogroundwater. The differences observed between gypsum at -120 m and -290 m deep could be explained by selenite crystals formed under different climatic conditions, as revealed by previous geochronological studies on these speleothems. Changes in the main moisture source of precipitation (Pacific Ocean/Gulf of Mexico) affected the isotopic composition of the meteoric water in this area during the Quaternary. Alternatively, $\delta^{18}O$ and δD of gypsum precipitated during the Holocene at -120 m show that evaporation of the shallower aquifer affected the isotopic composition of the groundwater during that period. In conclusion, we confirm that the huge gypsum speleothems of the Naica caves precipitated from water of meteoric origin that infiltrated in the hydrothermal aquifer of Naica, with indication of evaporation during the Holocene. Our preliminary results suggest that phreatic gypsum speleothems constitute a potentially promesing archive for palaeogroundwater and palaeoclimate reconstruction.

1. Introduction

The caves of the Naica Mine (Chihuahua, Mexico) host some of the largest hydrothermal gypsum speleothems worldwide (García-Ruiz et al. 1997; Forti 2010). In the Cueva de los Cristales ("Crystals Cave"), at at depth of -290 m, huge selenite crystals up to 11 m in length are found (Badino et al. 2009).

In addition, other smaller caves hosting selenite speleothems were discovered at -290 m below surface when in 2000, the mining galleries intercepted the natural cavities. For instance, Ojo de la Reina Cave, which consists of a narrow sub-vertical fracture parallel to a fault, is totally filled with giant prismatic selenite crystals (Badino et al. 2011). Cueva de las Espadas ("Sword Cave") at -120 m below the surface was discovered in the 20th century. This small cave is home of the "espada" speleothems, consisting of prismatic selenite crystals covered by a layer of carbonate (aragonite and calcite) and gypsum (Gázquez et al. 2012a).

Over the past decade, the mineralogy, and some geochemical characteristics of these striking speleothems have been studied (García-Ruiz et al. 2007; Sanna et al. 2010; Garofalo et al. 2010; Badino et al. 2011; Gázquez et al. 2012a,b), as well as the mechanism of formation (García-Ruíz et al. 2007; Forti 2010). In some of this work, the speleothems of Naica caves have been proposed as palaeoclimate indicators (Garofalo et al. 2010; Gázquez et al. 2011; Gázquez et al. 2012a,b). Nevertheless, some questions remain about the characteristics of the hydrothermal water that gave rise to gypsum speleothems precipitation in the Naica system.

Figure 1. Location of the main caves in the Naica Mine in which gypsum speleothems have been studied as part of this study.

Hydration water of gypsum has been demonstrated to be a powerful tool for studying the isotopic composition of the water from which gypsum precipitates. Applications include pedogenic gypsum (Farpoor et al. 2004; Bruck and Van Hoesen 2005) and gypsiferous sediments from lakes (Hodell et al. 2012).

In this study, we have measured the isotopic ratios ($\delta^{18}O$ and δD) of gypsum hydration water in selenite speleothems from the Cueva de los Cristales, Cueva de las Espadas and Ojo de la Reina Cave. The objective is to reconstruct the isotopic composition of the palaeogroundwater of the Naica aquifer from which the gypsum precipitated as well as the possible causes of isotopic variations.

2. Geological setting

The Naica mining district, located in Chihuahua State, Northern Mexico, has been one of the most important areas for lead and silver production in the world since the middle of the nineteenth century (Fig. 1). At the Naica Mine, the mining activities are centred around extracting zinc and lead sulphides enriched in silver (Ruiz et al. 1985). Up to 1 million tons of material are extracted each year from the mine resulting in 150 tons of silver and 50,000 tons of lead (Giulivo et al. 2007).

The current climate of the Naica region is typical of the Chihuahua desert with temperatures greater than 35–50 ºC in summer but slightly colder than in the neighbouring deserts of Sonora and Mojave. Annual precipitation is less than 250 mm with most rainfall occurring in the monsoon season during late summer (Hoy and Gross 1982).

The entrance to the mine lies at 1385 m.a.s.l. on the southern face of an anticline structure called Sierra de Naica. The regional stratigraphy comprises limestone and dolostone with interbedded clays and silts (Albian and Cenomanian) (Franco-Rubio 1978). Intrusive magmatic activity during the Tertiary is evidenced by acid dikes in the carbonate series (Alva-Valdivia et al. 2003) (Fig. 1A). The contact between the groundwater and these igneous bodies created a hydrothermal system containing brines, which flowed along lines of weakness that follow the alignment of the dikes and faults (Ruiz et al. 1985). These brines interacted with felsic materials and limestone, giving rise to new minerals (Megaw et al. 1988). In fact, the development of the natural cavities in the Sierra de Naica Mountain is closely related to the main faults in this system, the Naica Fault and the Montaña Fault (Fig. 1) (Forti 2010).

The gradual cooling of the aquifer water resulted in precipitation of low-temperature hydrothermal minerals such as quartz, calcite, aragonite, anhydrite, and eventually gypsum (Erwood et al. 1979). Oxidation of metal sulphides enriched the groundwater in sulphates and led to precipitation of anhydrite at high temperature. Later, gradual cooling of the system caused dissolution of anhydrite, slightly supersaturating the water in gypsum below 58 ºC (García-Ruiz et al. 2007).

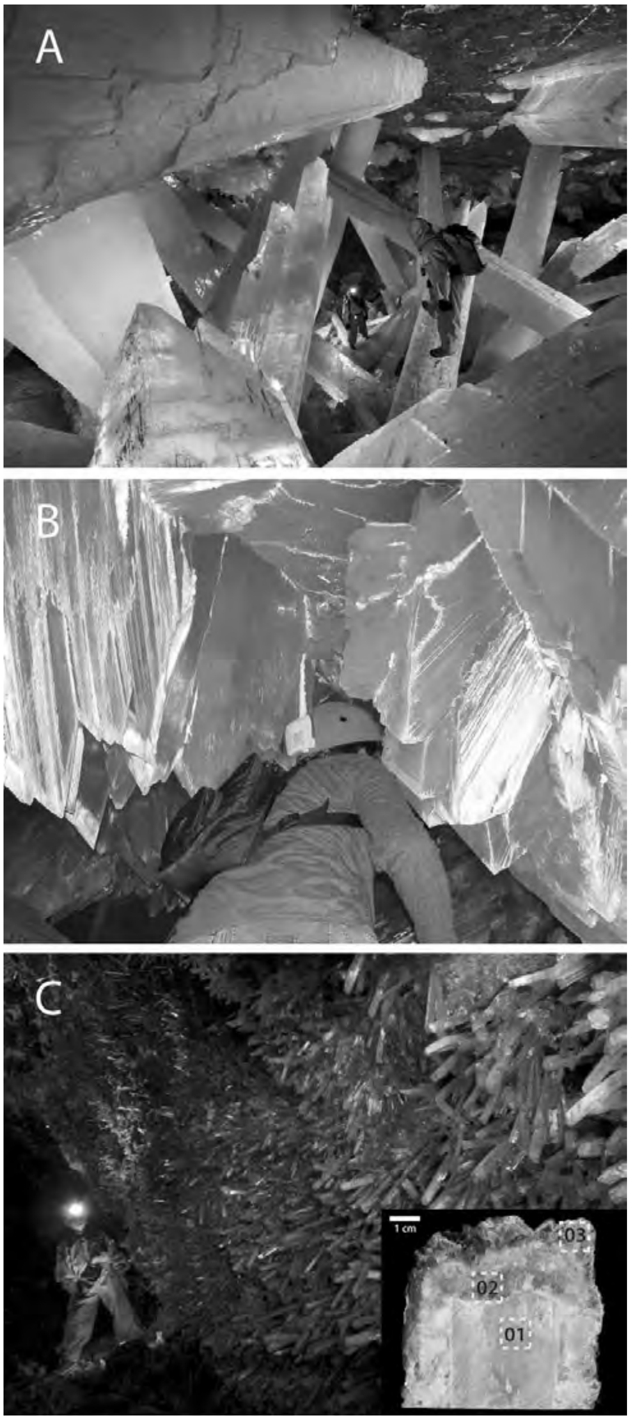

Figure 2. Gypsum speleothems studied in this work. A. Cueva de los Cristales, where the gypsum sample was taken from the inner central part of a huge selenite crystal; B. Ojo de la Reina Cave. The sample were collected from basal part of a gypsum wall; C. Cueva de las Espadas. Samples were extracted from different gypsum layers of an "espada" speleothem (see main text and Gázquez et al. 2012a).

3. Methods

Five gypsum samples were examined in this work coming from Cueva de los Cristales (CRI-01), Ojo de la Reina Cave (OJO-01), and Cueva de las Espadas (ESP-01, ESP-02, ESP-03).

Powdered subsamples were extracted by using a Dremel® drill. Sample CRI-01 comes from the inner central part of a fragment of a huge selenite crystal that rested on the floor of the Cueva de los Cristales (-290 m level). Sample OJO-01 was collected from the basal part of the selenite deposits that cover the walls of Ojo de la Reina Cave (-290 m level). Finally, samples ESP-01, ESP-02 and ESP-03 were extracted from an "espada" speleothem of the Cueva de las Espadas (-120 m level). ESP-01 was taken from the selenite core of the speleothem, while ESP-02 and ESP-03 were extracted from two layers composed of microcrystalline gypsum that are separated by aragonite laminae (Fig. 2C), as previously identified by Raman spectroscopy (Gázquez et al. 2012a).

The isotopic analyses of gypsum hydration water were carried out in the Godwin Laboratory for Palaeoclimate Research (Department of Earth Science) at the University of Cambridge (UK) following the method of Hodell et al. (2012). About 300–400 mg of gypsum was gently ground, loaded into glass boats, and placed in a vacuum extraction line and evacuated to a pressure of 10^{-3} mbars. Samples were pumped on for 3 hours at room temperature with a liquid nitrogen trap fitted on the pumping line to remove absorbed water and fluid inclusions from the ground gypsum. This low-vacuum pumping was found to be effective at removing absorbed water with no detectable loss of hydration water (Playa et al. 2005).

Crystallization water in gypsum was released by slowly heating the sample to 450 ºC *in vacuo* and freezing the hydration water in a 6-mm-OD breakseal tube, immersed in liquid nitrogen for at least 45 minutes. Non-condensable gases were pumped for 30 seconds before flame sealing the tube. Samples were weighed before and after heating to determine weight loss as a measure of the mass of hydration water extracted.

The 6-mm-OD tube containing 60–80 µl of hydration water was scored and broken to a fixed height and inserted into a 2-ml septum-capped vial and placed in the autosampler of the water isotope analyzer. Water oxygen and hydrogen isotopes were measured simultaneously by cavity ringdown laser spectroscopy (CRDS) using a L1102-*i* Picarro water isotope analyzer and A0211 high-precision vaporizer. Each sample was injected nine times into the vaporizer.

Memory effects from previous samples were avoided by rejecting the first three analyses. Values for the final six injections were averaged with in-run precision of less than ±0.1 for $\delta^{18}O$ and ±1 for δD (1-standard deviation). Calibration of results to V-SMOW was achieved by analyzing internal standards before and after each set of 7 or 8 samples. Internal standards were calibrated against V-SMOW, GISP, and SLAP. All results are reported in parts per thousand (‰) relative to V-SMOW. External precision was estimated by repeated analysis of the internal gypsum standard, Cambridge Gypsum (CamGyp), with $\delta^{18}O$ = -5.0 ±0.1‰ and δD = -71 ±1.4‰ (n=9).

4. Results

On the basis of the $\delta^{18}O$ and δD (Table 1), the gypsum samples examined in this work can be split into two groups. First, the selenite samples from the caves at -290 m deep (CRI-01 and OJO-01) show the lowest $\delta^{18}O$ and δD values of the whole sample set, around -4.54‰ ±0.16 and -80.70‰ ±1.54 (n=2), respectively. Meanwhile, the gypsum samples from the Cueva de las Espadas (at the -120 level) are more enriched in the heavier isotopes of hydrogen and oxygen, showing values around -3.35‰ ±0.13 and -72.01‰ ±0.63 (n=3) for $\delta^{18}O$ and δD, respectively.

In the Cueva de las Espadas speleothem, the hydration water of the selenite core of the "espada" speleothem is marginally isotopically lighter (-3.50‰ and -72.68‰ for $\delta^{18}O$ and δD, respectively) than the external gypsum layers (-3.27‰ ±0.01 and -71.67‰ ± 0.34 (n=2) for $\delta^{18}O$ and δD, respectively).

Table 1. Isotopic composition of the gypsum samples analyzed in this study ($\delta^{18}O_{gyp}$ and δD_{gyp}) and the inferred values for the palaeogroundwater of the Naica aquifer ($\delta^{18}O_w$ and δD_w) utilizing the fractionation coefficients obtained by Hodell et al. (2012).

Sample	Cave	$\delta^{18}O_{gyp}$	δD_{gyp}	$\delta^{18}O_w$	δD_w
OJO-01	Reina	-4.42	-79.61	-8.39	-60.83
CRI-01	Cristales	-4.66	-81.78	-8.62	-63.04
ESP01	Espadas	-3.50	-72.68	-7.47	-53.75
ESP02	Espadas	-3.26	-71.43	-7.23	-52.48
ESP03	Espadas	-3.28	-71.92	-7.25	-52.98

By studying the the isotopes of hydration water of gypsum in the speleothems of the Naica Mine, it has been possible to infer the isotopic characteristics of the deep aquifer of Naica during gypsum precipitation.

Classic studies of light isotopes in gypsum demonstrate that the δD of gypsum is around 19‰ lower than the solution from which it derives, whilst $\delta^{18}O$ of hydration water is enriched by about 4‰ (Fontes and Gonfiantini 1967; Sofer 1978; Pradhananga and Matsuo 1985). Isotope fractionations of hydrogen ($\alpha D_{gyp-H2O}$=0.985) and oxygen isotopes ($\alpha^{18}O_{gyp-H2O}$=1.004) are virtually independent of temperature below 58 ºC (Gonfiantini and Fontes 1963; Fontes and Gonfiantini 1967; Hodell et al. 2012).

By using this fractionation factor we found that the δD of the aquifer water during the formation of the gypsum speleothems of Naica ranged between -63.04‰ and -52.48‰ for δD and between -8.62‰ and -7.23 for $\delta^{18}O$ (Table 1). Regarding differences between crystals precipitated at -120 m and -290 m below the mine entrance, gypsum precipitated in Cueva de las Espadas is enriched in heavier isotopes with respect to the speleothems of Cueva de los Cristales and Ojo de la Reina by around 10‰ and 1‰ for δD and $\delta^{18}O$, respectively. (Table 1 and Fig. 3).

Regarding only the samples from the Cueva de las Espadas, the isotopic differences observed between them suggests that the selenite core of the "espada" speleothems (ESP-01) precipitated from water slightly depleted in the heavier isotopes compared to the external gypsum layers (ESP-02 and ESP-03).

5. Discussion

The isotopic composition of the Naica aquifer inferred from the gypsum hydration water of selenite speleothems from Cueva de los Cristales, Ojo de la Reina and the selenite crystals of Cueva de las Espadas fall on a line expressed by:

$$\delta D = 7.97\ \delta^{18}O + 5.81$$

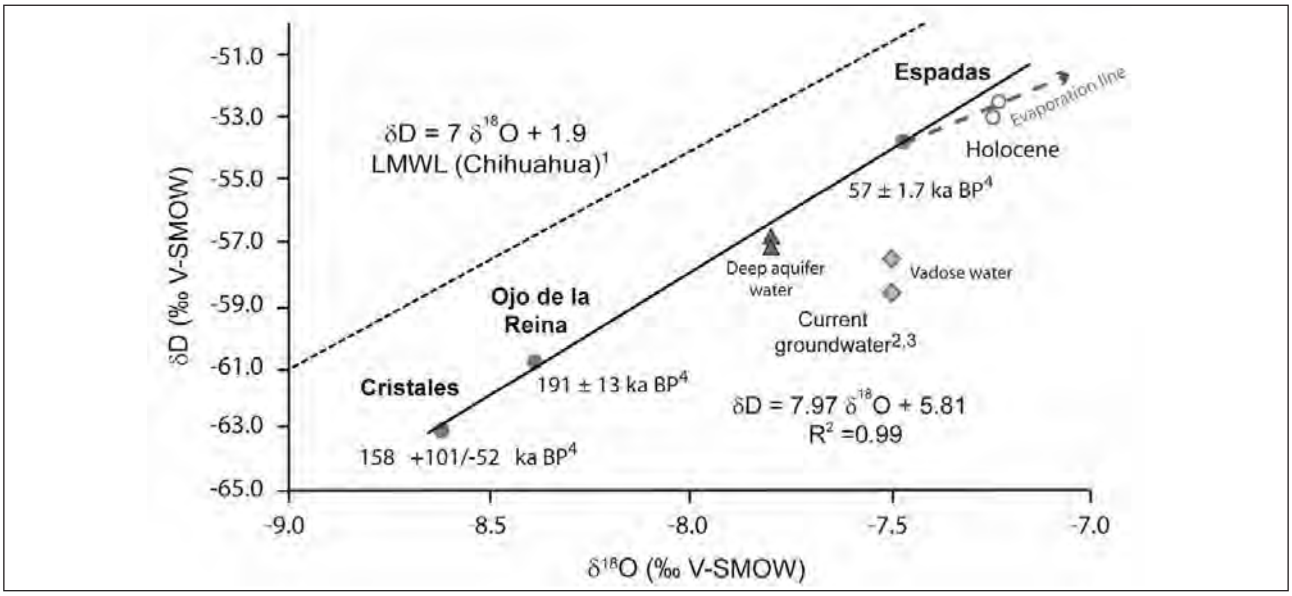

Figure 3. Isotopic composition ($\delta^{18}O$ and δD) of the palaeogroundwater of the Naica aquifer inferred from gypsum hydration water of selenite speleothems. Data from the huge crystals from Cueva de los Cristales, Ojo de la Reina and Cueva de las Espadas (core of the "espada" speleothem) fit a line that is close to the local meteoric water line (LMWL) at the Chihuahua setting (Cortés et al. 1997[1]). Data from the external gypsum layers of the"espada" speleothems of Cueva de las Espadas suggest that gypsum precipitated from evaporated water during Holocene. The isotopic values of the current groundwater have been also represented, after Dames and More (1977)[2] and García-Ruíz et al. (2007)[3]. The age of the samples obtained by Sanna et al. (2010)[4] have been also indicated.

Such a relationship between δD and $\delta^{18}O$ is typical of meteoric water (Craig 1961) and is close to the local meteoric water line of the Chihuahua setting (Cortés et al. 1997) (Fig. 3). This fact points to the aqueous solution that gave rise to gypsum precipitation in the Naica caves consisted of meteoric water that infiltrated in the Naica aquifer and underwent changes in chemical composition and temperature (Fig. 4).

The isotopic values of the current aquifer water also fit this line. Dames and More (1977), and later García-Ruíz et al. (2007) reported values of -57.0‰ ±0.1 and -7.80‰, for δD and $\delta^{18}O$ respectively, in the thermal water around the deepest level of the mine, at -430 m and -640 m in 1976 and 2002, respectively (Fig. 3). However, the isotopic composition of the samples collected at the shallower levels of the mine (-290 and -530 in 1976 and 2003, respectively) fall slightly off this trend. This observation suggests that gypsum speleothems in the Naica caves was formed from deep-aquifer water, which represents the mean regional isotopic composition of the meteoric water in the Chihuahua setting (regional recharge). Meanwhile, samples taken at the shallower levels could represent vadose water; therefore, the isotopic composition of the local meteoric water at the location of the Sierra de Naica Mountain (local recharge) was probably affected by evaporation (Fig. 4).

The age of several gypsum speleothems of the Naica caves were reported by Sanna et al. (2010). According to these authors, the oldest selenite crystals in the Naica mine are located at the -290 m level, where gypsum started to precipitate before 191 ± 16 ka BP (Sanna et al. 2011) as indicated by the age of the basal gypsum crystal of Ojo de la Reina Cave (sample OJO-01 in this work). Nevertheless, regarding the imprecise age of the inner central part of the huge crystals of Cueva de los Cristales (158 +101/-52 ka BP, CRI-01 in this work), gypsum precipitation in the Naica Mine could have started even before that date.

In Cueva de las Espadas, gypsum precipitated around 57 ± 1.7 ka BP (Sanna et al. 2010; sample ESP-01 in this work) and during some periods of the Holocene (Sanna et al. 2010; Gázquez et al. 2012a), giving rise to the "espada" speleothems.

The solution that generated the external gypsum layer of the "espada" speleothems during the Holocene had isotopic values that below the $\delta^{18}O$-δD line of the Naica aquifer palaeogroundwater. These data follow an evaporation line, indicating that these gypsum layers came from solutions that had previously evaporated in the shallower level of the aquifer when the water table was near the Cueva de las Espadas level (Fig. 4). This interpretation is supported by earlier studies of fluid inclusions that determined that the external gypsum layers of the "espada" speleothems are considerably more saline than the fluid inclusions of the selenite core, and also than those of the crystals at -290 m deep (Garofalo et al. 2010).

Considering the wide period of time along which gypsum precipitated in the Naica system, the differences observed in δD and $\delta^{18}O$ are undoubtedly linked to changes in the isotopic composition of the hydrothermal water of the aquifer, probably as a consequence of palaeoclimate changes that affected the isotopes of the meteoric water in northern Mexico.

Isotopic variability in meteoric water in northern Mexico has been demonstrated to be dependent of moisture source changes at seasonal (Hoy and Gross 1982; Yapp 1985) and palaeoclimate scales (Harmon et al. 1979; Asmerom et al. 2010). In this area, recharge responds most strongly to changing precipitation delivered by the North American summer monsoon. Currently the region receives precipitation from Pacific winter cyclones, but the majority (>50 %) is derived from the summer monsoon system in the Gulf of Mexico (Hoy and Gross 1982).

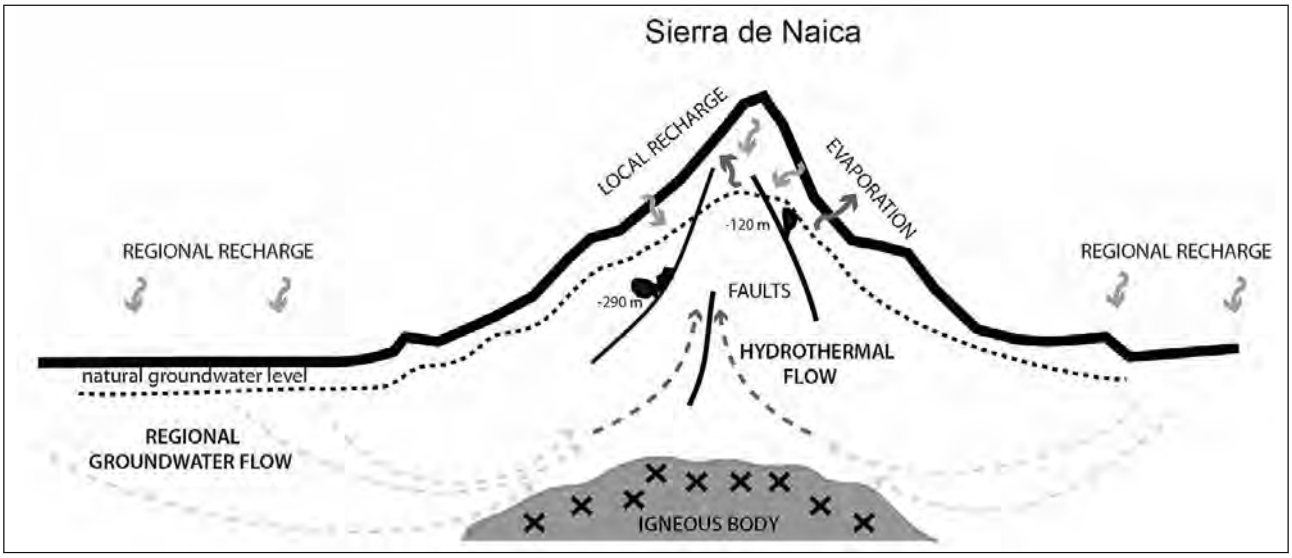

Figure 4. Hydrogeological sketch of the Naica aquifer. The hydrothermal system is fed by the regional groundwater flow from the vicinity of the Sierra de Naica mountain range (regional recharge) and the seepage of meteoric water in the Naica karst (local recharge). Evaporation in the aquifer surface led to precipitation of gypsum isotopically enriched ($\delta^{18}O$ and δD of hydration water) and with high-saline fluid inclusion in Cueva de las Espadas (-120 m level) during the Holocene, when the water table was near the cave level.

The proportional contributions to the regional precipitations from these two areas have changed on palaeoclimatic time scales (Harmon et al. 1979; Asmerom et al. 2010). When moisture comes mainly from the Pacific Ocean, the rainfall is isotopically depleted compared to reainfall derived during the summer monsoon from the Gulf of Mexico rainfall. Considering that the gypsum crystals of the Naica caves grew during a period of at least 200 ka, the isotopic composition of the aquifer water could be affected by isotopic changes in the recharge as a response to climate cycles over the Quaternary.

Thus, it is possible to track changes in the moisture source through time. Our data obtained from the gypsum speleothems of Naica show that δD of the thermal water could range by around 10‰, whilst $\delta^{18}O$ oscillated up to 1.5‰ during the different stages of gypsum precipitation.

During the Holocene, evaporation enriched the shallower aquifer in the heavier isotopes by around 0.25‰ for $\delta^{18}O$ and by 1‰ for δD as observed in the external gypsum layer of the "espada" speleothems. In contrast, the expected isotopic variations due to changes in the main moisture source of precipitation would be around 9‰ and 1.25‰ for δD and $\delta^{18}O$, respectively.

Asmerom et al. (2010) determined that $\delta^{18}O$ of rainfall in New Mexico (USA) changed by 6‰ during the Pleistocene-Holocene transition by analyzing a calcite stalagmite from Fort Stanton Cave. In addition, other studies showed that during the Last Glacial stage, meteoric water was depleted in deuterium by 12‰ relative to the Eemian Interglacial (Harmon et al. 1979).

These earlier studies revealed that displacements of both the intertropical convergence zone and the polar jet casued changes in the main moisture source of precipitation in this area.

From a palaeoclimatic point of view, and considering the ages of the crystals at -290 m deep, these speleothems precipitated from themal water during the marine isotopic stage 7 (*MIS* 7), whereas the first stage of gypsum precipitation at the -120 m level occurred during *MIS* 3.

Our data reveal that the recharge of the aquifer was considerably depleted in heavier isotopes around 200 ka BP with respect to 60 ka BP and the Holocene. Thus, moisture contribution from the Pacific Ocean was more relevant in this area during *MIS* 7 compared to *MIS* 3 and the Holocene. Finally, the external gypsum layers of the "espada" speleothems of the Cueva de las Espadas grew during the Holocene from water isotopically heavier than in previous stages. Nevertheless, in this case evaporation could play a main role during its crystallization, so more data will be necessary to estimate the isotopic composition of the solution prior to evaporation.

6. Conclusions

1) The isotopic values of the Naica aquifer inferred from gypsum speleothems all on a line that is close to the current meteoric water line for the Naica region. In addition, the isotopic composition of the current aquifer water fits this line. Consequently, we conclude that the huge gypsum speleothems of the Naica caves precipitated from water of meteoric origin that changed in temperature and chemical composition along its flowpath through the Naica aquifer.
2) Variations in the isotopic value of the Naica aquifer changed over the past 200 ka BP as a result of regional palaeoclimate changes, and particularly in response to changes of the main moisture source (Pacific Ocean/Gulf of Mexico).
3) Evaporation affected the isotopic composition of the hydrothermal solution when the water table was near the Cueva de las Espadas level, as recorded by the Holocene gypsum layers of the "espada" speleothems.
4) According to these preliminary data, phreatic gypsum speleothems are potential archives for future study of palaeogroundwater and palaeoclimate.

Acknowledgments

Financial support for this work was made available through the "PALAEOGYP" International Collaboration Project (CGL2006-01707/BTE Ministry of Science and Innovation, Spain and FEDER funds of EU), the Spanish Science grant AP-2007-02799, and the U.K. National Environmental Research Council (NERC). The authors would like to thank the Peñoles Company for allowing access inside the Naica Mine and for their support during field work. Logistics was carried out by "NAICA PROJECT" Speleoresearch and Films of Mexico City in co-operation with La Venta Exploring Team (Italy). Photographs of Naica caves were kindly provided by La Venta and S/F Archives.

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FORTY YEARS OF PHREATIC OVERGROWTHS ON SPELEOTHEMS (POS) RESEARCH IN COASTAL CAVES OF MALLORCA*

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The littoral caves of southeastern Mallorca have formed by the mixing of freshwater and seawater in the coastal phreatic zone, and are extensively decorated with speleothems that formed during Quaternary times when the caves become air-filled chambers. Throughout the Middle and Upper Pleistocene the caves were repeatedly flooded by glacio-eustatic sea level oscillations. The water level of each flooding event was recorded by a distinct encrustation (a Phreatic Overgrowth on Speleothems, POS) of calcite or aragonite over existing speleothems and along cave walls. These carbonate precipitates, which appear as horizontal alignments of crystallizations delimiting the tidal fluctuation range of the coastal water-table, are excellent recorders of sea level changes, being readily datable by U-series methods. Through the last four decades, a new approach to the Mediterranean sea level history has arisen from the interdisciplinary study of such particular type of speleothems in the littoral caves of Mallorca Island. More than 50 POS, collected from 17 littoral caves, have provided 97 U-series ages in the range from 0.6 ka to >350 ka BP. On the basis of these data, accurate elevations of sea level stands both during the Holocene and over the MIS 5 and 4 can be determined.

1. Introduction: Phreatic Overgrowths on Speleothems (POS) from Mallorca Island

Karst landforms are abundant along the southern and eastern coasts of Mallorca, particularly in the Upper Miocene post-orogenic carbonate rocks (Ginés 2000; Ginés et al. 2012a). One of the most distinctive features of the coastal caves on Mallorca Island is the presence of extensive subterranean brackish pools. These ponds are currently flooding the lower parts of the caves, in elevational and hydrodynamic correspondence with present-day Mediterranean sea level (Pomar et al. 1979; Ginés and Ginés 2007). The sea level control over the littoral cave pools is evident since their surface undergoes daily fluctuations, related to minor tidal and/or barometric sea level oscillations.

In this particular microenvironment, geochemically characterized by relatively elevated contents of chloride, sulfate, magnesium, and calcium, it is possible to observe freshly precipitated carbonates (phreatic overgrowths forming horizontal bands, floating calcite rafts, etc.) linked to the surface of these subterranean ponds (Pomar et al 1976, 1979; Tuccimei et al. 2010; Ginés et al. 2012b; Onac et al. 2012). Just as these POS record the current sea level position, ancient crystallizations of the same type – situated both above and below the present-day ±0 elevation datum – prove to be an excellent register of past sea level (Figure 1), a fact documented in a number of papers (Vesica et al. 2000; Fornós et al. 2002; Tuccimei et al. 2006; Dorale et al. 2010).

Generally speaking, the POS from Mallorcan littoral caves are crystalline coatings that define strictly horizontal bands. These carbonate encrustations develop along the cave walls, or over any suitable support (for example, common vadose speleothems) penetrating below the surface of the subterranean pools (Figure 2). The morphology of these coatings is bulky and its maximum thickness corresponds to the mean position of the water table. As a rule, the thickest part of the overgrowth is located in the middle of the crystallizations belt, gradually decreasing upward and downward. The belt-like form of POS deposits has a rather simple statistical explanation that relates to the position of the water table, where the maximum thickness occurs at the mean sea level during its growth period (Pomar et al. 1979).

The morphological variety of phreatic speleothems is enormous (Ginés and Ginés 1974; Ginés et al. 2005). Very abundant and conspicuous are those globular forms described above. At the same time, some other forms are represented, but to a lesser extent, as for example the deposits of floating calcite and/or aragonite rafts, as well as cave cones produced by the accumulation of sunken floating rafts (Pomar et al. 1976; Ginés et al. 2005). These variegated phreatic crystallizations constrain (in a very noticeable manner) fully horizontal belts of encrustations, whose elevation correspondence with contemporaneous sea level is the central to the present investigations, as earlier postulated by Ginés and Ginés (1974) and Ginés et al. (1981a).

* The present publication is an abridged version of the chapter *Phreatic overgrowths on speleothems (POS) from Mallorca, Spain: Updating forty years of research* published with the occasion of the *Sea-level changes into MIS 5: from observation to prediction* Workshop, held in Palma de Mallorca between April 10–14, 2012. The full text is available at: http://www.shnb.org/monografies/monografia18/Mon_Soc_Hist_Nat_Balears_18_2012.pdf

Currently up to 30 paleolevels of POS (ranging from +46 m ASL to -23 m below the current ±0 datum) have been recognized in Mallorcan caves (Ginés 2000). Overall, the POS alignments that are localized at positive elevations record transgressive high-stands associated with interglacial or interstadial periods, whereas the speleothem bands or overgrowths situated below the current sea level may correspond to regressive pulsations linked to glacial or stadial conditions.

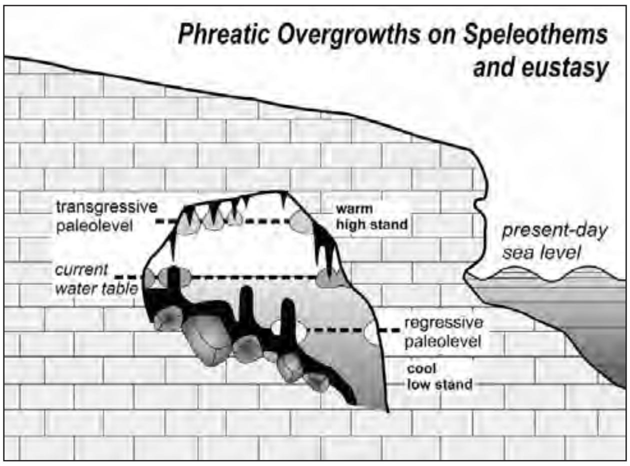

Figure 1. Sketch of a karstic littoral cave of Mallorca hosting present-day as well as ancient POS deposits. Broken lines represent the mean elevation attained by the ground water table during each recorded sea stand.

Referring briefly to the mineralogy of POS, it is possible to assess how calcite and (in a lesser extent) aragonite are predominant in these deposits. Aragonite crystallizations occur particularly in some paleolevels located above the current sea level, as well as Holocene POS in the Cova des Pas de Vallgornera. The aragonitic mineralogy likely has paleoclimatic significance (Pomar et al. 1976; Ginés et al. 1981b; Vesica et al. 2000; Csoma et al. 2006), being present in samples belonging to warmer substages of MIS 5. Aragonite encrustations originate characteristic smooth coatings, whereas calcite POS show macrocrystalline textures with rough surfaces.

2. Investigations of Mallorcan POS: a four decades story

Examination of phreatic speleothems in littoral caves of Mallorca Island started in 1972, when striking bands of subaqueous crystallizations were observed in Cova de sa Bassa Blanca (Alcúdia) being tentatively credited to represent past Pleistocene sea stands. The first research on Mallorcan POS focused on correlating their elevation with the fossil beach sequences, abundant along the coasts of the island. Using this approach, the phreatic speleothems bands, distributed from the current sea level to +35 m ASL, were correlated to ancient coast lines encompassing the time span from the Last Interglacial to the Middle Pleistocene for the highest observed POS (Ginés and Ginés 1974). Furthermore, early mineralogical and crystallographical studies on POS identified the presence of aragonite deposits, pointing out their potential paleoclimatic significance (Pomar et al. 1976). All these aspects were internationally disseminated during the *8th International Congress of Speleology* held in Bowling Green (USA), in two papers dealing with the morphology and mineralogy of POS and, especially, to their potential as records of past sea levels (Ginés et al. 1981a, 1981b). These investigations, that started from the Mallorcan speleological scene owing to the already cited works by A. Ginés and J. Ginés, very early were developed as a collaborative project within the *Universitat de les Illes Balears* (UIB), particularly with L. Pomar and subsequently with J.J. Fornós.

During the 1980s, a programme of U-series datings was commenced due to the interest and dedication of the late G.J. Hennig. Up to 16 U/Th ages on POS were performed at the *Niedersächsisches Landesamt für Bodenforschung* (Köln, Germany) by means of alpha-spectrometry techniques. The obtained ages range from Holocene to older than 350 ka BP, including samples that clearly corresponded to the Last Interglacial (Hennig et al. 1981). During these years, electron spin resonance (ESR) measurements were also conducted in order to obtain additional geochronological data on Mallorcan POS (Grün 1985, 1986).

Between 1995 and 2000, a second U-series dating programme was conducted in collaborative research with the *Università Roma Tre* (Rome, Italy), under the leadership of Paola Tuccimei. More than 30 U/Th ages were published during this period, corresponding to POS paleolevels situated both above and below the current sea level (Tuccimei et al. 1997, 2000). The tasks of sampling the submerged phreatic speleothems were accomplished during important underwater exploration carried out by an extremely active and dedicated team of Mallorcan speleo-divers. Most of the U-series analyses resulting from this dating campaign were performed by means of alpha-counting techniques, with only a few obtained by thermal ionisation mass spectrometry (TIMS). The ages range between 67 ka and >350 ka BP, with over 16 dates corresponding to different substages of MIS 5. These allowed our team to reconstruct, for the first time, a detailed sea level curve for Western Mediterranean basin between 150 and 60 ka BP (Tuccimei et al. 2000; Ginés et al. 2002). The geochronological investigations carried out along this period were complemented with a few stable isotopes data on POS, meant to provide some preliminary paleoclimate information (Vesica et al. 2000). Furthermore, research on Mallorca's recent tectonics was evaluated in a paper that highlights the potential use of POS in structural geology studies (Fornós et al. 2002).

During the most recent decade, a third programme of radiometric investigation commenced on POS with a two-fold purpose: first, to obtain accurate U/Th ages by means of multi-collector inductively coupled plasma mass-spectrometry technique (MC-ICPMS) and second, to study in detail the Holocene POS. Over 47 mass-spectrometry datings were performed mainly at the laboratory of the Institute of Geology from the *University of Bern* (Switzerland) – owing to the collaboration of Jan Kramers and Igor M. Villa – as well as 12 additional dates completed by Bogdan P. Onac (*University of South Florida*) and Jeffrey A. Dorale (*University of Iowa*) who in the last years joined this research project. The recent research on subactual POS have supplied new data on Holocene samples from Mallorca (Tuccimei et al. 2010, 2011) allowing to the generation of an accurate sea level curve (for the Last Interglacial to Holocene times) based on the available U-series data on POS. Some of the new dates, especially those falling between 150 and 60 ka BP, provide reliable information about sea level history during MIS 5 in Mallorca (Tuccimei et al. 2006), novel data on the MIS 5a high sea stand (Onac et al. 2006; Dorale et al. 2010), and on the Glacial Isostatic Adjustment (GIA) in the Western Mediterranean area (Tuccimei et al. 2012).

3. Phreatic Overgrowths on Speleothems: a useful tool for Quaternary sea level studies

During the last decades, a new approach to the Mediterranean sea level history has arisen from the interdisciplinary study of the Phreatic Overgrowths on Speleothems (POS) found in the littoral caves of Mallorca. A comprehensive bibliographic revision on this topic is provided by Ginés (2000), whereas recent updated data sets are available in Tuccimei et al. (2006, 2010) and Dorale et al. (2010). The geomorphological approach to these karst deposits has been fully supported by chronological information obtained from U-series datings of the POS samples. The data gathered altogether represent a very precise archive of glacioeustatic fluctuations during the Quaternary in the studied area. The sea level curve for the time span between 150 and 60 ka BP is especially detailed (Figure 3).

The early U/Th dating programmes conducted by means of alpha-spectrometry on phreatic speleothems from Mallorca – collected both above and below the current sea level – yielded ages from about 63 ka to >350 ka BP (Hennig et al. 1981; Tuccimei et al. 1997, 2000). Apart from a few POS samples presumably corresponding to MIS 7 or even earlier (MIS 9 or 11), the vast majority of ages were in the range 150–60 ka BP providing valuable information on sea level history during MIS 5. Additional research, taking advantage of recent mass-spectrometry techniques, have allowed lately constraining a more detailed and accurate Upper Pleistocene sea level curve for the Western Mediterranean basin (Tuccimei et al. 2006; Dorale et al. 2010). In total, more than 50 phreatic speleothems collected in 17 littoral caves of Mallorca were investigated over the last four decades. From such a background of 97 U-series ages ranging from 0.6 ka to >350 ka BP (44 based on alpha-counting techniques and 53 obtained by means of mass-spectrometry measurements), up to 55 dates cluster between 60 and 150 ka BP (Ginés et al. 2012b). On the basis of these data accurate elevations of sea level high- and low-stands both during the Holocene and over the MIS 5 and 4 can be determined.

The eastern littoral area of Mallorca has proven to be suitable for sea level change studies because it is considered tectonically stable, although affected by some recent minor tectonic activity. U-series dating of emerged POS demonstrated a maximum of 1 m vertical displacement among encrustations formed during MIS 5e and 5a in several caves (Fornós et al. 2002). These authors have discussed the slightly different elevations of coeval POS samples, in light of other regional geomorphological, structural, and stratigraphical evidence. This approach has outlined a general tectonic tilting of the eastern part of Mallorca, with a maximum displacement of 1.5 m, which results in a progressive lowering of the southern end of the island. The proposed tilting has occurred, at least partially, after MIS 5a, because the deposits of that age also seem to be affected. The rate of tectonic lowering was evaluated at 0.02 mm/year (Fornós et al. 2002).

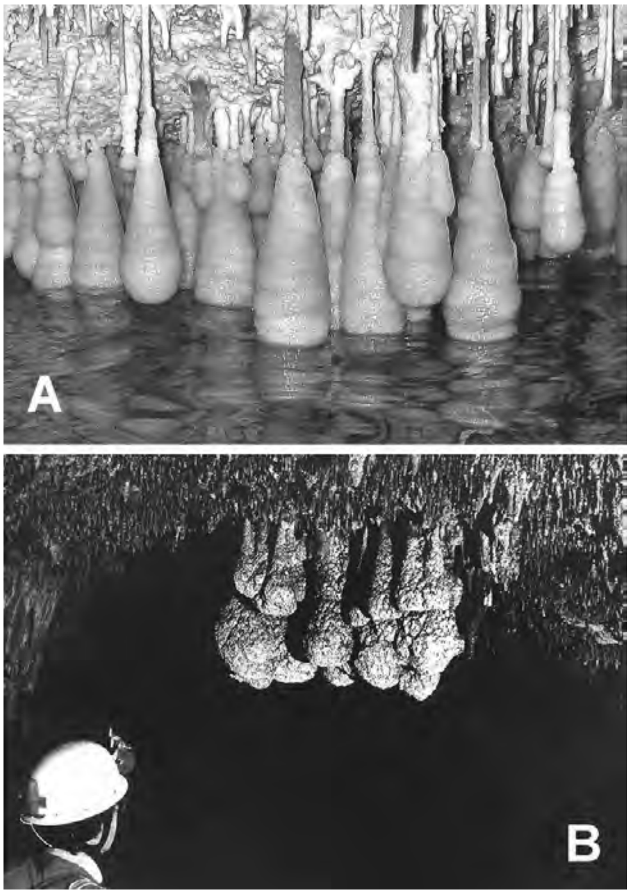

Figure 2. Photos of Phreatic Overgrowths on Speleothems (POS) from two Mallorcan caves. A: nice aragonite encrustations growing at the current water table in Cova des Pas de Vallgornera, Llucmajor. (Photo: A. Merino). B: group of POS crystallizations that record an ancient sea stand in Coves del Drac (Manacor), at an elevation of +4 m above the present-day sea level. (Photo: J. Ginés).

These small tectonic disturbances can be considered negligible with respect to the fluctuation amplitudes existing between the high and low stands recorded in the studied caves; therefore, the Mallorcan POS arise as valuable and accurate proxies of sea level in the Western Mediterranean basin, at least during Holocene and Upper Pleistocene times. Within this context, and taking into account the fact that MIS 5e POS deposits are located at a mean height of +2 m ASL – hence, not substantially uplifted by tectonic movements –, the presence of MIS 5a encrustations between +1.3 and +1.9 m ASL, clearly indicate a sea stand higher than the current one that is not, by any means, the result of tectonic uplifting of deposits precipitated at lower elevations. In other words, it is implausible that MIS 5a deposits could have been significantly elevated by tectonics while MIS 5e deposits were not.

A significant background of ages of phreatic overgrowths, dated by means of TIMS and MC-ICPMS techniques, range from 143.6 to 77.8 ka BP, covering the entire Last Interglacial interval. If chronological data from emerged and submerged POS are plotted versus their elevation with respect to present sea level, a tentative sea level curve (Figure 3) for the Last Interglacial in Mallorca can be generated (Tuccimei et al. 2006) with accuracy greater than other approaches based on conventional geomorphological records (i.e. fossil beaches with diagnostic faunal content). According to our findings, Western Mediterranean sea level reached approximately the same elevations (~+1.5/+2.5 m ASL) during the past high stands recorded in correspondence with MIS 5a and 5e ($5e_1$ and $5e_2$). Sea level fluctuations during the Last Interglacial seem to occur in the following pattern: periods of sea stands (long enough to allow the formation of POS at a given elevation) alternate with rapid sea level changes (positive and negative), greater than 18 m in amplitude, occurring within intervals shorter than 5 ka. An approximation of the duration of sea stand episodes can be deduced from the dates obtained from Holocene POS (Tuccimei et al. 2010), now growing at the present sea level in numerous littoral caves of the island; these U-series age determinations suggest that at least more than 1 ka of sea level stabilization may be necessary for the formation of a significant POS encrustation. It is worth to outline that the duration of the high stands $5e_2$ and $5e_1$ has been estimated on the order of 10 ka, on the basis of several high precision dates (Tuccimei et al. 2006).

The rates of sea level changes that can be deduced from our data range from a minimum of 2.9 mm/year to a maximum of 20 mm/year, with average figures of 5.9 mm/year (Tuccimei et al. 2006; Dorale et al. 2010). These values have been inferred by taking into account the age calculated for each sample, without considering the quoted errors of the datings. The sea level drop that occurred during MIS 5e was presumably very fast; especially rapid was the rising trend associated with the onset of MIS $5e_1$. In the same manner, the rise from MIS 5b to MIS 5a happened at the highest rate (>8 mm/year) throughout MIS 5. Such tendencies agree with quicker sea level shifts during transgressions as discussed in the available literature.

Recently, new insights on the ~81 ka BP high stand (MIS 5a) recorded in Mallorca have been provided by Dorale et al. (2010). These authors study POS encrustations collected from +1.3 to +1.6 m ASL in five different caves of southern and eastern coasts of the island, obtaining TIMS U/Th ages ranging from 82.0 to 80.1 ka BP. These geochronological data undoubtedly confirm the existence of a sea level stand higher than the current one during MIS 5a, as was previously recognized by Tuccimei et al. (2006). The suggestion that MIS 5a sea level was higher than present, and only slightly lower than the MIS 5e sea level, implies that most of the ice built up during MIS 5b would have melted during the onset of MIS 5a. From the data on Mallorcan POS supplied by Tuccimei et al. (2006), Onac et al. (2006), and Dorale et al. (2010), it seems well-

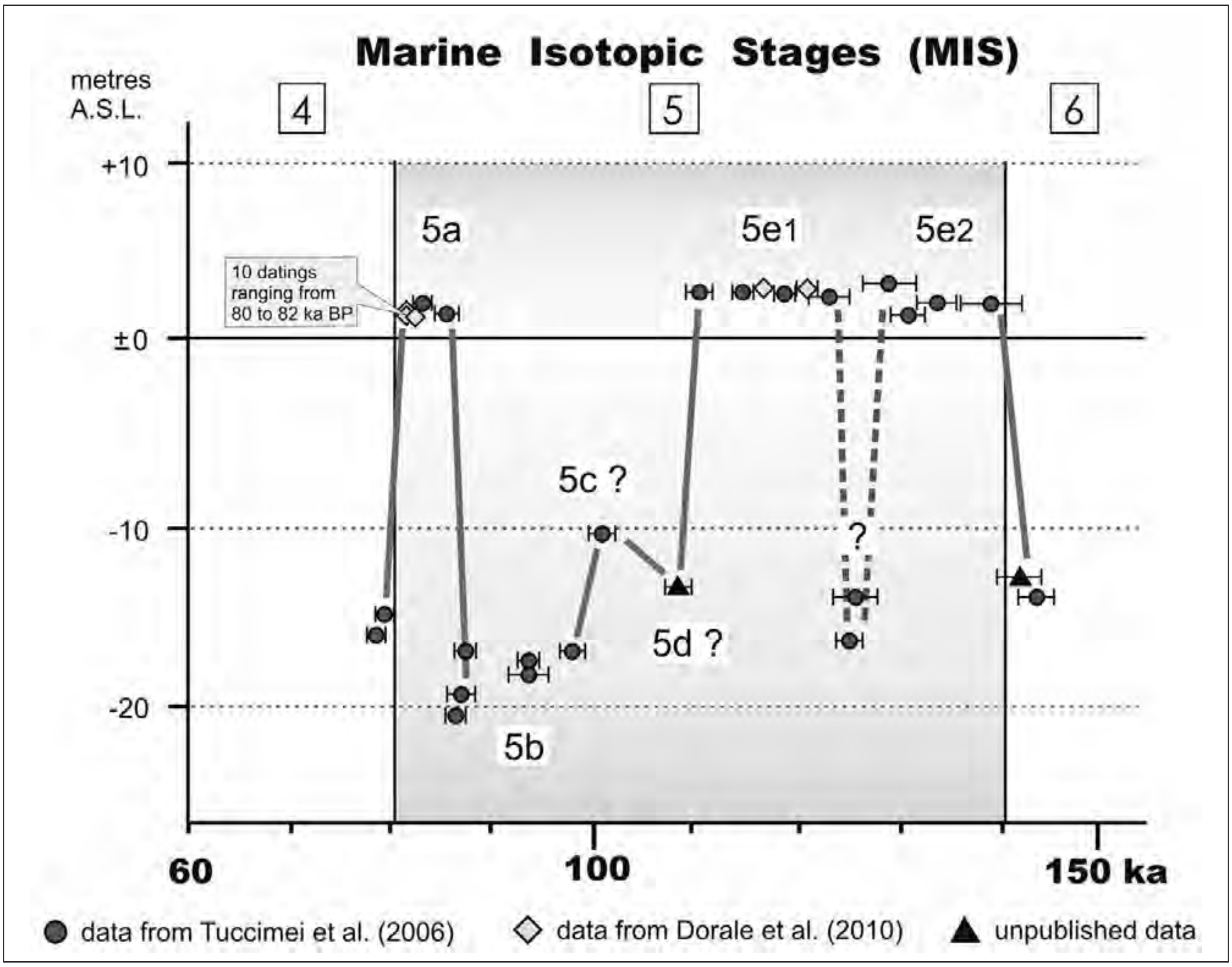

Figure 3. Sea level curve during MIS 5 deduced on the basis of U/Th ages of Phreatic Overgrowths on Speleothems (POS) from Mallorca Island. Circles refer to datings from Tuccimei et al. (2006); squares correspond to data from Dorale et al. (2010). Errors are quoted as 2 σ.

constrained that MIS 5a sea level high stand involved a very rapid ice melting leading up to this event, which had an estimated maximum duration of 4 ka, from 84 to 80 ka BP. Therefore, Dorale et al. (2010) have elaborated on a rather alternative view that argues that this substage was as ice-free as the present, challenging the conventional view of MIS 5 sea level history and certain facets of ice-age theory. Furthermore, they propose that the Glacial Isostatic Adjustment (GIA) effects have been overestimated for the Mediterranean region, suggesting the possibility that Mallorca occupies a narrow transition zone between regions of emergence and submergence in the Mediterranean Basin, where sea level nearly follows the eustatic curve. This point of view was recently substantiated by Tuccimei et al. (2012).

Additional studies were directed towards the ^{14}C dating of Holocene POS. The aim of these investigations was to compare the ^{14}C and U/Th ages previously obtained and determine whether incorporation of dead carbon inherited from the dissolution of ^{14}C-free limestone poses any problems. Generally speaking, the ^{14}C ages are consistent with those generated by U/Th dating (Tuccimei et al. 2011), although some of the results prove to be site dependent and linked to the local residence time of waters. It seems that the use of radiocarbon dating in POS geochronological studies is promising, but in some situations might be problematic due to the so-called reservoir effect. Obviously, its use is restricted to the investigation of Last Glaciation and post-glacial samples.

4. Conclusions: state-of-the-art and future perspectives

The time span elapsed since the beginning of our studies on POS of Mallorcan caves – about 40 years – allowed us to gain a proper perspective on the geochronological relevance and possible limitations concerning this particular record of the sea level history (Ginés et al. 2012b). Based on a remarkable set of geomorphological and U/Th data produced since 1972, today is possible to emphasize the reliability of this special proxy for Quaternary sea level reconstruction (Onac et al. 2012). The radiometric dating programmes confirmed the Holocene age for the POS deposited around the current sea level (Tuccimei et al. 2010, 2011), as well as the general stratigraphic consistency of the U/Th dates on all the other samples covering the Upper Pleistocene (Tuccimei et al. 2006).

The analytical results also pointed out the possibility that neomorphic processes affecting the POS might be responsible for some of the inconsistent ages obtained by means of U/Th dating method. In this respect, the recrystallization processes that affect certain speleothems are relatively more frequent among the samples that are older; especially those of Middle Pleistocene age (Ginés 2000).

To the above-mentioned problems, post-depositional diagenesis of the isotopic content of some POS samples also need to be considered. These processes seem to be relatively common for most of the speleothems collected below the present sea level (i.e. corresponding to regressive events). It seems reasonable to predict that the prolonged and repeated immersion of these POS in the coastal mixing zone caused, in some cases, the partial dissolution of these deposits (i.e. open geochemical system), triggering all the dating problems that this process entails. To minimize such problems, several age determinations were conducted on each speleothem. Doing so, the lack of samples out of stratigraphic order gives support to the assumption that the geochemical system remained closed.

Regarding the paleoclimatic data that POS can provide, it is necessary to recognize some important limitations related to the fragmentary nature of this record. This is because both in time and space, each marine sea-stand is only documented by the period of stabilization of the coastal water table at a given elevation. Obviously, this means that there is not a continuous record of POS over the last 500 ka. Therefore, stable isotope data obtained are scarce and poorly illustrative. However, this does not diminish the possibility of obtaining detailed paleoclimatic data, particularly in what concerns specific geochronological events such as the Holocene sea level or the high sea stands related to the Last Interglacial, for instance.

So far, the geomorphological and chronological data set accumulated during the last four decades, has allowed the reconstruction of a fairly detailed sea level curve in the Western Mediterranean basin for the time span between 150 and 60 ka BP (Tuccimei et al. 2006). This curve (Figure 3) highlights the existence of a high sea level stand ~81 ka ago, during MIS 5a (Dorale et al. 2010), a finding that is criticized by some scientists, because GIA was not used to reconcile this high stand.

In the current state of knowledge, it becomes increasingly clear that the study of coastal phreatic speleothems (POS) constitutes a new tool with established validity for the study of sea level history in limestone coastal areas. This particular kind of speleothem encrustations favorably complements the conventional littoral records (beaches, ancient shorelines, coastal fossil deposits, etc.), providing even more accurate data on the elevation of the coastlines and the magnitude of tidal fluctuation. In addition, the geographic setting (karst caves) of this type of phreatic crystallizations protects them against the dynamics that marine erosion imposes to the evolution of the coastline. Undoubtedly, the data supplied by the POS deposits existing in coastal caves from other parts of the world could contribute important data to the global sea level history, effectively complementing other proxy records. With over one third of the world's population living within coastline regions, understanding the history and future impacts of global sea level change ranks as a top priority in the Earth Sciences.

Acknowledgments

These investigations are integrated within the research project CGL2010-18616 of the Spanish Government (MINECO – FEDER). Part of this material is based upon work supported by the NSF AGS-1103108 grant to BPO.

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AIR CO_2 IN COMBLAIN-AU-PONT CAVE (BELGIUM) RELATIONSHIPS WITH SOIL CO_2 AND OPEN AIR METEOROLOGY

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The Comblain-au-Pont Cave is located in Belgium, 25 km south of Liège, at 180 m altitude, in a temperate oceanic climate. Our measurements of CO_2 in the cave and different surrounding soils show the relationships between cave climate, outer atmosphere meteorology and CO_2 production in the soils.

Carbon dioxide (thought to come in the main from plant root and biomass respiration) displays seasonal variations related to outside temperature, but some oscillations of the CO_2 content of cave air are related to surface barometric variations (i.e. when the barometric pressure falls, a certain amount of air trapped in the remote parts of the system leaks outside and vice versa).

A sudden drop of temperature, inducing a chimney effect may cause a drop of the air-CO_2 content of a deep pit from 4,000 to 1,300 ppm.

Most of our recent findings are due to the use of continuous loggers, whereas our old methods were based on sporadic measurements, only made at the time of our visits to the cave.

1. Introduction

Caves usually display a very stable, uniform, climate. Temperature and humidity are generally very constant. However, closer investigation shows important variations in some climatic parameters. We have studied some of them over many years, and particularly the CO_2 content of the air (Ek 1960a, 1979, 1990; Ek et al. 1968; Ek and Gewelt 1985; Ek and Godissart 2007, 2009; Ek et al. 1969; Delecour 1968; Godissart 1994; Godissart and Ek 2009; Godissart and Ek 2011; Godissart and Delvenne 1975).

We are presently improving our knowledge of the climate of the Comblain-au-Pont Cave, a little touristic cave located 25 km south of Liège (Belgium).

The Comblain-au-Pont Cave lies in a syncline of Carboniferous Limestone, specifically Visean Limestone, in a brecciated formation, folded by variscian orogenesis. The entrance lies at an altitude of 180 m. The region has an oceanic temperate climate. Land use over the cave includes forest, meadows and cultivation. Tourist frequentation is weak, about 6,000 persons a year.

The cave morphology is simple (Fig. 1). The only natural entrance is a 22 m shaft. A tunnel was drilled to allow entry. The cave consists of a string of chambers connected by narrow passages; most of these lie at a low level, at the bottom of the chambers.

We were able to deepen our knowledge of the cave thanks to monitoring devices provided by the Service public de Wallonie (S.P.W., Walloon Region Administration).

2. Technical procedures

We measure CO_2 content of the air with two hand-held devices.

The Gastec pump uses a hydrazine cell. Hydrazine reacts with CO_2 and a scale on the cell indicates the amount of reagent used, hence the quantity of CO_2.

The Draeger X-am 7000 is a practical and fast infrared CO_2-meter. It provides an instantaneous reading on a LCD screen.

Both devices have been described in previous papers, and particularly in Ek C, Godissart J, 2009. We still use them.

A new device at our disposal is the Vaisala Carbocap carbon dioxide meter GM70, which includes a data logger. Its CO_2 sensor works by IR absorption. The reading accuracy is 10 ppm, and the measurement repeatability around 20 ppm. We got three of them.

3. Results and discussion

We will deal here with the Comblain-au-Pont Cave only, and we will give a few examples of the relationships between cave atmosphere and meteorological events outside.

3.1. Seasonal variations (Figs. 1 and 2)

Temperature and humidity are quite constant in the cave throughout the year, at least in the most remote half of the cave. Humidity is about 100 % and temperature 10,4 °C.

But it is very different with CO_2, as is already well known in other caves (Ek 1990; Ek and Gewelt 1985; Baldini et al. 2006; Mitchell and Mitchell 2009; Mattey et al. 2010; etc.).

In the Comblain-au-Pont Cave, there is much more CO_2 in the air at the end of summer than at the end of winter. At the end of winter, the maximum content of cave air is about 1,600 ppm at the far end (Fig. 1). This is approximately four times the CO_2 concentration in open air.

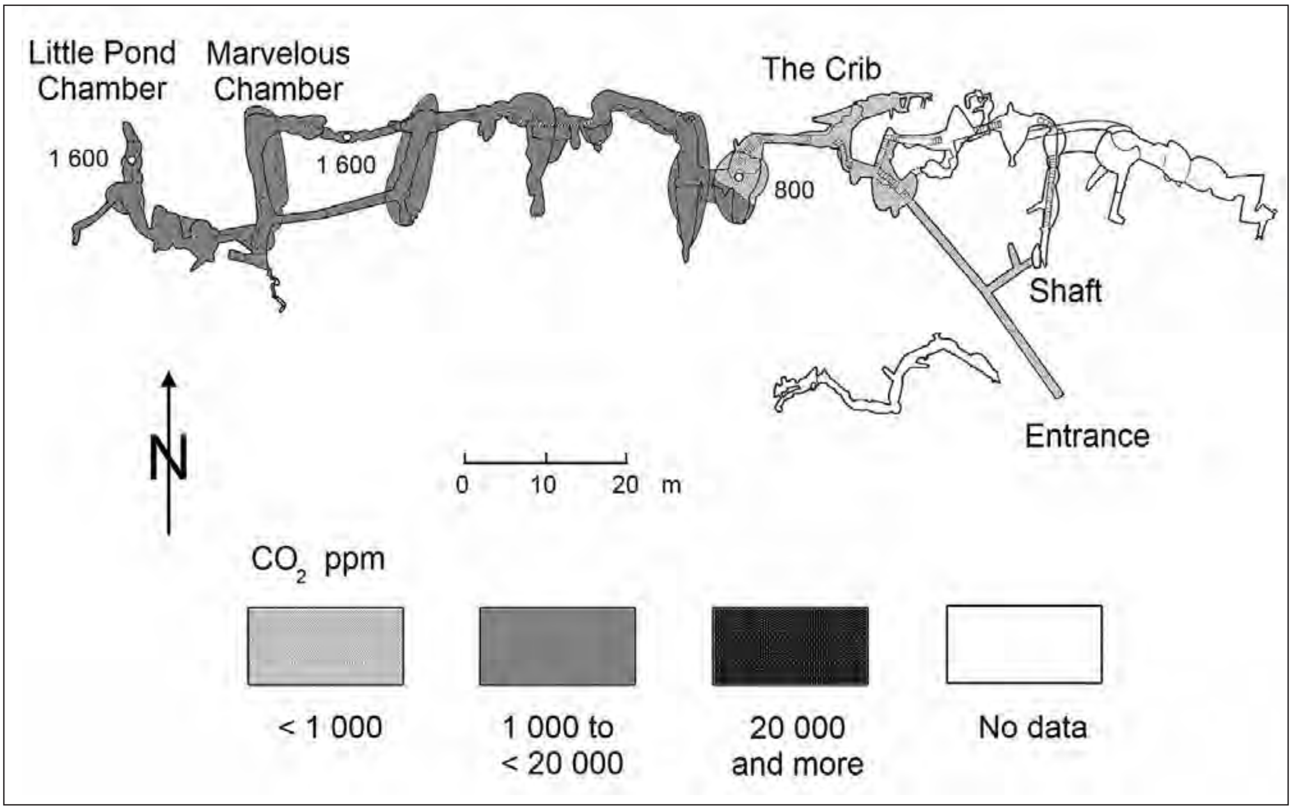

Figure 1. CO_2 content of the air in the Comblain-au-Pont Cave in winter (February 8, 2012).

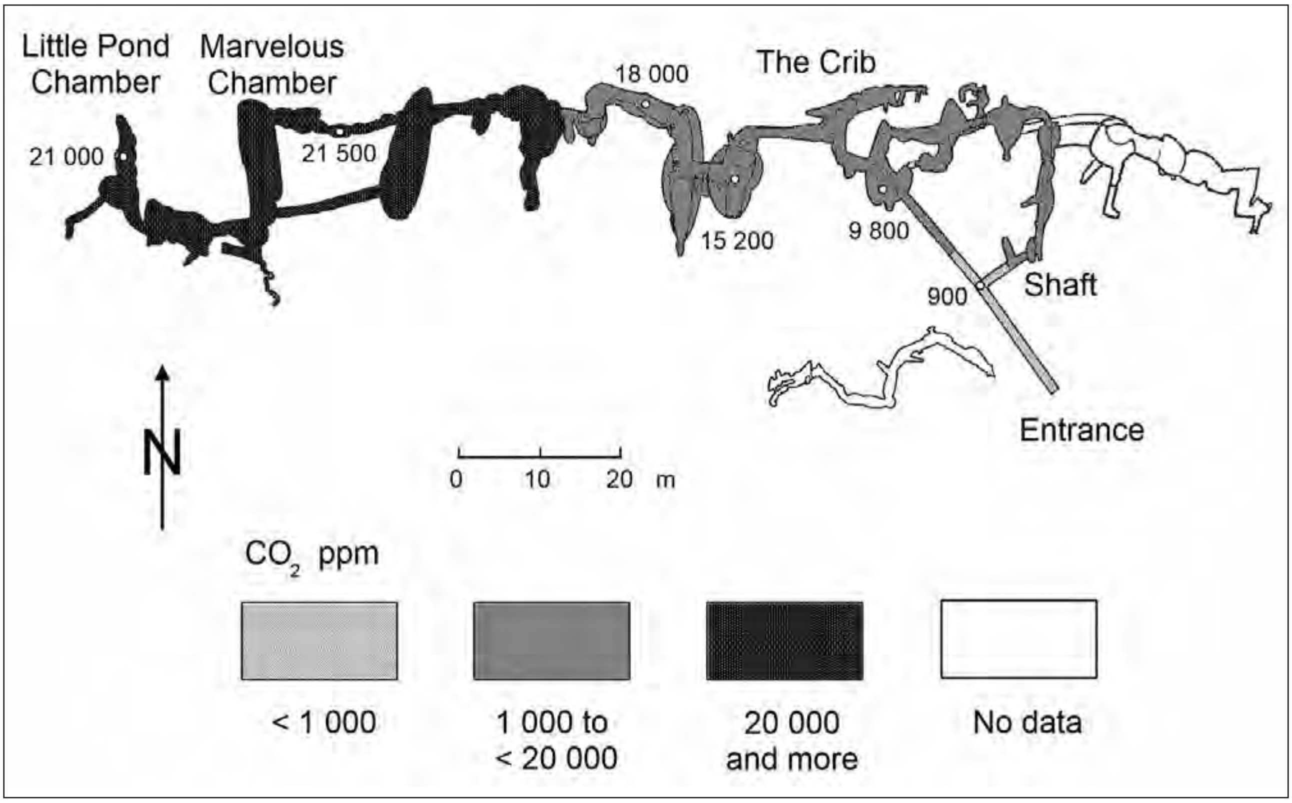

Figure 2. CO_2 content of the air in the Comblain-au-Pont Cave in summer (August 27, 2012).

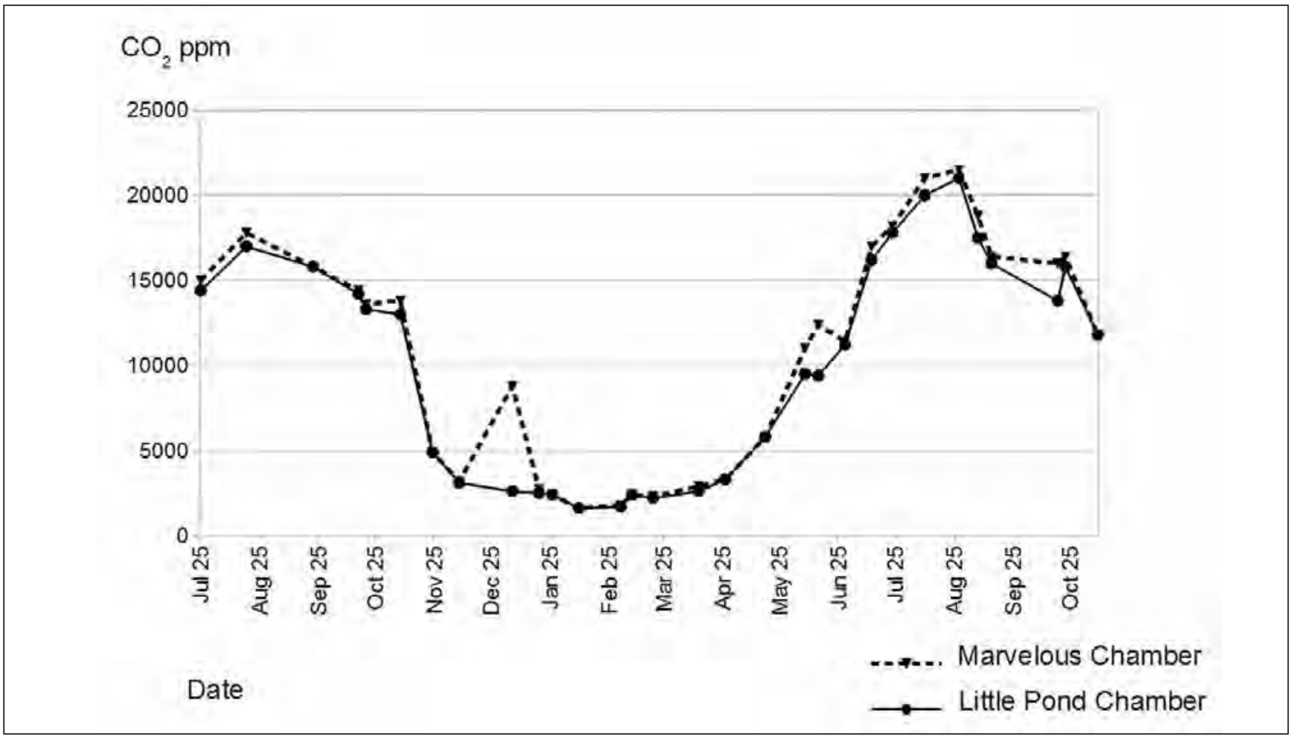

Figure 3. CO_2 seasonal variation in the cave, at the Little Pond Chamber (far end of the cave) and at the lower part of the Marvellous Chamber (a low-level site), from July 2011 to November 2012.

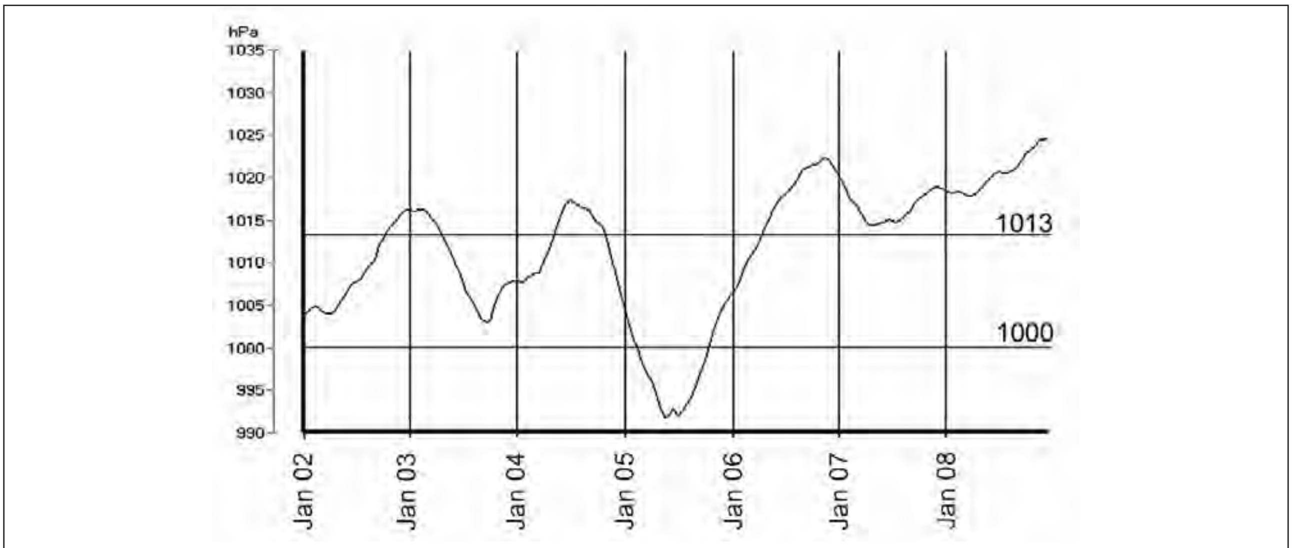

Figure 4. Barometric pressure at Soumagne "Phitofa" meteo station, January 2 to 8, 2012. A noticeable low occurs on January 5.

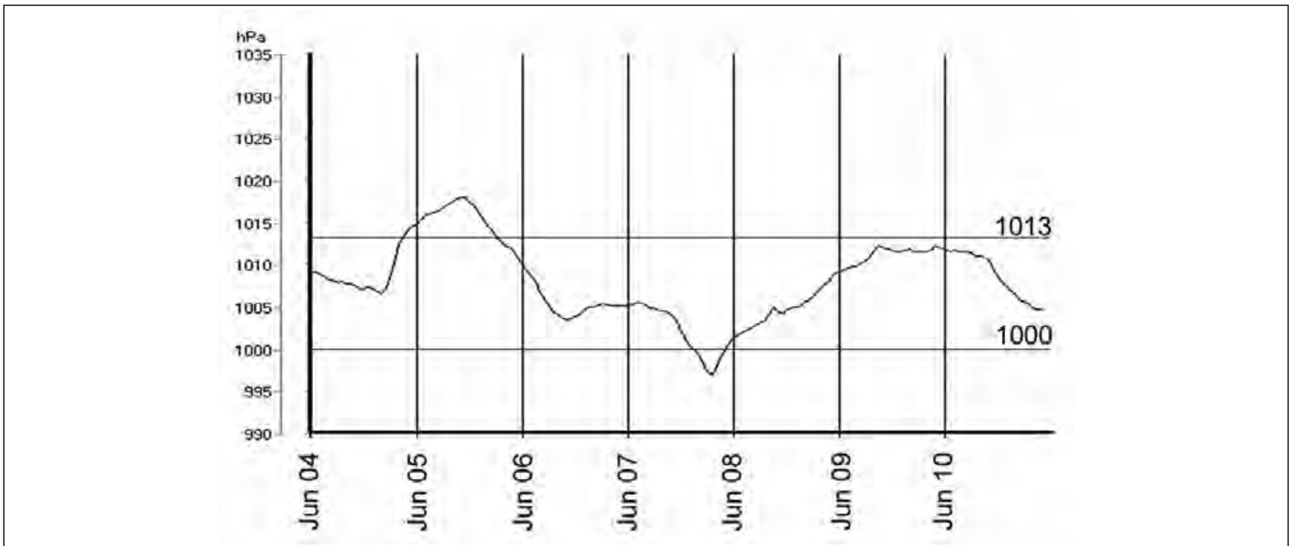

Figure 5. Barometric pressure at Soumagne "Phitofa" meteo station, June 4 to 10, 2012. A noticeable low occurs on June 7.

At the end of summer, in August, the amount of CO_2, rises to 21,000 ppm, i.e. 2.1 % (Fig. 2), more than fifty times the figure in outer atmosphere.

This maximum is highly variable. In this cave, we have registered summer maximums between 17,600 ppm (September, 2011) and 26,500 ppm (September, 2009).

The minimum always occurs just after the coldest period of the year, and the maximum at the end of the summer. We think that this is related to temperature, but also to vegetation, which also depends on temperature. We had noticed in another cave (Ek and Gewelt 1985) that the maximum CO_2 content in cave air was sometimes earlier in the upper levels of a cave than in the lower chambers.

In Comblain-au-Pont, we also measure the CO_2 content of soil air. And we have sometimes noted that the soil maximum occurs in May or June, much earlier than in the cave; air descends slowly from the soil to the caves. But this year, we observed a maximum CO_2 content in the soil in August. It is thus important not to infer too fast a conclusion from a correlation observed once.

However, it is clear that the CO_2 levels observed in the caves are more similar to soil CO_2 levels than to open air CO_2 amounts (Latte 2010). And the rhythm is somewhat parallel to the one of the soils.

3.2. A barometric low can influence the cave atmosphere (Figs. 3 to 5)

Cave air contains high levels of CO_2 in August and September and much less in winter, from December to March: this is confirmed by figure 3, which shows the annual cycle of 2012 in two different places: the Little Pond Chamber, at the very end of the cave, and the lower passage near the Marvellous Chamber. However, there are two moments where the “Marvellous” curve shows a sharp and temporary peak: about January 5 and June 7, 2012. Looking at a meteo station nearby (at Soumagne, 20 km NE of Comblain-au-Pont), we observe a strong barometric low on January 5, and another on June 7 (Fig. 4 and 5). We think that the explanation lies in the cave morphology and hydrology.

The low-level gallery below the Marvellous Chamber is more than 10 meters lower than Pond Lake. It is thus closer to the underground drainage below the accessible passages of the cave. When atmospheric pressure drops outside, cave air leaks out, sucking air from the remote parts of the system. This air, confined for a long time, is richer in CO_2, hence the peaks observed on Figure 3.

On January 5 and June 7, we observed a slight flood in the low level gallery beneath the Marvellous Chamber: water was invading the deepest cave passages because of the rains accompanying the barometric lows. Similar relationships between barometric changes and CO_2 level variations have also been observed by Baldini et al. (2006) and by Mitchell and Mitchell (2009).

It is thus clear that changes in outside air pressure induce changes in the cave.

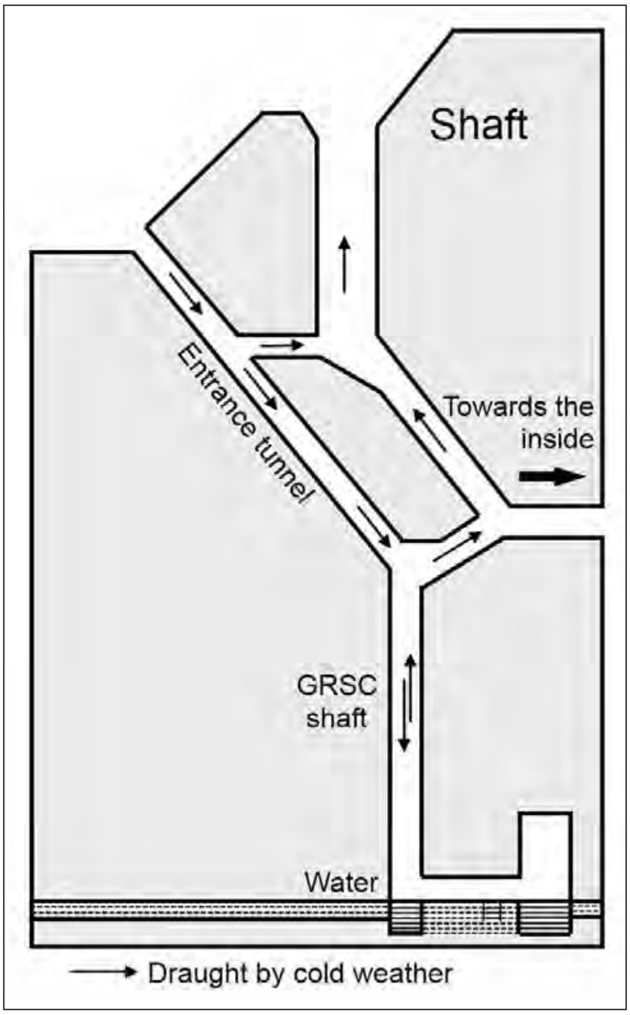

Figure 6. Draught occurring in cold weather in the entrance tunnel and in the GRSC shaft. A chimney effect is due to the difference of level of the two entrances.

3.3. Influence of some changes in outside temperature

3.3.1. Circadian CO_2 oscillations (Figs. 6 and 7)

We placed a data logger in the Crib, a small chamber, not far from the entrance tunnel, and about 50 m away from the entrance.

As previously noted, the cave has two entrances at different levels: the shaft mouth is about 10 m higher than the tunnel entrance. A draught sometimes blows in the galleries connecting these two entrances (Fig. 6). Although not in this circuit, the Crib lies nearby (about 15 m).

A data logger set in the Crib from April 12 to April 26, 2012, registered the air CO_2 concentration every three hours for 15 days. We computed the average CO_2 concentrations and the graph clearly shows a statistical trend to a morning minimum, between 6 and 9 a.m., and an afternoon maximum, between 3 and 6 p.m.

Early in the morning, CO_2-poor cold air from outside flows into the cave, whereas in the afternoon, when the outside atmosphere is warmer, air does not flow into the cave.

This data logging shows that daily oscillations of temperature induce a circadian rhythm in the CO_2 concentration of some parts of the cave.

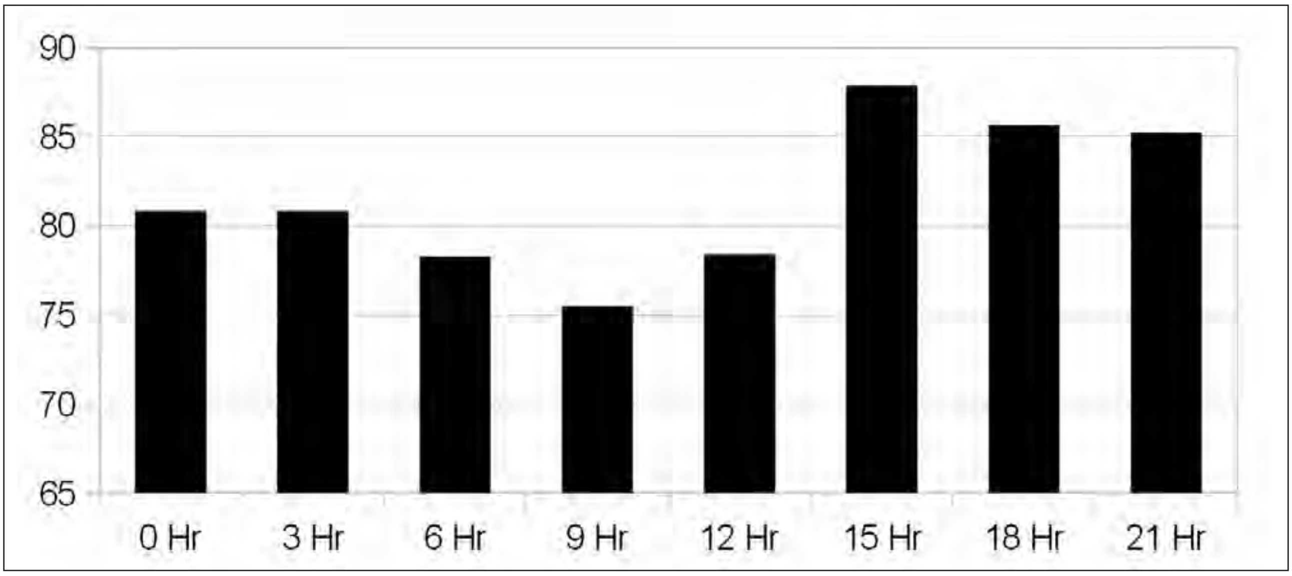

Figure 8. CO_2 in the GRSC shaft from May 25 to June 6, 2012, and surface temperature during the same period. Air temperature falls below +5 °C on June 5 (at dawn).

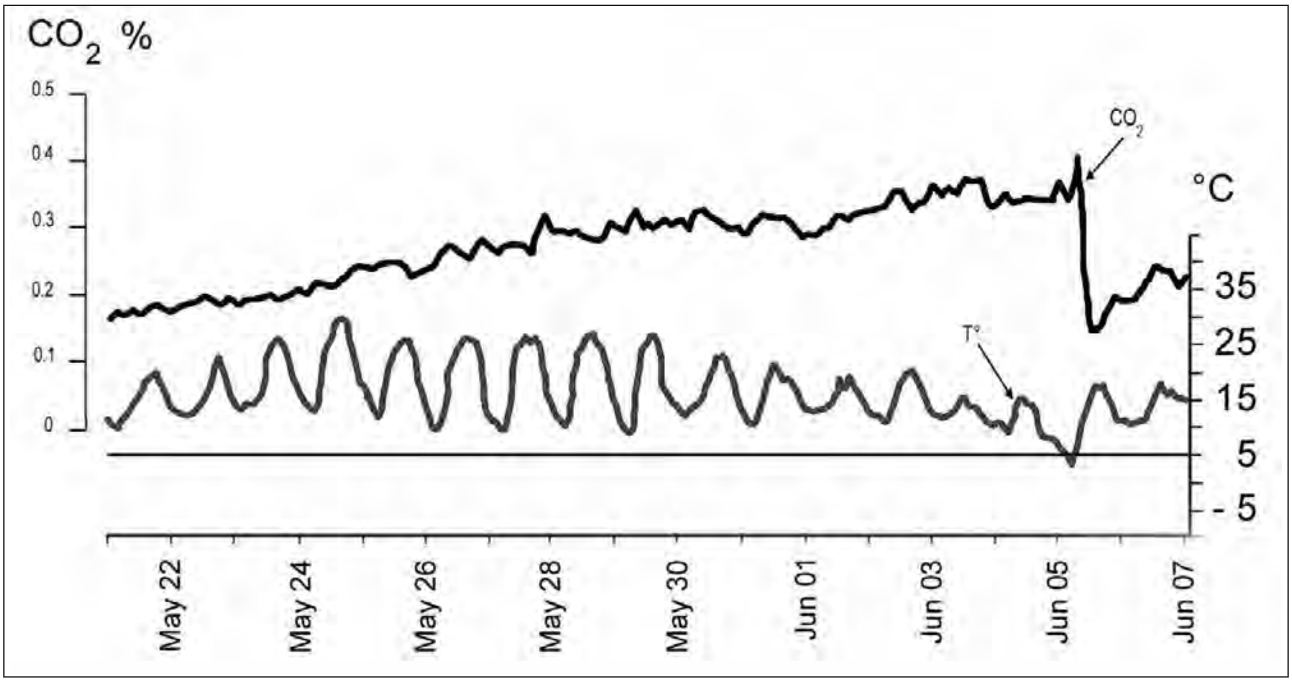

Figure 7. Mean CO_2 content of the air in the Crib from April 12 to April 26, 2012. CO_2 was measured every three hours during these two weeks. Mean values only are presented here.

3.3.2. A sharp fall of CO_2 concentration in a pit (Fig. 8)

Because of the existence of two entrances at different levels, the cave is sometimes subjected to a chimney effect: when the outer temperature drops below +5 °C, cold air enters in the tunnel entrance – the lower one – and cave air (at +10,4 °C) gets out through the shaft (Fig. 5).

We have observed that there is no draught when the temperature at the surface is +5 °C or more. Near the entrances, in a low-level zone, there is a deep pit in the cave floor. The water filling the bottom of this 35 m-deep shaft is the only indication of the underground drainage of the cave (Fig. 6).

We logged the CO_2 content of the pit air about 5 m below its top from May 21 to June 7, 2012. In the spring, the CO_2 concentration in the cave increased the log displaying a serrated rise. But on June 5, early in the morning, the CO_2 curve rose abruptly and, immediately after, collapsed to less than one half of its previous value: from 4,000 to 1,300 ppm! (Fig. 8).

The cause of this sharp drop in CO_2 concentration is the fall in outside temperature to below 5 °C (Fig. 8) – allowing cold and dense air to rush down into the pit and replace the stale air at the bottom.

4. Conclusions

With the previous methods we could only perform sporadic measurements, at the time of our visits to the caves. Data logging allows continuous tracking of several physical parameters. Simultaneous logging of several parameters leads to correlations between various phenomena.

Surface barometric variations induce noticeable movements underground. When pressure is low, air trapped in the interconnected parts of the limestone is carried from the most remote voids to the cave by advection and conversely by highs.

A deep pit, the GRSC shaft, going down to the watertable, is filled with CO_2 rich air. In winter, when the temperature is below 5°C and the chimney effect is working, cold air flows into the cave and invades the pit, driving out the CO_2 rich air from the shaft and replacing it with fresh air.

Monthly surveys of the cave show the close relationship of its CO_2 content with outside climate, and particularly pedoclimate.

Acknowledgments

This work has been supported by the Service public de Wallonie, who provided us with data loggers and other analytic devices. We are grateful to the S.P.W. for this backing. We thank the “Découvertes de Comblain”, the Association that manages the studied cave, and its Director Julien Goijen, for effective technical support.

We are grateful to Dr.Vincent Brahy, Dr. Patrick Engels, Dr. Jacques Hébert and Dr. Philippe Meus, for their useful scientific advice and presence on the field.

Peter Blackie corrected our English. The remaining mistakes are ours. Nicolas Klingler and Barnabé Ek provided helpful technical collaboration.

Our best thanks to Philippe Labarbe who drew all our figures. Last but not least, we are grateful to Marie-Claire Cellier for the layout of this paper.

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CLIMATIC AND ENVIRONMENTAL CHANGES BETWEEN 130–230 KA RECORDED IN AN ALPINE STALAGMITE FROM SWITZERLAND

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Here we report new high-resolution stable isotope (i.e. δ^{18}O and δ^{13}C) and trace element profiles from stalagmite MF3 that cover the 230 to 130 ka time interval. The MF3 is currently one of the few absolutely-dated temperature-dependent δ^{18}O records from the northern side of the Alps, an area that is highly sensible to the North Atlantic climatic variations. In addition, environmental insides in a region where other terrestrial evidences were eroded by later glacial erosion can be given.

Stalagmite MF3 was collected in Schafsloch Cave, located in the Appenzell Alps, eastern Switzerland (47°14'N, 9°23'E, 1,890 m asl), a mountain range slightly detached from the main alpine body. The cave is located in the pure planktonic limestone of Seewerkalk Formation, approximately 20 m below the surface.

The high U content of the sample (between 0.8 and 9 ppm), allowed the analysis of very small sample (1 mg calcite) with the MC ICPMS technique, and determination of very precise ^{230}Th/U-ages. Stable isotopes measurements (730 samples) were performed at a resolution of 0.1 to 0.5 mm interval, corresponding to 38–120 year resolution.

Rainfall/snow water is suggested to be the drip water supply in the Schafsloch Cave. Based on this, cave air temperatures above 0°C allowed the (slow) precipitation of calcite in the cave during eight individual growth phases: ~225.6 ka, 204.8–219.2 ka, ~198.7 ka, 188.4–189.0 ka, 181.2–182.5 ka, ~159.2 ka, 136.5–132.6 ka, and 131.6–130.2 ka. These growth phases coincide with the warmer phases of the MIS 7.3 and MIS 7.5, the MIS 6 and the transition into the MIS 5.

Laser ablation ICP MS trace elements analysis were carried on selected areas of the sample attributed to the MIS 7 interglacial, MIS 6 glacial period and the transition into MIS 5 interglacial (Termination II). Chemical changes in the stalagmite were observed particularly during the Termination II, coupled with temperature and precipitation water availability.

We will compare our stalagmite record with precisely dated climate records on a regional and on a global scale.

SPURIOUS THERMOLUMINESCENCE IN SPELEOTHEM: IMPLICATION FOR PALEOCLIAMTE

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Spurious thermoluminescence (TL) is an intrinsic non-dose-dependent emission, which is common in natural calcite, such as speleothem. Previous studies explain the spurious TL as triboluminescence due to grinding, charge transfer from deeper traps due to light exposure and chemiluminescence produced by surface oxidation during TL readout. Spurious TL has been widely investigated for avoiding the interference of the dating of calcite, but less has the purpose of the paleoclimatic reconstruction. In this paper we first investigate the thermoluminesence of the calcite in two absolute-dated speleothems (HS2 and HS4) from Heshang cave, Qingjiang valley, China, and interpret the spurious TL as the indicator of East Asian Monsoon. We heat the calcite powder (~200 mesh) from 50 to 400 °C at a heating rate of 5 °C /s in an air atmosphere to measure the natural thermoluminescence intensity of the speleothems. It is observed that speleothems produce the typical natural TL of calcite with a glow peak at ~370 °C. TL signal can be reduced or even eliminated by using an CO_2 atmosphere during TL readout, which suggests that a spurious TL originated from the chemiluminesence by oxidation of these organic matter exists in speleothem. TL intensity was lower in the last deglaciation, but increased in the early Holocence and decreased in the late Holocence (Fig. 1). Speleothem TL variation coincides with the speleothem $\delta^{18}O$ during the last 20 ka, implying the spurious TL can be a proxy for East Asian monsoon. When East Asian summer monsoon prevails, the warm and humid climate results in strong microbiological processes in the soil, which contributes to abundant organic matter (mainly humus) in dripping water, and thus in formed speleothem. Therefore, the spurious thermoluminescence in speleothem is a new proxy for monsoon. The correlation of TL to the organic matter should be investigated in the future.

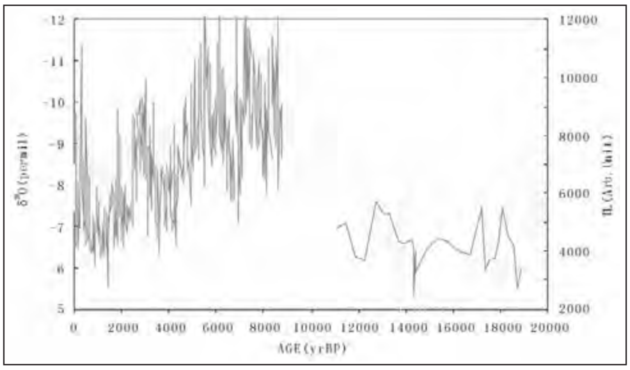

Figure 1. Variation in speleothem TL in last 20ka and comparison to $\delta^{18}O$ record. Red line – TL of speleothem HS2, purple line – TL of speleothem HS4 and green line is oxygen isotope record from the same speleothem.

PRESENTATION OF A WATER INJECTION SYSTEM TO CONTROL THE GROWTH OF SPELEOTHEMS AT THE MILANDRE TEST-SITE, JU, SWITZERLAND

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Speleothems in the Milandre Cave are threatened by the construction of a motorway above it. The sealing of land-surface would stop groundwater recharge feeding the speleothems, which would dry up and cease growing. Since the cave was recognized as a geotope of national significance, several protection measures have been taken in order to reduce the impact of the road construction on the cave environment. An artificial infiltration system of CO_2-enriched water has been designed and implemented. This paper mainly describes the design process and the characteristics of the infiltration system. Investigations for designing the system, as well as monitoring during the construction and the first period of injection provide interesting results on water infiltration from the land surface to cave, which are sketched here and will be presented in future papers.

1. Introduction

1.1. The site and its context

Milandre Cave (total length of 10.5 km) is situated in Northwestern Switzerland (Figure 1), close to the French border at the eastern edge of the Jura mountains. The cave is one of the longest and mostly decorated cave of this region and is recognized as a geotope of national significance. The cave was first explored in the early nineteen-sixties, with an inventory of 5 km of stream passage developed 40 to 70 meters below ground, from the spring upwards. The cave ends in breakdown below a large doline. An artificial shaft of 21 meters was dug at this location giving an easy access to the upstream part of the cave.

The presence of a long and accessible underground stream made the site attractive for academic research and a large number of investigations on karst hydrology, hydrochemistry, particle transport and geophysics have been conducted during the past 30 years (see reference list). In the late nineteen eighties it was decided to build a motorway over the cave and a large monitoring network was set up accordingly. A series of measures have been applied in order to restrict the impact of the road construction on the cave and groundwater (see reference list).

1.2. Reasons behind the injection system

The part of the cave stretching 45 m below the motorway is particularly rich in active speleothems. At this place the motorway is also wider than usual because it enters a tunnel immediately to the North. As the water of the cave stream is used for drinking water supply, it was decided to collect all road runoff waters and to direct them outside of the karst catchment in order to prevent any pollution spills from the motorway. Therefore, a 50 m large band of land directly stretching over about 200 m of profusely decorated cave passage is being strongly reshaped and mostly sealed.

The first studies, carried out in 2000–2001, found that the road construction will seal most of groundwater recharge and will lead to the drying up of many speleothems in the cave. The solution suggested to the engineers in charge of the road construction was to inject water artificially below the road. This solution was accepted taking into consideration the high patrimonial value of the cave passage and the reasonable cost of the proposed protection measure (when compared to the total cost of the road construction).

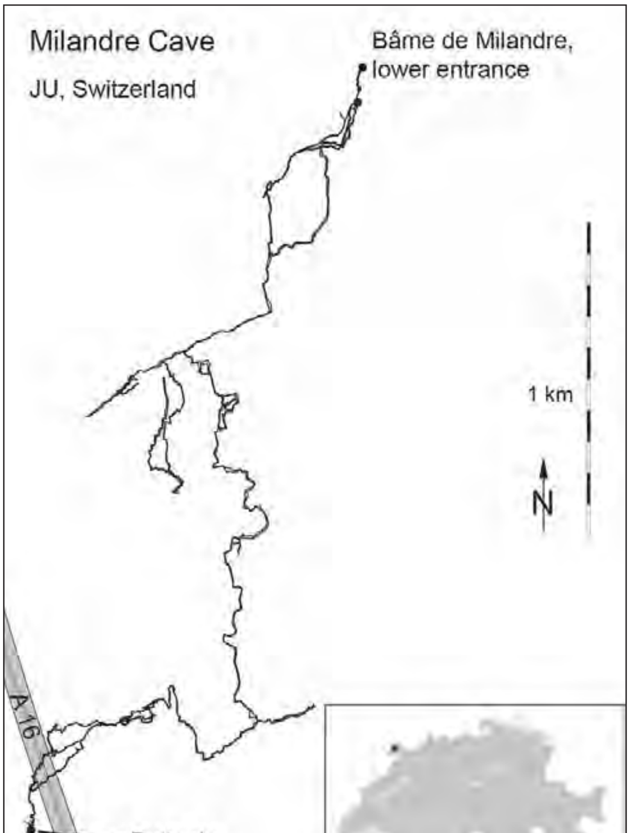

Figure 1. Map of the cave network showing the position of the newly built motorway (A16). In the lower right corner, the star shows the location of the site on a map of Switzerland.

2. Design of the injection system

Once the set up had been decided, the water infiltration system had to be designed. Constraints were mainly the following: 1) Define the quantity, quality and origin of the water to be injected; 2) Define the best location for feeding the cave; 3) Define characteristics of the infiltration device; 4) Define the best location with respect to technical constraints of the motorway.

2.1. Water quantity, quality and origin

The assessment of water quantity flowing in the cave, as well as the rate of groundwater recharge determined from hydrological modeling in this region provided an insight into the necessary injection rate. A rate of 1 to 5 m^3/day is necessary for the compensation of the missing infiltration. Concerning water quality, the injection is supposed to replace (or reproduce) processes taking place in the soil and the epikarst subsystems which lie over the cave (recharge is strictly diffuse in this region). The main characteristics of these two subsystems are significant storage, significant enrichment in CO_2, as well as significant increase in dissolved calcium and carbonates in the water. After having considered various options, it was decided to inject water from the drinking water distribution network (water which is largely oversaturated in dissolved calcite) and to enrich it with CO_2 in order to prevent calcite deposition in the infiltration plant. CO_2 concentration of the infiltrated water should therefore be slightly above CO_2 concentration in the cave, in order to guarantee some degassing and the possibility of calcite deposition on speleothems in the cave.

2.2. Best location for feeding the cave and its speleothems

The catchment areas of the speleothems observed in the cave were delineated in order to make sure that the injection system would effectively feed the speleothems. The catchment size was assessed from discharge rates observed in the cave and a catchment area was delineated almost vertically above the cave. The position was then verified by a series of tracer tests (Figure 2). Tracers where first injected by sprinkling the tagged water on top of the soil cover. This produced significant retardation (requiring several months for a flow of 40–50 meters down to the cave). A second series of tracing experiments was conducted by injecting tagged water directly into the epikarst after removal of the soil. Responses were then much quicker. Catchment areas could be delineated from these experiments with a reasonable degree of confidence. It must be mentioned here that the pluviometer "pluvio 1" ("Tôle ondulée" station) has its catchment West of the trench and partly outside the perimeter of the road (between the motorway and a minor road to the West. It should therefore not be too much influenced by injections in the trench.

2.3. Characterization of the infiltration device

The soil and most of the epikarst was removed by the construction. In order to spill water over a large surface into

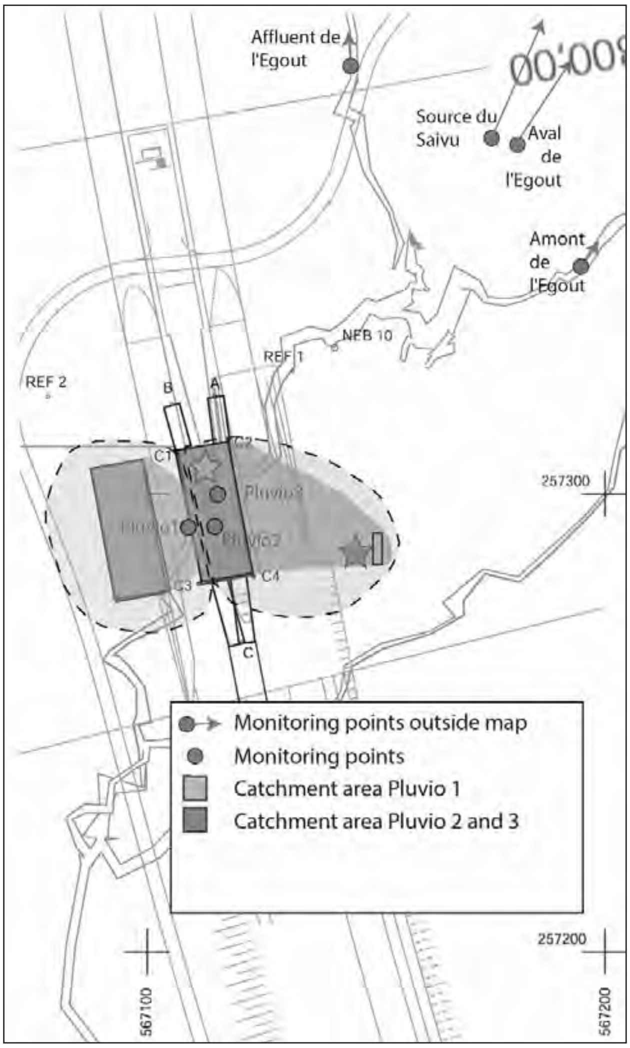

Figure 2. Detailed map of the injection systems, with the catchment areas determined by tracer tests. The motorway, the injection system and the cave network are drawn in brown, black and blue, respectively.

several fissures of the bedrock, it was decided to make a trench at the top of the limestone and to bring water to 16 points along the trench with a series of pipes. Walls and ceiling of the trench were sealed with a PVC-foil in order to limit CO_2 degassing.

2.4. Conditions related to the motorway

In order to keep costs at a reasonable level the trench could only be placed between the two traffic lanes. The vicinity of the tunnel portal required dividing the trench into two branches in its Northern part because supports of the tunnel gate had to be placed in the centre. The trench was filled with quartz gravels in order to avoid any dissolution in the infilling material and prevent any possible subsidence.

The resulting trench design is presented in Figure 3.

3. Results

Two main results are presented here: 1) the evolution of the drip rates in the cave during the road construction, and 2) the effect of the infiltrations.

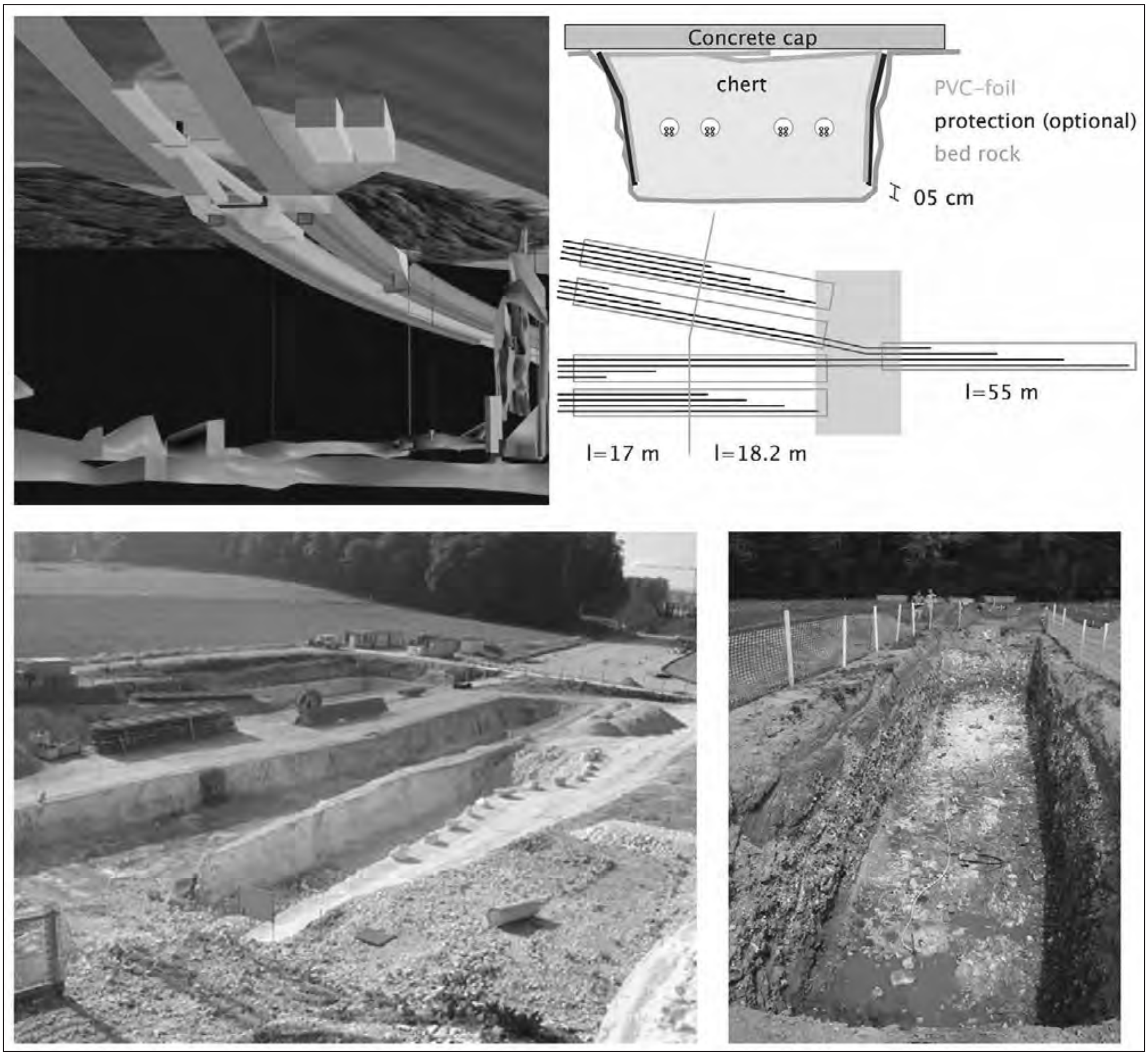

Figure 3. Three-dimensional model of the injection system below the motorway (in blue) and above the cave. Cross-section and plan-view of the injection system: 16 pipes deliver water at 16 locations along the trench. Pictures of the constrution of the injection system (left) and of a tracer injection.

3.1. Evolution of drip rates after soil/epikarst removal and impermeable sealing of the road

The drip rate has been recorded at three stations in the cave since the end of 2002 (Figure 4). The first period of time (up to Sept 2006) was not influenced by any roadwork and the land was used for agriculture. The two thin peaks visible in April and June 2004 are related to artificial injections into trenches dug in the soil down to the top of the epikarst. Year 2003 was extremely dry. During this period of time the behavior of all three stations is broadly similar with one or two main peaks in winter and a steady but slow decrease during the spring, summer and early autumn.

In August 2005 the soil and part of the epikarst were removed for the construction, and the remaining epikarst and bedrock were exposed to rain events. Station 1 (red curve) displays an increased variability with many more peaks exceeding the the measurement capacity than before. Station 2 (pink curve) shows an increased variability and a general decrease of the average discharge rate. Unfortunately station 3 (Plafond) was mainly out of order during the period. It worked again at the end of the period and clearly has a more jagged behavior than before. The soil removal clearly decreased the storage capacity of the upper part of the vadose zone, inducing a more jagged ("flashy") behavior in all three stations.

The motorway was covered by asphalt and runoff waters drained away at the beginning of 2010. All three stations are obviously still fed by rain events, as evidenced by the peaks. However, their discharge rate decreased significantly, especially in 2011, which was a very dry year (although not as dry as 2003). All three stations displayed their lowest ever measured discharge rate in the summer of 2011.

3.2. The effect of the infiltration

Artificial infiltration started in October 2011. The effect is clearly visible in "goutte à goutte" (pink curve) and "Plafond" (violet curve) stations. This highlights the efficiency of the infiltration system and show that the speleothems are indeed fed by the infiltrating water. The

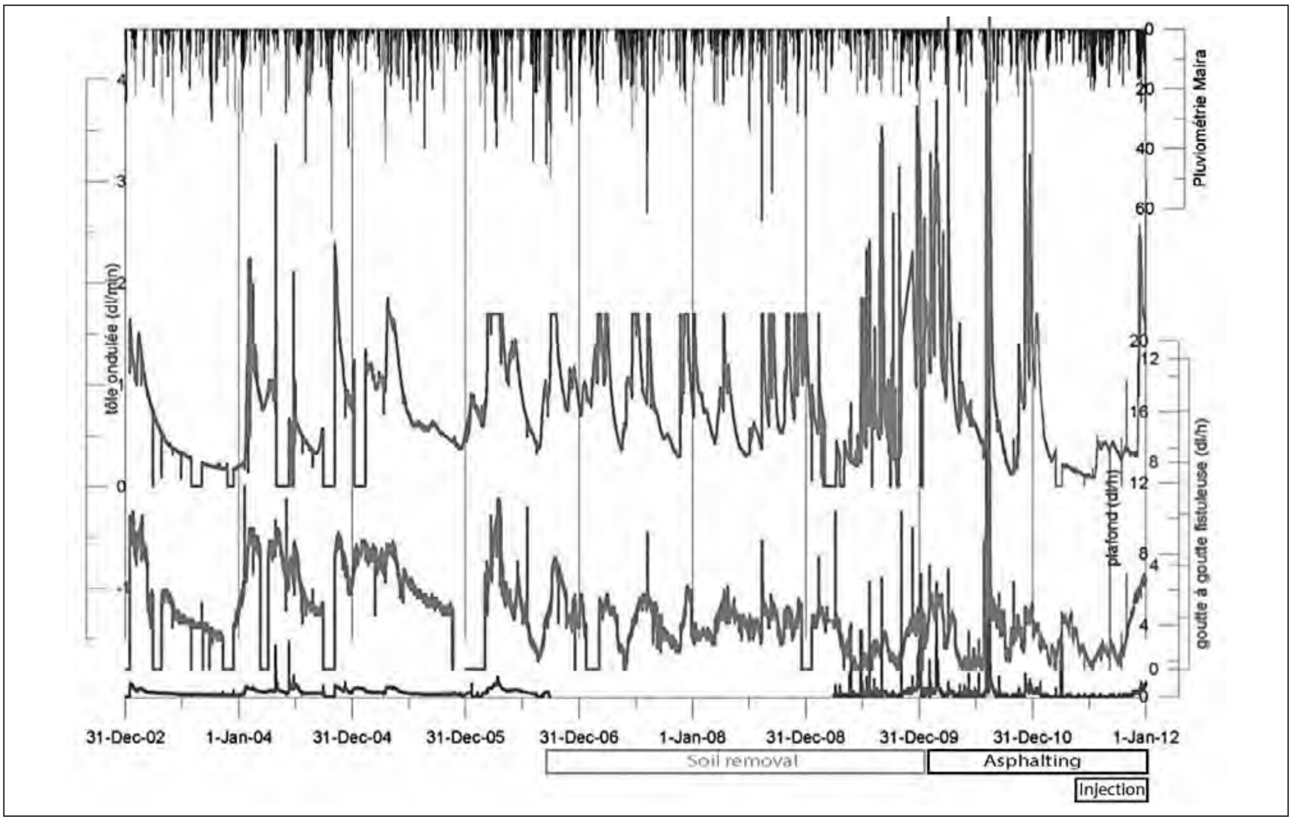

Figure 4. Precipitation and dripping rates in the cave before and during construction, and after setup of the injection system.

effect is less clear in "Tôle ondulée" station. Very high rates are observed in December 2011, but could be related to a strong recharge. It was however expected that injections should mainly feed the other two stations. Longer monitoring and adjustments in the injected rates will show if the natural behavior of the system can be approached.

4. Discussion and conclusions

The removal of soil and epikarst clearly changed the regime of drip rates measured at the three stations in the cave. Storage was obviously reduced, inducing a smoother regime. The impermeable sealingtorway reduced the infiltration of rain events, but all three stations still receive water from natural rain. This shows that horizontal transfer in the epikarst can be at least as great as 20 to 30 meters.

The injection system does react as expected by feeding mainly speleothems measured in stations 2 and 3. However, the CO_2 content in the injection-trench does not correspond to what was expected, and further investigations are being made to better understand this aspect.

A detailed model of the infiltration in this site is being constructed using all the acquired data. It will provide interesting information on the respective effects of flow processes in soil, in the epikarst and in the vadose zone.

This site gives a unique opportunity to carry out dedicated experiments on flow and transport within the unsaturated zone of a karst system. It will also allow observation of the effect of the induced regime variations that have been observed on the growth of speleothems. The first experiments are already ongoing.

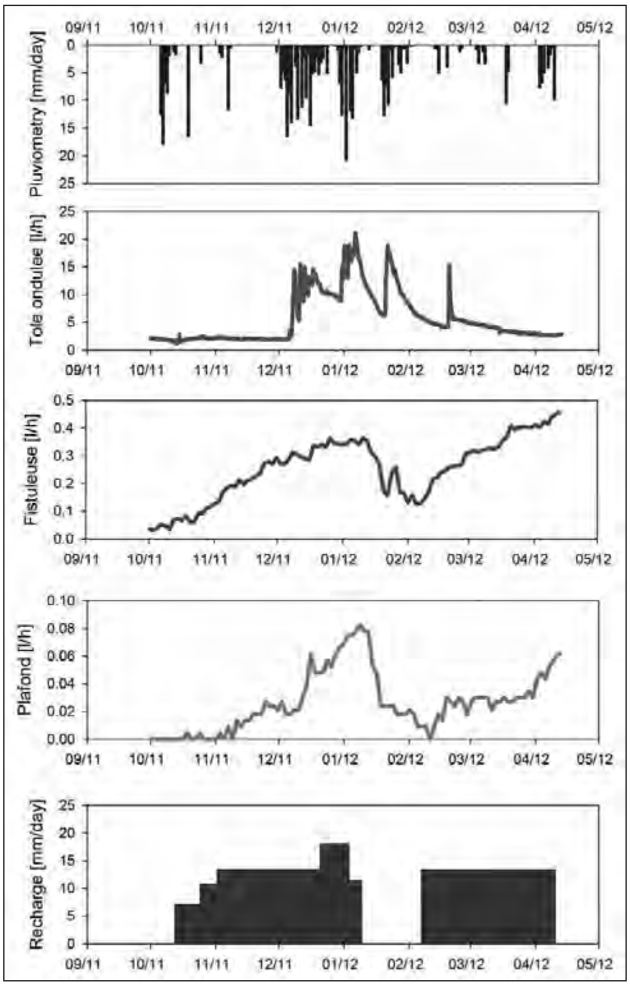

Figure 5. Precipitation, dripping rates in the cave and artificial recharge at the injection site during the first weeks of injections.

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HIGH RESOLUTION TEMPERATURE SAMPLING OF CAVE CLIMATE VARIATION AS A FUNCTION OF ALLOGENIC RECHARGE, COLDWATER CAVE, IOWA, USA

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Variations in cave stream temperature from allogenic recharge can cause significant fluctuations in cave air temperature. Coldwater Cave, a component of the Coldwater Cave groundwater basin in northeast Iowa, USA, is a dendritic cave system draining a 50-km^2 watershed shown to be recharged by a series of sinking/loosing streams and a network of sinkholes and drained by two spring resurgences. The only human-enterable entrance is by SCUBA through one of the spring resurgences. There are two man-made shafts installed for human entry and they have air-lock entrances. This hydrologically dynamic system provides a unique opportunity to study the affects of allogenic recharge on cave climate. Data loggers, recording at 10-minute intervals, were installed at six in-cave sites to measure air and stream temperatures, and at the two springs to measure water temperature. Weather stations located above the cave and from a local climate station documented surface air temperature. This eight-year study demonstrated that both resurgences, and in-cave sites proximal to surface recharge points displayed significant variation in water and air temperature hourly, daily and seasonally as well as during storm events. In-cave sites that were located farthest from surface recharge showed very little fluctuation in water and air temperature and corresponded to the mean annual temperature of the area. These results offer important implications in terms of the study of aquifer vulnerability to surface contaminants, cave ecosystems, speleothem development, and thermodynamic controls on subterranean karst processes.

1. Introduction

Factors that affect contemporary cave climate within a fluvio-karst cave system include air flow from open surface entrances, and allogenic recharge. Cave airflow in this setting is a function of air exchange with the surface environment driven by barometric fluctuations. Variations in cave stream temperature from allogenic recharge can also cause significant fluctuations in cave air temperature. Coldwater Cave, a component of the Coldwater Cave groundwater basin in northeast Iowa, is a dendritic cave system draining a 50-km^2 watershed shown to be recharged by a series of sinking/loosing streams, and a network of sinkholes. The cave has two spring entrances that are water-filled and two air-closed man-made shafts. This hydrologically dynamic system provides a unique opportunity to study the affects of allogenic recharge on cave climate.

Data loggers, recording at 10-minute intervals, were installed at six in-cave sites to measure air and stream temperatures, and at the two springs to measure water temperature. Weather stations located above the cave and from a local climate station documented surface air temperature. This eight-year study demonstrated that both resurgences, and in-cave sites proximal to surface recharge points displayed significant variations in water and air temperature hourly, daily, and seasonally as well as during recharge events. In-cave sites that were located farthest from surface recharge showed very little fluctuation in water and air temperature and corresponded to the mean annual temperature of the area. These results offer important implications in terms of the study of aquifer vulnerability to surface contaminants, cave ecosystems, speleothem development, and thermodynamic controls on subterranean karst processes.

2. Site Description

The study area is located in the Driftless region of the Upper Midwest in northeast Winneshiek County, Iowa and southeast Fillmore County, Minnesota USA within the Coldwater Cave groundwater basin of the Upper Iowa River watershed (Figure 1). The watershed is formed on a highly karstified landscape that is drained by surface creeks and by conduit flow within the Coldwater Cave system. The Coldwater Cave groundwater basin was initially delineated in a series of dye traces that were conducted in 1986 (Wheeler et al. 1988) and further defined by dye tracing conducted in 2002–2005 (Kambesis 2007).

Figure 1. Location of study area.

The Coldwater Cave groundwater basin underlies the Coldwater Creek and Pine Creek sub-basins. Streams from both of the watersheds lose water to the subterranean drainage system either via swallets or through stream sieves. During precipitation events or freeze-thaw events, sinkholes in the study area also contribute recharge to the groundwater basin. The mean annual surface temperature of the area is 8 °C with a record high of 40 °C and low of -41 °C. (Midwestern Regional Climate Center 2012). The mean annual precipitation in the study area is 853 mm and for snow is 1,010 mm.

The Coldwater Cave System (Figure 2) is Iowa's longest cave, developed in the Ordovician-aged Dunlieth Formation, and has been mapped to 28 kilometers in length with a vertical extent of 35 meters (Kambesis 2003). There are no natural open surface entrances to the system. Primary access to the cave is through a 29-meter man-made shaft (Flatland entrance) that was drilled in the early 1970's by the state of Iowa for researcher access. A wooden platform was installed at the base of the shaft. The State also constructed a metal building over the shaft entrance that now serves as a field house and research station. A second privately owned shaft entrance was drilled in 2003, and is located approximately two kilometers south of the Flatland entrance. Both man-made entrances are airlock sealed when the cave is not in use.

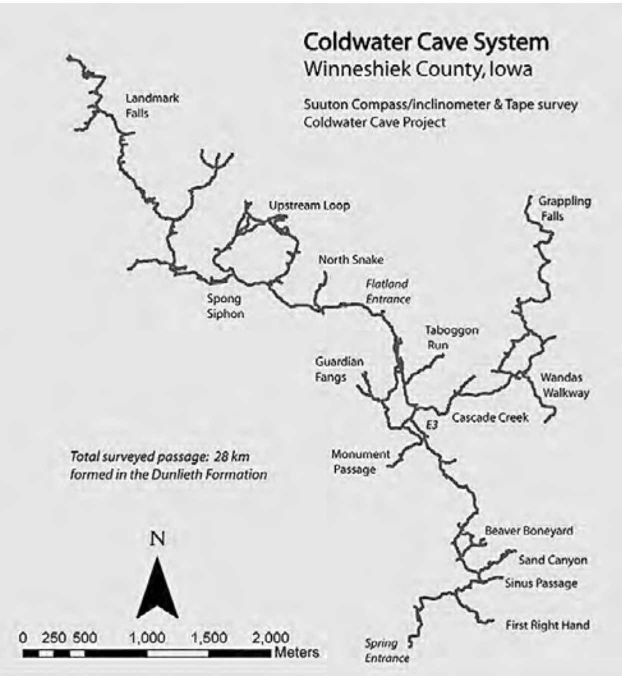

Figure 2. Map of Coldwater Cave, Iowa, USA.

Coldwater Cave System is dendritic in its layout that is indicative of many points of recharge from the surface. The subterranean streams of the Coldwater Cave System resurge to the surface via two spring outlets and during high recharge events, at an overflow spring. The main outlet is Coldwater Spring that has a discharge rate of 548 liters/second during base flow conditions (Koch and Case 1974). Carolan Spring is a secondary outlet that discharges at 160 liters/second. Both springs form spring-runs that flow to the Upper Iowa River located a kilometer to the southeast. Coldwater Spring is the only natural entrance to the cave and issues from the base of a 30-meter-tall bluff located within the Cold Water Creek Conservation Area. Access to the cave via this entrance requires SCUBA.

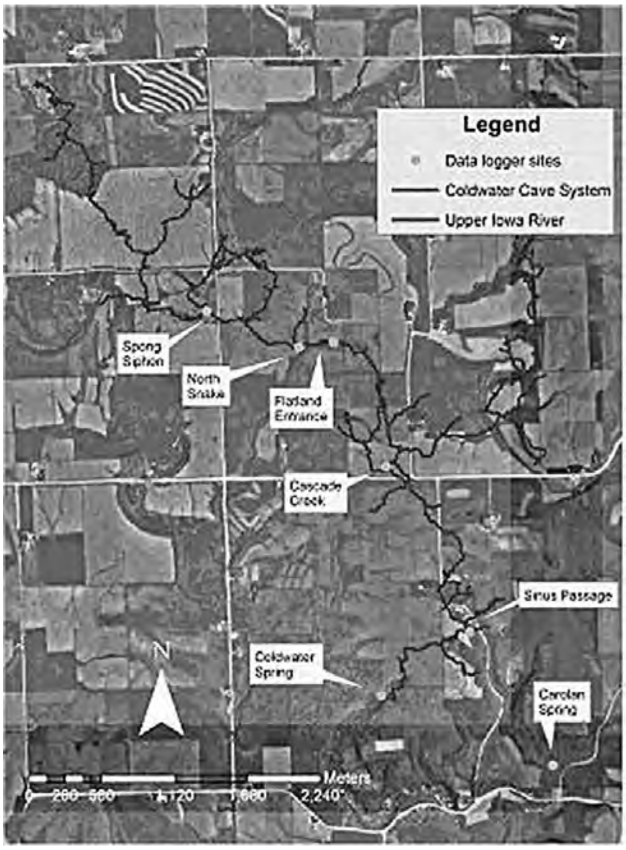

Figure 3. Data logger locations.

3. Methods

In 2003, water temperature data loggers were installed at five in-cave sites and at the springs that drain the Coldwater Cave System (Figure 4). Additional data loggers were added in 2005 to measure air temperature. Data from loggers were downloaded every other month except for those in remote locations that were downloaded quarterly. Onset-Brand Optic Stowaway temperature data loggers (32K) (Figure 4) were anchored with 1.3-kg plastic-coated weights and installed at the seven locations. The sampling interval was set at ten minutes. An Onset-Brand optical shuttle was used to download data. The data were uploaded into the Boxcar brand software package that comes with the Onset temperature loggers.

Precipitation data were obtained from the Minnesota Climatology Working Group web page (http://climate.umn.edu/doc/historical.htm 2012). Precipitation data originated from the Harmony, Minnesota weather station that is located at the northern edge of the study area. Precipitation is recorded daily from rain gauges located on-site.

Daily maximum and minimum surface temperature data were also obtained from the Minnesota Climatology Working Group website. Daily temperatures are measured in Preston, Minnesota using a minimum/maximum thermometer and documented by observation volunteers.

The climate data were used in conjunction with hydrologic data to determine the timing of recharge events, to relate precipitation to spring discharge and, to correlate surface temperature to subsurface stream water temperatures. For this study, recharge events are defined as climatic conditions that cause an increase in cave stream discharge. Such events include rainfall and/or increases in winter surface temperatures to above freezing (freeze-thaw events).

Figure 4. Onset data logger. Precision of loggers are 0.01 degrees.

4. Results

The mean annual temperature of the springs that drain the cave is 8.9 °C. However, some of the cave streams and associated passages, and all of the discharge springs for the Coldwater Cave groundwater system display fluctuations in water temperature as high as nine degrees above and seven degrees below the mean annual temperature of spring. Air temperatures are typically three to five degrees higher than water temperatures. There is a 3–4 hour lag between corresponding water and air temperature.

There are signicant temperature variations between different parts of the cave system (Figure 5). The diurnal and seasonal variations in surface temperature, are reflected in the cave stream temperature graphs (Figures 6a and 6b) for passages that are located less than 500 meters from surface stream sink points.

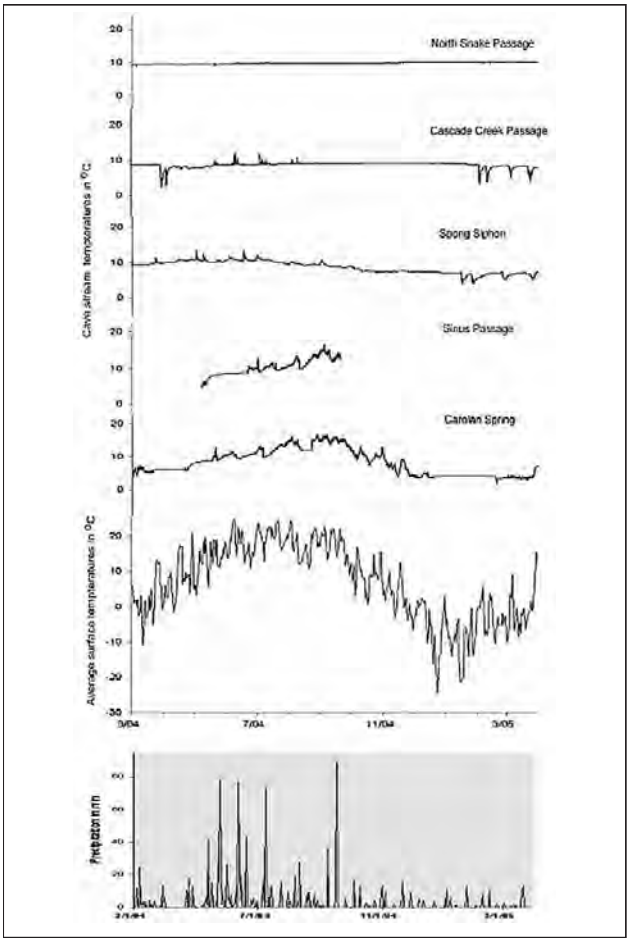

Figure 5. Spatial variation of cave stream temperature and precipitation events.

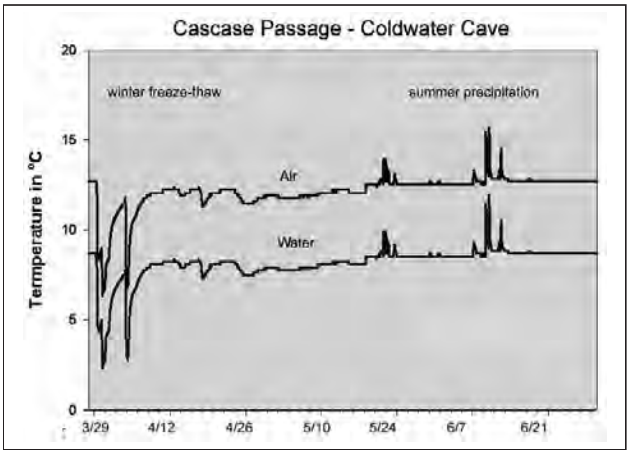

Figure 6a. Seasonal temperature variation.

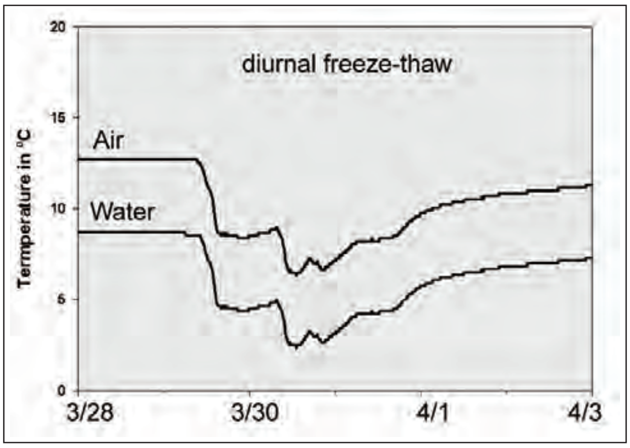

Figure 6b. Diurnal temperature variation.

5. Discussion

Cave spring and cave stream graphs (Figure 5) are based on 10-minute resolution data. Cave water and surface temperatures were highest from April through October, lowest from November through January and fluctuate above and below freezing in February and March.

Temperature variations are also caused by recharge events. The period between March and October have the most precipitation and this is reflected in the spiky nature of the cave stream temperature graphs during that time span. Even the North Snake Passage, which shows the least effect from surface influences displays a little noise in the March through October time period. Though the period between November and March did not receive storm event precipitation, the cave temperature graphs showed fluctuations during this time period because of the diurnal freeze-thaw affect.

There are signicant temperature variations between different parts of the cave system. The diurnal and seasonal variations in surface temperature, are reflected in the cave stream temperature graphs for passages that are located less than 500 meters from surface stream sink points. Table 1 lists in-cave locations and their locations from surface inputs that have been confirmed by dye-trace.

The cave streams that showed significant temperature ranges had headwaters that were located directly under or within 200 meters of surface streams. Surface waters enter and move through the system at high velocities such that they do not

Table 1. Data logger locations and distance from surface inputs.

Data logger location	Distance (meters) of data logger location from surface stream input	Associated surface stream (confirmed via dye trace)
North Snake Passage	820*	Pine Creek
Entrance Platform	730*	Deer and Pine Creeks
Cascade Creek	198**	Pine Creek
Sinus Passage	133**	Pine Creek
Spong Siphon	30**	Deer Creek
Carolan Spring	10	Pine Creek

* very little variation in stream and air temperature
** water temperature variations five degrees above and seven degrees below mean annual spring outlet temperature

equilibrate with the ambient underground temperature. As a consequence, the springs that discharge the cave stream water also display significant ranges in temperature.

6. Conclusions

The Coldwater Cave System has no open air entrances with the surface so major temperature fluxes result from allogenic recharge. The temperature graphs for Coldwater Cave display temporal, recharge event related, and spatial differences. Temporal variations are seasonally in phase with surface temperatures. Recharge events such as storm events or freeze-thaw events cause diurinal temperature variations. Both of these reflect the low thermal capacity of recharge water and the rock that contains the aquifer. However, there are some sections of the cave that show minimal variation in temperature. The sites are located more than 500 meters from surface recharge and do not show seasonal or diurinal variation because recharging waters are moving slow enough to equilibrate to the temperature of the aquifer bedrock.

Acknowlegements

We would like to thank Hoffman Environmental Research Institute, Upper Iowa River Watershed Alliance, National Speleological Society and Cave Research Foundtion for financial support; Upper Iowa River Watershed Alliance for laboratory support; field work support from volunteers of the Coldwater Cave Project and the Iowa Grotto. Most of all we thank the landowners Kenny and Wanda Flatland for their friendship and long-term logistical support.

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PERCOLATION INTO DRAGON'S TOOTH CAVE, FLORIDA, USA

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Investigations of epikarst hydrological characteristics are important for understanding the complex relationships between cave calcite chemistry and changes in net rainfall, cave drip rates, and fluctuations in cave dripwater. We instrumented Dragon's Tooth Cave (Marianna, Florida, USA) with an array of instruments to characterize individual rainfall events above the cave and measure hourly in situ drip rates at selected stalactites within the cave. Drip rates at most of the instrumented stalactites increased in response to heavy summer-season precipitation. A sharp increase in drip rates was also observed after several fall/winter months of low to negative net rainfall (i.e. when evaporation > precipitation). This phenomenon may indicate that the stalactites are being fed by a series of connecting reservoirs feeding cracks of various geometries and flow rates. Geological surveys, tracer experiments, and additional time-series data collection will be conducted to further investigate reservoir existence and behaviour. The findings have important implications for the interpretation of speleothem paleoclimate records in terms of both geochemistry and seasonal growth rates.

1. Introduction

Accurate interpretation of karst-cave paleoclimate records requires an understanding of water transport, flow routes, and water residence times in the limestone above the cave. Even within a single cave room, the properties of individual drips are unique, dependent on complex flow routes. Flow rate usually varies with seasonal changes in barometric pressure and water percolation into the aquifer (Genty and Deflandre 1998).

Travel paths of water flowing from the ground surface to speleothems have been studied at caves in Europe and Australia (Tooth and Fairchild 2003; Fairchild et al. 2006; Baker and Bradley 2010). With a few exceptions (e.g., Wong et al. 2011; Tremaine et al. 2011; Tremaine and Froelich 2013), caves in the United States remain poorly studied.

The relationship between above-ground precipitation and cave drip-rate intensity reflects the water balance that results from atmospheric and cave processes. One objective of this study was to continuously measure rainfall and hydrological parameters at Dragon's Tooth Cave, a poorly characterized limestone cave with a relatively thin (3.5 m) epikarst. A second objective is to develop a "reservoirs-cracks" water-flow model that can be tested using the time-series field data. Understanding drip-rate behavior will allow us to isolate particular reservoirs, thus setting the stage for detailed three-dimensional geological surveys and quantitative field tests of water flow.

2. Study Site

Dragon's Tooth Cave (DTC; Fig. 1) is located in Florida Caverns State Park in Marianna, Florida, approximately 100 km northwest of Tallahassee. One of the state's most unusual parks Florida Caverns contains more than 30 named caves (Ludlow 1997). Most have been mapped by caving groups. Caverns in the park vary in condition. Some are severely damaged, while others remain pristine (Ludlow 1997). Several caves, including DTC, have been gated to protect their geological formations and rare cave biota.

Dragon's Tooth is one of the park's largest and most predominant vadose cave passages. Dragon's Belly, one of the largest dry cave rooms in Florida, is approximately 41 m long, 17 m wide, and 6 m high. The latest map of DTC with the "Dragon's Belly" extension (Fig. 1) was created in 1986.

Most of large caves are developed in the upper Bumpnose member of the Crystal River formation. The Dragon's Tooth ceiling consists of two limestone layers: Marianna Limestone, a resistant, hard-to-soft, white-to-cream marine limestone and the Bumpnose, a soft, white fossiliferous limestone. The DTC roof is approximately 3.5 m thick. (Fig. 2)

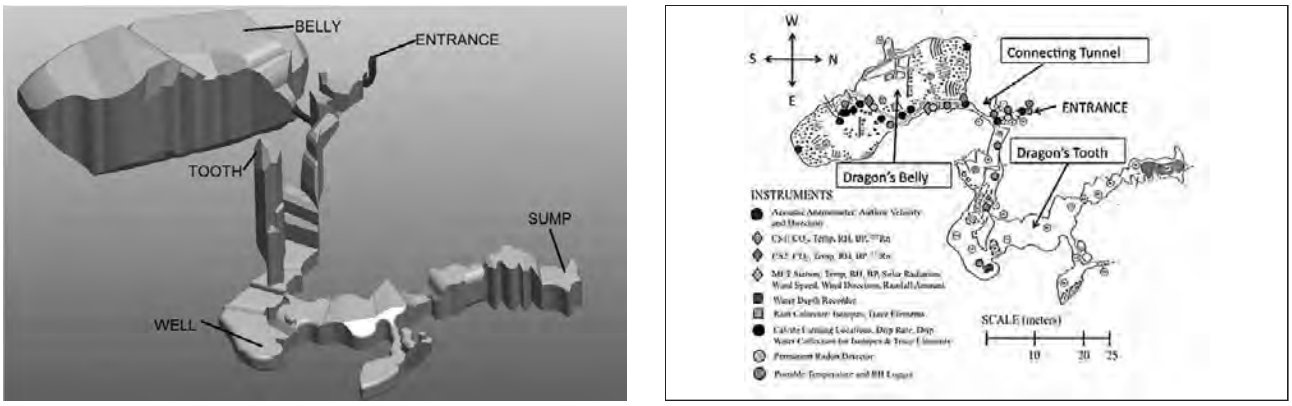

Figure 1. Left: Three-dimensional illustration of Dragon's Tooth Cave Right: Plan view of Dragon's Tooth Cave with instrument locations, calcite farms, and dripwater collection sites.

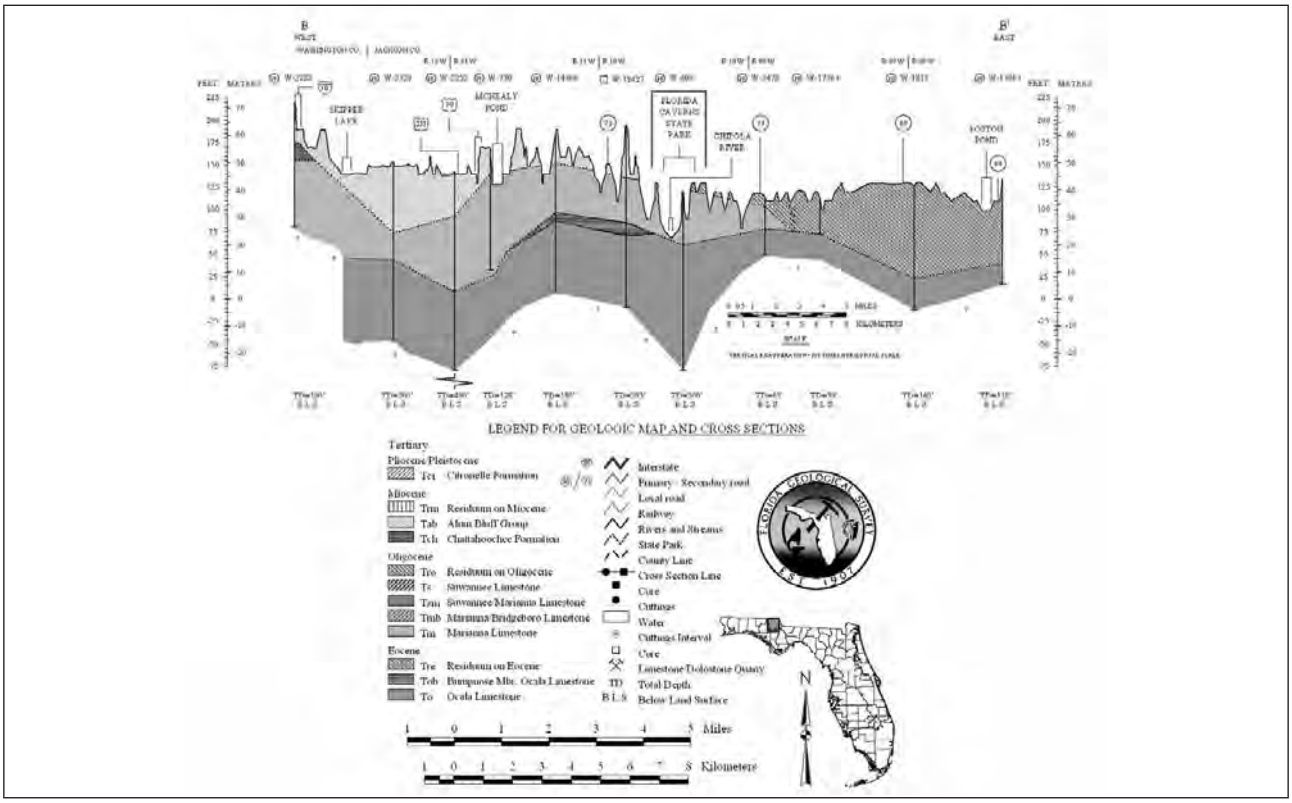

Figure 2. Geologic map of the Dragon's Tooth Cave area. Modified from Green et al. (2003).

Cave development in the park is promoted along three planes: two vertical joint directions plus a horizontal direction parallel to bedding (Boyer, 1975). DTC displays preferential development along a vertical controlling joint at approximately N 30° W, parallel to the orientation of the nearby Chipola River (Boyer 1975).

Cave hydrology is controlled by both precipitation and evaporation. Precipitation is important because it serves as a source of dripwater. Mean annual precipitation in Quincy, Florida (35 km east of Marianna) is approximately 1,377 mm yr^{-1} (Fig. 3). Evapotranspiration is important because it removes water from the soil, thus concentrating ions in soil water by up to a factor of ten. In northwest-central Florida, approximately 80% (±7%) of the rainfall is evaporated (Bidlake et al. 1996), even in summer when precipitation rates are high (Tremaine and Froelich 2013). This evaporation rate is typical for subtropical pine flatwood ecosystems (Bidlake et al. 1996). In fall and winter, temperatures are lower and plants take up water less readily. Evapotranspiration is thereby diminished, and positive net rainfall (i.e. precipitation > evapotranspiration) is more likely.

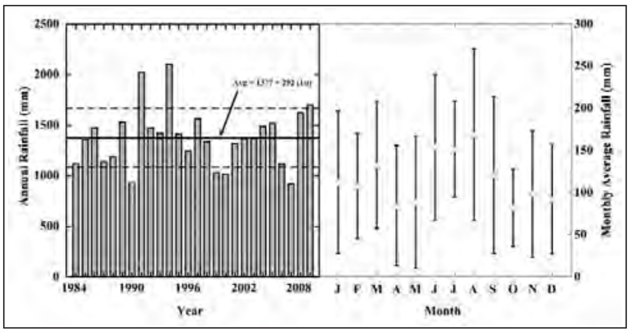

Figure 3. Left: Annual rainfall in Quincy, Florida, 1984–2010 (www.ncdc.noaa.gov). Right: Monthly rainfall averages and 1-sigma ranges from the same data set.

3. Methods

3.1. Field Measurements

To understand cave hydrologic responses to precipitation, continuous records are required for rainfall amounts, drip rates, and the meteorological parameters that determine evapotranspiration rates. A meteorological station was therefore installed above Dragon's Tooth Cave in May 2012 to continuously measure rainfall, barometric pressure, relative humidity, air temperature, wind speed and direction, and solar irradiance at 15-minute intervals. An automatic precipitation sampler (MDN 00-125-4) was installed in June 2012. This collector captures samples from individual rainfall events, thus allowing direct correlation of isotopic and trace element compositions in rainwaters and the resulting dripwaters. Such correlations allow for estimates of water residence times and preferential penetration routes through the epikarst.

To measure DTC drip rates, acoustic drip counters mounted on tripods were deployed under eight stalactites (Fig. 4). These stalagmate acoustic drip counters work as a microphone, recording the number of drops falling on a box top over a user-defined time interval (Collister and Mattey 2008). Drip rates have been continuously recorded at seven stalactites at 1-hour intervals from May 2012 to present.

3.2. Two-Dimensional Dripping Model

Precipitation that is not intercepted by evapotranspiration percolates through unsaturated porous geologic media by following the fastest paths – i.e. fractures (Pendexter 1996). The karst above Dragon's Tooth Cave is heterogeneous and highly fractured, with many voids and pockets.

Figure 4. Left: Dripwater logger (white box) mounted atop a tripod. Right: Southern section of the "Dragon's Belly".

Several models have been recently constructed to determine hydrological variations in caves (Tooth and Fairchild 2003; Fairchild et al. 2006; Baker and Bradley 2010). These models describe flow within a system of connected reservoirs that feed stalactites, with an emphasis on reservoir storage capacities and water discharge.

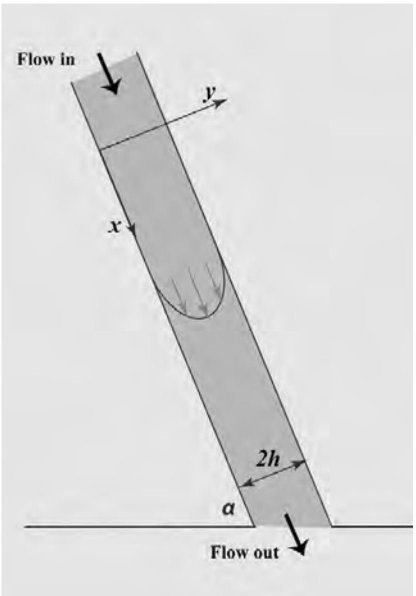

Figure 5. Flow through a model crack. Crack width is 2h. The parameter a represents the size of the crack.

In this study we considered that pockets in the karst are connected through a complex system of cracks. Water movement in cracks of different sizes and orientations can be examined (Fig. 5).

Here we outline the primary set of equations used to model flow through the roof of Dragon's Tooth Cave. We assume that the flow is laminar with a fluid velocity U flowing in the x direction, varying only in y. The dominant force balance in the x direction is between viscous forces and gravitation:

$$U = [U(y), 0, 0] \quad (1)$$

$$0 = -\frac{1}{\rho}\frac{\partial P}{\partial x} + \nu \frac{d^2U}{dy^2} + g\sin\alpha \quad (2)$$

$$0 = -\frac{1}{\rho}\frac{\partial P}{\partial y} - g\cos\alpha \quad (3)$$

where U is fluid velocity, P is pressure, g is gravitational acceleration, and α is angle between crack and horizontal axis. Fluid characteristics are given by ρ (density) and ν (viscosity).

Discharge per unit width, q, is derived from equations (1) – (3):

$$q = \frac{2gh^3}{3\nu}\sin\alpha \quad (4)$$

where h is half the distance between the crack walls (Fig. 5).

In the future, the water-transport model will be further developed by the addition of reservoirs. Modeled discharge rates will be compared to rates measured in situ.

4. Results and Discussion

Measured monthly rainfall above Dragon's Tooth Cave (May 2012 – February 2013) averaged 109 mm, ranging from a low of 13 mm (January 2013) to a high of 304 mm (August 2012). Heavy rainfall events occurred from June through September. Throughout our study, regional evapotranspiration rates were approximately 100 mm month^{-1}. Net rainfall amounts were near zero at the beginning of the study (May), positive during the summer rainy season (June–August), near zero during the transition month of September, and negative in the winter months of October–January (Fig. 6).

Temporal dripwater patterns at the instrumented stalactite sites within Dragon's Tooth Cave were generally similar.

Most sites exhibited drip rates that varied seasonally. Site DT #2 was an exception, with a nearly constant rate of 130–170 drips/hour (Fig. 7). Most sites also exhibited seasonal variation in lag period (i.e. time between a rainfall event and a subsequently increased drip rate), ranging from 14 to 45 days. Drip rates were spatially variable, with stalactites less than a half a meter apart exhibiting different drip-rate ranges and lag times (e.g., DT #4 and DT #7; Fig. 8). Maximum drip rates varied from 120 to 850 drips/hour.

Most monitored stalactite sites were responsive to precipitation. In August 2012, several rain events occurred, producing a monthly rainfall total of 300 mm (Fig. 6). Significantly higher drip rates were observed within the cave in September (Fig. 8). At sites 1, 3, 5, 6, and 7, drip rates increased from 0 to up to 550 drips/hour.

Drip rates at several locations (Fig. 8 A-D) increased even more during the time of negative net rainfall than immediately after the high-precipitation summer period. The phenomenon of negative net rainfall and high drip rates could be explained by a system of interconnected reservoirs that feed cracks of various sizes, locations, and flow velocities. If cracks within a particular reservoir occur on the walls but not the floor, the reservoir will leak only after the water level reaches a certain height. To determine whether our rain-event sensor might have malfunctioned and missed some post-September rainfall, we cross-checked our measured precipitation rates against data collected at the Florida Caverns ranger station and at the Marianna Airport (5 km distant).

The velocity of water travel between a reservoir and its destination stalactites will further depend on the characteristics of the fractures themselves. The supposition of reservoir existence and delayed water delivery at Dragon's Tooth Cave will be further explored using ground-penetrating radar surveys and natural-tracer (SF6) pulse-chase experiments.

5. Summary and Conclusion

This paper describes nine months of preliminary time-series data (net rainfall and stalactite drip rates) indicative of percolation processes at Dragon's Tooth Cave in Florida. This cave is overlain by a shallow soil cover and a 3.5 m unsaturated zone in karstified, fractured limestone. At most of the instrumented stalactites, drip rates increased in response to heavy summer-season precipitation. A sharp increase in drip rates was also observed after several fall/winter months of low to negative net rainfall. This phenomenon may indicate that the stalactites are being fed by a series of connecting reservoirs that feed cracks of various geometries and flow rates. Geological (ground-pentrating radar) surveys will be conducted to determine the existence of such reservoirs. Pulse-chase tracer experiments will also be conducted to estimate residence times. Additional time-series data will be collected for detailed statistical analyses and numerical modeling studies.

Acknowledgments

The concepts discussed in this paper benefited from insightful comments provided by Darrel Tremaine, Drs. Markus Huettel and Bill Hu of Florida State University, as well as Harley Means and Tom Greenhalgh of the Florida Geological Survey.

We also thank the management staff of Florida Caverns State Park, especially Kelly Banta, for giving us an incredible opportunity to study one of the park's caves. Without their collaboration, this project would not have been possible.

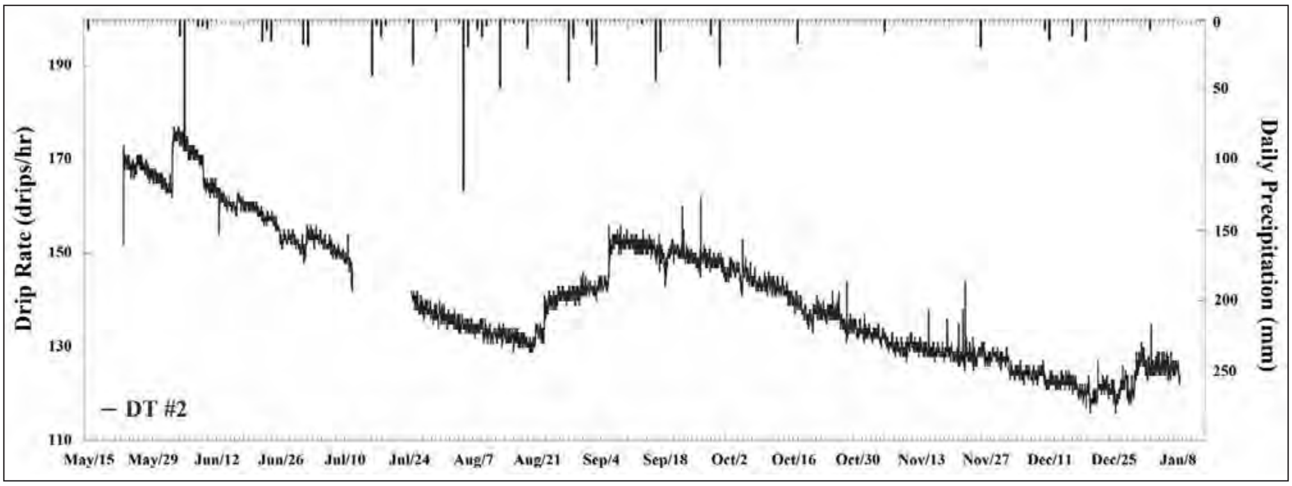

Figure 7. Daily rainfall totals (black descending bars) and DT #2 hourly stalactite drip rates.

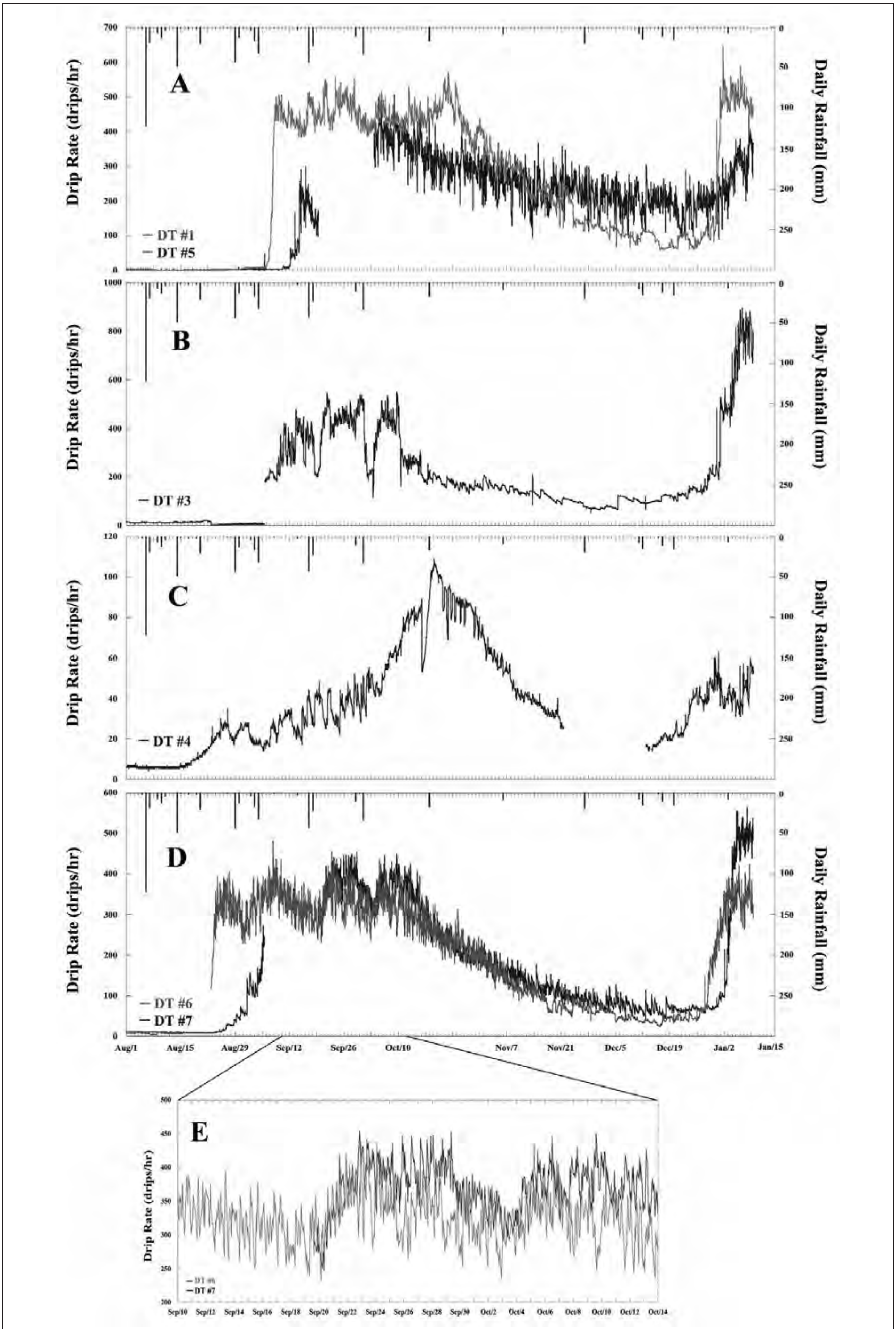

Figure 8. (A–D) Daily rainfall totals (black descending bars) and hourly drip rate, at six stalactite sites. (E)DT #6 and DT #7 hourly stalactite drip rates from September 10th to October 12th. Note the different vertical scales.

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PRELIMINARY RESULTS ON PALEOCLIMATE RESEARCH IN MECSEK MTS, HUNGARY

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The geochemical analyses of karst springs and their freshwater carbonate deposits provide an opportunity to reconstruct past climate changes. Nevertheless, there are still very few paleoclimate records obtained from freshwater carbonate deposits in Hungary. The present study focuses on some recently depositing freshwater tufa sites and two caves located in Mecsek Mts (Southern Hungary) as possible sources for Holocene paleoclimate research. Both carbonate and water samples were collected for stable isotope analyses in June and August 2011 and a monitoring programme was started in October 2011 at five sites. The stable isotope analyses of the rock samples reflect the effect of continentality and suggest strong soil zone CO_2 contribution.

1. Introduction

Terrestrial carbonate deposits (travertines, freshwater tufas and speleothems) are of particular importance in paleoclimatological, paleoenvironmental and geological studies. Speleothems, such as stalagmites, stalactites and flowstones, are a rich archive of terrestrial paleoclimate information (e.g., Wang et al. 2001) particularly since they offer the dual advantages of being closely tied to the mean hydrological balance and being a nearly ideal material for high precision U/Th disequilibrium series dating. Recent studies have proved that freshwater carbonate deposits, such as travertines and tufas can also be used in paleoenvironmental reconstruction (Andrews 2006, Lojen et al. 2009, Cremaschi et al. 2010) and their geochemical composition can be correlated with climate records gained from lake sediment, ice-cores (Stuiver et al. 1995) and marine sediments (Imbrie et al. 1984). The effects of global climate changes can be studied on them, since these deposits reflect local paleo-precipitation patterns and preserve key information on the paleoenvironment, as well.

In Hungary, in spite of the existence of large karst areas such studies have been delayed and there are still very few paleoclimate records obtained from terrestrial carbonate deposits (Kele et al. 2006; Kele 2009; Siklósy et al. 2009). Five carbonate depositing springs and two caves are taken under scrutiny in Western and Eastern Mecsek for paleoclimatic investigation. Our main aim is to reconstruct the Holocene paleoclimate of the study areas by doing a comparative geochemical analysis of these carbonate deposits. In this paper we would like to present the preliminary results of the research we started in the summer of 2011.

2. The study area

Mecsek Mountains is divided into Western and Eastern Mecsek. The karst areas of Western Mecsek are built up by well-karstifiable, Triassic rocks (Lapisi Limestone Formation, Zuhányai Limestone Formation, Csukma Dolomite Formation) in which numerous small caves, dolines and karst springs were formed. Three of the regularly studied springs (Kánya Spring, Anyák Spring and Dagonyászó Spring) and both caves are located here. In Eastern Mecsek karstic rocks are of Jurassic origin and have less suitable petrographic characteristics for karstification and speleogenesis. Two springs sites (Csurgó Spring and Pásztor Spring) have been monitored here (Fig. 1).

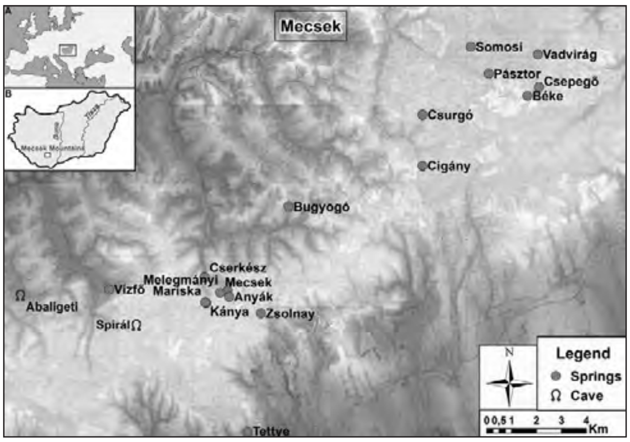

Figure 1. The study area (based on 1:10,000 scale topographic map in EOTR (Uniform National Mapping System of Hungary).

3. Methods

Recently deposited freshwater tufa samples were collected for stable isotope ($\delta^{18}O$, $\delta^{13}C$) analyses in June and August 2011 at 10 sites and water samples at 17 sites. In case of five springs monthly observations have been carried out for 10 months since October 2011. Two measurement points were set at each spring sites where the basic physicochemical parameters of water (pH, conductivity, temperature) were measured *in situ* once every month by using a WTW device. Water samples were collected in 100 ml bottles for determining alkalinity which were analysed within 48 hours by acid-based titration with 0.1 M HCl. Two meteorological parameters (air temperature and relative humidity) were also recorded at each measurement points at the time of measuring the other parameters.

Figure 2. The drilling site and the drilling core of Anyák Spring, Western Mecsek.

Besides, core drillings were carried out at three places on the surface (Anyák Spring, Csurgó Spring and Pásztor Spring, Fig. 2) and in case of two speleothems in Abaliget and Spirál caves.

The stable isotope analyses were performed at the Institute for Geological and Geochemical Research, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, Budapest, Hungary. Oxygen and carbon isotopes of bulk carbonate were determined using a Finnigan delta plus XP mass spectrometer. Oxygen and hydrogen isotopic measurements of water samples were done on LGR LWIA-24d liquid water isotope analyser. Isotopic compositions are expressed in the traditional δ notation in parts per thousands (‰) relative to VPDB ($\delta^{18}O$, $\delta^{13}C$) and VSMOW ($\delta^{18}O$, δD). Reproducibilities are better than ±0.2 ‰ for the $\delta^{18}O$ and $\delta^{13}C$ values of carbonates and ±0.2‰ for the $\delta^{18}O$ and ±0.6‰ for the δD values of water.

4. Results and discussion

4.1. Physicochemical water parameters

Water temperature shows a regular seasonal pattern reflecting the variation in air temperature, being higher in summer and lower in winter. Due to the moderating effect of the karst aquifer the amplitude of changes were 4.6 °C, 4.0 °C, 3.8 °C, 3.0 °C and 2.9 °C at Csurgó Spring, Pásztor Spring, Anyák Spring, Kánya Spring and Dagonyászó Spring, respectively. The reason behind this high amplitude in the case of Csurgó Spring is that there is no specific spring source, water appears in the stream bed and consequently it starts to equilibrate with surface temperature. The highest temperatures were recorded in April and July and the lowest in October and January.

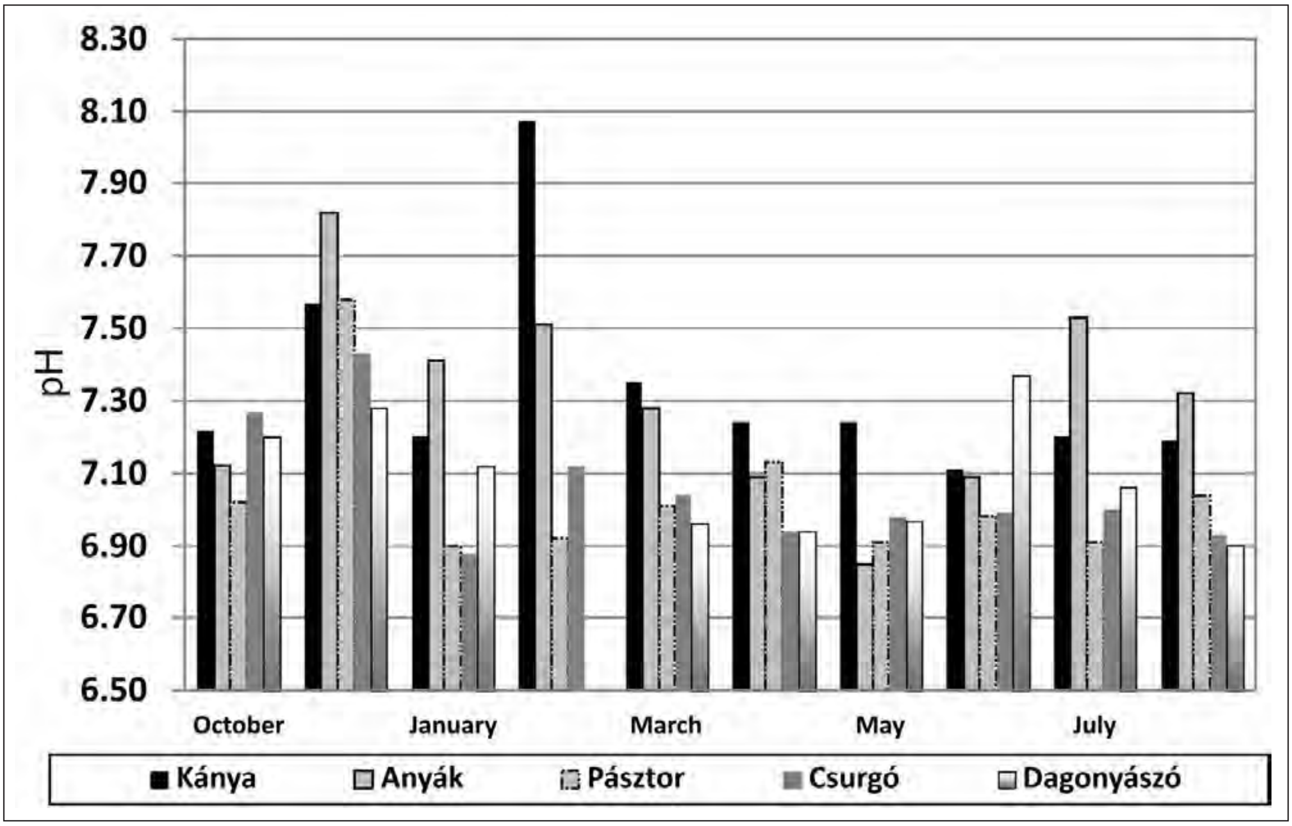

Figure 3. Monthly changes of pH, 2011–2012.

Downstream the water temperature increased in summer and decreased in winter. The seasonal amplitude rose to 14.5 °C, 18.1 °C, 19.1 °C, 8.9 °C and 7.8 °C, respectively.

Alkalinity had a similar seasonal pattern as water temperature. It was higher from late spring to autumn and lower from winter to early spring. Similarly to electric conductivity, alkalinity decreased downstream due to tufa deposition. The highest values of electric conductivity were measured at Anyák and Kánya springs (655–766 µS/cm and 702–755 µS/cm, respectively), while Pásztor Spring was usually characterised by much lower values (570–680 µS/cm). This is probably due to the differing geological characteristics of the limestone aquifer. Similarly low values were recorded at other springs in the same area (Vár Valley and in Óbánya Valley).

Contrary to electric conductivity and alkalinity, pH values gradually increase downstream. According to Kano et al. (1999) the seasonal variation of pH is characterized by high winter and low summer values, since more uptake of soil-originated CO_2 intensifies the dissolution of $CaCO_3$ and reduces the pH of the water. Soil pCO_2 is the highest from July to September and changes of the Ca^{2+} content, alkalinity and pH usually follow its seasonal variation with a delay of 1 or 2 months (Kano et al. 1999; Kawai et al. 2006). In Mecsek Mts. the highest pH levels were measured at the end of November and a second peak was observed at the end of January. Except for Pásztor and Kánya springs a pH values slightly increased at the beginning of summer (Fig. 3) and decreased in August.

Usually, Anyák and Kánya springs are characterized by higher pH levels than the other springs, most likely owing to differing aquifer conditions.

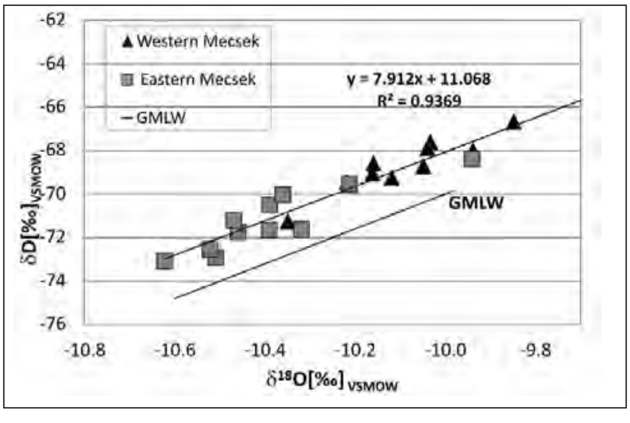

Figure 4. Stable isotopic composition of spring waters.

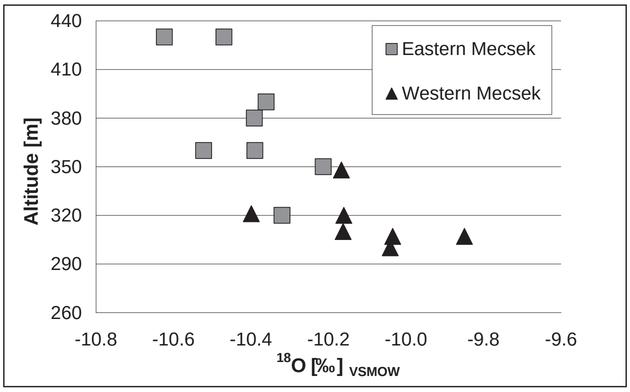

Figure 5. $\delta^{18}O$ values of spring waters plotted against sample altitude.

4.2. Stable isotopes

Stable isotope analyses of the 17 karst springs revealed unambiguous differences between Eastern and Western Mecsek (Fig. 4). The possible cause of this difference could be the so-called "altitude effect" or the "amount effect". The springs of Eastern Mecsek are located at higher altitude and have their catchment areas at higher elevation than the ones in Western Mecsek. Therefore, the investigated springs in Eastern Mecsek are characterized by more negative isotope values (Figs. 4 and 5).

At some springs (e.g., Anyák Spring) monthly differences can be observed in the isotope composition of the karst water, reflecting seasonal changes in precipitation $\delta^{18}O$. Nevertheless, isotopic values change little ($\delta^{18}O$: 0.4‰ both at the spring and at the tufa site). The δD and $\delta^{18}O$ data of the studied springs fit the Global Meteoric Water Line, indicating their meteoric origin. The mean values are -69.8‰ and -10.2‰, respectively.

The observed difference between Eastern and Western Mecsek in the $\delta^{18}O$ data cannot be seen in case of tufa samples which can be a result of the difference in water temperatures in which the tufa calcite forms. Unfortunately, all the parameters were recorded once a month so we can only estimate the mean water temperature at the places of tufa deposition. Kinetic effects might occur, as well. Further investigations are needed to understand this difference. In order to monitor the $\delta^{18}O$ and $\delta^{13}C$ changes of recently depositing freshwater tufas, glass substrates were put at the measurement points in September 2012. Unfortunately, we have no reportable results yet.

Table 1. Stable isotopic composition of carbonates.

Tufa-depositing springs	$\delta^{18}O$ ‰ (VPDB)	$\delta^{13}C$ ‰ (VPDB)	Altitude (m)
Kánya Spring	-8.6	-9.9	307
	-8.7	-11.2	307
Anyák Spring	-9.3	-9.9	320
	-9.4	-10.1	319
	-9.2	-10.6	318
Pásztor Spring	-9.1	-11.1	430
Tettye Spring	-9.3	-10.7	208
	-9.1	-10.4	208
Zsolnay Spring	-8.6	-10.0	348
Dagonyászó Spring	-9.2	-11.6	321
Mecsek Spring	-8.5	-11.4	310
Bugyogó Spring	-8.7	-9.4	350
Vadvirág Spring	-8.6	-9.0	360
	-8.6	-9.2	360
Csurgó Spring	-8.9	-11.0	320

Table 1 shows the isotope composition of the tufa samples. The $\delta^{13}C$ values of our tufa samples range between -9.0‰ and -11.6‰ (VPDB) with a mean value of -10.3‰, suggesting strong soil-zone CO_2 contribution. Comparing our stable isotope data with the database established by Andrews et al. (1997) the samples from Mecsek Mountains are similar to the tufas collected in Poland and in the Dinaric Karst concerning $\delta^{18}O$ values, reflecting the effect of continentality in contrast to the tufas collected from Western-Europe.

The freshwater tufa cores were quite porous and therefore were embedded in epoxy amber. The most recent part of the speleothem core from Abaliget Cave was micro-drilled with approximately 1 mm intervals and samples for Hendy-test were prepared which suggest that the speleothem core is suitable for further investigations. The stable isotope measurements of the freshwater tufa and speleothem cores are still in progress. We intend to use U/Th method for the dating of these samples. We tried ^{14}C for dating the tufa cores, however further measurements are needed in order to interpret the results correctly.

5. Conclusions

The stable isotope analysis of the tufa-depositing streams suggests that these waters are of meteoric origin. A significant difference was found between the two study areas, Eastern and Western Mecsek most probably as a result of difference in the elevation of the catchment areas.

The seasonal variation of the different physicochemical parameters of water was observed during the monitoring period. It also became evident that pH increases, while alkalinity and electric conductivity decreases downstream. The downcurrent changes of water temperature depend on air temperature.

Stable isotope analysis of bulk carbonate samples showed that the isotopic composition of these deposits reflect the effects of continentality and strong soil-zone CO_2 contribution by C3 vegetation.

Acknowledgements

The authors express their gratitude to the reviewers for their useful comments that improved the quality of the paper. Special thanks goes to A. Demény who allowed us to analyse these samples at the Institute for Geological and Geochemical Research. A. Boros and K. Kármán are acknowledged for performing the stable isotope measurements.

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A STUDY OF TEMPERATURE CHARACTERISTICS IN THE SHALLOW KARSTIC VELIKA PASICA CAVE, SLOVENIA

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The precipitation, surface air temperature, the cave air and the cave drip water temperatures were monitored over two years in order to interpret the cave climate in a shallow karstic cave located in central Slovenia. The cave temperature is controlled by the external climate, due to seasonal oscillations. The temperature curve of inner cave area was much smoother in comparison with the surface indicating that thermal energy was transferred from the surface through the matrix by conduction. Air convection also occurred in the cave, especially during the winter time in the section close to the entrance. The colder, heavier air flowed through the entrance into the cave, which resulted in significant and irregular temperature variation. In addition, the temperature variations in dripping water during the rain events indicated strong relationship between the water discharge and drip water temperature.

1. Introduction

Heat flow theory can be applied to the development of ground water hydrological science since heat has proven to be a useful tracer in groundwater systems (Anderson 2005). While some papers are related to deep aquifers (phreatic zone), which do not connect strictly with annual periodical temperature changes from the surface, other papers primarily focus on geothermal energy sources (Garg and Kassoy 1981), and mining engineering (Williams et al. 1999). Bundschuh (1993) reported that heat is not an ideal tracer. Nevertheless, Milanovic (2001) considered water temperature as a non conservative tracer in karst aquifers. In Bundschuh's research (1993), temperature was shown as a parameter in order to indicate the components of different aquifers in spring water. Genthon et al. (2005) used temperature as a marker for karstic water hydrodynamics in La Peyrere Cave (France). Potentially useful information for thermal patterns of karst cave streams was considered for aquifer morphology and recharge (Luhmann et al. 2011). Contrary to deep aquifers, fundamental studies on heat transport and temperature gradients for shallow sub-surface karstic cave systems are limited in the literature, especially for cave drip water.

Although the ceiling of the Velika Pasica Cave is thin (on some places only 2–5 m), relative thermal isolation from the surface occurs. Generally, at about 1 m below the surface daily variations in temperature in the soil and rock disappear, although the annual variations in temperature can be observed as deep as 20–24 m below surface, depending on the rock and soil types (Thakur and Momoh 1983). Thus, a shallow cave with an average depth of 10–12 m below surface could be a good intermediate window for tracing temperature variation underground.

The Velika Pasica Cave can be divided into two parts: A) the outer section (close to entrance) and B) the inner section (far from entrance). The investigation and interpretation of climate variation within the cave was carried out by monitoring the precipitation, the surface ground temperature ($T_{outside}$), the air temperature in the cave (T_{air}) and the cave drip water temperature (T_{water}). Furthermore, exploration of the possibility to apply temperature as a natural tracer for hydro-geological research, have been considered with a special emphasis on the cave drip water and concurrent ecosystem studies.

2. Location and cave description

The Velika Pasica Cave (45º55'14"N, 14º29'41"E) (Fig. 1) is located at an elevation of 662 m a.s.l. in the village Gornji Ig, approximately 20km south of Ljubljana. The bedrock in the cave area is the thin Norian-Retian dolomite of the Upper Triassic, with the strata inclining to the north at 10–15°. A thin soil layer, 0–20 cm in depth, lays over the surface above the cave. Below, an average thickness of 10–12 m of ceiling covers the gallery, which characterises the cave as a typical shallow cave (Jeannin et al. 2007). At some points the ceiling is only 2–5 m thick (Brancelj 2002).

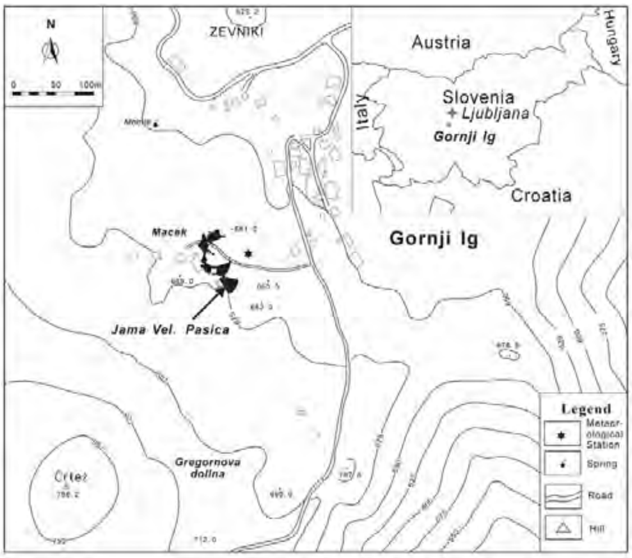

*Figure 1. Location of the Velika Pasica Cave (Slovenia). The black figure – the study cave; * – the meteorological station.*

The cave is an approximately 110 m long horizontal gallery, rich in flowstone decorations. The entrance to the cave is at the bottom of a 10 m deep circular depression (dolina) with a diameter of 15 m. Two sections exist in the cave, connected by 0.7 × 1.0 m² sized passage (Fig. 2): the outer section with two chambers and the inner part with another two chambers.

Four permanent drips, designated as VP1, VP2, VP3, and VP4, are located within the cave. Drips VP1 and VP2 are located in the outer part and drips VP3 and VP4 are in the inner part of the cave (Fig. 2).

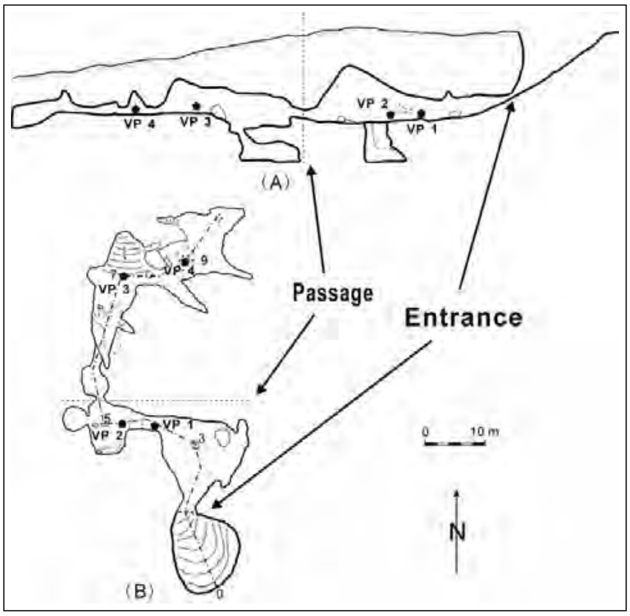

Figure 2. Cross-section (A) and ground plan (B) of the Velika Pasica Cave (Slovenia). VP1–VP4: permanent dripping points, where data on percolation have been continuously recorded at one-hour intervals since May 2006. The arrow indicates the entrance of the cave and the passage which divides the cave into two sections.

3. Methods

Two data-loggers (Delta-T Device Company) were set up for the study in order to interpret the climatic variation of the inner and outer cave environments. The first data-logger was set in the cave and was connected to: four temperature sensors for air temperature, four sensors for water temperature of each permanent drip, four rain gauges for the discharge and one sensor for humidity in the outer section of the cave (Fig. 2).

Each rain gauge in the cave, placed under the drips, was equipped with a plastic screen (2 m x 2 m) in order to collect dripping water and focus it into the funnel of the rain gauge. Probes for water temperature were inserted into the funnel of each rain gauge, while probes for air temperature were 50 cm away from rain gauge and 1 m above the cave floor. Other sensors for air temperature, precipitation and soil humidity were located on the surface close to the cave entrance and connected to the second data logger. Precipitation was recorded once per hour. All the temperature sensors were measured in 4-hour intervals. Both data-loggers were synchronised for data recording.

4. Results and Discussion

4.1. The environmental temperature and precipitation

In the Ljubljana area, the climate has continental characteristics with warm summers and moderately cold winters (www.arso.gov.si). Seasonal micro-climates apparently varied in the cave area (Fig. 3), which have been monitored since 2006. During the observation period, July and August were the hottest months and the highest temperature was 32 °C on July 23rd in 2006. December and January were the coldest months and the lowest temperature recorded was on December 22nd, 2007, at -11.35 °C (Table 1).

On the surface, the temperature differences between day and night were frequently over 10°C, shown as the SD (standard deviation) as high as 7.76 (Table 1). For example, on July 23rd, 2006, the difference was approximately 13 °C. The intensity of the rainfall in spring (April and May) was not high, but it was frequent; while in summer, the frequency of rain events decreased but several heavy storms occurred; the strongest one on 20th June, 2010 (44 mm of rain in 24 hours).

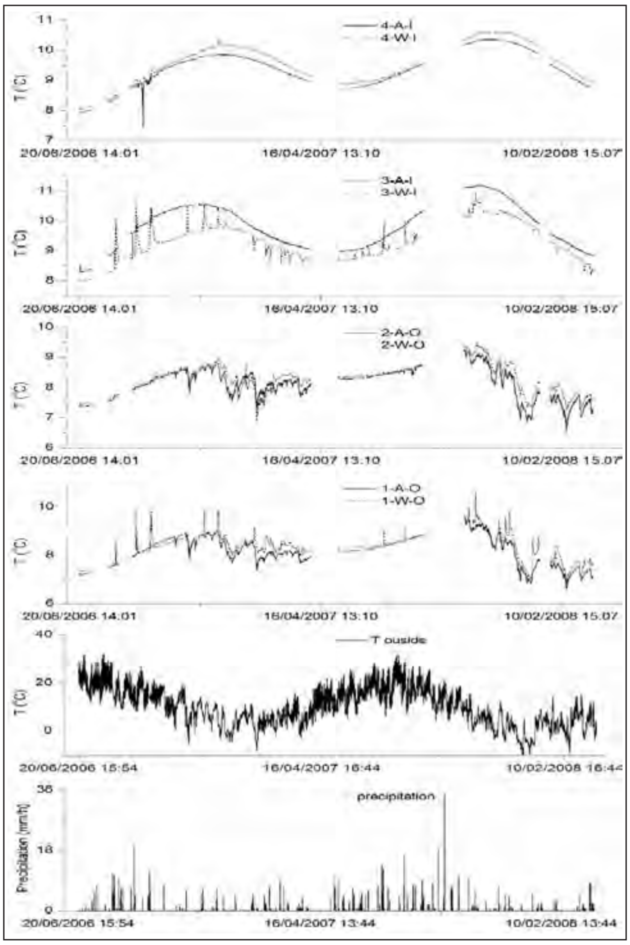

Figure 3. The temperature (°C), precipitation (mm per hour) from outside the cave, the water temperatures of four drips (°C) and adjacent air temperature of each drip (°C) recorded from 20th June, 2006 to 22nd March, 2008. X-A/W-O/I indicates: the air/water temperature at Drip X from outer or inner section of the cave.

4.2. The temperature variation inside the cave

Inside the cave, the temperature was more constant compared to the surface temperature. The variation range was smaller and the SD much lower (Table 1).

Cave temperature is generally directly connected with the external climate (Badino 2004), especially within shallow caves. In the Velika Pasica Cave, the average thickness of the ceiling above the cave is 10–12 m (Brancelj 2002). This resulted in a quick and intensive reaction of cave meteorology to the outer conditions. The temperature inside the cave, (both of air and dripping water) showed a similar

Table 1. Descriptive statistics for temperatures inside and outside the cave from 20th June, 2006 to 22nd June, 2007. X-A/W-O/I indicates: the air/water temperature near Drip X from outer or inner section of the cave.; $T_{outside}$ is the surface air temperature.

	1-A-O (°C)	2-A-O (°C)	3-A-I (°C)	4-A-I (°C)	$T_{outside}$ (°C)	1-W-O (°C)	2-W-O (°C)	3-W-I (°C)	4-W-I (°C)
max	9.65	9.26	11.18	10.35	32.01	10.62	9.48	10.93	10.61
min	6.55	6.50	8.30	7.45	-11.35	6.85	6.87	7.98	7.52
average	8.20	8.15	9.86	9.41	9.80	8.36	8.30	9.34	9.60
SD	0.58	0.50	0.71	0.57	7.76	0.53	0.47	0.59	0.62

SD: standard deviation.

trend with distinct seasonal variations: rising during summer and autumn, and dropped in winter and spring (Fig. 3).

However, there was a time difference in variation trend between outside and inside the cave. On the surface, temperature increased from the lowest point -4.4 °C at the end of December 2006, until the middle of July 2007, when the highest temperature record reached 31.7 °C. Within the cave, the temperature of the drips usually reached the highest recorded peak during a similar period, which was around 10.5 °C (as averaged from all sensors) in the inner section and 9.5 °C in the outer section. For example, the air temperature of VP3 reached the highest point, 10.5 °C, at the end of November 2006. Thereafter, the temperature in the cave started to drop until the beginning of May 2007(Fig. 4). These lags are a result of heat conduction which determined the thermal condition within the cave system (Covington et al. 2011). As a result, the inside temperature keep rising when the temperature on the surface was higher, then heat was transferred from outside to inside.

However, although the surface was much hotter than the cave interior during summer, the variation inside the cave was only between 6.5 °C and 11.0 °C. In addition, the internal temperature did not response immediately when the surface temperature dropped to lower than inside, which was a lag of 49 days as measured by the air temperature decrease at VP3. It therefore, indicated that the mass of epikarst has an ability to store some heat. Although the external surface was colder than the interior, the epikarst was still warmer than the cave, and maintained heat transference to the cave. Until the matrix cooled down and became colder than the cave interior, the direction of heat conduction could not change, as shown when the cave air temperature started to decrease. This shows that the direction of heat conduction was, therefore, driven by the temperature difference.

There were considerable differences also in the environments between the two sections within the cave. Both inner and outer sections had apparent seasonal variation in temperature and the overall trend showed a similar pattern. The outer section was cooler than the inner parts, and the average temperature was more than 1 °C lower than those in the inner (Fig. 3; Table 1). The outer section had a straight-forward connection with the surface environment as a result of the cave entrance morphology. The temperatures in the outer section varied more abruptly and irregularly, especially during cold weather, which commenced in late August. Temperature change was mainly due to the convective airflows (Wefer 1994). The entrance

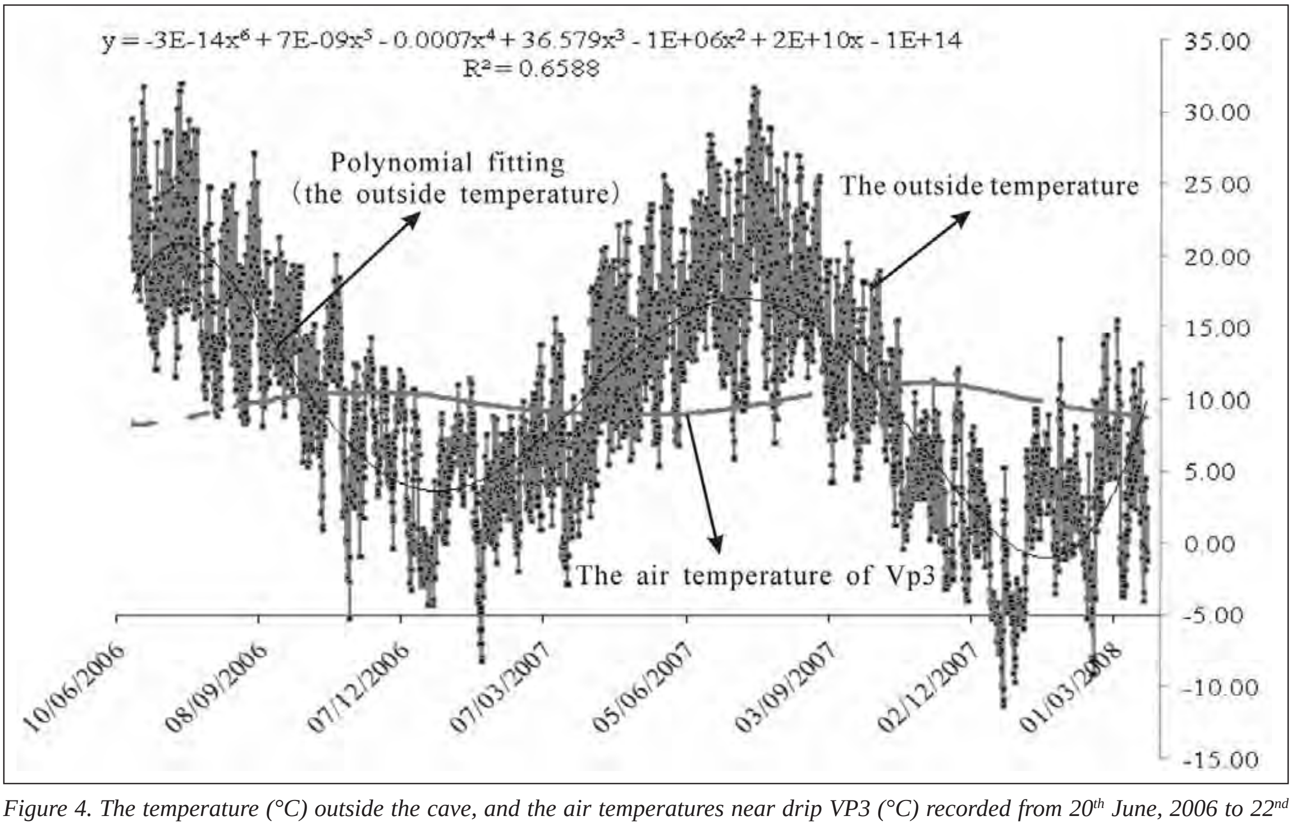

Figure 4. The temperature (°C) outside the cave, and the air temperatures near drip VP3 (°C) recorded from 20th June, 2006 to 22nd March, 2008. The equation presents the fitted line for the outside temperature variation.

passage slopes downward into the cave. During winter, cold air can flow in along the floor of the cave while lighter and warmer air escapes out of the cave along the ceiling toward the entrance. In contrast, the inner section represented a relatively close system and had less impact from outside, therefore, the variation in temperatures showed slighter and smoother oscillations when compared with the outer section. For that reason the inner chamber was insulated as the passage between them was constricted and prevented convective flows sufficiently.

4.3. Response to the rain events signal

Precipitation is the only replenishment source for the cave drip water in the Velika Pasica Cave area (Liu and Brancelj 2011). One rain event in September 2006 is presented here as an example of the impact of a rain event on the cave's climate (Fig. 5). Two storms occurred during September with different patterns (Liu and Brancelj 2011): the first one, on 29th August 2006, came as a short but heavy rainfall (47.4 mm in 7 hours); while the other lasted 84 hours, from 15th September 2006, with 96.4 mm of rainfall.

According to the speed and intensity in response to the precipitation, the drips in the cave can be divided into four types: "rapid response without hysteresis" (VP1); "fast response with lag" (VP3); "rapid response with congest discharge" (VP4) and "no response with congest discharge" (VP2) (Liu and Brancelj in preparation). The temperature of the drip water reflected a strong relationship with the amount of discharge (Fig. 5).

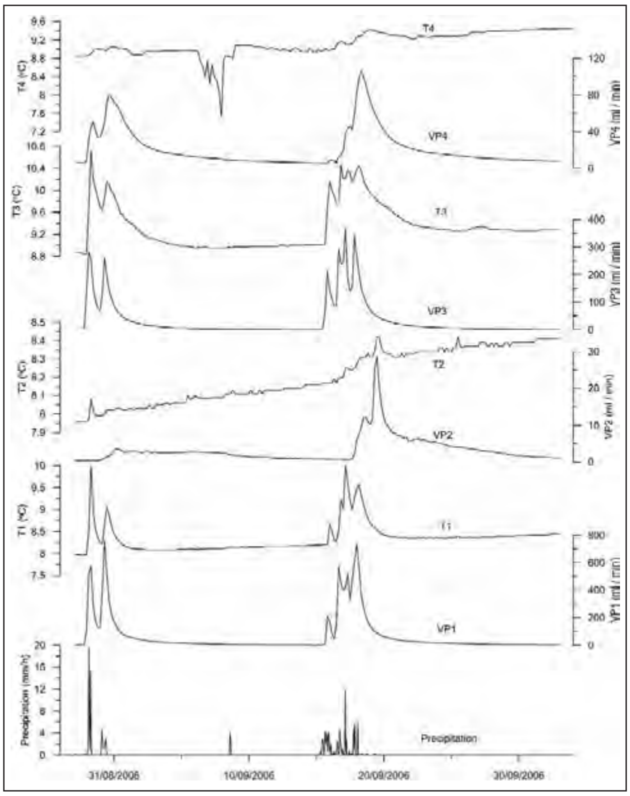

Figure 5. The response of the discharge and temperature of the four drips to the rain events in summer 2006 (from 28th August to 2nd October).

The temperature of drip water of VP1 and VP3 showed a more instant and apparent response. In both drips, the larger discharge indicated higher efficiency and speed of water flow. However, the drips VP2 and VP4 had less discharge and consequently smaller variation in drip water temperature. Cronaton et al. (2002) and Liedl et al. (2003) described this feature as a result of the dual media system. Thus, heat also could be the tracer for the hydrodynamic of ground flow.

The cave temperature principally followed general trend in surface climate. At the same time the rain events were also an important parameter which briefly impacted the temperature balance inside the cave. The fast flow, which ran quickly, did not exchange heat adequately within the soil and epikarstic zone. It was reflected in the apparent temperature peaks during the rain events. Difference in the temperature of the drip water depends on difference between surface and cave temperature and discharge, namely higher discharge larger differences. When the rain ceased, and the drip flow slowed down, the drip water, air, and rock surrounding the cave chambers get in equilibrium. Although the air temperature was more stable than the percolating water, when larger rain events occurred, there was sufficient flow of water into the drips to transfer some of the outside heat, which can have an influence on the air temperature in the cave (Fig. 3).

5. Conclusion

Caves in shallow carbonate terrains have air temperatures that mimic the mean yearly temperature of the surrounding surface. Rock and soil cover acts as a thermal insulator and prevent significant temperature variations inside most shallow caves. Such thermal insulation also creates stable temperature variations in the Velika Pasica Cave. Temperature was principally controlled by conduction of heat by the overlying rock. Another important element in cave's climate was air convection, which was significant near entrance during the cold period of the year. The third element, which effected temperature conditions in the cave, was precipitation as drip water also acts as a thermal source for the cave. At the same time it could act as the tracer for hydrodynamic process of underground flow in epikarst.

Acknowledgements

Authors would like to extend thanks to colleagues from the National Institute of Biology who contributed to field work, in collecting data and maintaining instruments. This Research was founded by the Slovenian Research Agency (ARRS) within the programme P1-0255 (Structure, function and communications in ecosystems) and within the Program for Young Researchers (Contract no. 1000-11-310196).

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CLIMATIC FEATURES OF DIFFERENT KARST CAVES IN HUNGARY

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Due to some extreme weather conditions (e.g., droughts, inland waters or floods etc.) occurring in Carpathian Basin, climatic fluctuations can be detected in Hungary which can modify some environmental factors in caves. In our study we were determined to enquire to which extent do surface temperature changes influence cave air temperature. Three different types of caves were selected for the analysis: a hypogene cave (Hideglyuk), a tectonically performed epigenetic cave (Hajnóczy Cave) and a typical swallet cave (Trió Cave). Cave air temperature was determined in order to delineate the degree of anthropogenic impact, as well as to investigate how long it takes the surface temperature to have an effect on the cave air temperature. To test applicability of a wireless sensor network in cave temperature measurement, UC Mote Mini low power wireless sensor module was used for our measurements. Temperature data were recorded at 10 minutes intervals. The obtained data were evaluated using a matrix of correlation coefficients as to identify the communication network between the passages.

In Hajnóczy Cave the delay effect of the passages can be detected: a decrease in surface temperature can only be seen after 2 days and 4 days at measurement points No. 2 (“Entrance”) and No. 3, (“Housetop”), respectively. In Hideg-lyuk, two different circulations can be distinguished: a large one covering the studied area and a small one that most probably connects the channel with undiscovered passages. The human impact on the air temperature of Trió Cave is unambiguous, raising the inside temperature with 0.05 °C or 0.6 °C in the case of three and twenty-eight visitors, respectively.

1. Introduction

Cave air temperature is mostly considered to be constant, nevertheless several factors, such as surface temperature, affect cave air flow even if their influence is more moderate in the passages. Cave climate is dependent on the energy balance of the cave and on the energy exchange between the cave and the surface. Furthermore, the climatic conditions and the morphology of the surface are also important controlling factors of cave climate (Fodor 1981). Hence, each cave has a unique air flow and a special climate. Caves are different in their morphology, fracture network, as well as in their entrance position and all these parameters exert an influence on the air flow (Rajczy 2000). The beneficial effects of caves have been shown due to the high humidity and the constant temperature of cave air, which is about 10 °C in Hungary. This dust, germ and allergen-free environment can mitigate the unpleasant symptoms of many people suffering from upper respiratory tract infections, leading to complete recovery (Jakucs 1999).

The long-term monitoring of climatic parameters in caves can provide information on whether the surface climate change has any negative influence on cave climate and its therapeutic effects. Moreover, these measurements are very essential from the viewpoint of cave utilization since visitors can also modify cave climate. The climatic studies of caves can support the cave tourism of national parks as the surplus heat caused by several visitors can have an adverse effect on the characteristics of caves (Kaffai 2008).

The major aims of present study can be summarized as follows:

(1) to delineate how surface temperature influences cave air temperature in the three different karst caves; (2) to reveal how long it takes the surface temperature to modify the temperature of cave air; (3) to test a wireless sensor network in order to determine its applicability in cave air temperature, relative humidity and atmospheric pressure measurements; (4) with the help of the investigations mentioned above we intend to study the convectional system of these caves, and the degree of anthropogenic impact on them.

2. Sampling area

Three Hungarian caves were selected as sample areas (Fig. 1).

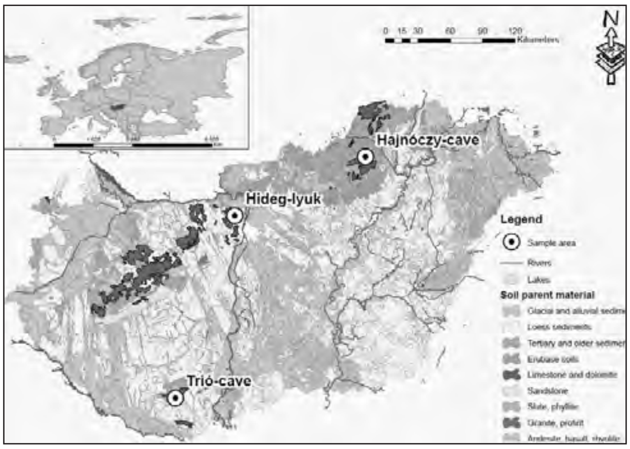

Figure 1. The petrographic map of Hungary and the location of the monitored caves.

2.1. Hajnóczy Cave

Hajnóczy Cave is situated in the SW Bükk and was formed in Ladinian-Carnian flint and flint-free grey limestone. It is a shallow cave with more than 3 km long passages and with a maximum depth of 135 m. The entrance of the cave is located on a hillside, 475 meters above sea level (Varga 2003).

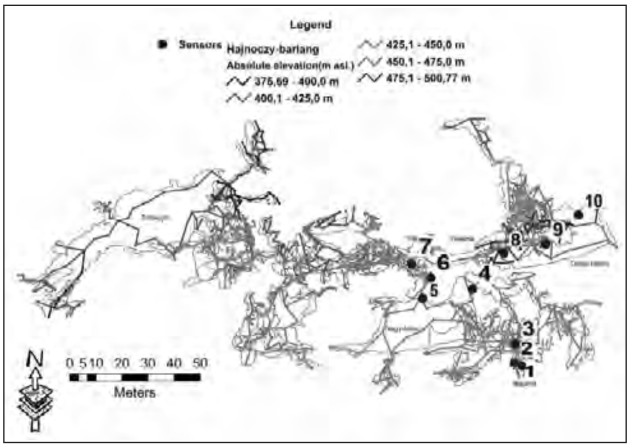

Figure 2. The polygon of Hajnóczy Cave with the places of the sensors.

The cave passages are of N-NE-S-SW direction with a perpendicular joint system. The cave can be divided into two distinct parts: (1) the passage system which is rich in keyholes and was formed by anastomosis and corrosion processes. This extends from the entrance to the Great Hall. (2) The section that was formed by dominant erosion processes and is characterized by large forms (e.g., Giant Hall: 40 × 20 m), debris fans and keyholes between large rooms (e.g., Almond: 0.7 × 0.4 m) (Fig. 2).

2.2. Hideg-lyuk

Hideg-lyuk is of hypogenic origin and is situated in Buda Hills, in the NW part of Pálvölgyi quarry composed of Triassic limestone and dolomite. Since Buda Hills. were elevated along a fault line, thermal waters could emerge from the depth along the cracks (Kordos 1984).

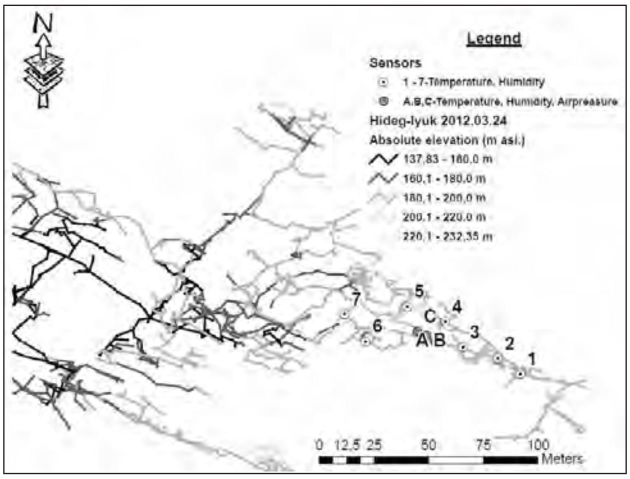

Figure 3. The location of the sensors in Hideg-lyuk.

József Szabó Cave Research Group began the research in 2008 of Hideg-lyuk, since the intense cold summer airflow attracted the researchers' attention. The maximum depth was 92 m at that time. In December 2011 the cave was connected to the other caves in the quarry and became the member of the 28.6 km long Szépvölgyi Cave System (Fig. 3).

2.3. Trió Cave

Trió Cave is situated in the lithologically homogeneous Triassic limestones of the Western Mecsek karst area. It is a typical swallow cave (255 m, depth: -58) of the Szuadó Valley, however due to the development of other sinkholes Trió Cave has only a temporary activity nowadays (Barta and Tarnai1999).

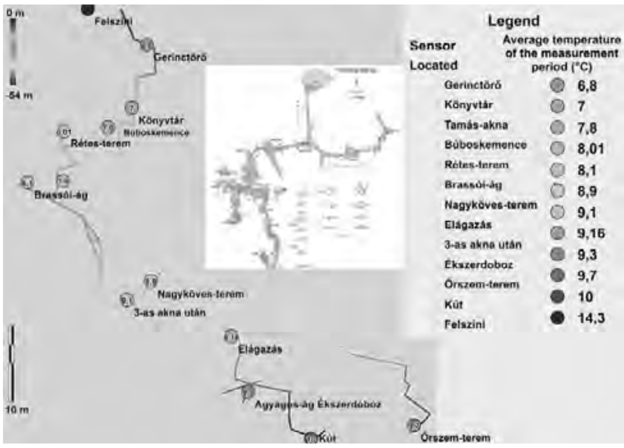

Figure 4. The cross-section of Trió Cave and the location of the deployed devices.

It is the seventh longest (255 m), and the second deepest (58 m) cave in Mecsek Mountains. The cave can be morphologically divided into three parts (Fig. 4). The first section is a narrow passage system. After passing the second part of the cave, the pit-system, the two end-points can be reached along Agyagos and Vizes branches (Bauer 2011).

3. Material and methods

UC Mote Mini low power wireless sensor module, which was developed at the University of Szeged, was used for our measurements. This device promotes IEEE 802.15.4/ZigBee wireless communication protocol in order to realize low data rate. The radio module can operate at a data rate of 250 kbps in ISM 2.4 GHz band. The control is regulated by 16 MHz Atmel ATmega128RFA1 microprocessor with 128 kB RAM. Several types of sensors are integrated into this device (Fig. 5):

1) light sensor
2) pressure sensor
3) temperature sensor
4) humidity sensor

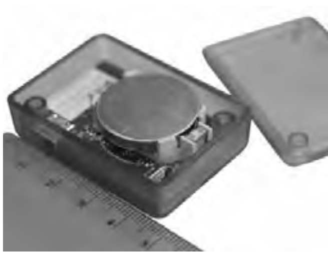

Figure 5. Uc Mote Mini (source: www.unicomp.hu).

Figure 6. Uc Mote Mini in Hideg-lyuk.

The accuracy and the scale of SHT21 temperature and the humidity sensor are ±0,3 °C, 0,01 °C and ±02.0 % RH, 0,04 % RH, respectively. Data collection can be realized with 2MB external flash TinyOS, which is a small open-source energy-efficient software operating system, supporting large scale self-configuring sensor networks. The device is powered by LIR2450 battery (Fig. 5). During our study, data were recorded in every 10 minutes. The sensors could be used for more than 3 months without battery replacement (Senirion).

The temperature and relative humidity of cave air were detected using ten sensors (three of them can also measure air pressure) in Hajnóczy Cave and in Hideg-lyuk. In each case one out of ten sensors was placed near the cave entrance to measure surface temperature (Figs. 2, 3 and 6). In Trió Cave only periodic observations were performed using thirteen sensors (Fig. 4).

Even thought the sensors can communicate up to 100 m on the surface, this distance is reduced to 20–25 m in the underground depending on cave geometry (Muladi 2012). The radio module was only used while data were downloaded and sensor network maps were created.

The data obtained in every 10 minutes were evaluated using a matrix of correlation coefficients. First, data were averaged according to hour and day, resulting in a new dataset. Then these data were processed with pairwise correlation coefficients in order to investigate the direct and indirect relationships among cave airflows.

4. Results and discussion

4.1. Hajnóczy Cave

The climate of this cave was periodically studied in the past (e.g., cave temperature was measured by Gábor Miklós and József Városi from 1975 to 1977 in summers and Gyula Németh performed some radon measurements in the 1980s). These investigations can provide reference data for our current research.

Our monitoring started in December 2011 and lasted more than a year in order to observe the differences of cave air flow between the summer and the winter period.

Due to the limited length of the paper only the data collected between 10. 03. 2012 and 14. 04. 2012 are presented (Fig. 7).

The cave air temperature data measured by ten sensors can be seen here. The data of measurement sections No. 1 ("Surface") and No. 2 ("Entrance") are illustrated in the secondary axis, whereas those of other measurement points are demonstrated in the primary axis.

According to the daily minimum and maximum values of point No. 1, we could examine how surface temperature influenced the different sections of the cave. Based on the data of No. 2 and No. 3 ("Housetop"), the diurnal fluctuation of temperature is obvious, although various differences can be detected. This daily variation ranges between 0.5 and 1 °C in the case of point No. 2, while it changes between 0.2 and 0.3 °C in the case of point No. 3. Furthermore, the retarding effect of temperature can also be observed: the decrease in surface temperature can be registered after 2 and 4 days in the case of points No. 2 and No. 3, respectively (Fig. 7). The correlation value between the measurement points No. 2 and No. 3 is 0.7290. Point No. 3 shows strong correlation with some measurement points: 0.8040 and 0.8996 are with No. 3 ("Leyla") and No. 7 ("Amygdala"), respectively (Table 1).

Point No. 4 ("Flat hall") is further and deeper than point No. 2. Even though the diurnal temperature range can not be detected, a temperature change caused by a drop in surface temperature can be noticed. Based on the correlation coefficient, point No. 4 has a very strong (0.9960) and a strong (0.7272) relationship with points No. 2, 3, respectively (Table 1). No. 4 shows moderately strong correlation with point No. 7 (0.5639), and No. 6 (0.6424).

In the case of points No. 6 and No. 7, the cross-sections of the passages is narrowed. Thus, higher diurnal temperature range could be registered in their cases. Although, the cross-section of passage No. 7 is smaller than that of No. 6, the values are still very similar. This is also confirmed by their correlation coefficient (0.8280).

Table 1. The correlation matrix of Hajnóczy-cave's temperature data (12. 03. 2012. – 11. 04. 2012) (significance level 0.01; 0.05).

Measuring points	Between Gallery and Giant hall (9)	Housetop (3)	Almond (7)	Leyla (6)	Flat hall (4)	Surface (1)	Gallery (8)	Giant hall (10)	Entrance (2)
Between Gallery and Giant hall (9)	1								
Housetop (3)	**-0.6174**	1							
Almond (7)	-0.2911	**0.8996**	1						
Leyla (6)	-0.3172	**0.8040**	**0.8280**	1					
Flat hall (4)	**-0.4941**	**0.7272**	**0.5639**	**0.6424**	1				
Surface (1)	-0.1984	-0.2953	-0.4924	**-0.4679**	-0.2286	1			
Gallery (8)	-0.0765	0.1808	0.3089	0.3663	-0.2242	-0.3119	1		
Giant hall (10)	-0.1986	-0.2651	-0.4102	-0.1385	0.1223	0.1502	0.1257	1	
Entrance (2)	-0.4356	**0.7290**	**0.5927**	**0.6577**	**0.9960**	-0.2670	-0.2372	0.0818	1

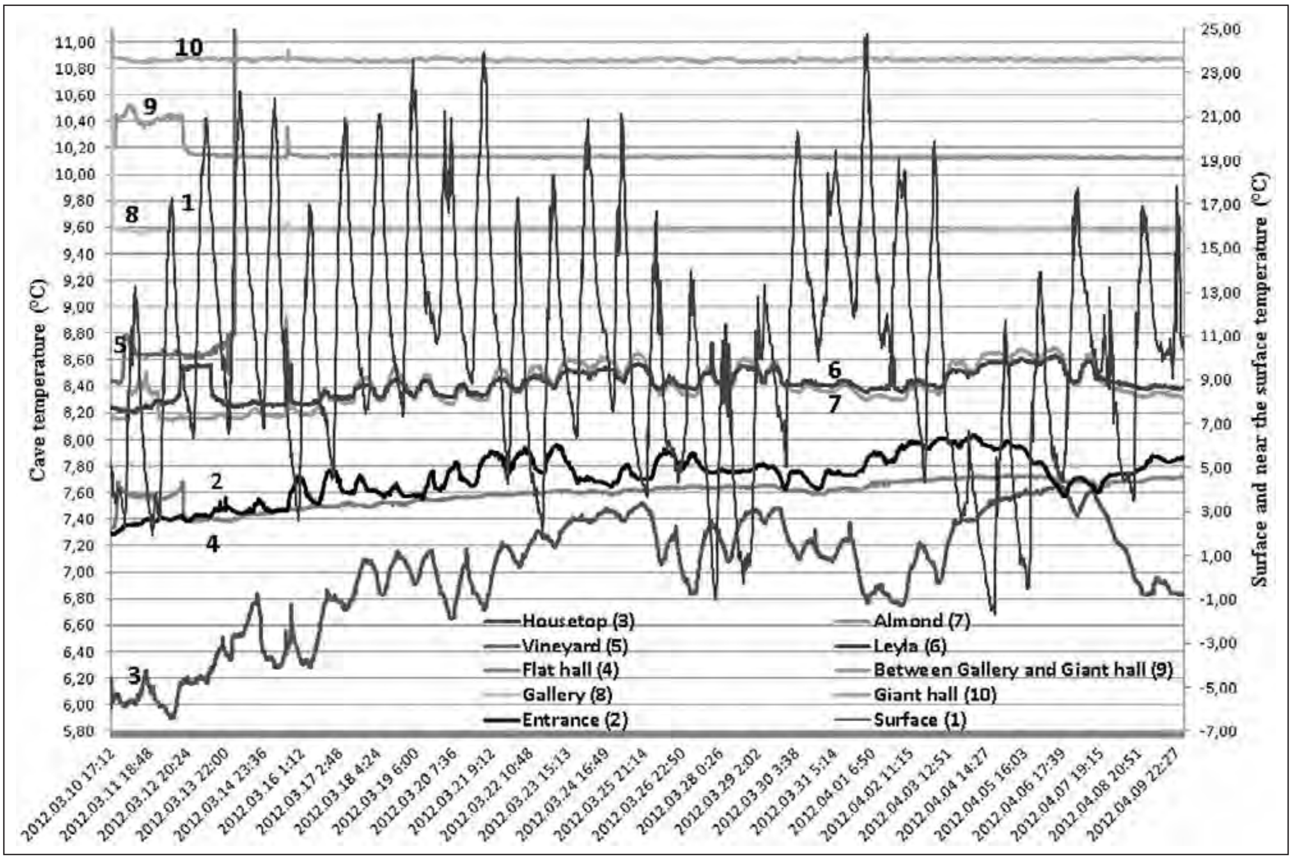

Figure 7. Temperature data for Hajnóczy Cave (10. 03. 2012 – 14. 04. 2012).

All this can be explained with the spatial proximity of the two measurement points (<5 m). The minimum and maximum values can be detected better in the case of point No. 7 due to the narrow cross section of the measurement point. Here, the diurnal fluctuation of temperature range only varies between 0.1 and 0.2 °C, while point No. 1 shows inverse correlation with No. 7 (-0.4924) and No. 6 (-0.4679). Point No. 2 shows a moderately strong correlation with points No. 7 (0.5927) and No. 6 (0.6577).

There is temperature difference among the passages where point No. 8 ("Gallery"), No. 9 ("Between Gallery and Giant hall Giant") and No. 10 ("Giant hall") were set (Fig. 4). The surface temperature has small effect on these sections of the cave in studied period. The diurnal temperature change can be slightly detected in the point No. 10 owing to its spatial proximity to the surface. Point No. 9 shows an inverse correlation with points No. 3 (-0.6174) and No. 4 (-0.4941).

4.2. Hideg-lyuk

The aim of cave researches in Hideg-lyuk is to discover new passages using air circulation investigations. Our intention was to contribute to these discoveries by studying the characteristics of airflow inside the cave.

We started our study here on 21. 04. 2012. In this paper, data from the period between 11. 09. 2012 and 21. 10. 2012 are presented (Fig. 6). In Fig. 8, the data of measurement points No. 4 ("Surface") and No. 1 ("Entrance") are illustrated in the secondary axis. Overall, the difference in average temperatures between the passages can also be detected here. The mean air temperature is increasing towards the inner passages. The extent of diurnal temperature fluctuation can be observed at the different measurement points.

During the data evaluation an interesting phenomenon was discovered: at measurement point No. 1 cold air flows out intensely, which is supported by its moderately strong correlation with point No. 4 (0.4364). Interestingly, No. 1 has an even stronger correlation (0.5858) with the deeper passages, e.g., measurement point B ("Guillotine") (Table 2).

Measurement point No. 2 ("Mine support") has much stronger relationship (0.6748) with No. 4 than No.1.

Since too many relationships can be detected concerning the other sites due to the fact that the various passages can communicate with each other through the fractures, we would like to highlight only some of them. The strongest correlation (0.9939) can be explored between points No. 3. ("Copper canon") and No. 6 ("Reference bivouac") while the weakest relationship (0.4068) can be revealed between point A (Bear trap) and No. 7 ("Christmas").

In accordance with the results of selected points, point No. 5 ("Seal") do not participate in the large air flow. As its correlation coefficient is inversely proportional to the others, its microclimate is affected either by upper passages or a new passage system. Measurement point B is the only site that has moderate or strong correlation with all measurement points except for No. 5 with which the correlation is reverse.

Table 2. The correlation matrix of the temperature data collected in Hideg-lyuk (11. 09. 2012.–21.10.2012) (significance level 0.01; 0.05).

Measuring points	Bear trap (A)	Guillotine (B)	Step screws (C)	Entrance (1)	Mine support (2)	Copper cannon (3)	Surface (4)	Seal (5)	Reference Bivouac (6)	Christmas (7)
Bear trap (A)	1									
Guillotine (B)	0.5084	1								
Step screws (C)	0.4584	0.4828	1							
Entrance (1)	0.1959	0.5858	0.4071	1						
Mine support (2)	0.2703	0.4692	0.7177	0.3866	1					
Copper cannon (3)	0.3140	0.7395	0.0735	0.3623	0.0827	1				
Surface (4)	0.4969	0.5526	0.6597	0.4364	0.6748	0.0146	1			
Seal (5)	-0.1143	-0.4237	-0.4148	-0.5289	-0.2271	0.0017	-0.3036	1		
Bivouac (6)	0.3355	0.7920	0.1113	0.3952	0.1091	0.9936	0.0601	-0.0899	1	
Christmas (7)	0.4068	0.8358	0.7391	0.3034	0.7219	0.5795	0.7240	0.1149	0.7336	1

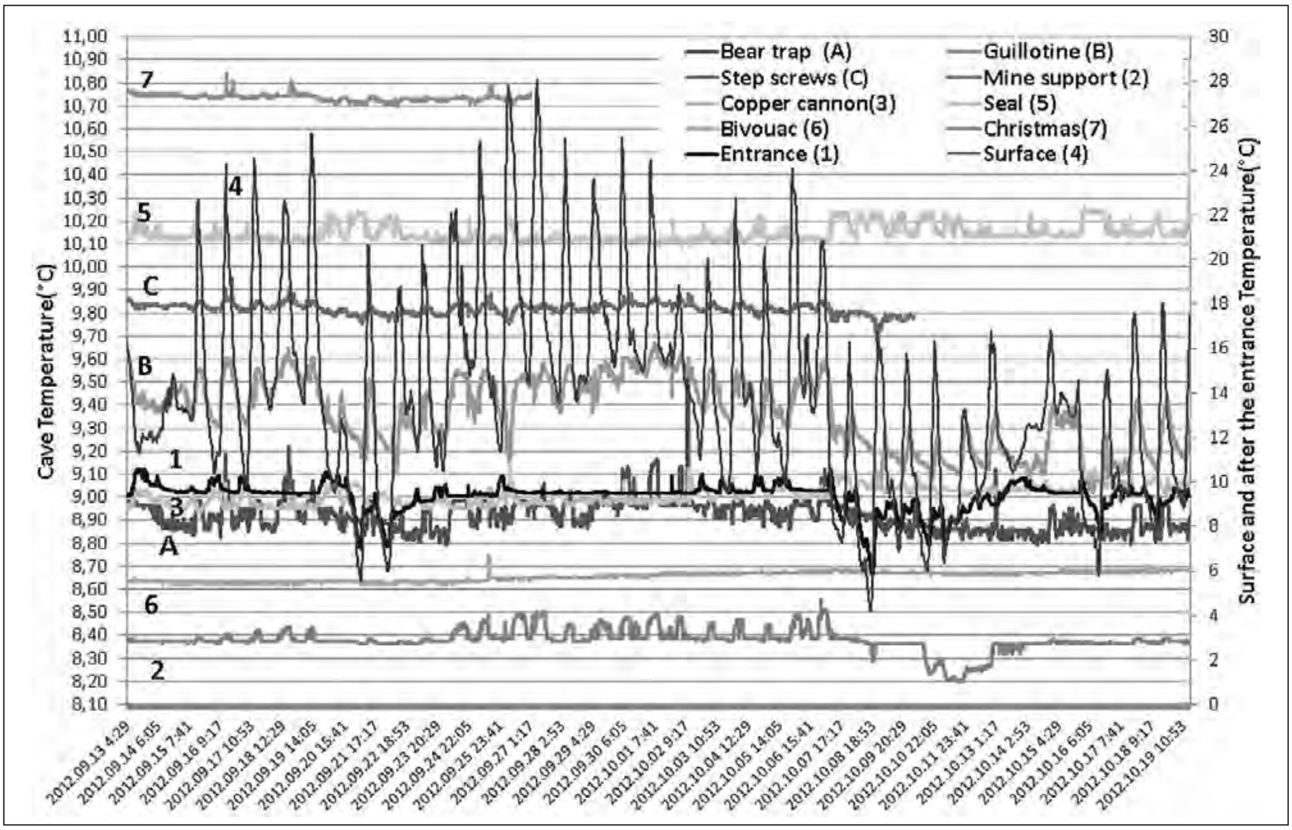

Figure 8. Data for Hideg-lyuk (11. 09. 2012–21. 10. 2012).

4.3. Trió Cave

The investigation period lasted from 19. 04. 2012 till 16. 06. 2012. Twelve sensors were deployed at different sections of the cave: the entrance, the pits and the two end points (Fig. 4). During the monitoring period the number of visitors and the times of the guided trips were recorded. According to average temperature values, the temperature was higher in the end points than in the entrance (Fig. 4). The surface temperature has not had any influence on the inner cave sections from pit No. 3.

In the section called “Beehive oven”, a temperature rise that was caused by a tour group can be observed (Fig. 9). Comparing the number of visitors with the temperature change, it can be claimed that the 28 visitors initiated a 0.6 °C rise. During the two-month monitoring period the diurnal temperature fluctuation was 0.05 °C inside the cave. Besides, a rising trend in temperature (0.4 °C) can be noticed most probably due to gradual increase in the daily average surface temperature (Fig. 9).

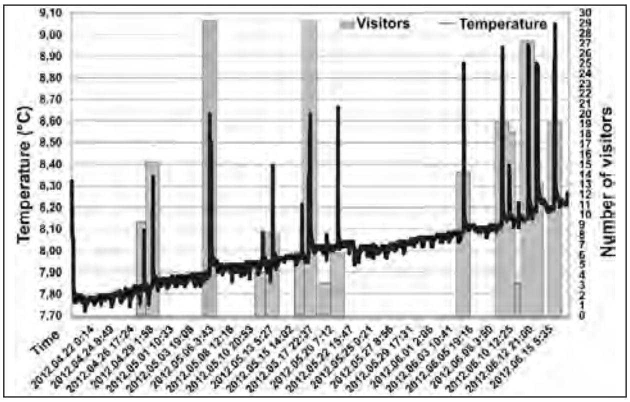

Figure 9. Relationships between cave air temperature and the number of visitors at ”Beehive oven”, Trió Cave (19. 04. 2012. – 16. 06. 2012).

5. Conclusions

Cave climate measurements can greatly contribute to gaining more information on environmental factors in caves.

The investigations mentioned above have proven that the UC Mote Mini wireless sensor network applied in this study is eligible for measuring the temperature and relative humidity of cave air. Temperature difference among the passages can be clearly seen in all the studied caves.

The delay effect of the influencing factors in Hajnóczy Cave can be observed: a drop in surface temperature can be registered after 2 and 4 days at measurement points No 2, 3, respectively.

In Hideg-lyuk, two distinct air flows can be distinguished: a large one covering the studied area and a small one circulating in the passage where measurement point No. 5 was set (“Seal”). It is likely to be connected to other, perhaps undiscovered sections of the cave, which is justified by the negative correlation (-0.5289) experienced between measurement points No 5. and No. 4 (“Surface”).

In Trió Cave human impacts on cave air temperature were shown. This rise in temperature caused by visitors ranged between 0.05 °C and 0.6 °C in the case of three and twenty-eight visitors, respectively.

Future plans include the more precise thermal mapping of the various cave sections. We are about to prepare an isotherm map and to expand the number of devices as to explore the connections among the cave sections more profoundly. Besides, we will focus on gaining more information on the turning points of the direction of air flow in caves. We would also like to measure the radon and the CO_2 concentration of cave air and carry out the statistical analysis of all the above mentioned parameters in order to explore more relationships among them and visualize these data by modelling air circulation.

Acknowledgement

We would like to express our appreciation to all those who contributed to our work. Special thanks goes to Dr. Miklós Maróti, András Nagy Ádám Polyák, Csaba Varga, Ákos Mező and Károly Barta for their help.

This research was partially supported by the TÁMOP-4.2.2/08/1/2008-0008 program of the Hungarian National Development Agency.

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HOLOCENE PALEOCLIMATE RECONSTRUCTION BASED ON STALAGMITE STUDIES FROM LEBANON

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Since 2005 studies on speleothems have been undertaken in Lebanon for the first time, aiming at reconstructing the paleoclimate in this special location in the Levant climate belt. First, absolute-dated oxygen and carbon isotopic profiles from a Holocene stalagmite (11.9–1.1 ka) from Jeita Cave (coastal, central Lebanon) showed generally high $\delta^{18}O$ and $\delta^{13}C$ values during the late–glacial, low values during the early Holocene, and again high values after 5.8 ka, suggesting a transition from wet conditions in the early Holocene towards drier conditions in the mid-Holocene. Additional work was undertaken on speleothems of Jeita Cave in order to find younger records to complete the profiles to the present time (i.e. covering parts of the last 1 ka). In addition, one small stalagmite was retrieved from Qadisha Cave, about 1,750 m above sea-level in northern Lebanon, and is currently being investigated. Samples having similar ages from different altitudes, yet relatively close locations from central and northern Lebanon are believed to reveal invaluable information on the Holocene paleoclimate in the Levant region and on the altitudinal influences.

1. Introduction

Located on the central eastern coast of the Mediterranean sea, Lebanon occupies the heart of the Levant region (Lebanon, Israel/Palestine, Syria and Cyprus). This region straddles the arid/semi-arid to temperate climatic belt and has a long history of human settlement and habitation (for at least the last 5,000 years). This witnessed important Glacial – Interglacial (G-IG) climate changes (Robinson et al. 2006). The Lebanese mountains with altitudes reaching 3,000 m must have played an important role in providing specific, localized climate zones, which is clearly expressed by the prevailing vegetation cover (Fig. 1). This paper updates previous studies (Nader et al. 2007; Verheyden et al. 2008) and presents ongoing work on the Holocene paleoclimatic and environmental evolution of Lebanon based on speleothems studies, and correlated to (pre-) historical proxies.

Since 2005, we have been working on the studies of Lebanese speleothems in order to infer about the past climate in this region. Two caves have been investigated so far with limited speleothem material (as we adhere to the recommendations of the UIS for limiting sampling in caves). The two caves were chosen are the coastal Jeita Cave in central Lebanon and the high altitude Qadisha Cave in northern Lebanon. The invesigated stalagmites provided records covering the Holocene and could be used to deduce the effect of altitude on oxygen and carbon istopic signatures. In addition, invaluable information about the climatic conditions at the coast and in the highland of Mount Lebanon is revealed.

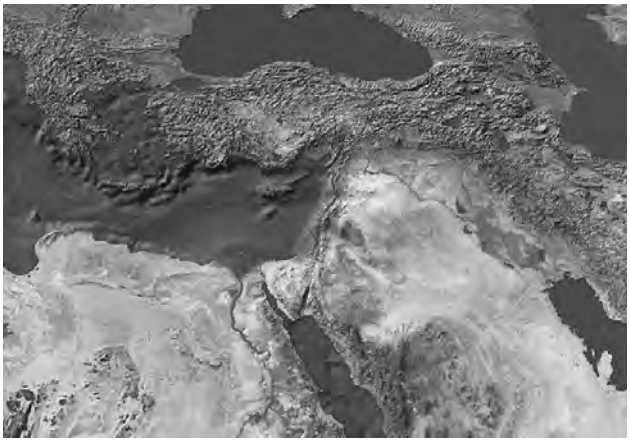

Figure 1. Satelite image showing the eastern Mediterranian region (Levant). The darker color represents areas with dense vegetation cover and the transition from light to dark shows the arid/semi-arid temperate climatic belt.

2. Geographical and Geological Settings

The climate in Lebanon is seasonal, with rainy winters (between November and February) and dry, relatively hot summers (usually the period from May to October). Precipitation rates can exceed 1,500 mm per year on the highlands (as rain and snow), while in some places they do not reach 300 mm per year (Fig. 2).

Jeita Cave is the longest (ca. 10 km) and most well-known cave in Lebanon (Nader 2004). It is located within the western flank of central Mount Lebanon. The natural entrance of the cave is situated at about 100 m above sea-level, ~5 km East of the Mediterranean coastline (Fig. 2). The average annual precipitation rate at the cave site today is estimated around 1000 mm (UNDP, 1970), and the Jeita underground river drains the Jurassic aquifer which is fed by surface water at much higher elevation. In fact, the cave system is entirely developed in Jurassic grayish fossiliferous limestone rocks (the Nahr Ibrahim Member), a part of the Kesrouane Formation, which has an average stratigraphic thickness of 1,000 m (Dubertret 1975).

Qadisha Cave has been known since 1903, and its exploration was associated with the constructions of hydro-power plants in the Qadisha valley in the 1920s. Its entrance is located around 5 km east of Bcharreh town and around

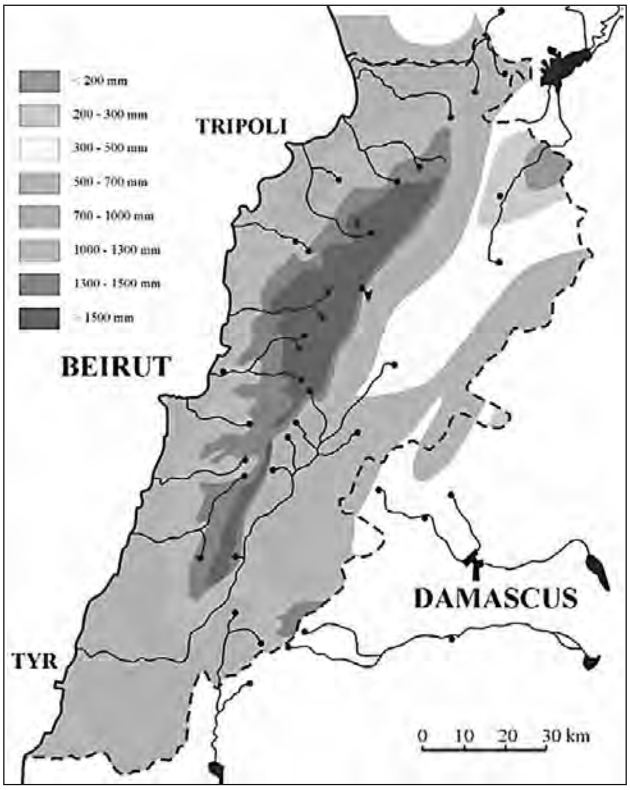

Figure 2. Simplified hydrological map of Lebanon showing the distribution of precipitations rates (mm per year) and the major springs and rivers (modified from UNDP, 1970). The Jeita and Qadisha caves (which also are springs) are indicated by [J] and [Q] respectively.

1,750 m above sea-level in the northern highlands of Mount Lebanon (Fig. 2). The average annual precipitation rate at the Qadisha Cave site exceeds 1,500 mm (UNDP, 1970), mostly in the form of snow that stays at least for three months a year. The cave system (ca. 900 m long) is fed by relatively close intake of surface waters in the Quaternary colluvium of the Cedars plateau. Indirectly the Cretaceous limestone and dolomite aquifers are believed also to feed the cave underground river.

3. Results

Two stalagmite samples have been already analysed from the Jeita Cave: (i) JeG-stm-1 stalagmite (Verheyden et al. 2008); and (ii) Jeg-stm-3. The JeG-stm-1 stalagmite is 121.5 cm long, displaying regular deposition of dense calcite, varying in colour from dark grey to light yellow-beige. Regular lamination with very thin layers (< 0.2 mm) is present but generally only visible at the sides of the speleothem. The stalagmite diameter is variable, thickened in its middle part, with a maximal diameter of 18 cm. It becomes thinner towards the top with a diameter of 7 cm at its topmost part and more whitish calcite without dish-stacks structure and a more classical candle-shaped structure.

Dating results presented in this paper are originally published in a previous paper (Verheyden et al. 2008). Uranium-series dating indicates that stalagmite JeG-stm-1 was deposited between 11.9 ±0.1 (2σ) ka and 1.1 (extrapolated) ka, when the stalagmite stopped growing – or was broken. Growth rate varied between 0.50 and 2.62 cm/100 yrs, with no important growth hiatus. The highest growth rates are observed in the parts of the stalagmite, where the diameter is the thickest and where the pile-of-plates structure prevails.

The $\delta^{18}O$ and the $\delta^{13}C$ records roughly follow the same trend with relatively high values between 11.9 ka and 11.2 ka as at 10.3 ka (Fig. 3). Generally lower values (~ 11.2 ka onwards with the lowest values (-6.1‰ for $\delta^{18}O$ and -11.2‰ for $\delta^{13}C$) occurring between 8.6 and 6.5 ka (Fig. 2). At 6.5 ka, $\delta^{18}O$ as well as $\delta^{13}C$ start increasing progressively, and, after a short return to lower values (at 5.9 ka), increases again in less than a century and remain relatively high until the top of the stalagmite at 1.1 ka, except for the period between 3.5 and 3.0 ka. According to the $\delta^{18}O$ and $\delta^{13}C$ curves, the stalagmite shows a tripartite partition with a base featuring relatively high carbon signature, a middle part showing decreasing values, and an upper part characterized with relatively higher $\delta^{18}O$ and $\delta^{13}C$ values (Fig. 3).

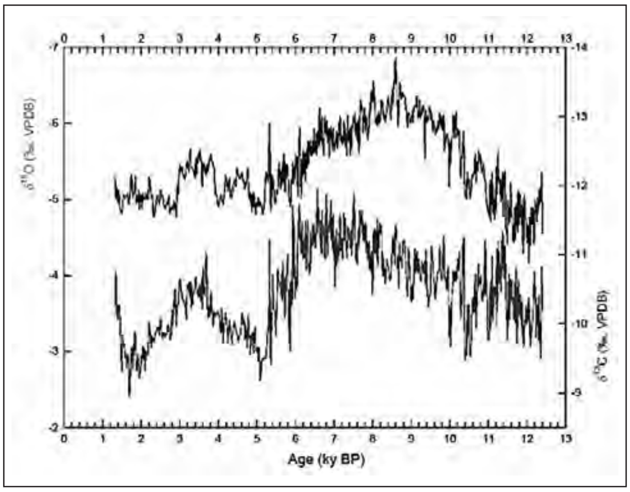

Figure 3. $\delta^{18}O$ and $\delta^{13}C$ profiles (values are in ‰ VPDB) of the JeG-stm-1 stalagmite (Jeita Cave, Lebanon).

Stalagmite JeG-stm-3 was retrieved from the same location as JeG-stm-1. It is 18.6 cm long, with an average width in the order of 5 cm (Fig. 4). Initial dating revealed that the sample age spans 806.2±22a and 578±77a. The first isotopic data revealed a shift in the observed trends for JeG-stm-1, with decreasing $\delta^{18}O$ and $\delta^{13}C$ values.

The Qadisha stalagmite (QaG-stm-1) was retrieved from a relatively high chamber in the cave with probably only a few tens of meters of Quaternary carbonate colluvium overburden. The stalagmite is only 15 cm long with an average diameter in the order of 3 cm (Fig. 5). Initial dating revealed the age of the sample between 6,482±32a and 3,247±127a (before 1950).

4. Discussion

Both stalagmites from Jeita Cave cover the Holocene, while the satalagmite from Qadisha Cave (which is located some 1,650 m higher than Jeita Cave, on the western flanks of Mount Lebanon) covers the period spaning from around 6.5 to 3.2 ka. Hence, comparing the isotopic profiles will allow us to deduce changes that might be related to the altitude differences, the water recharge pathways, precipitation and climatic conditions.

In our previous published paper (Verheyden et al. 2008),

Figure 4. Cut-face of the JeG-stm-3 stalagmite (Jeita Cave, Lebanon), with indications of initial dating results. The sample length is 18.6 cm.

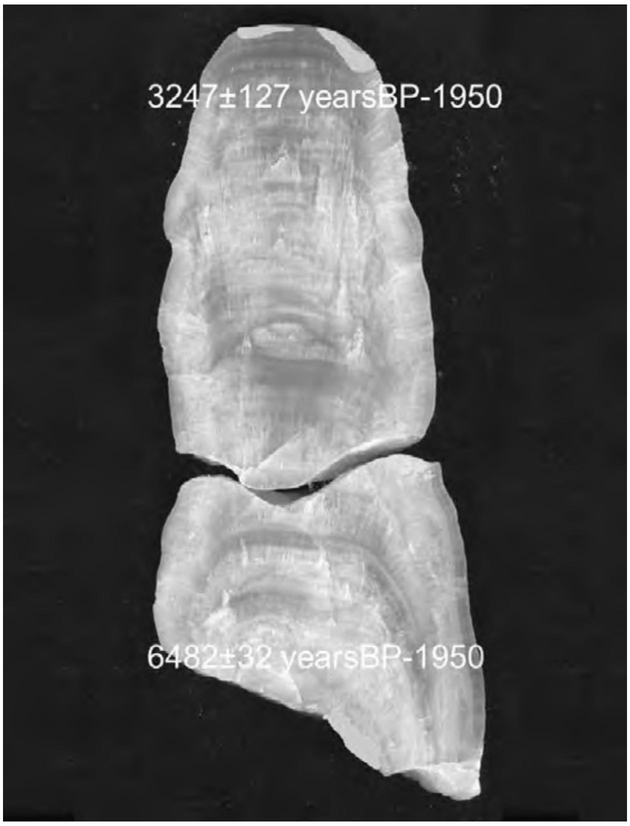

Figure 5. Cut-face of the QaG-stm-1 stalagmite (Qadisha Cave, Lebanon), with indications of initial dating results. The sample length is 15 cm.

we correlated the profiles of JeG-stm-1 with the time-equivalent records of speleothems from Israel. We have also inferred that the Holocene could be subdivided in three distinct periods. While the work on JeG-stm-3 is still in progress, we still can anticipate a fourth period (0.8 to 0.5 ka). In addition the Qadisha stalagmite will provide new insights for the third period described below (5.8 to 1.1 ka) from the high altitude location.

<u>Period from 11.9 to 10.1 ka:</u>

The Jeita Cave record starts at 11.9 ka with high $\delta^{18}O$ values consistent with higher aridity during the YD. The Jeita $\delta^{18}O$ record begins to decrease at 11.2 ka. The carbon record starts (at the base of the stalagmite) with relatively high values (-9.8‰) in agreement with a less favourable period for soil activity, associated with the drier conditions of the YD, however not dry enough to significantly decrease speleothem deposition as suggested by a still relatively high growth rate (1.65 cm/100 yrs) and thick speleothem diameter (between ten and eighteen centimetres).

<u>Period from 10.0 to 5.8 ka:</u>

During the period 10.0–5.8 ka (Early Holocene), the JeG-stm-1 displays particular low $\delta^{18}O$ and $\delta^{13}C$ values compared to the rest of the stalagmite. The isotopic data indicate that during the Holocene, most humid conditions in western Lebanon occurred between 9.2 and 6.5 ka. This period corresponds to parts of the stalagmite with particularly high growth rates (between 1.17 and 2.62 cm/100 yrs) and in general the thickest stalagmite diameter giving further evidence for a high water availability and/or a high $CaCO_3$ saturation of the depositing water linked with an active vegetation above the cave. Simultaneously, clear pile-of-plates stalagmite morphology occurs, which needs a high ceiling (Hill and Forti 1997).

Several other proxy data also indicate a warm and wet Early Holocene in the Levant region (Robinson et al. 2006). The Early Holocene (9.5–7.0 ka) could have been the wettest phase of the last 25,000 years across much of the Eastern Mediterranean. A sudden increase in $\delta^{18}O$ and $\delta^{13}C$ values in the JeG-stm-1 suggests a decline from wet to drier conditions at around 6.0 ka. This is supported by the decrease in stalagmite diameter, the drop in growth rate and a progressive change towards a matt white porous calcite.

<u>Period from 5.8 to 1.1 ka</u>

Indications of dry conditions prevail until the end of stalagmite deposition (1.1 ka) through high $\delta^{18}O$ and $\delta^{13}C$ values and smaller stalagmite diameter, as well as changes to a more whitish porous stalagmite without pile-of-plates morphology. An exception could be inferred for the period from 4.0 to 3.0 ka, as a slight decrease in isotopic values may suggest a gradual change towards less dry conditions to 3.0 ka.

Severe drought is known from historical records during the so-called 4.2 ka climate event brought in relation with the decline of the Accadian empire (Demenocal 2001) and several other civilizations of the Indus Valley (Staubwasser and Weiss 2006). After the 4.2 ka event, entire regions of northern Mesopotamia, Syria and Palestine were intensively resettled (Staubwasser and Weiss 2006). This could be associated with a return to slightly more humid conditions (as indicated by the JeG-stm-1 records). Between 3.0 and 1.1 ka, soil activity progressively decreased as indicated by increasing $\delta^{13}C$ values; while $\delta^{18}O$ values show more variability and could be ascribed to a decrease in soil activity linked with increasing agriculture and/or grazing.

The fact that the extrapolated termination of JeG-stm-1 is around 1.1 ka made us search for a reason behind such a cessation of stalagmite growth. Obviously, if the dripping point in the ceiling was plugged or if the floor moved and no more dripping water was available the stalagmite would stop growing. Interestingly, several major earthquakes have been recorded in the same time range of the stalagmite top (1063: earthquake of magnitude ~7.1, felt in Tyre and up to Antakya; 1170: earthquake of magnitude 7.5–7.9, felt in northwestern Syria; 1202: magnitude 7.5 in the Bekaa; 1339: earthquake felt in Tripoli; Elias et al. 2007).

<u>Period from 0.8 to 0.5 ka</u>

The JeG-stm-3, which grew on another broken stalagmite, has recorded a more recent time. While work is still in progress, the initial $\delta^{18}O$ and $\delta^{13}C$ profiles reveal decreasing values that could relate to return to relatively humid climatic conditions.

5. Conclusions

Studies of speleothems from Lebanon started in 2005 and are still on-going, yielding rewarding results. The work carried out on the Jeita Cave stalagmites (11.1 to 0.5 ka) from coastal, central Mount Lebanon resulted in distinguishing four distinct periods covering the Holocene until almost present time.

The wettest period in western central Lebanon occurred from 9.2 to 6.5 ka.

There was a dry Mid- to Late Holocene until around 1.1 ka, with exception of a relatively wetter period between 4.0 and 3.0 ka.

A return to more humid conditions in the last millennium is anticipated with the early results of JeG-stm-3, while the comparision of Jeita and Qadisha speleothems is expected to reveal invaluable information on altitude controls.

Acknowledgments

The authors would like to acknowledge the director of MAPAS (operator of Jeita Grotto showcave) and the Municipality of Bcharreh town for their hospitability and support. Members of the Spéléo-Club du Liban are thanked for their help during the fieldwork (inside the caves) and for providing maps and data concerning the caves. Mr. S. Karkabi is acknowledged for fruitful discussion and guidance.

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PHYSICAL RESEARCH IN CROATIA'S DEEPEST CAVE SYSTEM: LUKINA JAMA-TROJAMA, MT. VELEBIT

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The objective of this study is to present the first results of research conducted in the 1,421 m deep cave system Lukina Jama during 2010 and 2011. The cave is situated in the area of Hajdučki kukovi in Northern Velebit National Park (Croatia) and is the deepest cave system in the Dinaric karst. *In situ* measurements of microclimate parameters and radon concentrations were performed at 20 measuring points. Two temperature gradients were detected: dT/dh = -3.65 ±0.3 °C/100 m from the entrance to a depth of 200 m and dT/dh = +0.39 ±0.04 °C/100 m to the bottom of the cave. Ice and snow dynamics influenced microclimate parameters to a depth of 200 m. Mean radon concentrations changed with distance, from 200–600 Bq/m^3 in the upper cave sections, to 1,139 Bq/m^3 in the lower sections. This increase is in correlation with the partial pressure of carbon dioxide, which is an important factor in a variety of geochemical processes occurring in caves. Speleothems occur rarely in the deep caves of Mt. Velebit, and therefore the microclimate and geological conditions at the locations where they occur. As reported here, microclimate conditions below a depth of 220 m to the bottom are very stable, so speleothems are good candidates for further paleoclimate investigation.

1. Introduction

Mt. Velebit is a 145 km long mountain in the Croatian Dinaric Karst area, lying between the Adriatic Sea and the Ličko Polje and Gacko Polje fields. It is characterized by deep karst developed in thick carbonate beds (Velić and Velić 2009). Its deep aquifers are the result of complex geological structures and hydrogeological conditions influenced by the presence of clastites deep in the anticlines cores (Stroj 2011). Owing to its position between the Adriatic Sea and the continental Lika region and altitudes up to 1,757 m, the mountain also serves as an important climatological border. The consequence is climate diversity, changing from a dominant temperate humid climate (*Cfb*) towards a humid boreal climate (*Df*) in the highest parts, and a submediteranean climate (*Cfa*) along the Adriatic coast. Such a border position, in addition to temperature diversity, also results in high precipitation (>3,500 mm/y). Both factors are important for geomorphological and physical processes observed in caves.

The northern Velebit region is important because of a significant number of extremely vertical and deep caves discovered and explored in the last 20 years (Bakšić 2006) (*Table 1*).

These caves provide an excellent means of gathering new insights on the geology and geomorphology of Mt. Velebit (Lacković 1999; Kuhta 2001; Bočić 2006), karst hydrology (Stroj 2010) and subterranean fauna (Bedek et al. 2012). Therefore, the aim of scientific research is to gather as much information on the properties and characteristics of these caves during speleological expeditions.

The aim of the present study is to present the preliminary results of research conducted in the 1,421 m deep cave system Lukina Jama-Trojama during 2010 and 2011. This system is situated in the area of Hajdučki kukovi in Northern Velebit National Park and it is the deepest Croatian cave investigated since 1993. Although the widely accepted name is Lukina Jama, this is actually a cave system Lukina Jama-Trojama because of the two entrances and shafts that are connected at a depth of 558 m. During 2010 and 2011, the Lukina Jama entrance (altitude 1,438 m) was choked with snow and ice at a depth of around 70 m. This condition, not consistent with the trends of global warming, has been ongoing for years, unlike in the 1990s when the entrance was passable. The second entrance, Trojama, at an elevation 37 m higher (1,475 m) was

Table 1. Deep caves of Northern Velebit.

Cave name	Depth (m)	Length (m)	Explorations
Cave system Lukina Jama	-1,421	3,730	1992–1995 2010–2011
Slovačka Jama	-1,320	5,677	1998–2002
Cave system Velebita	-1,026	3,176	2003–2008 2011–2012
Jama Meduza	-679	1,393	2001,2003
Patkov Gušt	-553	601	1997
Jama Olimp	-537	633	1998–2000
Ledena Jama in Lomska duliba	-536	629	1962,1977 1992–1998
Lubuška jama	-531	2164	2000–2001 2006,2009

passable, and therefore the scientific research was conducted through this entrance.

These entrances experience differing ice and snow conditions. During previous expeditions, ice and snow were recorded at the Lukina Jama entrance down to a depth of 556 m (Buzjak et al. 2010). In the Trojama entrance, ice and snow are only present at depths between 25 and 200 m.

Figure 1. Ice in the cave system Lukina Jama at -50 m (photo by D. Paar). The deepest ice location is at -556 m (Buzjak et al. 2010).

2. Methods

In situ measurements of microclimate parameters and radon concentrations were performed at 20 measuring points (Fig. 2).

Microclimatic parameters (T, RH and dew point) were measured using Onset Hobo Temp/RH, Oakton RH/Temp data loggers and Telaire 7001 Carbon Dioxide Monitor. The logging intervals were 1 and 2 hours.

Integrated measurements of radon and its short-lived progenies in the air were performed by means of the passive track etching method with type II LR-115 SSNT detectors (Kodak-Pathé, France). The cylindrical detector cup, with a diameter and length of 11 cm and 7 cm respectively, was either covered with a paper filter with a 0.078 kg/m^2 surface density (diffusion detector), or was open. Radon concentration in the air was determined as a product of the sensitivity coefficient and track density of the diffusion detector. The measurement method with two detectors (diffusion and open) enables determination of the equilibrium factor for radon and its progenies in the air (Planinić et al. 1997).

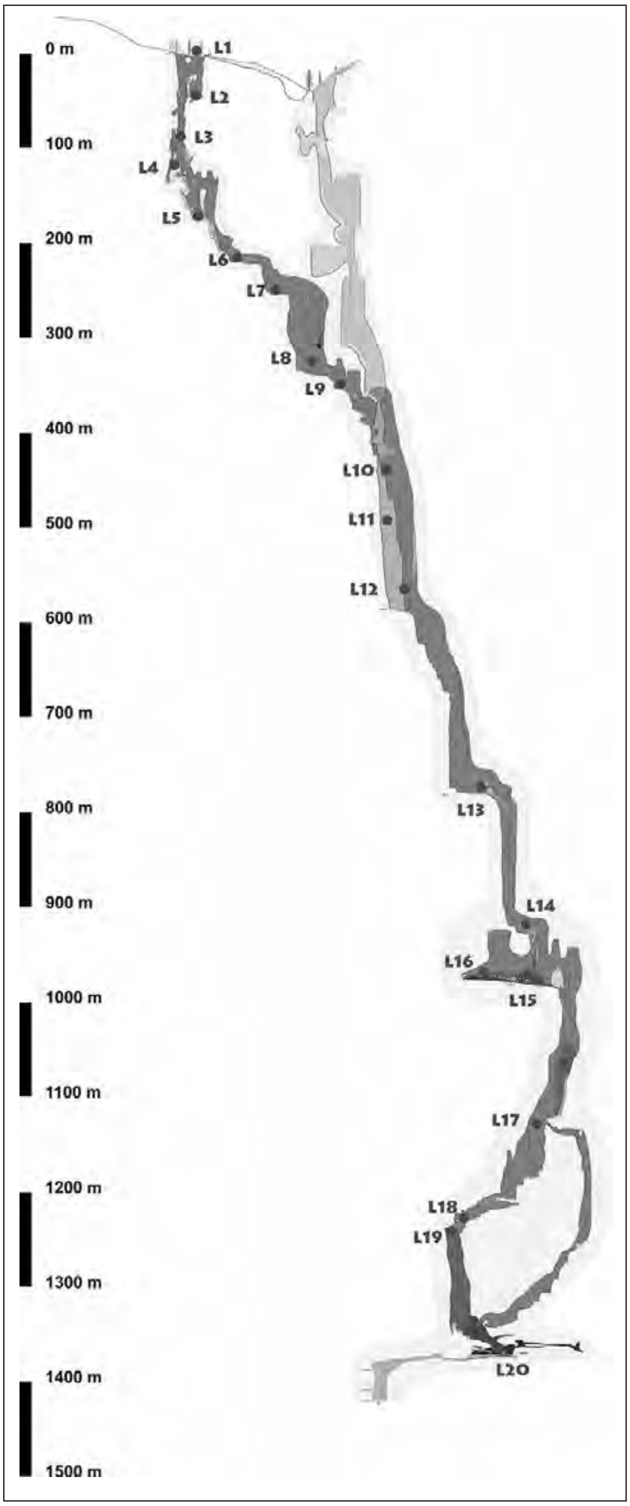

Figure 2. Cave system Lukina Jama (profile) with measuring points L1-L20. Cave map edited by D. Bakšić and L. Mudronja.

3. Results and Discussion

In order to obtain a complete overview of the microclimatic parameters, monitoring should be undertaken over an extended period of time (Cigna 2002; Buzjak 2012). However, deep pits do not allow this due to the very complex access to measuring points. Consequently, at most points, the cave microclimatic parameters were monitored during speleological exploration, though monitoring over a one-year period was conducted at a few selected points.

Results of the microclimate measurements are presented in

Figure 3. Instruments at -1,225 m (one year logging).

Table 2. Microclimate measurements in Lukina Jama.

	Depth (m)	Tmean (°C)	Tmax (°C)	Tmin (°C)	RH (%)	Time (h)
L1	0	13.2±7	22	8.3	77.6±4	179.0
L2	-45	3.8±0.2	4.1	3.6	95.7±4	71.4
L3	-95	2.0±0.6	2.0	2.0	100.0±6	67.7
L4	-115	0.8±0.2	0.9	0.5	100.0±4	260.0
L5	-180	-0.7±1.2	0.5	-5.8	100.0±5	8,793.0
L6	-220	0.0±0.2	0.2	0.0	95.2±4	96.5
L7	-260	0.7±0.6	1.0	0.7	89.7±6	157.0
L8	-320	0.6±0.2	0.7	0.6	96.6±4	145.0
L9	-350	0.9±0.2	1.7	0.8	95.6±4	98.8
L10	-435	1.3±0.2	2.1	1.3	100.0±4	205.8
L11	-495	2.1±0.6	2.7	2.0	100.0±6	40.5
L12	-580	2.0±0.6	2.7	2.0	98.2±6	226.4
L13	-795	2.5±0.2	2.6	2.5	100.0±4	133.3
L14	-935	3.0±0.2	3.1	3.0	95.9±4	24.4
L15	-987	3.3±0.2	3.7	3.3	98.4±4	216.4
L16	-987	3.3±0.2	3.4	3.3	96.3±4	21.1
L17	-1,145	3.7±0.2	4.3	3.6		0.8
L18	-1,225	3.6±0.2	3.7	3.6	100.0±4	8,666.5
L19	-1,250	4.30±0.07	4.40	4.22		0.8
L20	-1,368	4.97±0.03	5.02	4.95		1.0

Table 2. The important question is to determine the point in the cave at which the influence of external changes of microclimate parameters are minimised and cease to exist. A comparison of the one-year microclimate measurements on the ground surface (Fig. 4) showing high daily and seasonal amplitudes, with the one-year records in the cave at depths of 180 m and 1,225 m shows T and RH disturbances at a smaller scale (Figs. 5 and 6). On the other hand, values at greater depths are very stable. At 180 m there is substantial ice and snow throughout the year and there are likely strong dynamics during winter or periods with high percolation and low temperatures.

Deep in the cave, T is very stable, under the instrumental error of 0.2 °C and RH approaches 100 %. From these measurements, it can be concluded that at depths greater than 220 m, even short time measurements give relevant results.

According to the parameter trends, two temperature gradients can be determined (Fig. 8): one from the entrance to a depth of 200 m, and a second from 200 m to the bottom of the cave. At 200 m there is a change in the cave morphology with a narrow passage in a meander (with air circulation). Below this point there is no snow and ice, so it is expected that there will be some small influence of the geothermal gradient and temperature gradient will change a sign and value (from -3.65 to +0.39 °C/100 m).

If the presented temperature gradients are compared with previously obtained values (Paar et al. 2008) from the 1026 m deep cave system Velebita, virtually the same gradients are evident in the upper parts of the caves (Table 3). However, differences occur in the lower cave sections. There is likely a less significant external influence than the influences due to cave geomorphology, hydrology and other properties. One substantial difference is that there is no ice and snow in the cave system Velebita, as both entrances are horizontal (as opposed to both entrances of the cave system

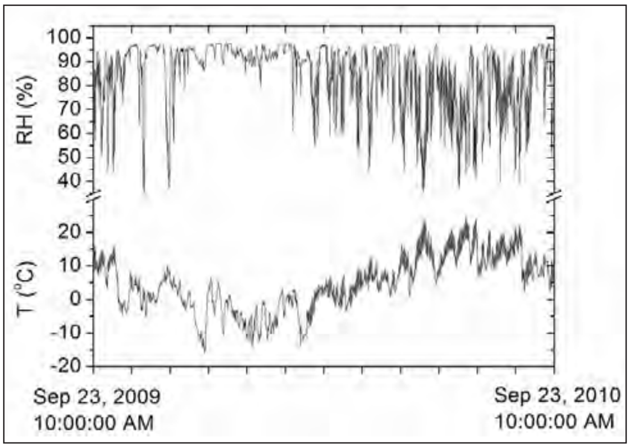

Figure 4. One year microclimate measurements on the surface near the cave system Lukina Jama.

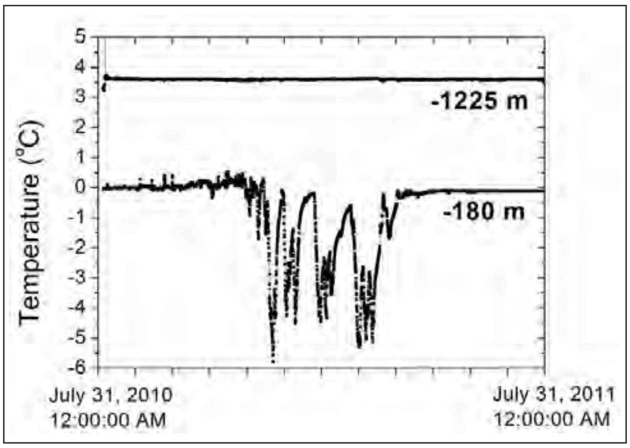

Figure 5. One year temperature measurements at depths of 180 and 1,225 m in the cave system Lukina Jama.

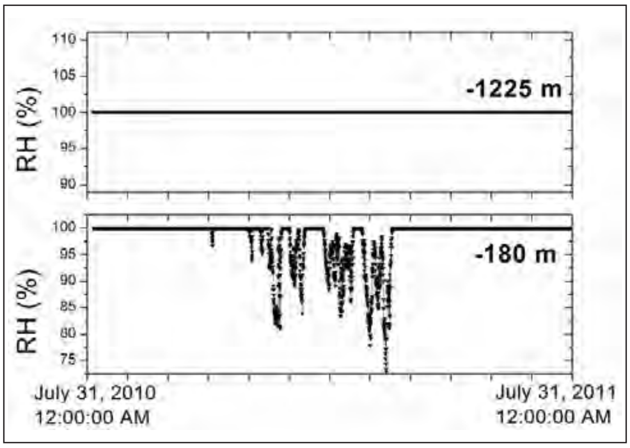

Figure 6. One year relative humidity measurements at depths of 180 and 1,225 m in the cave system Lukina Jama.

Lukina Jama which are vertical). This is also likely the reason why the change from a negative to a positive temperature gradient occurs at different depths.

As shown previously, in the cave system Velebita there is an entrance to a 513 m long shaft at a depth of 100 m, and this change can be attributed to cave morphology and detected air circulation in the upper part of the pit where air circulation changes the temperature gradient by condensation or evaporation which releases or absorbs heat (Paar et al. 2008). In the lower part, the temperature increases with depth because of the Earth's geothermal gradient. It is also shown that small water masses flowing into a mountain are able to peturb the rock temperature (Badino 2005).

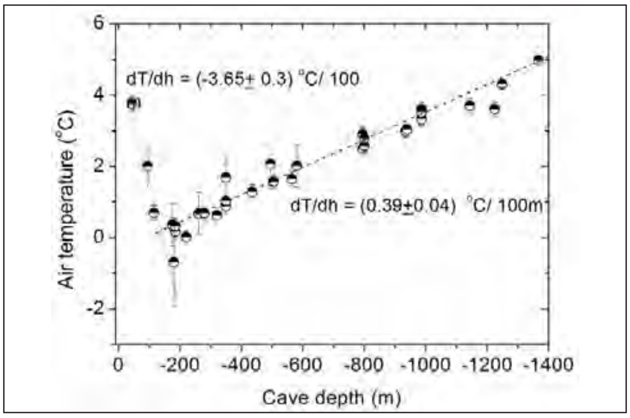

Figure 7. Two temperature gradients in the cave system Lukina Jama.

In the Trojama entrance of the Lukina Jama system, the temperature gradient change occurs at a depth of 200 m, around the lower level of ice and snow. There is a narrow entrance to a meander that continues down to a depth of 520 m where the entrances are connected.

In analysing speleothems to obtain paleoclimate information, it is important to know the stability of cave environment so as to estimate if speleothems are formed under conditions of istopic equilibrium of carbon and oxygen (Fairchild and Baker 2012). Speleothems rarely occur in the deep caves of Mt. Velebit, and therefore it is important to know the microclimate and geological conditions at the location where they occur. In Lukina Jama, speleothem samples were collected at depths between 900 and 987 m. As shown in the present study, at those depths,

Table 3. Comparison of temperature gradients in the Lukina Jama and Velebita cave systems (Paar et al. 2008).

	Lukina Jama	Velebita
dT/dh_1	-3.65 ± 0.3 °C/100 m	-3.5 ± 0.2 °C/100 m
dT/dh_2	+0.39 ± 0.04 °C/100 m	+0.25 ± 0.03 °C/100 m
Gradient change at	-200 m	-100 m

the microclimate conditions are very stable, and therefore speleothems are good candidates for further paleoclimate investigation. In deep caves, temperature dependence with depth is additional factor that must be considered in the analysis.

The average radon concentrations varied with location from 200–600 Bq/m^3 in the upper part of the cave, up to 1,139 Bq/m^3 in the lower section (Fig. 8). These values are much lower than in other Croatian caves, where concentrations of up to 25,000 Bq/m^3 were measured (Radolić 2009; Paar et al. 2005). The highest value in caves on Mt. Velebit was measured in Lubuška Jama, c = 3800 Bq/m^3 (Radolić 2011). This cave is very close to Lukina Jama, but in comparison with Lukina Jama, it has very narrow meanders, which likely results in much lower air circulation.

In 2011, the slope of the radon concentration change with depth was twice that in 2010. The preliminary measurements indicated an increase of the carbon dioxide partial pressure in Lukina Jama from 380 ppm at the entrance to 1,005 ± 50 ppm at a depth of 1,368 m (siphon at the bottom of the cave).

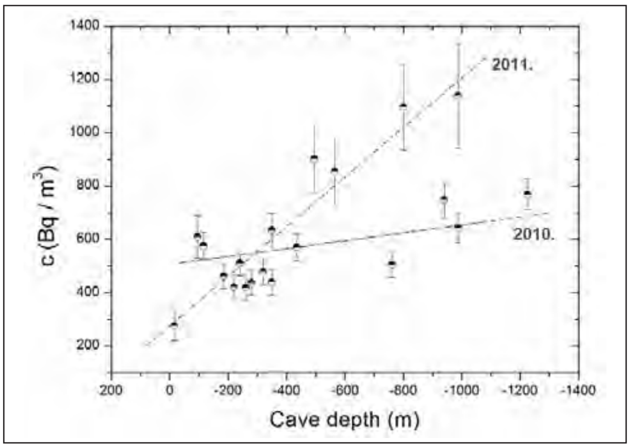

Figure 8. Measurements of radon concentration c at various depths in the cave system Lukina Jama.

4. Conclusions

This paper presents new data on the microclimate parameters and radon concentrations in the cave system Lukina Jama, the deepest cave in the Dinaric karst. Microclimate dependence with cave depth was discussed.Two temperature gradients were detected in the Lukina Jama and Velebita systems: T drop in vertical passages at depths of 100–200 m and T rise below those depths. Such T distribution is influenced by the permanent ice and snow distribution. At depths below 220 m, the microclimate conditions are very stable, and speleothems samples collected below a depth of 900 m are good candidates for paleoclimate investigations.

The measurements showed an increase of radon concentrations with depth. Further analysis of radon concentrations as a natural tracer can help us to understand transport processes at the interfaces of the lithosphere, hydrosphere and cave atmosphere. This may provide a large amount of information on the development and changes of the cave microclimate, particularly in correlation with carbon dioxide, which is an important factor in a variety of geochemical processes occurring in caves.

Acknowledgments

The authors would like to thank the Northern Velebit National Park and the Croatian Environmental Protection and Energy Efficiency Fund for supporting the study. Thanks also go to the members of the Velebit Speleological Society Zagreb, and the Speleological Committee of the Croatian Mountaineering Association for their assistance in field work.

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GROWTH AND DIAGENETIC HISTORY OF ARAGONITE-CALCITE SPELEOTHEMS, IMPLICATIONS FOR ENVIRONMENTAL STUDIES

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Speleothem formation is linked in a number of ways to a set of environmental parameters interfering from micro- to regional, or even global scales. Variation of such parameters with time occurs with two fundamental implications: 1) speleothem material potentially represents excellent archives for fine-scale reconstruction of past environments and climates, 2) physical and chemical modifications of the microenvironment may induce diagenetic transformation of the existing speleothems, which hence are in a nearly continuous evolution. The purpose of this work is to identify the different processes involved in the formation and the the post-depositional evolution of speleothems from the Pont-de-Ratz Cave (Hérault, S. France) and to provide reliable criteria for the distinction of primary and diagenetic features. The main objective is to discriminate products and processes involved in the development of speleothem ("spelean growth history") and those involved in the transformation of a pre-existing speleothem structure ("spelean diagenetic history"). These results highlight the diversity of potential diagenetic modifications of both initial aragonite and calcite precipitates, together with the strong interest of using coupled petrography and geochemistry for precisely deciphering the nature and origin of the different spelean products, thereby providing a reliable tool for chronological reconstruction of events interfering in connection with speleothem development.

1. Introduction

Over the past two decades, carbonate speleothems have been increasingly used as powerful terrestrial proxy, potentially offering high resolution for the long-term record of paleoclimate history (e.g., Lauritzen and Lundberg 1999; Finch et al. 2001, 2003; Tan et al. 2006; Lachniet 2009). Their growth is linked in a number of ways to several climatic parameters such as temperature and humidity, making them excellent candidates as highly sensitive natural archives of climate changes (e.g., Fairchild et al. 2006; Drysdale et al. 2009; Asmeron et al. 2010).

Their primary features (texture, mineralogy, geochemical composition) are strongly dependent from environmental parameters at a large variety of scales, especially: 1) the local microenvironment inside the cave, 2) the geological and hydrogeological cave setting, and 3) the regional and global climatic conditions. Some of these different parameters may change with time, producing modifications of the physical and chemical microenvironment, which in turn may induce diagenetic alteration of the spelean initial features (Frisia et al. 2002; Railsback et al. 2002; Hopley et al. 2009; Martin-Garcia et al. 2009; Melim and Spilde 2011; Martin-Perez et al. 2012). Speleothem material is therefore in a nearly continuous evolution and hence, potentially records the physico-chemical conditions prevailing at the time of primary mineral precipitation but also the following changes of these conditions during cave history.

The aim of this work is to identify the various diagenetic processes undergone by aragonite and calcite speleothems from the Pont-de-Ratz Cave (Hérault, S. France) after initial precipitation of carbonate mineral and to provide discriminant criteria for distinguishing primary (initial precipitation) and secondary features.

2. Location and geological setting

The Pont-de-Ratz Cave is located on the southern margin of the Montagne Noire (Hérault, S. France). The cave is open into dolomites and limestones of Devonian age.

The speleothem samples, including stalagmites, stalactites and stalagmitic floor, were collected in the same room of this cave. Fifteen of them have been studied in details for this project.

3. Methods

For this purpose, we used a process-based approach, which strongly relies on detailed optical petrographical analyses associated with complementary geochemical, ultrastructural and mineralogical data provided by a step-by-step suite of analytical methodologies (SEM, EDS and WDS microprobes, XRF-EDS spectrometry and Raman microspectrometry).

4. Results

4.1. Mineralogy

Identification of minerals is based firstly on their optical properties under the light microscope, and on analysis of

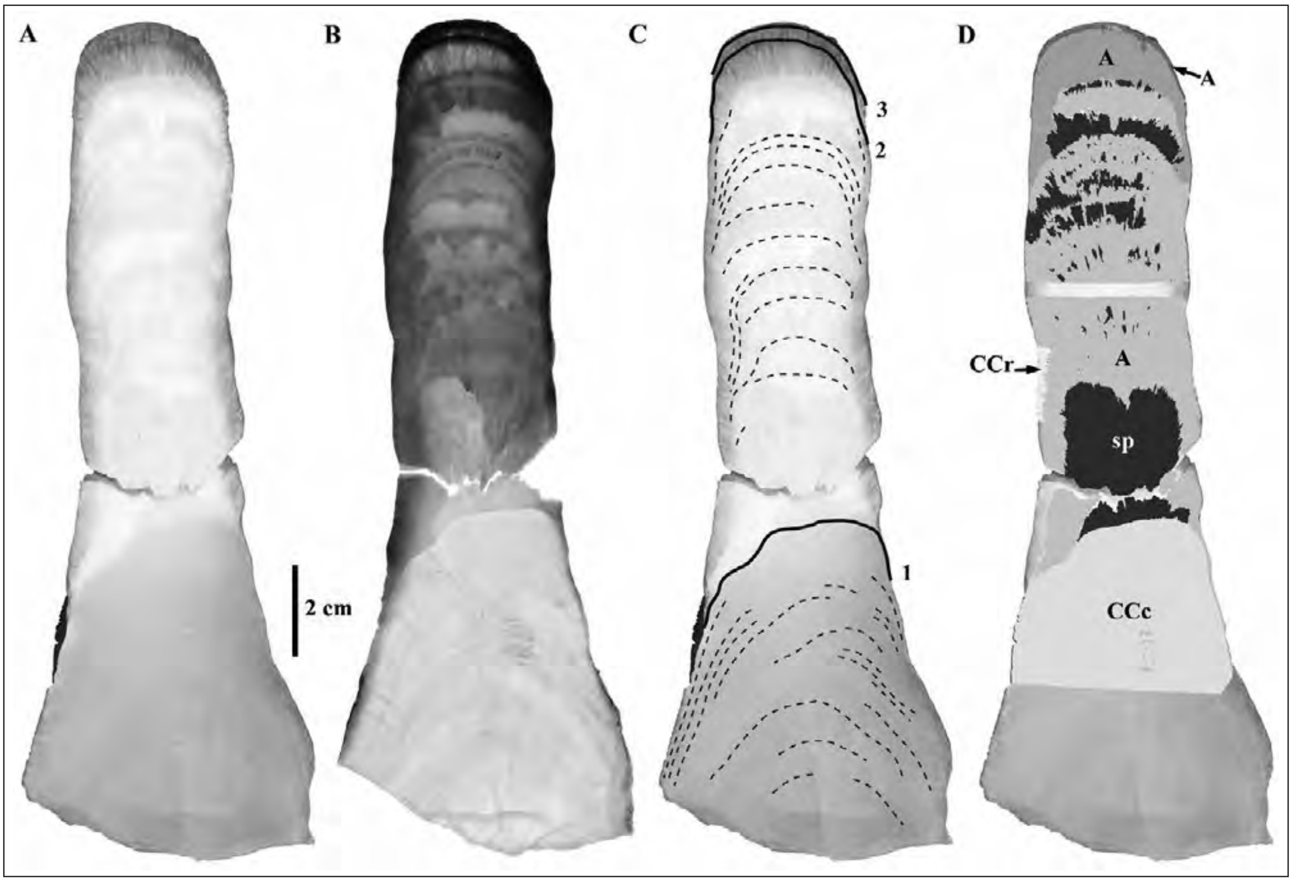

Figure 1. Example of detailed analysis of a stalagmite from Pont-de-Ratz Cave. A. Stalagmite slab seen in reflected light. B. Same stalagmite seen in transmitted light. C. Growth banding (dotted lines) is observed both in the calcite part (lower part of sample) and in the aragonitic part (upper part of sample), now partially recrystallized in calcite. Three discontinuity surfaces are indicated by continuous black lines. Growth discontinuity 1 results from a mineralogical change in carbonate precipitation where columnar calcite is relayed by aragonite. Growth discontinuities 2 and 3 correspond to ancient growth surfaces marked by inclusion levels and discontinuous thin argilaceous micro-layer. D. Mapping of the diverse original precipitates and post-depositional products identified in the three thin sections cutted in this sample. A, aragonite cements; CCc, columnar calcite cement; CCr, columnar calcite of recrystallization; sp, sparitic calcite resulting from recrystallization of aragonite cement.

selected samples with a Raman microspectrometer. The Raman spectra record bands characterizing aragonite, or calcite or a mixture of both minerals at very fine spatial scale.

4.2. Cementation

Two aragonite cements are distinguished from crystal morphology and arrangement and from a slightly different Sr content.

Three different types of calcite cements include: columnar calcite, sparite and small isolated rhomboedral crystals. The two later are developed in primary porosity of pre-existing spelean structure.

4.3. Growth discontinuities and inclusion levels

Five types of growth surfaces and growth discontinuities, some of which associated to inclusion levels, are identified in our samples. These surfaces correspond to ancient external surface of the stalagmite and some of them indicate a stop in the speleothem growth.

4.4. Internal sediment

Small amount of argilaceous sediment form uncommon geopetal deposits in primary porosity of the columnar calcite cement.

4.5. Dissolution

Selective dissolution features are observed either in aragonite or along jointive crystal faces of the columnar calcite cement.

4.6. Recrystallization

Recrystallization processes are evidenced from the observation of crystal remnants of the mineralogical precursor (i.e. "relics") embedded within the secondary mineral, under the light microscope or the SEM.

Recrystallization features include 1) textural change of original aragonite precipitates (aragonite – aragonite recrystallization), and 2) two distinct types of mineralogical changes from aragonite to calcite. The last two processes correspond to recrystallization of aragonite into sparitic calcite, and recrystallization of aragonite into low-magnesian columnar calcite. Additionally to the presence of aragonite relics, this secondary columnar calcite has a slightly higher Mg content than the primary columnar calcite (cement). We suggest that the two aragonite – calcite recrystallizations reflect differences in composition of the diagenetic fluids and in the relative balance between the rate of fluid recharge and the rate of recrystallization process.

4.7. Discriminating spelean growth history and diagenetic history (Fig. 1)

Results show that in Pont-de-Ratz Cave, stalagmite growth is alternatively represented by aragonite and calcite mineralogy (cements of aragonite and columnar calcite).

Growth surfaces and discontinuities are taking place during the formation of the studied speleothems, attesting for the discontinuous and irregular growth of stalagmites in this cave. Such discontinuities potentially record environmental events, including changes in the composition and drip-rates of feeding waters or even feeding breaks, at different spatial scales.

Post-depositional diagenetic processes involve cementation occurring within porosity of pre-existing speleothem (sparite and micro-rhomboedral calcite), internal sedimentation, selective dissolution of aragonite or calcite and recrystallization processes.

5. Conclusions

These results highlight the importance of diagenesis in vadose speleothems and the large variety of potential post-formational modifications of the initial aragonite and calcite precipitates in these cave environments, together with important implications for paleoclimatic studies based on the interpretation of geochemical proxies.

Moreover, the clear distinction of processes according to their relation with growth history or diagenetic history of the speleothem and the detailed mapping of related products within stalagmite samples allow a suitable selection of sub-samples for the following geochronological and paleoenvironmental studies.

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ULTRA-HIGH RESOLUTION SPELEOTHEM RECORDS – HOW FAR WE CAN PUSH THE TIME RESOLUTION?

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Here we use laser luminescence multi-zonal analysis (LLMZA) to measure several ultra-high resolution paleoluminescence speleothem records in an extremely high quality speleothem sample from Coldwater Cave, Iowa. The sampling of these records is 6 and 12 hours per data point (4 and 2 measurements per day accordingly). This particular sample allows resolving of real variations of the surface conditions above the cave longer than 24 hours due to the rapid percolation of the rain waters through the bedrock. These records still remain one of the highest-resolution paleoclimatic records ever measured. They rise the question how far we can push the time resolution of speleothem records?

We found sub-annual cycles with duration of 27–30 and 14 days in an one of these records. Such cycles can be caused by the period of rotation of the Sun We compared cycles obtained in this paleoluminescence record with the cycles of variations of the Solar constant measured from space. Obtained striking similarity in the structure of their cycles suggests that this speleothem paleoluminescence record recorded real variations shorter than one week.

1. Introduction

Paleoluminescence records represent records of variations of the intensity of luminescence of different growth layers of the speleothem. It can be measured properly to represent variations of the past temperature or insolation only using the original LLMZA (Shopov 1987) or IPL (Shopov 2004) equipment

2. Results and discussion

Here we use LLMZA to measure several ultra-high resolution paleoluminescence speleothem records in an extremely high quality speleothem sample from Coldwater Cave, Iowa. The sampling of these records is 6 and 12 hours per data point (4 and 2 measurements per day accordingly). This particular sample allows resolving of real variations of the surface conditions above the cave longer than 24 hours due to the rapid percolation of the rain waters through the bedrock (Stoykova et al., 2008). These records still remain one of the highest-resolution paleoclimatic records ever measured. Some of them were reported previously (Shopov et al., 1992, Shopov et al., 1994), but short cycles represented in these records were not discussed because reliable mechanisms of production of such cycles were not established at that time.

We used a new real-space periodogramme analysis algorithm (Shopov 2002) to calculate, compare and calibrate the real intensity of the cycles in the ultra-high resolution paleoluminescence records. In addition to the annual cycle produced by the Earth's rotation we found sub-annual cycles with duration of 27–30 and 14 days in an extremely high-resolution luminescent record from Cold Water Cave, Iowa (Fig. 1). Such cycles can be caused by the period of rotation of the Sun, which produces variations in the solar wind modulating the geomagnetic field (Shapiro 1967; Mursula and Zieger 1996). Both solar wind and the geomagnetic field modulate cosmic ray flux. Cosmic rays induce condensation of the water in clouds (Svensmark and Friis-Christensen 1997). They are strongly modulated by the solar wind. Stronger solar wind produces weaker cosmic rays flux, so less clouds and higher sky transparency, and stronger irradiation at the Earth's surface. Variations of Solar luminosity correlate with these of the solar wind. So, this mechanism may thus multiply about 100 times the impacts of variation of solar luminosity on the solar radiation reaching Earth's surface and to produce a strong positive correlation between the solar activity and global temperatures despite the small variations of solar luminosity (Stoykova et al. 2008).

Solar rotation can produce sky transparency cycles due to periodic appearance of coronal holes on the visible solar surface. They generate solar wind, which modulates the cosmic ray flux.

The periodicity of sunspots and coronal holes on the visible solar surface varies from 27 to 30 days, depending on the latitude on the solar surface. The latitude of sunspots on the visible solar surface varies with the phase of the 11-year cycle. Sometimes different sunspots may appear at different latitudes during the same solar rotation. All these phenomena are producing a number of short cycles with slightly different periods. Longer time series should contain larger numbers of such narrow cycles. Indeed the longer record (Fig. 2-down) contains far more cycles than the 10 times shorter one (Figs. 1, 2-up)

Combination of these processes may cause observed splitting of the solar rotation cycle in variations of the solar emissions (Fig. 2).

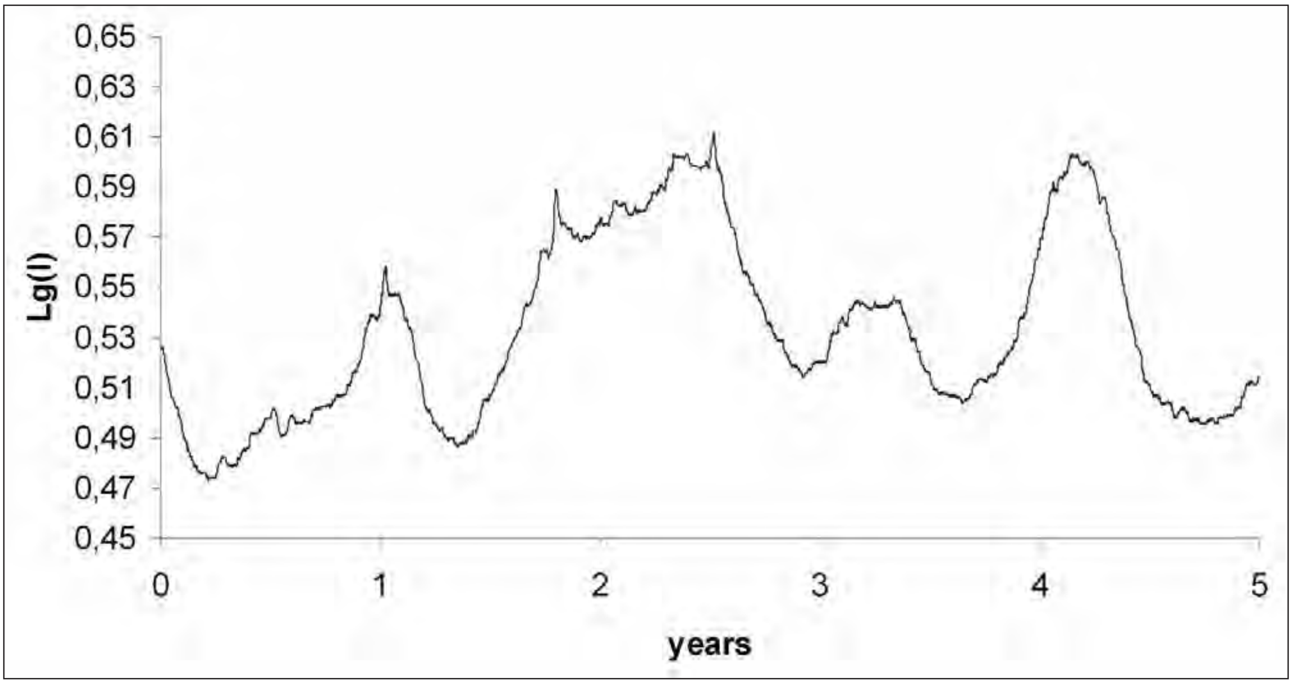

Figure 1. Ultra-high resolution (12 hours = 2 px per day) paleoluminescence record of solar insolation at about 1000 yrs BP from a speleothem from Cold Water Cave, Iowa. This speleothem sample has been dated by 9 TIMS U/Th ages (Shopov et al. 1994).

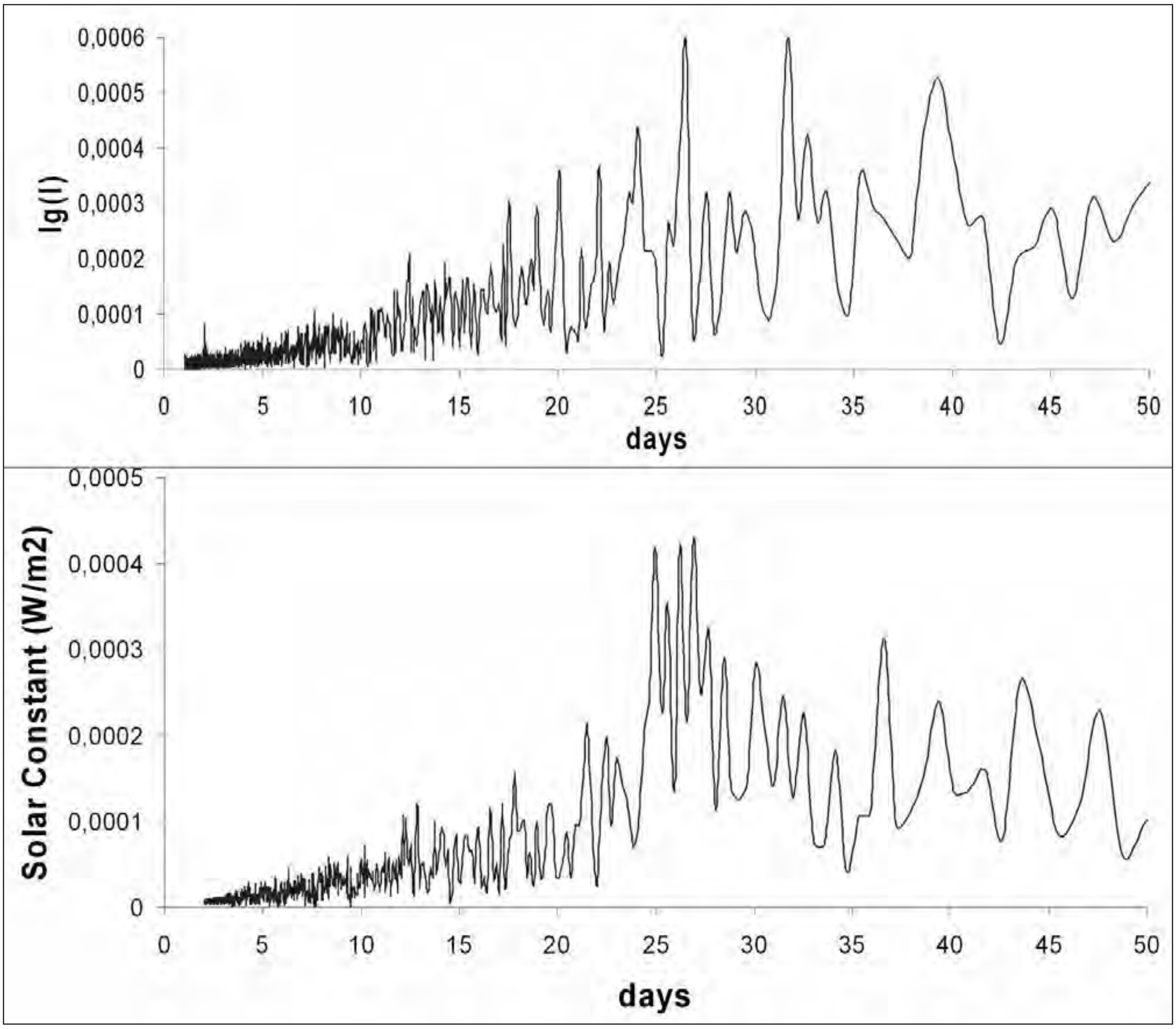

Figure 2. Cycles of variations in the ultra-high resolution paleoluminescence record of solar insolation from Figure 1 (up) and of variations of the Solar constant for the last 50 years (down).

3. Conclusion

Speleothem paleoluminescence records can record real variations shorter than one week.

Acknowledgments

This research has been funded by grant NZ 811/ 98 of Bulgarian Science Foundation to Y. Shopov.

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VARIATIONS OF ANNUAL KARST DENUDATION RATES IN THE LAST TWO MILLENNIA OBTAINED FROM SPELEOTHEM RECORDS

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We used the Shopov quantitative theory of solubility of karst rocks as dependent on the temperature and other thermodynamic parameters to make reconstructions of past carbonate denudation rates. This theory yielded equations assessing the carbonate denudation rates as dependent on the temperature or on the precipitation. We used an estimate of the averaged denudation rate from meteorological data for Kananaskis karst region, Alberta, Canada based on integrated carbonate hardness data and the water from springs, rivers, cave pools and dripping water and average precipitation rate (of 470 mm/yr). The denudation rate obtained was 14 mm/kyr or 38 t/km^2 per year. We used this estimate as a starting point and substituted our proxy records of the annual temperature and the annual precipitation into the equations of karst denudation rates. By this way we reconstructed variations of the annual karst denudation rate for the last 280 years in relation to the annual precipitation and for the last 1250 years in relation to the temperature. Both reconstructions are made for equilibrium conditions and do not take into account variations of evapotranspiration, but they produce quite reasonable estimates of the variations of carbonate denudation which are within the observed range of 8 to 20 mm/kyr (86 % variation). Variation of annual precipitation produces 79 % variation in the denudation rates, from a reconstructed variation of 300 mm/yr between the driest and wettest years of the last 280 years. The temperature dependence of carbonate denudation due to the temperature dependence of the solubility of carbonate dioxide produced only 9.3 % variation in the denudation rate from a reconstructed variation of 4.7 deg. C during the last 1,250 years, so it is negligible in comparison to the precipitation dependence.

We measured a very high-resolution luminescence record covering the last 2,028 ±100 years from Savi Cave, Trieste, Italy, which allows precise determination of growth rate of the stalagmite. It consists of 40106 data points compiled of 16 overlapping scans. Its time steps vary from 15.6 days to 19.9 days. We made a reconstruction of the annual growth rate variations for the last 2,028 years, which represents annual precipitation for the region of the cave. It allows us to estimate the range of the annual variations of karst denudation in northern Italy.

We found that the strongest cycle in the annual rainfall in the Trieste region has a duration of about 300 years. Several other cycles with durations of 160, 130, 68, 38, 30.2, 18.4, 9.4, 6.8 and 5.8 years also occur in the precipitation there. They should produce variations of the same duration in the karst denudation rates.

1. Introduction

Calcite speleothems usually display luminescence produced by calcium salts of humic and fulvic acids derived from soils above the cave (White and Brennan 1989). These acids are released by the roots of living plants and by the decomposition of dead vegetative matter. Root release is modulated by the visible solar radiation via photosynthesis, while rates of decomposition depend exponentially on soil temperature. Soil temperature depends mainly on solar infrared and visible radiation in the case where the cave is covered only by grass or upon air temperature in the case where it is covered by forest or bush (Shopov et al. 1994). In the first case the zonality of luminescence can be used as a proxy of solar insolation and in the second case it can be used as a paleotemperature proxy.

The luminescent index has high resolution as in the case where one step in a record is less than one month and the signal contains mainly climatic modulation. But in the case where the step is greater than one year the climatic modulation of signal is in the range of the experimental error and the luminescent record becomes a proxy of solar insolation.

Speleothem growth rate variations represent mainly rainfall variations. Speleothem luminescence often displays annual microbanding. We used this to derive proxy records of the annual precipitation at the cave site by measuring the distance between all adjacent annual maxima of the intensity of luminescence. The resultant growth rates correlate with the actual annual precipitation (summed from August to August).

2. Experimental part

High-resolution fluorescence records are obtained using LLMZA analysis equipment described in Shopov, (1987) with excitation wavelength from 200 to 240 nm. The pictures obtained are scanned by the precision professional scanner EPSON 1650 with a step of 8 μm. We choose a string with width of 200 μm from scans and transform the string into luminescent curve by a computer program specially written for this purpose. This program integrates pixels contained in a window of 20 × 200 μm that is moving along the string with a step of 10 μm. This digital procedure is equivalent to scanning film negatives with a scanning microdensitometer (PDS or Joyce Loebl 6). So this way a record of the distribution of the optical density luminescence (decimal logarithm of the intensity of luminescence) of the speleothem along its growth axis is obtained. It is linearly proportional to the concentration of the luminescent compounds in the calcite. Such records are proxies of the solar radiation or paleotemperature in the past if all these compounds are only organic.

Luminescent records were transformed into luminescent time series by using absolute dating.

3. Results and discussion

We studied a 35 mm long stalagmite from Rats Nest Cave (RNC), Alberta, Canada, obtaining a stacked 66000-data point luminescent record that covers the last 1450 yrs with step resolution of about 8 days for most of the time span. Paleoclimatic records have been derived from speleothem luminescence by calculation of the average annual intensity of luminescence and measurements of annual growth rate values. The annual record obtained has been calibrated by actual climatic records from the nearby climatic station in Banff, Alberta, located in the same valley, 50 km NW of the cave (Shopov et. al, 1996 a, b). This way we reconstructed annual air temperatures for last 1450 years at the cave site with an estimated error of 0.35 °C, where the error of the station direct measurements is 0.1 °C.

Speleothem growth rate variations represent mainly rainfall variations. We obtained a reconstruction of the annual precipitation for the last 280 years at the cave site with an estimated statistical error of 80 mm/year. Annual speleothem growth rate was independent of the intensity of luminescence, of annual temperature and of solar luminosity over this time span (zero correlation).

Speleothem luminescence often displays annual microbanding (Lauritzen and Kihle 1996). We used for relative and absolute dating of speleothems the Autocalibration dating technique of Shopov et al. (1991a) and ^{14}C dating.

1. The TAMS ^{14}C dating produced an age of 1450 ± 150 years (2 sigma) for the base of the stalagmite. The 14-C date is corrected for "dead" carbon by its measurement in modern speleothem calcite in RNC.
2. The Autocalibration dating produced a better precision of 1,450 ± 80 years.

We used the quantitative theory of solubility of karst rocks of Shopov et. al, (1989), Shopov and Georgiev (1991) as dependent on temperature and other thermodynamic parameters to make reconstructions of past carbonate denudation rates. The dependence of carbonate denudation rates (**D**) on the precipitation and on the temperature is expressed as:

$$\mathbf{D= k. R. [CaCO_3],} \qquad \mathbf{(1)}$$

where **k** – is the ratio between the amount of water passed through the karst rock and the total precipitation, **R** – is precipitation and $\mathbf{[CaCO_3]}$ – concentration of calcium carbonate in the karst waters

$$\mathbf{[CaCO_3]= [CaCO_3]_0. pCO_2^{1/3}. e^{-0.02t}} \qquad \mathbf{(2)}$$

where $\mathbf{pCO_2}$ is the partial pressure of $\mathbf{CO_2}$ in the bedrock, $\mathbf{[CaCO_3]_0}$- is the solubility of the rock at standard thermodynamic conditions (25 °C, 1 atm. $\mathbf{pCO_2}$) which can be measured in the lab, **t** is the temperature in the bedrock in °C (Shopov et al., 1998).

Usually $\mathbf{[CaCO_3]_0.\ pCO_2^{1/3}}$ is constant with time. So combining equations 1 and 2 we obtain:

$$\mathbf{D=k. R. [CaCO_3]_0. pCO_2^{1/3}. e^{-0.02t}=const. R. e^{-0.02t}(3)}$$

If we presume that annual temperature is constant we may study the precipitation dependence of karst denudation. If we presume that annual precipitation is constant we may study the temperature dependence. We do this in order to evaluate the importance of the influence of the time variations of both factors on the denudation:

We used an estimate of the averaged denudation rate in the region based on integrated data of the carbonate hardness of the water from springs, rivers, cave pools and dripping water and average precipitation rate (of 470 mm/yr) from meteorological data. The denudation rate obtained is 14 mm/kyr or 38 t/km^2 per year. We used this estimate as a starting point and substituted our proxy record of the annual precipitation (for the last 280 years) in Equation (3), presuming that **t** was constant equal to the average annual temperature of the cave region, to reconstruct the karst denudation variations in dependence on the annual precipitation (Fig. 1).

We substituted our proxy record of the annual temperature for the last 1,250 years into Equation (3), presuming that **R** was constant equal to average annual precipitation (of 470 mm/yr) in the cave region, to reconstruct the dependence of karst denudation variations on temperature (Fig. 2). Both reconstructions are made for equilibrium conditions and do not take into account variations of evapotranspiration, but they produce quite reasonable estimate of the variations of carbonate denudation which are within the observed variation of 8 to 20 mm/kyr (86% variation). The precipitation dependence of carbonate denudation explains 79% of the variation in the denudation rate, a result of the reconstructed variation of 300 mm/yr between the driest and wettest years during the last 280 years. The temperature dependence of carbonate denudation (due to temperature dependence of solubility of carbonate dioxide) explains only 9.3% of variation in the denudation rate, a result of the reconstructed variation of 4.7 deg. C during the last 1,250 years, so it is negligible compared to the precipitation effect.

We studied a sample from Grotta Savi, in the Trieste Karst, NE Italy, which is a 27-cm long, 5-mm thick polished section of an active calcite stalagmite along its growth axis. It has been dated by means of 18 U/Th MC-ICPMS analyses (Borsato et al. 2004). After identification of positions of U/Th dates along the luminescent scans we transformed them into luminescent time series. The whole stalagmite consists of translucent, columnar calcite, and is characterised by visible growth laminae.

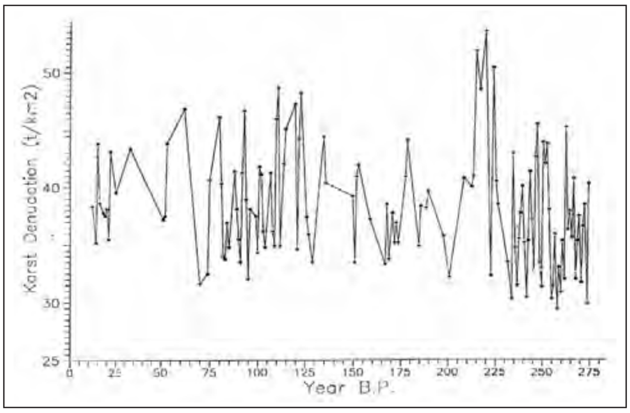

Figure 1. Reconstruction of variations of carbonate denudation rates in the Kananaskis karst region, Alberta, Canada in the last 280 years, treated as dependent on the annual precipitation.

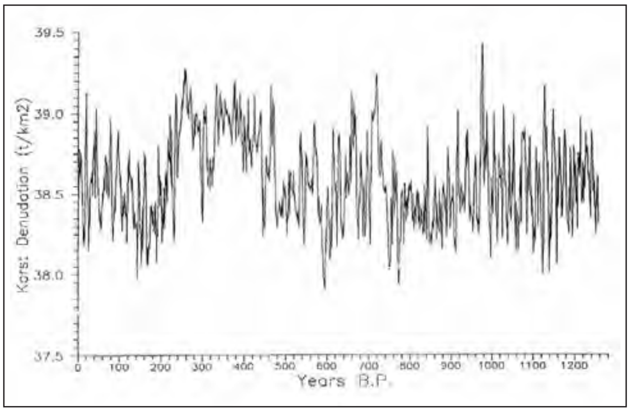

Figure 2. Reconstruction of annual variations of carbonate denudation rates in the Kananaskis karst region, Alberta, Canada in the last 1,250 years treated as dependent on the temperature.

We composed a very high-resolution composite record covering the last 2,028±100 years (2δ) (the upper 20 mm of the sample) with several hiatuses. This composite record consists of 40,106 data points and has been compiled from 16 overlapping scans of 4,800 data points each. It has a resolution from 15.6 days to 19.9 days (Fig. 3). It allows precise measurements of the annual growth rate of the speleothem, which ranged from 2.2 to 45.4±0.5 microns/year about its mean value of 6.36 microns/year.

We used this record to measure the full record of annual growth of the speleothem. It covers 2028 years taking into account hiatuses in the record (Fig. 4). This record represents mainly the annual rainfall at the cave site. More precipitation leads to dissolving of more $CaCO_3$ from the carbonate rocks and its precipitation in cave speleothems. The range of the annual variations of the karst denudation is linearly proportional to the range of the variations of the annual precipitation. So the obtained curve represents relative variations of the past karst denudation during the last 2028 years in North Italy. More work is necessary in order to transform it into a quantitative reconstruction of the past karst denudation.

We used a special algorithm, called real-space periodogramme analysis introduced in Shopov et al. (2002) to calculate the intensity of the cycles of the annual precipitation at the cave site. The resulting periodogramme shown in Fig. 5 demonstrates that the strongest cycle of the annual rainfall in the region of Trieste, Italy is with duration of about 300 years. Several other cycles with duration of 160, 130, 68, 38, 30.2, 18.4, 9.4, 6.8 and 5.8 years exists in the precipitation there. They should produce variations with the same duration in the karst denudation rates in the region.

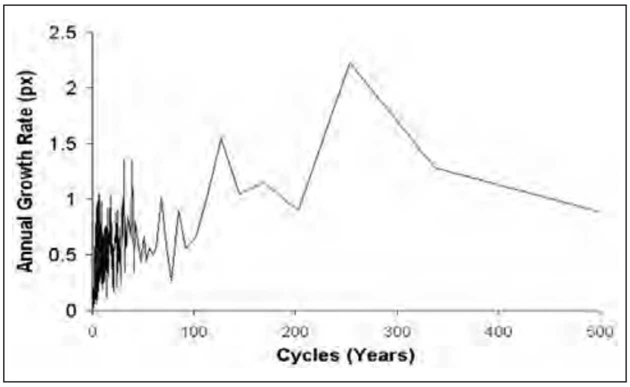

Figure 5. A periodogramme of the annual growth rate of SV1 stalagmite from cave Savi. It represents the cycles of the annual rainfall in the region of Trieste, Italy.

4. Conclusions

It is demonstrated that speleothem luminescence proxy records of annual values of the climatic parameters can be used for reconstruction of the variations of carbonate denudation for a time span far exceeding all historic records.

It is demonstrated that variations of carbonate denudation due to the temperature dependence of solubility of carbonate dioxide are negligible in comparison to the variations due to precipitation changes.

The strongest cycle of annual rainfall and of carbonate denudation in the region of Trieste, Italy has a duration of about 300 years. Several other cycles with durations of 160, 130, 68, 38, 30.2, 18.4, 9.4, 6.8 and 5.8 years also exist there.

Acknowledgements

This research has been funded by COFIN 2000 “Ricostruzione dell’evoluzione climatica e ambientale ad alta risoluzione da concrezioni di grotta lungo una traversa N-S in Italia con particolare riferimento all’intervallo Tardiglaciale-attuale”, coordinated by U. Sauro and supported by grant NZ 811/98 of Bulgarian Science Foundation to Y. Shopov and a NSERC strategic research grant to D.C. Ford.

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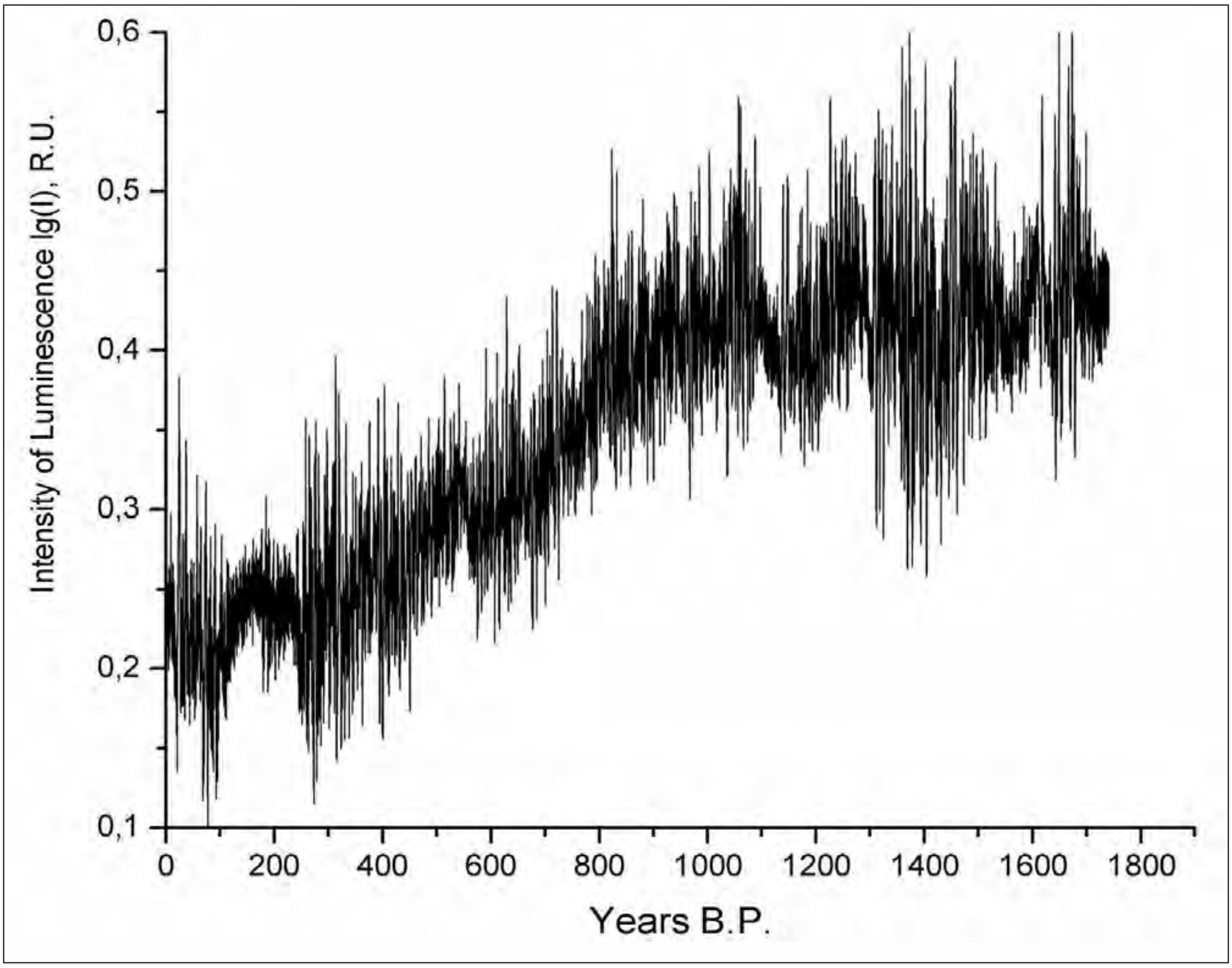

Figure 3. The highest resolution composite record of SV1 covers the last 2,028±100 years. It consists of 40,106 data points compiled from 16 overlapping scans. The individual time step range from 15.6 days to 19.9 days.

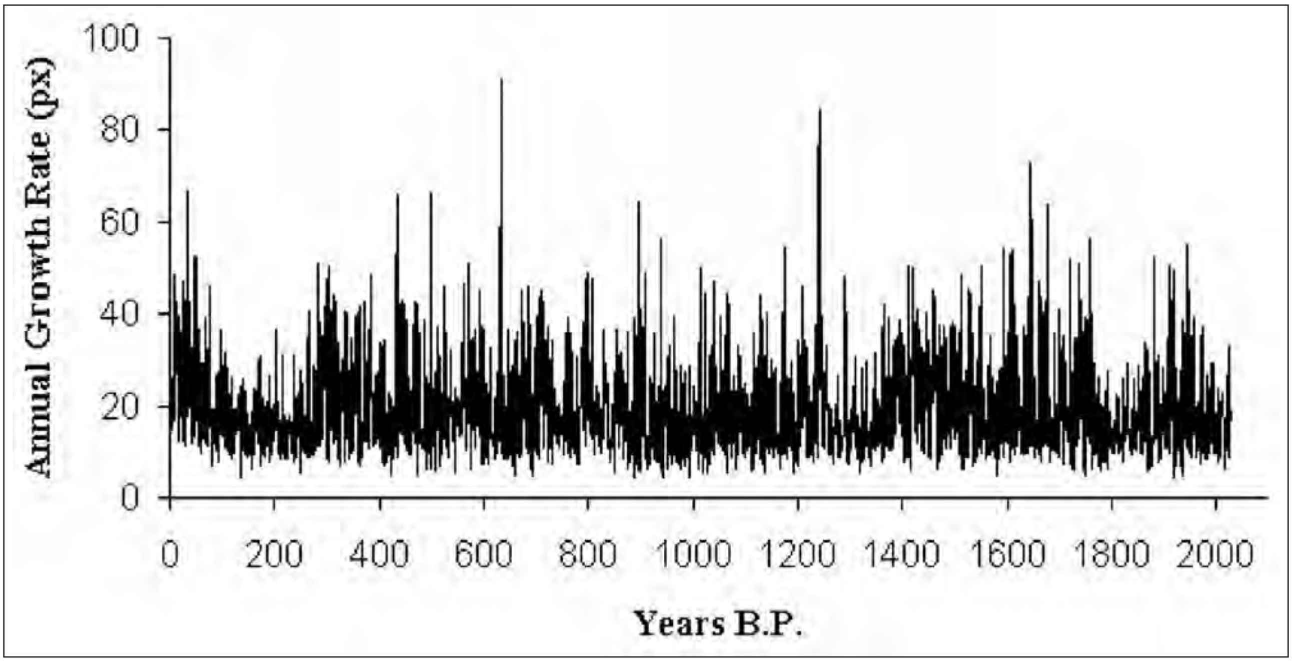

Figure 4. The annual growth rate of SV1 stalagmite derived from the record in Fig. 3. The mean annual growth rate is 6.36 microns/year and it varies from 2.2 to 45.4 ±0.5 microns/year. This record reflects mainly the annual rainfall at the cave site.

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A PRONOUNCED EXTENDED NEGATIVE TEMPERATURE GRADIENT IN THE POMERANZEN CAVE, SWITZERLAND

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The climatology of the Pomeranzen Cave (O91/92) in the Swiss Churfirsten Mountains at 1,746 m a.s.l. was studied during 2.5 years by means of 25 temperature loggers. In the uppermost part, a small chimney leading to few meters below the surface has a rather constant winter temperature of 4.7 °C which is 3.0 °C warmer than the mean annual temperature (1.7 °C). In contrast, the temperature in a nearby cave at the same altitude is 2.2 °C, as expected. Also the big Elysion hall is quite warm at the top (average 4.2 °C at -34 m) and much cooler at the bottom (3.4 °C at -90 m). Under a heavy snow cover, the negative gradient in this hall is even more pronounced (4.4 °C at -34 m vs 3.3 °C at 90 m). The negative gradient continues into the following pit zone (average 3.2 °C at -120 m, 2.9 °C in the winter 2011). From here, the average temperature gradient is slightly positive (0.1 °C/100 m) down to the deepest part of the cave at -340 m. There, 3.5 °C correspond to the expected mean annual outside temperature at this altitude.

The cave opens in a flat of open karst at about hundred meters distance from the slope of Chäserrugg Mountain which has a 70 meters low permeability formation just above the altitude of the cave. The exceptionally high temperature in the upper part of the cave may result from the higher temperature under the Chäserrugg Mountains. In addition, the coverage of the upper part of the cave – about 20 m – may be heated during the summer and thus serve as energy source under an insulating blanket of snow in winter.

1. Introduction

We describe the climatology of the Pomeranzen Cave O91/92 in the Churfirsten Mountains in eastern Switzerland (Fig. 1). This is a region with a high annual rainfall of 1,640 mm (MeteoSchweiz 2012) and extensive karstification.

The cave opens in the former glacier valley between Chäserrugg and Gamserrugg at 1,746 m a.s.l. and is actually 2.2 km long and 369 m deep and consists of two parts, O91 and O92 (Fig. 2), which are connected by a narrow passage. Both parts are not yet fully explored. For descriptions and plans see Stünzi (2006) for O91 and Stünzi (2009) for O92 till the bottom of the Elysion hall.

Here, we concentrate on the O92. Below the entrances a meander ascends gently to the south east from where the lower Hades-meander descends to the big Elysion hall in the North. The following pit zone is explored down to 369 m (Fig. 2).

The study with temperature loggers was undertaken because we observed very varying winds in the entrance part. We then detected a pronounced temperature inversion in Elysion Hall and down to -120 m. This temperature anomaly is the scope of the present work.

Figure 1. Geographical location of O91/O92.

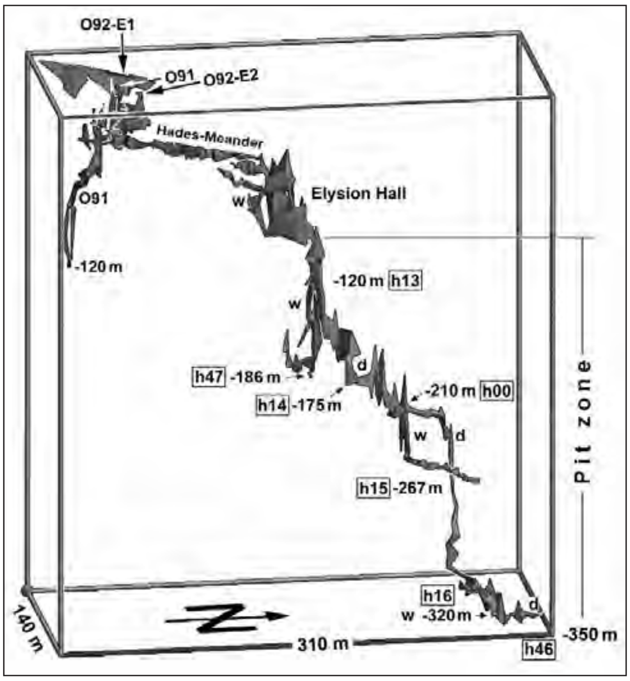

Figure 2. 3D-Sketch of O91/O92 (Franz, 2011) and logger positions in the pit zone."d": dry parts, "w": wet parts.

2. Geology

The Churfirsten Mountains are composed entirely of Mesozoic sediments. The cave O91/92 opens almost on top of a 200 m thick stratum of cretaceous limestone (Schrattenkalk), sloping downwards with about 10 degrees to the north. The underlying Drusberg formation (marls and limestone) is first encountered at -210 m, but then the cave continues in limestone down to its end. There must be a fault with significant vertical offset but its nature has not yet been elucidated. At -320 m the rock appears to be stressed by a fault.

3. Data collection

3.1. Temperature Loggers

The temperature measurements with three different types of loggers started in February 2010 and continued till October 2012:

In the entrance zone mostly i-buttons DS1921Z (accuracy ±1 °C, resolution ±0.12 °C) were used. Most of the results presented here are from Hobo loggers. Those with single digit numbers (e.g., h6) are Hobo Pendants (accuracy ±0.5 °C, resolution ±0.11 °C); those with double digit numbers (e.g., h06) are Hobo Water-Temp-Pro v2 (accuracy ±0.2 °C, resolution ±0.027 °C, in use since January 2011). Generally, data were collected with an hourly interval.

All readings are corrected for the calibration in ice water. Recalibrations showed that the reproducibility is much better than the accuracy.

3.2. Other meteorological data

From the the Swiss meteorological service we had temperatures of three stations in the region. The average of these temperatures, corrected for 0.5 °C per 100 m, gives an indication of the ambient temperature when the logger outside the cave was below the snow cover.

For the atmospheric pressure and rain we used data from the Säntis Mountain (9 km to the north, 2,500 m a.s.l).

4. The upper part of the cave

4.1. Description

For a detailed description see Stünzi (2009). The entrance E1 of O92 is a large chasm, usually snow filled (Fig. 3). An opening in 27 m depth gives access to a high gallery of about 3 m width. A meander starting 9 m above its ground features a nicely decorated initial ellipse. There, two stalagmites ended growing 420,000 years bp (Luetscher, pers. comm.)

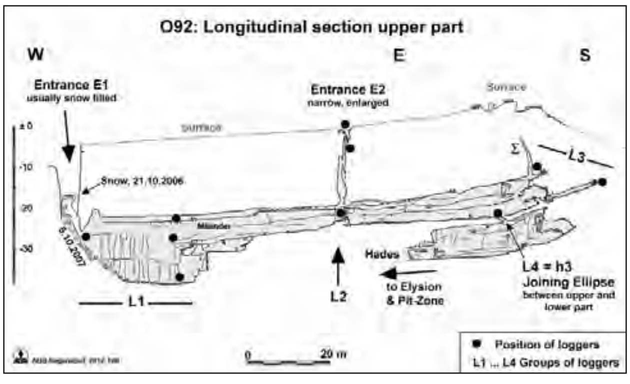

Figure 3. Position of the temperature loggers in the upper section of the cave.

Entrance E2 was found as a light spot from within the cave and had to be enlarged. It is now the usual access to the cave. The above mentioned meander continues, then turns southwards and ends in a breakdown zone. A small chimney (Σ in Fig. 3) ends few meters below the surface.

A declining tube of approx. 0.8 m width and 1.5 m height (“Joining Ellipse”) leads to the top of the Hades meander.

4.2. Logger results from the upper part

The positions of the loggers are given in Fig. 3. For the present work only summarizing results are pertinent. Some details are given in Stünzi (2010).

During winter, the temperatures of logger group L1 are ≥0 °C when the entrance E1 is closed by snow. The same holds for group L2 regarding the entrance E2.

The rather constant temperatures of the group L3 show that despite the near surface there is no inflow of air from the outside into the cave.

The logger L4 (h3) in the Joining Ellipse had a constant temperature of 3.9 °C during the winter 2012, when the entrances of the cave were blocked by snow. Over the whole period the temperature varied between 2.0 and 4.0 °C (3.73 ±0.15 °C) with 0.5 % of the readings below 3.2 °C. The latter indicate that cold air from the entrances can sometimes reach this point. However, the wind in the Joining Ellipse is generally upwards (towards the entrances).

5. The lower part of the cave

5.1. Description and Hydrology

The Hades meander is rather narrow with a trickle at the bottom. In the last 60 m before reaching the Elysion hall the lower part of the meander becomes impassibly narrow and progression continues in the initial ellipse (Fig. 4 and Stünzi 2009).

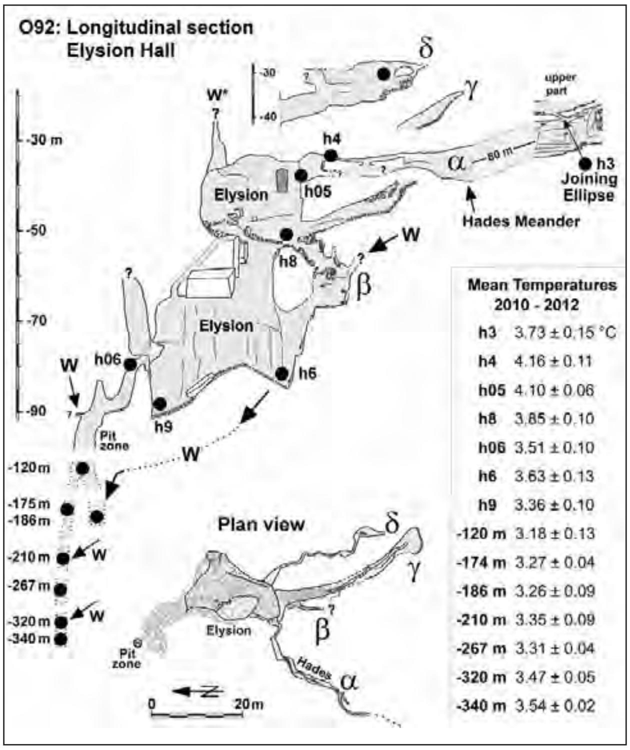

Figure 4. Longitudinal section and plan view of the Elysion hall. In the longitudinal section the positions of the temperature loggers are shown. The positions of the loggers in the pit zone (below -90 m) are not to scale. The Greek letters denote same places in both views. “W” indicates water flow, usually just a trickle. During heavy rain, water might enter via W. The roof of Elysion is approx. 20 m below the surface.*

From the Elysion hall two meanders (γ and δ in Fig. 4) ascend towards the bottom of a rock face in the small valley east of the cave. A laser distance measure into an unexplored chimney (W* in Fig. 4) ends about 10 m below the surface. About 20 m offset from this point there is a small depression on the surface filled with earth and blocks, some with reminings of dripstone.

There is a further gallery (β in Fig. 4). From a fissure at its south end a trickle enters and flows down to the bottom of the Elysion hall, where it disappears between the pebbles.

The pit zone opens 15 m above the north end of the hall. After a squeeze (at h06 in Fig. 4) the dimensions become more comfortable but dripwater enters through the roof of the second pit. At -120 m the shaft divides: one branch with drip water descends to -186 m followed by a chimney towards the Elysion hall (not yet fully explored). The other branch is rather dry down to -210 m, where divides again. Here, a trickle can increase to a dangerous water flow during snow melt. The water flows into a pit which is followed by a narrow meander ending at -262 m. From the division at -210 m, a short fossile gallery leads to further pits where a rivulet of approx. 5–10 L/s enters at 320 m. Its flow rate increased only slightly during the above mentioned snow melt. In the deepest part (-369 m) several branches – some fossile – await further exploration.

Table 1. Summer and winter temperatures (°C). Mean and standard deviations of hourly readings.

Logger	Depth	Summer 10.8.–6.10.11		Winter 21.1.–21.2.12		Diff. Su-Wi
	m	Mean	S.dev	Mean	S.dev	
Joining Ellipse						
h3	-22	3.82	±0.05	3.88	±0.00	-0.04
Elysion Hall						
h4	-34	4.18	±0.03	4.41	±0.00	-0.22
h05	-38	4.11	±0.01	4.15	±0.01	-0.04
h8	-51	3.93	±0.04	3.77	±0.00	0.16
h06	-79	3.57	±0.01	3.41	±0.02	0.14
h6	-82	3.64	±0.06	3.47	±0.00	0.17
h9	-90	3.47	±0.01	3.26	±0.00	0.21
Pit Zone						
h13	-120	3.18	±0.06	3.18	±0.03	0.02
h14	-175	3.30	±0.01	3.21	±0.01	0.09
h47	-186	3.24	±0.03	3.19	±0.01	0.05
h00	-210	3.36	±0.02	3.23	±0.01	0.13
h15	-267	3.37	±0.02	3.25	±0.01	0.12
h16	-320	3.49	±0.01	3.46	±0.01	0.03
h46	-340	3.56	±0.02	3.52	±0.01	0.04

5.2. Temperatures in the Elysion hall

The Elysion hall shows a marked negative temperature gradient (Fig. 4). In order to interpret this phenomenon we concentrate on 2 periods: Summer 2011 and winter 2012 with a heavy snow cover (Table 1, Fig. 5).

In the deeper parts the "summers" are delayed till end of November, thus mean temperatures of August and September are used as summer values. During this period the Joining Ellipse showed some variation due to the influence of the entrances, and at h6 (Fig. 4) the higher standard deviation may result from variations in water inflow from meander β. The other temperatures were rather constant. The gradient in the Elysion hall was 1.2 °C/100 m (R^2 = 0.97).

In February 2012 all temperatures were very constant (Table 1) with a temperature gradient of -1.8 °C/100 m (R^2 = 0.94) in the Elysion Hall. Also the temperatures below the entrance pits were constant during this month (E2: 3.51 ±0.04 °C, E1: 1.2 ±0.2 °C), indicating that the cave was closed by snow. The upper part (Elysion to Joining Ellipse) was warmer than in summer. This holds also for the small chimney in the uppermost part of the cave (Σ in Fig. 3) where the winter temperature (4.67 °C) was higher than in summer (4.12 °C).

An exeption is the small chamber an the end of branch δ (Fig. 4) which shows marked seasonal temperature variations from 3 °C in winter to 8 °C in summer (average 4.9 °C). Although this chamber is very near to the surface, the constant temperatures at positions h8 and h05 indicate no significant inflow of air.

5.3. Temperatures in the pit zone

The negative gradient continues into the pit zone which is still colder at -120 m than at the bottom of the Elysion Hall (Fig. 4 and Table 1). The temperatures in the pit zone were quite stable except a larger variation (±0.13 °C) at 120 m, probably due to variable dripwater from the pit above.

From -210 m down to -267 m the temparture remains almost constant and only below this depth a positive gradient of 0.3 °C/100 m is established.

5.4. Rain on 10 Oct. 2011

On 10 Oct. 2011 there was a widespread heavy rain, starting at midnight. It amounted to 107 mm at Säntis Mountain (9 km to the north, 2,500 m a.s.l) where it was accompanied by a sudden temperature increase from -5 to + 5 °C. This rain produced a sudden increase of the temperatures in the cave (Table 2 and Fig. 5), particularly those at the south bottom of Elysion (h6, Fig. 4), at -120 m and -186 m (dripwater), and at the water entries at -210 m and -320 m. The early increase at h8 in the center of Elysion indicates that some water entered also from the chimney W* in Fig. 4. After 2–4 days these temperatures returned to the previous values within 20 % of the peak.

The Joining Ellipse reacted much later, showing that the water does not flow via this point. The same is true for the deepest part of Elysion (h9).

The water entering through E2 flows into the gallery below the E1 (Fig. 3) and disappears between the pebbles of the floor. The peak maxima at the entrances (groups L1 and L2 in Fig. 3) were two hours later than in the Elysion Hall. Thus, the entrance-region of the cave does not contribute to the hydrology of Elysion and the pit zone.

Table 2. Influence of a heavy rain on 10 Oct. 2011 on the cave temperatures (Mean of hourly readings).

Logger	Depth m	9. 10. 11 mean °C	10. 10. 11 10–12 h °C	Diff. °C	onset# time
Joining Ellipse					
h3	-22	3.77	3.88	0.11	07:00
Elysion Hall					
h4	-34	4.20	4.31@	0.11	04:00
h05	-38	4.12	4.27	0.15	02:00*
h8	-51	3.88	4.50	0.62	01:00
h06	-79	3.55	3.81	0.26	03:00
h6	-82	3.58	4.63	1.05	03:00
h9	-90	3.47	3.69	0.22	08:00
Pit Zone					
h13	-120	3.21	4.26	1.05	03:00
h14	-175	3.25	3.41	0.16	03:00
h47	-186	3.23	3.83	0.60	03:00
h00	-210	3.33	4.14	0.81	04:00
h15	-267	3.30	3.30	0.00	
h16	-320	3.47	3.94	0.47	05:00
h46	-340	3.54	3.60	0.05	05:00
outside		1.1	4.41		
Entrance	-4	3.4	5.25		

#: 10 % of total temperature change
@: one single reading higher than 4.20 °C
*: first decrease to 4.07, increase started 06:00

For the depth between -38 m to -186 m the temperature maxima were recorded at 10:00 and one hour later for 210 m and -340 m. The logger at h4 showed two short impulses of -0.1 and +0.1 °C and had returned to normal by 13:00.

A similar sudden temperature increase was observed on 27 July 2012 at 15:00 (Fig. 5), simultaneously on all stations below -51 m. This must have been a local thunderstorm as there was no rain recorded at Säntis and two other stations in the region.

5.5. Snow melt 2012

On 25 April 2012 most temperatures started to increase quite markedly and rather simultaneously (Fig. 5). At 210 m, near a water entry, the temperature rose from 3.2 to 3.6 °C in the course of three days and then it took about two months to fall back to the summer temperature of 3.4 °C. The situation was similar at the other “wet” positions, i.e. h6 (increase of +0.4 °C), at 120 m (+0.3 °C), -186 m (+0.5 °C), see Fig. 4. Logger h8 showed a smaller temperature increase of 0.2 °C.

This temperature increase obviously marks the onset of the melting of the massive snow cover (>3 m above the cave). The temperature drop at the Joning Ellipse indicates inflow of cool air after melting of the snow cover of the entrance E2. Also the temperatures at the top of Elysion (h4 and h5) decreased by 0.2 °C. Water-induced mixing of the air might have brought up some cooler air from the bottom of the hall.

There was much less snow in the winter 2011 and correspondingly this snow melt had a much less pronounced effect on the cave temperatures (Fig. 5).

6. Interpretation and Discussion

6.1 Hydrology

As already mentioned, rain water from the entrances region does not flow into the Elysion and the pit zone.

The events mentioned under 5.4 and 5.5 show clearly that the position h6 (Fig. 4) is the point where the water leaves the Elysion hall. At this position there is usually some water flowing down from the meander β (Fig. 4). The large size of the pit between these positions indicates a sometimes significant water flow. Thus, β is likely to be a major contributor to the water in the pit zone. The second entry of water is at the top of the pit zone (Fig. 4).

The simultaneous, fast temperature peaks at all the positions indicate that

- there is only one major catchment area;
- the catchment area is in the vicinity of the cave;
- the pathways from catchment area to the cave are rather straight.

The catchment area may comprise the Karren field between cave and Chäserrugg, the small valley east of the cave and the flat ridge east of the cave (Fig. 6). 100 m west of Elysion there are 3 pit caves of which the largest opens at 1,730 m a.s.l. going down to 1,670 m a.s.l. These might feed the top of the pit zone at 1,655 m a.s.l. (-90 m). Four small pit caves 150 to 300 m to the east of Elysion indicate a well established karstification with a possible connection to meander β (Fig. 4).

The function of the trickle in the Hades meander remains obscure. Here, we have never observed an elevated water flow and there is no obvious inflow of the Hades-water into Elysion. The Temperature peaks from rain and snow melt at the top of Elysion (h05) are much smaller than those directly below β (h6). Thus, water inflow from the chimney in Elysion seems to be of minor importance.

6.2. The cave is too warm

Cave temperatures in karst regions usually correspond to the mean annual outside temperatures (Luetscher and Jeannin, 2004). This was observed in the nearby cave O17, 900 m SE from the O92 at 1870 m a.s.l. (Filipponi, 2004). In this cave, the temperature at 1746 m a.s.l. was 2.0 °C, which fits well the estimated outside temperature of 1.7 °C (Alpha-Innotec, 2012). However, the upper parts of O92 show temperatures up to 4.7 °C.

Only at -340 m (1,400 m a.s.l.) the cave temperature of 3.5 °C corresponds to the mean annual outside temperature at this altitude (3.7 °C, Alpha-Innotec, 2012). Similarly, the temperature at 1300 m a.s.l. in the Seichbergloch (1.3 km to the north) was about 4 °C (Dickert, 1995).

Water from melting snow infiltrating into the rock has about 0 °C but gets warmed up, as shown by the increases of the

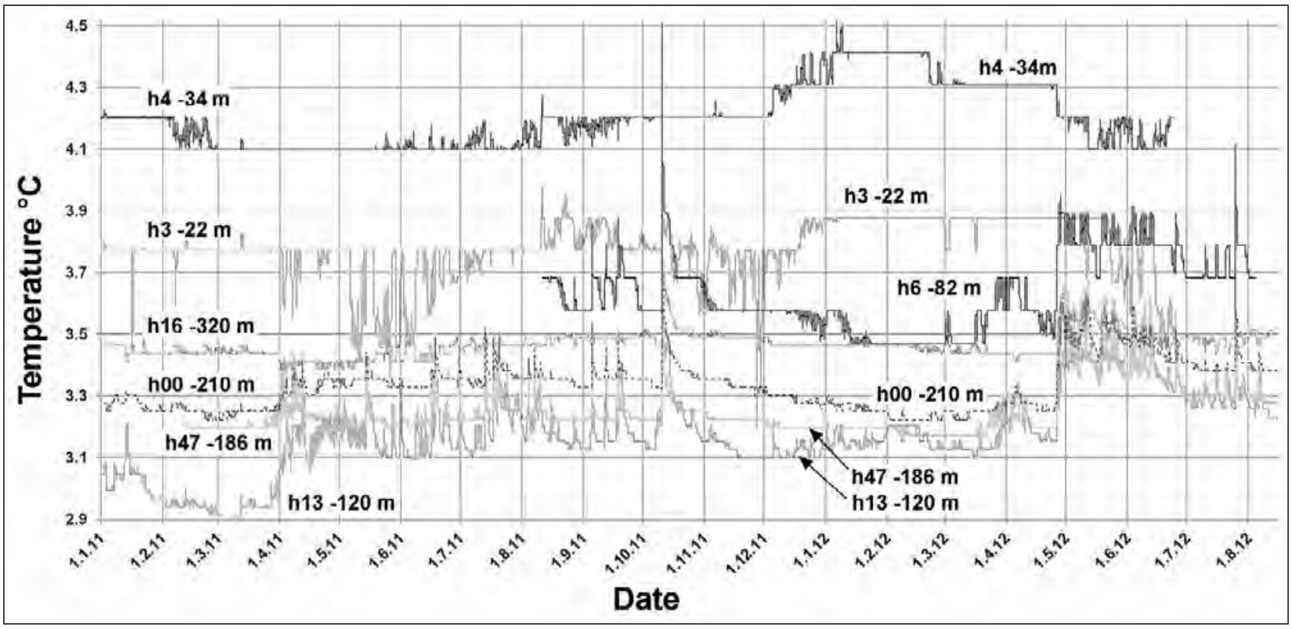

Figure 5. Selected Temperature Plots from January 2011 to August 2012.

cave temperatures, e.g., from 3.5 °C to 4.0 °C at 82 m in the Elysion hall (h6 in Fig. 4). This indicates that a significant portion of the rock is warm and tranfers the heat to the melt water.

Several reasons for the too high temperatures and the negative gradient may be excluded: (1) To our knowledge there is no increased geothermal flow in the Churfirsten Mountains which are composed entirely of Mesozoic sediments. (2) As the two entrances are on the top of the cave, there cannot be an inflow of warm summer air from the outside creating a warm air trap.

The situation in the Elysion Hall indicates a convective situation – less dense warm air at the top – especially during winter when the entrances are closed by snow.

But, where does the heat input come from?

6.3. Exposition and insulating snow cover

The mean annual temperature (2 years) of the logger outside the cave was 4.7 (from July 2010) and 4.6 °C (from June 2011). This is much higher than the expected mean annual outside temperature (1.7 °C) because the logger records temperatures around 0 °C under the snow cover instead of the negative winter air temperatures. A similar mean temperature (4.7 °C) was found in the chamber at the end of branche δ, which is situated close to an east exposed cliff.

This may be the "true" mean temperature of the plain under which the upper part of the cave develops some 20 m below the surface (Fig. 6). On this field of open karst there is almost no vegetation shielding the rock and no cooling evapotranspiration. It is thus conceavable that the "roof" of the cave has taken the mean annual temperature "below snow".

However, in the winter 2011 (20 Feb to 30 March, Fig. 5) the loggers below both entrances showed that these were closed by snow. Although the snow cover was less thick, the same average temperature would be expected in the rock 20 m below the surface. But the top of Elysion (-34 to -79 m) was colder by 0.1 to 0.3 °C, also at -120 m. This means that despite some obvious venting of the cave, a strongly negative temperature gradient persisted down to 120 m. The same is true during summer. However, in a vented pit zone with drip water, one would expect a temperature increase of approx. 0.5 °C from 80 to 180 m instead of the observed decrease by 0.2 °C.

6.4. Lateral spread of geothermal heat

An additional source of energy might be due to the normal geothermal heat flux with a gradient of approximately 3 °C/100 m below Chäserrugg. The marls with low thermal conductivity just above the cave altitude are even expected to accumulate heat which might spread laterally to heat the upper parts of the cave (Fig. 6).

A higher temperature below Chäserrugg would certainly be expected if there was no phreatic level below. This is not unrealistic in view of the low permeable marls of the Garschella formation (Fig. 6). In addition, the major vertical fault with about 30 m vertical offset running north-south along the Chäserrugg ("Bruch von Oberplisen", Heim 1917; Becker 2007) might be more prominent in the depth and even act as aquiclude.

A larger gradient and consequently higher temperatures can even be expected in a saturated confined karst below low permeability marls. Luetscher and Jeannin (2004) give an example of a gradient of 1.5 °C/100 m.

Under the entrance pit E2 (Fig. 3) there is a bedding plane parted by about 10 cm. A similar bedding plane parting is observed in the O91-part of the cave some 20 m deeper. And in the top of the meander going towards E1 there is a neotectonic horizontal displacement by about 10 cm. Could these features enhance the lateral flux of heat from below the Chäserrugg?

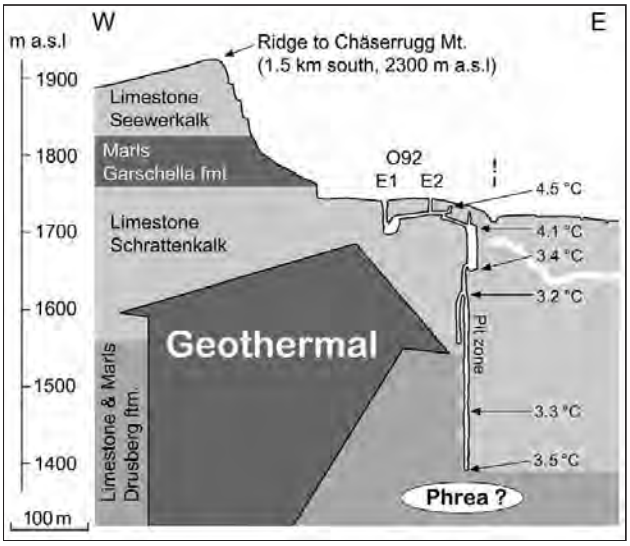

Figure 6. Geology of O91/O92 with some mean cave temperatures and proposed geothermal heat flux. The white line gives the surface over the deep end of the cave, which is 280 m north of the entrances. "-.-" marks the position of the major fault.

7. Conclusion

Thus, the temperature is "normal" at the bottom of O92 (340 m) but increasingly too high above -267 m. Two hypotheses for the heating of the top part of O92 are presented, i.e. convective situation due to insulation of the cave by snow and lateral spread of geothermal heat from the Chäserrugg. Both may contribute to the observed exceptional negative gradient.

Acknowledgments

We thank the Swiss Institute of Speleology and Karst Studies (SISKA) and the agricultural Research Station ART (Zürich) for the lending of the i-Buttons and Hobo Pendants, respectively, and the colleages who sponsored some of the Hobo Water-Temp-Pro v2 which surpassed the club budget. The project would not have been possible without the help of many members of the Speleo club AGS-Regensdorf with the frequent logger trips. I also thank Prof. A. Pflitsch (Ruhr-Universität Bochum), Dr. A. Becker and Ch. Sutter for valuable comments regarding this paper.

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GEOMORPHOLOGY OF FOSSIL SPRING MOUNDS NEAR EL GEDIDA VILLAGE, DAKHLA OASIS, WESTERN DESERT OF EGYPT

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Quaternary fluvio-lacustrine deposits in the currently arid Egyptian desert can be used as indicators for pluvial phases in the Sahara and a record of climatic change. Some fossil springs formed from tufa deposits were found along the edge of the Libyan plateau scarp in Dakhla Oasis, Egypt. At least eight major episodes of fossil spring mounds were discovered near El Gedida village, Dakhla Oasis, most of the mounds were deposited as a part of fluvial system characterized by terraced, vegetated pools and accumulated tufa dams and separated by low waterfalls.

This paper depends upon geomorphological, sedimentological and remote sensing methods, in addition to extensive field surveying, mapping and sampling for ^{12}C, ^{13}C and ^{14}C AMS dating, to develop a Pleistocene climatic chronology as paleo spring mounds are particularly amenable to AMS dating techniques for both tufa sediments as well as current spring hot water to define the sources of its acidifying gas and water, for more understanding of the desert pluvial events, and the time of human migration from this area of the western desert of Egypt, and finally it would also help to define water sources of the current hot springs and whether renewable sources or is it an ancient fossil water.

1. Introduction

El Gedida village is situated in the NW portion of the Dakhla depression, a deep wind-ablated but stratigraphically controlled depression to the south of the Libyan Plateau escarpment in the Western Desert of Egypt (Fig. 1). The current climate is hyperarid, with the region averaging 1 mm of rainfall per year (Vose et al. 1992).

1.1. Objective

This paper aims to explain the current geomorphic characteristics of some spring mounds fields as well as define the chronological evidence of its paleo karst formation.

1.2. Previous work

The first exploration of the paleo spring mounds in the Dakhla and Kharga Oasis's in the western desert of Egypt began in the early nineteenth century by the paleontologist on the Rohlfs expedition in 1873–1884 (Zittel 1883); by Bagnold (1931, 1933, 1939); Caton-Thompson and Gardner (1932); Caton-Thompson (1952); Gardner (1932, 1935); Peel (1941); Sandford (1933 a,b.); Butzer and Hansen (1968) reconstructed a late Cenozoic chronology of Kurkur Oasis, SSE of Dakhla Oasis for about 400 km, but (Ball 1990) wrote the first description of tufa as fossil spring deposits; followed by (Brookes, 1993) produced a research on the geomorphology and Quaternary geology of Dakhla Oasis region.

2. Regional setting

El Gedida village is situated on the southern margin of Dakhla Oasis. Some eroded spring mounds were found separated near the sandstone crest, weathered into blocks and partly moved down slope as talus. Numerous mounds distributed in the lowland embayment are east and west of

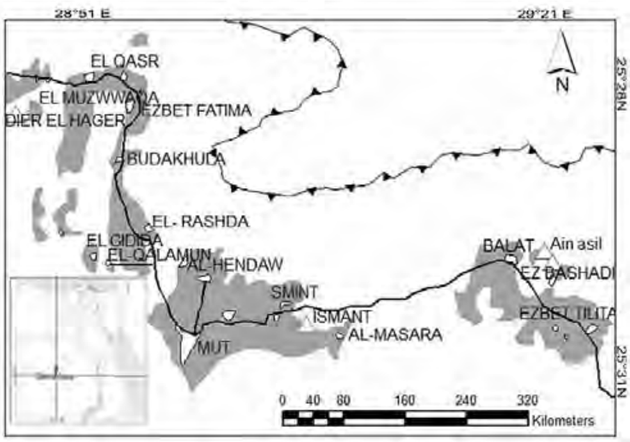

Figure 1. Settlements of the study area.

the dividing ridge related to sandstone-mudstone contact, its heights range between several meters to 20 meters, and its shapes are spherical, conical and dome shape.

2.1. Location

Dakhla Oasis is one of a chain of structural depressions in the Western Desert of Egypt, it's lactated (latitude 25.5° N, longitude 29.0° E) elongated 70 km from SE to NW, with maximum N–S dimensions of 20 km. The depression is bounded within the 140 m contour; current climate is very arid receiving a mean annual rainfall of 0.7 mm and potential evaporation of about 2,500 mm, but during the Quaternary climatic conditions across Libyan desert have oscillated between arid and humid (or pluvial), as indicated by the lacustrine, fluvial and spring-deposited sediments preserved (Smith et al. 2004) (Figs. 1, 2).

2.2. Geology

The Quseir and Dauwi formations, the local members of the Nubian Sandstone Aquifer System NSAS, are two of a series of sandstone units which extend through portions of

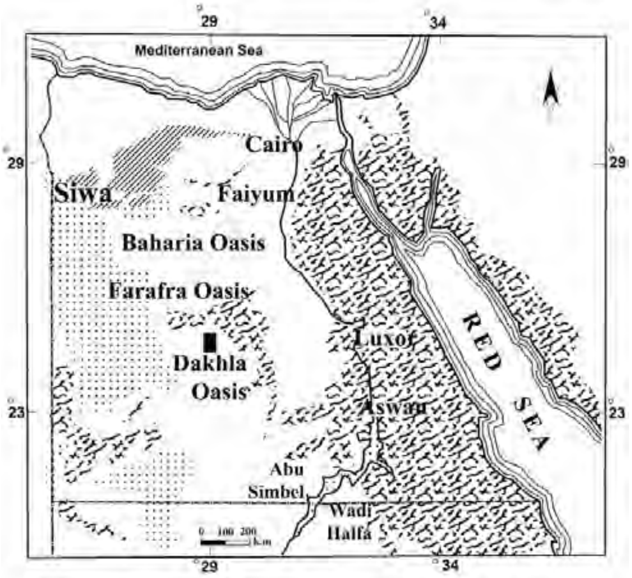

Figure 2. Location map.

Egypt, Libya, Chad, and Sudan. It consists of flaggy sandstone containing freshwater gastropods, plant, vertebrate remains and glauconitic sandstone overlain by white limestone and greyish marl with ammonites (Katherine et al. 2010; Conoco1987) (Fig. 3).

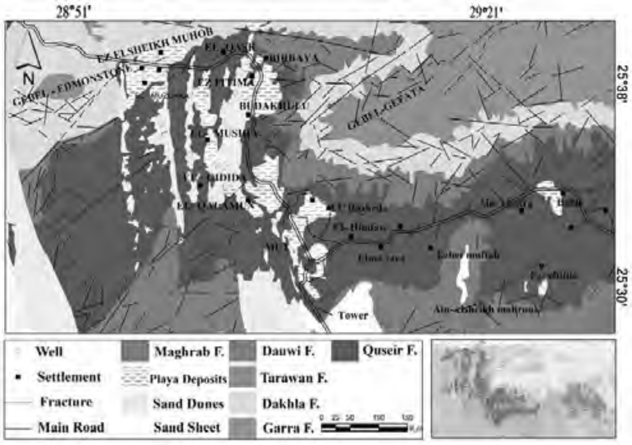

Figure 3. Geological map of northern portion of Dakhla depression (After Conoco 1987).

2.3. Geomorphic units

The major geomorphic units of the study area are the following landforms and Quaternary sediments units: (1) Libyan Plateau situated above Dakhla basin between 450–500 m asl, has a gentle dip to the north and is composed of Paleocene limestones, (2) North Dakhla Scarp and Piedmont: it is a free-face sharp escarpment with a height of approximately 200 m, cut in Dakhla formation shales, limestone and shaly colluvium. The Piedmont has bajada gravels, sand sheets and dunes, and is cut by gullies (3) Eastern and Western Dakhla basins are low lands, the western one being lower, (ranging 92–121 m asl), that are remains of ancient lakes. Ground water under both basins was used during historic times from the Old Kingdom ±2200 B.C. to later settlements (Brookes 1993). Some fossil spring mounds are seen on the paleolake shores (4) Sand dunes and Sand sheets separated on the Libyan plateau, scarp, piedmont and basin floor, moving from NW to SE (5) Sculpted surfaces (6) Fossil springs mounds on the paleolake shores (Fig. 4).

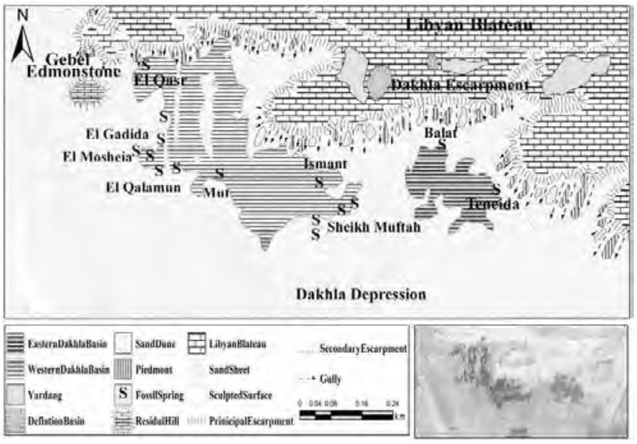

Figure 4. Geomorphological map.

2.4. Human Occupation of Dakhla Oasis during the Mid-Pleistocene

Human occupation of Dakhla depression began in the Mid-Pleistocene, some geomorphic and archaeological evidence were found in some sites, and also associated with the lakebeds and their shorelines These indicate that Mid-Pleistocene people used freshwater supplies from available springs during this time (Smith et al. 2008), (Fig. 5).

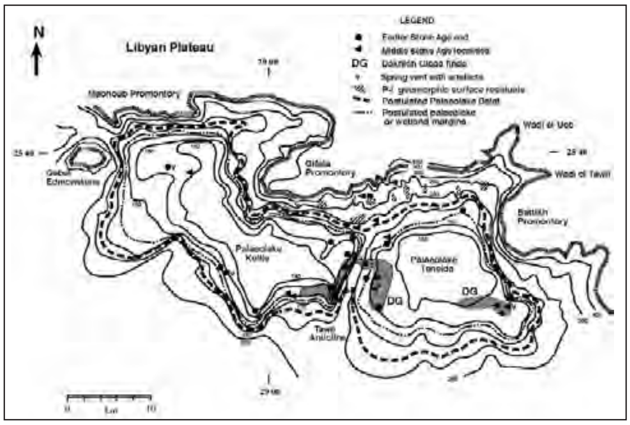

Figure 5. Paleo lakes of Dakhla depression (After Smith et al. 2008).

3. Methods

This paper depends upon the use of geomorphological, sedimentological and remote sensing methods, specially field geomorphic mapping and surveying of mound parameters, soil profile sampling and sediment analysis in addition to carbonate dating. Most mounds were digitally photographed using GPS and mapped by GIS techniques. The ^{12}C and ^{13}C and AMS dating results will help for reconstruction the Quaternary chronologies of this part of the Libyan plateau scarp in Dakhla Oasis, as well as to estimate the age of the groundwater to determine the possibility of its renewal at the present time.

4. Results

Some fossil spring mounds at the Dakhla paleo lakes shorelines observed, surveyed and its sediments were sampled in the field during 2011 and 2012. The spring mounds are approximately between 5.7–7.9 m high, 6.5–14 m diameter; the eroded mounds appear as circles and elliptical shapes (Tab. 1, Figs. 5, 7)

Figure 6. Eroded vent of fossil spring mound S El Gadida for about 3 km.

Figure 7. Fossil spring mound near El Qalamun.

4.1. Soil samples description and dating

Subsurface sediment samples were collected from each of 10 fossil spring mounds to provide information about grain size analysis (Fig. 8), age and conditions of spring flow (Tab. 1).

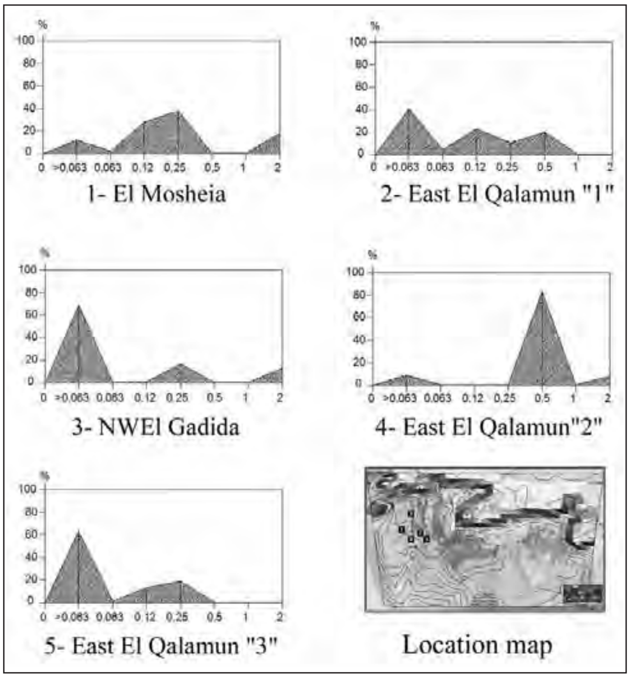

Figure 8. Grain size analysis of selected fossil spring mound's sediments.

The results of grain size analysis of the selected fossil spring mound sediments show that most of it consists of fine grain size mud or silt (> 0.63 mm), especially in E El Qalamun1, NW El Gadida and E El Qalamun3, indicating only weak paleo spring discharge. But most of the other two mounds consists of very coarse sand (1 mm), indicating of increasing paleo spring water discharge (Fig. 8).

Table 1. Characteristic and age of studied fossil spring mounds.

#	Location	Long	Lat	Level (m)	High (m)	Diameter (m)	Morphological remarks	Age (ka)
1	El Mosheia	28° 51' 152" E	25° 37' 064" N	122	6.8	13	Eroded vent	86±3
2	NWof El Gadida	28° 53' 368" E	25° 33' 499" N	112	7.3	12	Water flow	91±4
3	East of El Qalamun"1"	28° 55' 737" E	25° 31' 927" N	113	7.9	11	Paleo channel	101±4
4	East of El Qalamun"2"	28° 55' 891" E	25° 32' 017" N	112	6.9	14	Paleo channel	108±5
5	East of El Qalamun"3"	28° 55' 279" E	25° 32' 265" N	120	6.5	6.5	Paleo channel	112±7
6	SWof Sheikh Muftah	29° 07' 350" E	25° 29' 774" N	133	7.1	10.8	Eroded	111±7
7	Sheikh Muftah "2"	29° 07' 258" E	25° 29' 676" N	137	6.3	11	Paleo channel	109±6
8	Sheikh Muftah"3"	29° 06' 950" E	25° 30' 854" N	136	5.7	14	Eroded	121±9
9	Balat	29° 16' 196" E	25° 33' 371" N	130	5.8	11	Eroded	108±5
10	Tenieda	29° 20' 931" E	25° 30' 294" N	127	6.1	15	Eroded	109±6

The results of AMS dating of the fossil spring mound samples reveal two major age groups (86–101 and >108 ka) that correspond, with one exception, to the field groupings of the mounds on the paleo lakes shorelines (Eastern and Western Dakhla lakes).These results are presented in Table 1. Ten samples of the mounds were analyzed and yielded ages ranging from 86+3 ka (El Mosheia) to 109+6 ka (Tenieda).

4.2. Current ground water dating

One water sample has been collected from a current hot and acidic-gas spring at the city of Mut (well #3) in the Dakhla depression. It was analysis by AMS (Dating by Beta Analytic, Miami branch, USA: Measured age, 13C/12C, conventional age, 2 SIGMA.). The result of dating show that the measured age is 23430 ± 100 BP, meaning that the spring water source is from non-renewable fossil water due to pluvial phases of the Pleistocene, but later than the measured fossil spring mounds (86–101 and >108 ka). The dated mounds are older than the current hot spring water and formed during other pluvial phases of the Late Pleistocene.

5. Conclusions

Some fossil spring mounds found near El Gadida village, in the NW portion of Dakhla depression, they were produced by regional discharge during some pluvial phases during the Pleistocene.At least two fossil mounds that recorded the largest discharge were deposited near the El Mousheia and east El Qalamoun villages. The oldest fossil spring sediments are too old to be dated by the ^{14}C AMS method, its age being approximately 121±9 Ka BP, but the age of current hot spring at Mut city is not more 23.43 ±0.1Ka BP, meaning that it is non-renewable fossil water remaining from a pluvial phase during the Late Pleistocene.

Acknowledgements

The author would like to thank his master student Mr. Emad El Bardan and undergraduate student Mr. Mohamed Kholeif for design most figures and grain size analysis for collected samples of this paper.

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PALAEOCLIMATIC INVESTIGATION USING CAVE SPELEOTHES IN LIME DECORATED LAVA TUBE CAVES ON JEJU ISLAND, SOUTH KOREA

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Two stalagmites (YC-1 & YC-2) and one stalagmite (DC-1) of the Yongcheon and Dangcheomul lava tube caves were investigated to delineate paleoclimatic history of the Jeju Island for the past 2,000 years. High resolution carbon isotopic variations clearly show the period of the Current Warm Period (with global warming), Little Ice Age, Medieval Climate Anomaly, Dark Age Cold Period and Roman Warm Period. Detailed textural data combined with carbon isotope values clearly demonstrate the the termination of the Little Ice Age and the transitional period from LIA to Current Warm Period. Studies on fine scale variations in the isotopic composition of speleothems along with age control using U-series dating from the speleothems in Korean caves promise a great potential for the reconstruction of climate and environmental changes in East Asian monsoon system during the geologic past. Also, it is emphasized here that textural data can provided invaluable information on paleoclimatic history in addition to geochemical data.

1. Introduction

Speleothems have been used as a useful terrestrial proxy for paleoclimatic information due to several advantages such as their wide distribution, precise dating result, and continuous growth intervals for long periods of time compared to other paleoclimate archives (e.g., ice cores, loess and lake sediments) (Fleitmann and Spötl 2008). Numerous information has been revealed from all over the world (e.g., McDermott 2004), however speleothem records from northeastern Asian region including Korea have not yet been reported. Therefore, it is the objective of this study to report textural and stable isotopic records of a speleothem from South Korea to reconstruct the paleoenvironmental changes in eastern part of the Korean peninsula as well as to understand the evolutionary changes of East Asian monsoon system in northeast Asia. Also, we will make an emphasis on the use of $\delta^{13}C$ records to delineate East Asian monsoonal changes despite the fact that most previous studies for the same purpose have mainly used $\delta^{18}O$ records only.

2. Setting

2.1. Geographic setting

Located at the middle latitude (ca. 34–43 °N) in the northeast margin of Asia, Korean peninsula and its adjacent Jeju Island are strongly affected by the East Asian monsoon system with pronounced seasonal fluctuations in humidity, temperature, and atmospheric circulation. Major air masses that influence the climate of the Jeju Island are the Northern Pacific air mass, Siberian air mass, Yangtze River air mass and Okhotsk sea air mass. A low pressure cell above the central Eurasian continent during summer is associated with southwesterly winds that carry warm and moist air masses from the northwestern Pacific Ocean towards Japan and Korean peninsula. During winter seasons, reversed pressure gradients with prevailing northwesterly winds carry dry and cool air masses from the Eurasian continent towards the Pacific Ocean. When both Siberian and North Pacific highs are weak, Yangtze River and Okhotsk sea air masses control the climate of Korean peninsula during spring and autumn season. In early summer, heavy rainfall front (so-called "Jang-ma") pass through from south of the Korean peninsula to north by contact between Okhotsk sea air mass and Northern Pacific air mass. The westerly winds, blowing from west to east high up in the atmosphere at the mid-altitude, also contribute to the climate conditions in Korea. Path of the westerly jet is changed between summer and winter by 15 degree in latitude. Every year, the Korean peninsula is affected by typhoons several times between June and September. The long stretching mountain ranges have had great influence on climates in the eastern part of Korean peninsula. That is, for winter season temperature in same latitude, the eastern part of the peninsula represents higher temperature than western part. It is because the mountain ranges block cold and dry northwesterly during the winter resulting in the higher sea surface temperature (SST) of the eastern coast in Korean peninsula. The prevailling climate in the eastern part of the peninsula is characterized by a mean annual temperature of 12.9 °C with the mean annual maximum and minimum temperature of up to 17.4 and 8.9 °C, respectively, from 1971 to 2000 (Korea Meteorological Administration, http://www.kma.go.kr). The average annual precipitation in Korea is approximately 1,402 mm, and more than 3/4 of the annual precipitation takes place during the rainy season. Yongcheon and Dangcheomul caves are northeastern part of Jeju Island, which is about 100 km south of the Korean Peninsula.

2.2. Geological setting

Yongcheon lava tube was accidentally discovered when the Jeju Island power company was erecting an electric power pole in 2005 while Dangcheomul lava tube was through the roof of the cave. The ceiling discovered was accidentally discovered in 1995 by a local farmer when heavy earth-moving equipment broke and floor of both dark colored lava tubes are spectacularly adorned with various secondary white coloured speleothems such as stalactites, stalagmites, soda straws, columns, cave flowers, cave pearls, and rimstones, which is the best display in the world. Calcium and carbonate ions responsible for the formation of white carbonate speleothems were supplied by percolating rainwater from overlying carbonate sand dunes which are about a few meters to 10 m thick overlying two lava tube caves. Carbonate sand dunes were formed by transportation of carbonate beach sands nearby after the formation carbonate beach sands after sea level rose up to the present-day level about 6,000 years ago.

3. Methods

Samples were collected from two lava tube caves. To check growth patterns such as growth laminae, hiatuses, and possible diagenetic alteration, the samples were cut in half along the growth axis and polished. One half was thin-sectioned and examined with a polarizing microsope for textural description, and the other half was stained with Alizarine Red S and Feigl's solution to determine carbonate mineralogy. Subsequently, acetate peels were prepared in order to supplement thin-section examination and to examine the internal growth texture and the characteristics of growth laminae under a binocular microscope). Oxygen and carbon isotope ratios were analyzed. For each measurement, approximately 100 μg of powder samples were drilled along the growth axis of the speleothem and analyzed with an on-line, automated, carbonate preparation system (Kiel III), linked to a Finnigan MAT-253 ratio mass spectrometer. Samples were calibrated against the NBS-19 standard and are reported as per mil (‰) relative to the Vienna Pee Dee Belemnite (VPDB) standard. Duplicates were analyzed every 10 to 20 samples, all of which were replicated within 0.15‰ for oxygen and 0.20‰ for carbon. The sub-sampling interval is 1 mm. Sub-samples were prepared for ^{230}Th dating following procedures similar to those described by Edwards et al. (1987) and Dorale et al. (2004). Approximately 300 to 400 mg of calcite powder was drilled out from along the selected growth horizons. ICP-MS analyses were made at the Minnesota Isotope Laboratory on a Finnigan-MAT Element equipped with a double-focusing sector-field magnet in reversed Nier-Johnson geometry and a single MasCommultiplier. All reported ratios a reactivity ratios with 2σ errors given.

4. Results and discussion

4.1. Two stalagmites from Yongcheon Cave (YC1 & YC2)

The Yongcheon cave which contains numerous carbonate speleothems was the typical lava tube cave that probably formed between 0.2–0.4 Ma ago. A 6.8cm- and 11cm-long stalagmites (YC-1 & YC-2) were collected in its growth position in 2005 and 2008, respectively. The age of the stalagmites were determined by ^{210}Pb dating, radiocarbon dating and U/Th dating for the YC-1 and by counting growth laminae for the YC-2. Age dating revealed that the stalagmites are at least about 3,300 and 287 years old. High resolution stable isotope analyses were carried out for two stalagmites. The YC-1 clearly shows the Dark Age Cold Period, Medieval Cliamte Anomaly, Little Ice Age and Current Warm Period (including GlobalWarming). The YC-2 supports the data by the YC-1 and shows that textural data coincide well with geochemical data. Also, the YC-2 shows well defined transitional steps from the Little Ice Age to the present-day Current Warm Period (Ji et al. 2010). This study suggests that textural characteristics of speleothems can be used as a proxy to reconstruct paleoclimatic variations in addition to geochemical proxies.

4.2. A stalagmite from Dangcheomul Cave (DC-1)

Like the Yongcheon cave, Dangcheomul Cave also contains numerous carbonate speleothems. A 6.8 cm- and 11 cm-long stalagmites (YC-1 & YC-2) were collected in its growth position in 2005 and 2008, respectively. Late Holocene paleoclimate changes were inferred based on uranium-series dating, textural characteristics and geochemical compositions of the 225 mm-long DC-1 stalagmite by comparing with coeval Northern Hemispheric Δ^{14}C record by solar activity. Based on$^{2\ 30}$Th/^{234}Udating, four age data were obtained from the bottom of the stalagmite (2741±200 yrBP from 57.2 mm, 1950±117 yrBP from184 mm, 1332±57 yrBP from 215.1 mm and 589±107 yrBP from 215.1 mm). The radiocarbon age of the paleosol layer within overlying carbonates and dune is 4450±30 yrBP. Because this paleosol was developed after the deposition of carbonates in this area, the growth of stalagmite should have started to grow after 4450±30 yrBP.

The stalagmite DC-1 is composed of columnar calcite, and numerous growth laminae are present. The density of the growth laminae is indicative of the amount rainfall in this region. Therefore, five types of calcite texture can be divided based on growth rate, spacing between laminae and fluid inclusion density. Type I has the average spacing of growth laminae of 0.025 mm and the narrowest spacing indicates the slowest growth rate whereas Type V has the widest spacing of 0.42 mm indicating the fastest growth rate. It appears that the spacing of growth laminae is intimately related to the amount of rainfall together with carbon isotopic compositions. Thus, coordinated textural and geochemical data can be used for paleoclimatic reconstruction.

Stable isotope data show that carbon isotope values clearly demonstrate the climatic changes during the growth of the DC-1 stalagmite, however interpretation of oxygen isotope data is still problematic. It is especially notable that carbon isotopic compositions of the stalagmite correspond very well to Northern Hemispheric Δ^{14}C record. Carbon isotope trend coincides very excellently with sunspot activities for the past 2000 years showing the close relationship between the abrupt decrease in δ^{13}C values together with textural results and the minimal periods of solar activities (Oort minimum, Wolf minimum, Spörer minimum, Maunder minimum, and Dalton minimum). Periods of low solar activities are thought to result in dry climate. Also, carbon isotope values and Δ^{14}C records are highly fluctuating during the Little Ice Age, and this period is also characterized by more abundant abrupt climate changes under drier climate. Thus, it appears that past short-term climate changes are also well reflected from carbon isotope compositions of the stalagmite DC-1.

5. Conclusions

Paleoclimatic investigation using speleothems in natural caves in Jeju Island (South Korea) suggest that they will provide significant information on climate changes for the past 2,000 years. It is especially notable that carbon isotope compositions of speleothems are more useful to interpret paleoclimatic variations than oxygen isotope values for Korean speleothems.

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POSSIBLE EVIDENCE OF THE STAGES OF KARST DEVELOPMENT IN THE PINEGA REGION OF NORTHERN EUROPEAN RUSSIA

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Understanding of the mechanism of development of the environment can only be reached by knowing the Earth evolution history, its climate, geo environment and living nature evolution. Karst system characteristics (their structure, morphology, secondary deposits, etc) are indicators of certain geomorphologic, hydrogeological and hydro geochemical conditions and processes. Thus, karst-based and speleogenetic studies may yield useful data on the evolution of various conditions of geological environment. Unlike surface features, underground indicator features can be preserved for geologically long-lasting periods after their transition into a relict or fossil state.

The development of karst in Pinega Region was prefaced by a long period of general denudation, with karst processes active during the whole period of formation of the modern relief. The period of common denudation lasted from Mesozoic Era to middle of Neogene Period.

In the history of karst development of Pinega Region four stages can be distinguished theoretically.

The first stage started in the second part of the Neogene, when the territory resembled a peneplain with heights up to 100 m (Spiridonov 1978). In the Late Pliocene, uplift of the territory was accompanied with simultaneous regression of the Polar Basin and drainage of the relief. These changes helped the formation of a continuous net of narrow gullies and valley canyons with depths of more than 100 m. (Zarhidze et al. 1984). For the Pinega Region this stage of continental development probably was the most favorable for widespread large-scale karstification of the territory. The first stage lasted about 1.5 million years and ended in the middle of early Pleistocene.

The second stage of karstogenesis was active in the Middle Pleistocene age in conditions of constant change between warm and cold periods. The stage began with Lower Pleistocene lowering of territory and filling of valley canyons with lake-alluvial deposits (Lastochkin and Safonov 1984). Due to influence of three continental glaciations and the overall low character of the relief, karst processes were operating, on the whole, in unfavorable conditions. Still, due to degradation by glaciers and the effects of isostatic rebound, separate groups of large landforms and subterranean karst voids may have been formed intensively. The second stage lasted around 300 thousand years, 170 thousand years being glacier-free with relief developing in conditions of increasing erosion-denudation dissection.

The third stage of karstogenesis comprised the Late Pleistocene and lasted for 110 thousand years. It included the Mikulin Transgression – 30 kyears, cold Early and Middle Valdai – 69 kyears, Late Valdai continental glaciations – 11 kyears. The beginning of the stage was a climatic optimum with encroachment of the boreal sea (Devjatova et al., 1983). The orographic front of the relief was similar to modern. A river net was also formed that was close to the modern pattern of valleys with large and small rivers. The "Mikulin Sea" was shallow, its waters covering the Nijnepinskaya and Verhnekuloiskaya lowlands. In the south-east part of the Belomor-Kuloi plateau on the left bank of Pinega River an island of dry-land existed. The Sea cut inside it with narrow coves and extended up the river valleys.

The land was under comparatively active erosion dissection, of surface and subterranean karst. Most favorable for karstification was the higher part of Belomor-Kuloi plateau. Here, apart from typical dolines and sinkholes, a net of large depressions formed that has been preserved also in the modern relief.

During Mikulin time the creation of caves at several levels inpure gypsum beds was ongoing.

After regression of the Mikulin Sea (in the Valdai Period) most of the Pinega Region became dry land (Devjatova 1982). Climatic conditions became worse, resulting in a slowing down of erosional and and karst processes. Still, due to the long period of karstification and a low-amplitude uplift of the western part of territory overall extent of karstification in the Pinega Region was greater than in modern times.

During Early and Middle Valdai a network of valleys s was formed and karstified, a widely spread relief rich in dolines and other depressions. In the depths of the massifs speleological water-flow systems were formed.

During the Late Valdai glaciations surface karstification was halted until the glacier melted and disaggregated into separate tongues and masses of dead ice. The continental ice partly receded 13,000 years ago, and fully disappeared 9,800 years ago (Malkov 1983). By melting of remnants of the glacier cover, valley drainage of melt water, formation of dammed pools, conditions for intensive surface and subterranean karstification came into being. In all karst areas of the Pinega Region the surface karst has clear traces of inherited development from late-glaciation time. Parallel to new landforms, existing depressions were also widened, deepened and re-formed. In that time some of the old depressions were filled by sediments, but preserved on above dissected karstified floors. Other were opened and added to the valley relief. Many small karst voids were created in a covered or semi-covered state.

In this connection three morphogenetic specific features of Pinega karst may be noted. The first feature has to do with the external dynamics of the glaciations, the development of the Severodvinsky-Pinejsky and Kuloi glacier tongues, whose maximum extents were separated by a period of 10,000 years. In the middle section of the River Sotka a nunatak survived, not covered by the continental ice. In its reaches weak karst and erosion-denudation processes did not stop even in the most vigorous phases of the glaciations (Malkov et al. 1983, Structure and dynamics of natural components…, 2000).

The second specific feature of karstogenesis was determined by glacier inner dynamics. In its peripheral zone subglacial grooves and valleys were cut into the roofs of karst voids. The valleys and adjacent strips of the relief have clear signs of kartification before the collapse of glacier cover (Structure and dynamics of natural…, 2000).

The third feature of this karstogenesis was segmented topographyconsisting of gypsum rock covered by crust of dead ice. By their melting and karstification of the facture-rich basement the formation of the unique *shelopnyak* fields progressed.

Due to its abundant subglacial and melt output the Late Valdai glaciation had a strong effect on the subterranean karstification. This output, flowing through existing and newly made nets of karst denudation valleys, ensured concentrated water sinks and intensive growth of existing caves (Malkov et al. 1983; Structure and dynamics…, 2000).

Some caves under glacial forces and side cutting were exhumed and destroyed above different levels. Other caves ceased their growth after melting of the ice. A number of large caves developed with maximum discharges and interconnections between several gypsometric levels. Formation of most caves went on under pressure conditions (phreatic). This was conditioned both by subglacial position of the depressions, as well as by earth crustal depression beneath the spreading continental glaciation.

The activity of glacier pressure caused an uneven lowering of massifs, extension of tectonic cracks in carbonate sequences into sulfate layers and opening of fractures inside the sulphate mass. Under the influence of isostatic forces karst waters rose from undelyngcarbonates into the sulfate masses, together with dislocation of levels of flow upwards inside the cave blocks.

Thus, caves existed where sculptural relief was created out of tectonic fracturing and opening. Elements of the model of hypogene speleogenesis were first scientifically proved and thoroughly studied in the cave labyrinths of Podolje (Klimchuk 1990). The rapid development of Late Valdai caves lasted until regional degradation of the glaciers and isostatic rebound of the terrain which caused a reformation of drainage system and increasing drying out of the karst voids.

Thus, the third stage was most important for understanding the principles of development of surface and subterranean karst in the Pinega Region.

The fourth period of karstogenesis belongs to the Holocene. During this period following changes took place: degradation of the zone of long-period glaciation, formation of river outlets, entrenching of the erosion network, destruction of post-glacial lakes, development of forest cover, re-establishment of the rhythmic sequence of warm and cold seasons. The modern landscape and climatic conditions were fully established over two thousand years ago.

The Pinega Region in the beginning of Holocene (10,300 years ago) was a place of different natural conditions. The western part of territory was totally free from continental ice. Here was preserved a zone of island permafrost with large lake reservoirs in the watershed areas. In the eastern part, there was melting of remaining portions of the Kuloi Ice Cap (Malkov et al. 1983). With respect to drainage in the gypsumthe territory was lower than it is today. There was a remaining lake-glacier basin in the Kuloi River and Pinega River valleys that drained to the north into a freshwater bay of Early Holocene Sea (Stankovsky et al. 1980). Soon the basin was degraded and the sea extended to the south and occupied the basin. The duration of of the early basin and lake reservoir was about 1,000–1,300 years. In this time, due to ingression of sea the lower parts of valleys of the Polta, Kelda, Sotka, Soyana, Siya, Belaya rivers, and also karst-denuded valleys in areas of Kulogora, Vonga, Golubino widened. Caves located in the coastal stripexperienced development in a flooded regime with changing water levels.

The Boreal and Atlantic periods of the Holocene were most favorable for karstification, with rising air temperatures and increasing precipitation (Hotinsky 1977). Because of rising of the territory and entrenchment of river valleys down to the level of modern floodplains, the base levels of erosion lowered and simultaneously karst and erosion processes activated in all elements of surface and subterranean systems. Parallel to this, lakes lost a part of their water in depressions and then began to form swamps.

An interesting fature is the process of deposition of freshwater carbonate silts (sheetrock or marl) in karst lakes adjacent to the regional Belomor-Kuloi terrace. The absolute age of sheetrock in Lake Rodnichnoje (between Rivers Sotka and Kelda) was dated from 8,700± 120 years to 6,950±130 years (Gataullin and Kokarovzev 1986).

In the Late Holocene (4,500 years ago) climatic conditions became worse, and the natural landscape zones have moved to the south (Problems of geology and history, 1982). Then short-time warm and cold periods were followed by overall drying of the climate. Most significant cold spell were detected 2,100–2,000 and 700–600 years ago. A noticeable warming occurred 1,500 years ago. Due to of the drier climate and periodic strengthening of seasonal freezing processes, the relative tempo of karsitfication will have slowed down, too.

Conclusion

As potential artefacts which enable to obtain the evidence of the stage, morphologic development and typical dates of the karst formation in the region, carbonate flowstones in the modern upper cave levels and paleo-aggregate material (ancient cave alluvium) to be found in the upper karst channels that mark the beginning of karst processes in the Pinega massif should be investigated.

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THE 5.3 KA BP EXTREME / WEAKENING EVENT IN THE ASIAN MONSOON DURING THE MIDDLE HOLOCENE; A RECORD IN A STALAGMITE FROM WANXIANG CAVE, WESTERN CHINA LOESS PLATEAU

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Based on high-precision ^{230}Th dating method and high-resolution oxygen isotope ($\delta^{18}O$) data from stalagmite WXB07-4 from Wanxiang Cave, Wudu, Gansu, China, we established a 9-years-resolution East-Asian Summer Monsoon (EASM) record covering the 5.3 ka BP event in the EASM fringe. We characterized in detail the timing, structure and internal variability of the event. In our record, the 5.3 Ka BP event lasts approximately 575 years, characterized by a positive $\delta^{18}O$ excursion of 1.6‰. The event shows a "V" shape form centered at about 5,368 year BP, as inferred from the $\delta^{18}O$ record. Comparing with other stalagmite records from the Asian Monsoon region, it appears that all have recorded the 5.3 Ka BP event, have a similar pattern of changes and within dating errors happened at almost the same time, which indicates that this EASM event was essentially simultaneous. The possible trigger mechanism and the impact on the ancient civilization and culture of the 5.3 ka BP event in the region are discussed. Results from Greenland ice cores and sediments from the Atlantic Ocean are consistent with this event. During 5,000 to 5,500 year BP, the Northern Hemisphere temperature recorded by ice $\delta^{18}O$ was reduced e ice-rafted debris in the Northern Atlantic showed a remarkable increase, the AMOC slowed down, and the ITCZ moved southward.

AQUEOUS ISOTOPE ANALYSES IN TWO LITTORAL CAVES IN MALLORCA, SPAIN: PRELIMINARY RESULTS

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Mallorca's phreatic overgrowths on speleothems (POS) are widely used to trace paleo sea-level in the Western Mediterranean, and are also used in paleoclimate and tectonic studies. These encrustations accumulate on pre-existing carbonate supports (cave walls or submerged vadose speleothems) in partially flooded littoral cave passages that receive both meteoric and marine input. The preliminary stable isotope results from this study indicate that CO_2 degassing from the water surface allows precipitation of POS. Consideration of local precipitation will allow the construction of a local meteoric water line (LMWL) for Mallorca and the calculation of the deuterium excess, and therefore, the determination of the controls on δD and $\delta^{18}O$ in rainfall.

1. Introduction

Phreatic overgrowths on speleothems (POS), carbonate encrustations on pre-existing carbonate supports, form at the air-water interface in brackish phreatic pools within the littoral (coastal) caves of Mallorca, Spain. In these caves, the water table is coincident with sea level, thus making these encrustations desirable proxies for sea level reconstruction. POS are widespread in Mallorca and to a lesser extent in Sardinia (Tuccimei et al. 2007), Bermuda (Harmon et al. 1978), the Bahamas (Gascoyne et al. 1979), Nansei Islands, Japan (Urushibara-Yoshino 2003), and Christmas Island, Australia (Grimes 2001). These locations all have low tidal fluctuations and a specific geochemical environment that is conducive to the precipitation of POS.

Both calcite and aragonite POS are observed in Mallorca's littoral caves. Some caves contain POS bands of both minerals, where bands at different elevations correspond to different sea level elevations. The mineralogy of a POS band does not change for any given sea level stand, suggesting a relatively stable geochemical environment during each sea level stand.

Studying the variable mineralogy of a horizontal core of POS and vadose flowstone from Sa Bassa Blanca Cave (Mallorca), Csoma et al. (2006) identified the proximity of the POS to the water table, and therefore the ability of CO_2 to degass from the solution, as the major control on their precipitation. Hanor (1978) simulated the precipitation of beachrock cements in St. Croix by mixing variable proportions of groundwater, Caribbean Sea water and distilled water. Degassing of CO_2 was so significant that it overcame mixing corrosion (Bögli 1964) and formed carbonate precipitates within 12–36 hours in solutions of groundwater and seawater, and groundwater and distilled water. The rate of CO_2 degassing from the littoral cave phreatic pools may, in part, contribute to the variable mineralogy observed in Mallorca's POS. This can be quantified by the isotopic values of the phreatic pool water to determine water sources, interactions, and degassing of CO_2/equilibration with the cave atmosphere.

2. Study area

Mallorca is the largest island of the Balearic Archipelago, located in the Western Mediterranean (Fig. 1). Two mountain ranges, Serres de Tramuntana and Serres de Llevant, are oriented NE-SW and run along the northwest and southeast coasts of Mallorca respectively. Es Pla, the central, lowland region of the island, is a down-dropped graben resulting from extensional forces during the Miocene. The mountains are largely comprised of Mesozoic to Lower Miocene folded limestones but also marls, clays, and volcanic materials. The Migjorn region is comprised of Upper Miocene carbonates formed on the coastal lowlands, and is the location of both of the study caves (Fornós et al. 2002).

The current POS band in Cova des Pas de Vallgornera (Vallgornera) is aragonite, whereas in Coves del Drac (Drac) it is calcite.

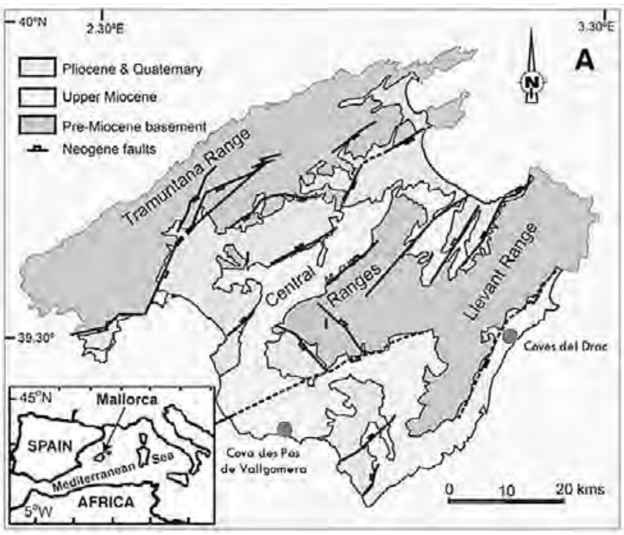

Figure 1. Study caves on the island of Mallorca (modified from Dorale et al. 2010).

Vallgornera was discovered near the village of Llucmajor in 1968, when a now-abandoned hotel expanded its septic system. Known as Mallorca's largest cave with over 70,000 m of mapped passage (Merino pers. comm.), Vallgornera formed by three distinct speleogenetic processes: saltwater/freshwater mixing dissolution (Gràcia et al. 2009), epigenetic, and geothermal hypogenic (Ginés et al. 2009; Merino et al. 2009). Vallgornera's morphology is strongly controlled by lithology: a maze pattern is observed in the reef front facies, while a joint-controlled pattern is observed in the outer lagoon facies. The overlying land use is moderately urbanized, with scrub vegetation. Vallgornera is a Natura 2000 protected site (European Council Directive 92/43/EEC).

Drac is located in the village of Porto Cristo. The land above the cave is developed with the infrastructure to support the cave's million annual tourists, which includes cafes, small shops and parking lots surrounded by scrub vegetation. From a speleogenetic point of view, Drac is a typical mixing-zone cave, reflected by its large, randomly oriented rooms that are connected by small breakdown passages (Ginés and Ginés 2007). The cave is developed in upper Miocene reef carbonates and is over 2,300 m in length (Fornós et al. 2012).

3. Methods

In this ongoing study, water samples are collected from depths of approximately -0.2 and -1 m in each cave, during monthly site visits since December 2011.

Samples were collected at 0.5 m intervals throughout the water column in each study pool during the April 2012 site visit. The depth of the each study pool limited the depth of each profile: the deepest reading in Vallgornera was -2.5 m; the deepest reading in Drac was -2.9 m.

δD, $\delta^{13}C$, $\delta^{18}O$, and dissolved inorganic carbon (DIC) were analyzed at the University of South Florida Department of Geology Stable Isotope Lab using a Thermo Fisher Scientific (Finnigan) Delta V Isotope Ratio Mass Spectrometer.

4. Preliminary results and discussion

The preliminary $\delta^{18}O$ data show distinct values for samples from each cave, and distinct values for depths less than and greater than -0.5 m (Table 1). Overall, Vallgornera has more negative $\delta^{18}O$ values than Drac, and in both caves, more negative $\delta^{18}O$ values are observed in the upper 0.5 m.

Table 1. Average stable isotope values for each type of sample, where V and D indicates Vallgornera and Drac, respectively. $\delta^{13}C$ and DIC were not analyzed in the precipitation samples.

Sample	δD (SMOW)	$\delta^{18}O$ (SMOW)	$\delta^{13}C$ (PDB)	DIC (mg/L)
Precipitation	-20.9‰	-3.4‰	–	–
V <0.5 m	-33.7‰	-4.5‰	-5.0‰	30.2
V >0.5 m	-38.2‰	-4.2‰	-9.5‰	59.5
D <0.5 m	-30.9‰	-4.0‰	-4.0‰	32.4
D >0.5 m	-28.7‰	-3.8‰	-11.2‰	92.1

A strong positive correlation exists between $\delta^{18}O$ and salinity in the cave water samples, Mediterranean Sea water (Pierre 1999), and Alcúdia precipitation (Fig. 2), defining a mixing line between marine and freshwater endmembers. The difference between the Vallgornera mixing line and that of Drac may indicate small differences in the fresh-marine water mixing ratio at each cave (supported by the differences in the salinity data). Precipitation samples (n = 2) have significantly more positive $\delta^{18}O$ values compared to the projected intercept of the freshwater endmember for each cave (mixing line y-intercepts). This implies that the fresh groundwater has a significantly more negative $\delta^{18}O$ value than the precipitation samples.

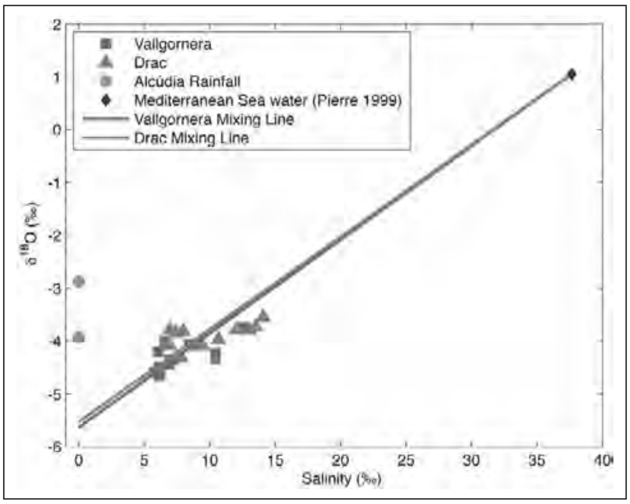

Figure 2. $\delta^{18}O$ (‰, SMOW) for samples collected from Drac and Vallgornera, as well as precipitation samples from Alcúdia, plotted versus salinity. The Mediterranean Sea water value is from Pierre (1999).

δD values display a similar pattern to that of $\delta^{18}O$, with more negative values observed in Drac than Vallgornera (Table 1). However, a consistent trend with depth is not observed between the two caves. δD and $\delta^{18}O$ values of precipitation are more positive than the values observed in both Vallgornera and Drac. More samples of precipitation and fresh groundwater are needed to construct a local meteoric water line (LMWL) for Mallorca, and to calculate the deuterium excess value. The latter parameter may reveal changing moisture sources in the region.

Distinct $\delta^{13}C$ and DIC ranges are observed in both Vallgornera and Drac, with more positive $\delta^{13}C$ values and lower concentrations of DIC observed in samples from less than -0.5 m in depth (Table 1). To exclude the effect of co-variation of salinity-DIC, the DIC value was normalized to salinity (Fig. 3). The data from each cave plot together, with the exception of the shallowest (0.0 m) samples from Drac, which are the most positive in the dataset. The sample collected from -0.4 m in Drac has a $\delta^{13}C$ value and DIC more consistent with the deeper values in Drac; this suggests that CO_2 degassing has only occurred in the uppermost layer (less than 0.4 m) in Drac.

Water profiles indicate differences between both study caves as well as stratification in each water column (Fig. 4). *δD* values show a consistent offset, with Drac samples more positive than Vallgornera at all depths (Fig. 4A). $\delta^{13}C$ values are more positive at all depths in Vallgornera, with the exception of the surface sample (Fig. 4B). The Vallgornera surface sample $\delta^{13}C$ value is more negative than that of Drac; the Drac surface $\delta^{13}C$ sample is the most positive value between both profiles. $\delta^{18}O$ values generally become more positive with depth in both caves

(Fig. 4C). The concentration of DIC is generally higher in Drac than in Vallgornera, but the surface value in Drac is lower, making the surface reading in both caves very similar (Fig. 4D).

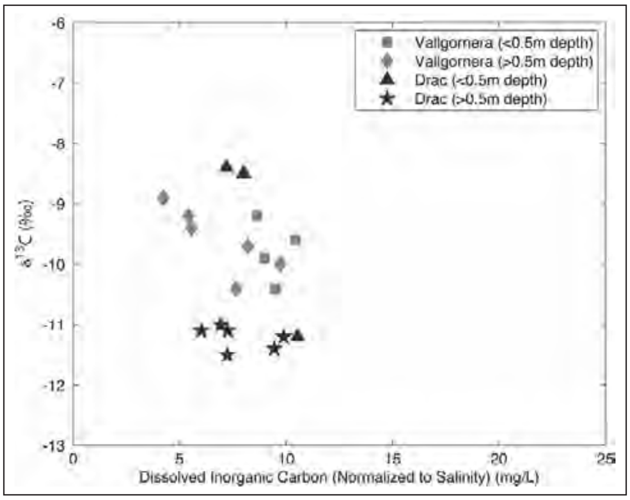

Figure 3. $\delta^{13}C$ (‰, PDB) and DIC (mg/L, normalized to salinity) for sample depths less than and greater than -0.5 m in Drac and Vallgornera.

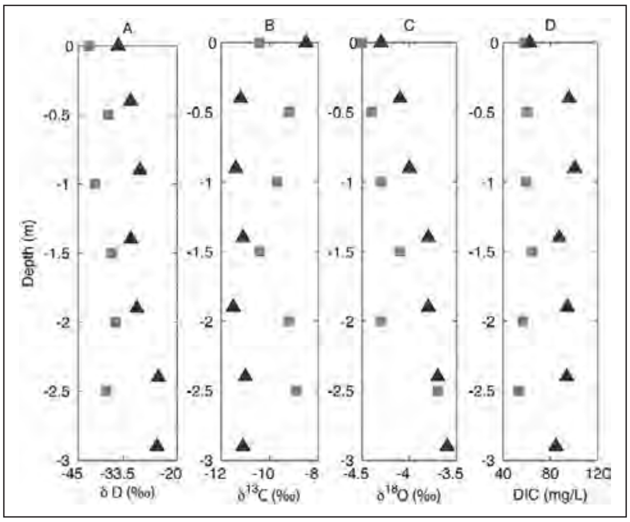

Figure 4. Water column profiles (April 2012) extending to a depth of -2.5 m in Vallgornera and -2.9 m in Drac. A: δD (‰, SMOW). B: $\delta^{13}C$ (‰, PDB). C: $\delta^{18}O$ (‰, SMOW). D: DIC (mg/L).

More positive $\delta^{13}C$ values and lower DIC concentrations at the surface of both study pools suggest degassing of CO_2 to the cave atmosphere and therefore, conditions conducive to supersaturation of carbonate minerals, and precipitation of POS. The more negative $\delta^{13}C$ values observed deeper in each pool may preserve the $\delta^{13}C$ signal of the water before degassing occurs; which may be controlled by contributions of biogenic CO_2 from the soil overlying the cave and/or microorganisims in the cave water.

5. Future directions

The preliminary data presented in this paper were collected between December 2011 and April 2012. More samples will be collected from each study cave, and more rainfall and Mediterranean Sea samples will also be analyzed. Fresh groundwater samples will also be collected to constrain the freshwater endmember for Mallorcan groundwater. Collection of more samples will allow for the construction of a LMWL for Mallorca, as well as calculation of the deuterium excess. Comparing the isotopic compositions of water (phreatic and vadose) within each cave to currently precipitating phreatic overgrowths and vadose speleothem samples, respectively, will answer questions related to the suitability of POS laminae for paleoclimate studies, mostly with regard to considerations about kinetic effects during precipitation, which are anticipated if CO_2 degassing is so rapid that the precipitate cannot equilibrate with the parent solution.

Acknowledgments

This material is based upon work supported by the National Science Foundation under grant AGS-1103108 to BPO, the MICINN project, CGL2010-18616 from the Spanish Government to JJF, and a GSA Graduate Student Research Grant and a National Speleological Society Research Grant to LMB. We express gratitude to the administration of the Coves del Drac (Porto Cristo), who facilitates our research in the cave.

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RADON MEASUREMENTS IN AUSTRIAN AND SLOVENIAN CAVES WITH AN ALPHAGUARD INSTRUMENT

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In September 2012, radon and CO_2 measurements were carried out in Lipiška jama and Mačkovica in Slovenia and Austria's Dachstein-Mammuthöhle. The AlphaGUARD proved to be a suitable device for long- and short-term radon measurements in caves. Values ranged from undetectable in some locations of Dachstein-Mammuthöhle to 4,920 ± 549 Bq m^{-3} in Mačkovica, presumably correlating with ventilation, material and size of the caves. A long-term measurement in Mačkovica revealed no diurnal variation pattern. In the old parts of Dachstein-Mammuthöhle there is no threat for workers or tourists from radiation.

1. Introduction

Radon measurements in caves can serve a variety of purposes. Radon is a tracer for cave climate and air circulation and important for the recognition of a potential thread for workers, speleologists or tourists.

There are numerous parameters affecting the variation of radon concentration in cave air. They are not easy to identify. Basically the radon concentration is determined by the release of radon from rocks, cave sediments and water, diffusive and advective transport processes in the cave and mixing with ambient atmospheric air.

^{222}Rn is a naturally occurring radioactive daughter product of ^{226}Ra from the ^{238}U decay chain. Thus, in a closed system, the radon content in soil gas is depending on the soil or rock type and its ^{226}Ra concentration which is directly related to the ^{238}U concentration.

The emanation coefficient of radon is dependent on different factors such as the mineralogy of the material, its density and porosity, its grain-size and -shape, the spatial occurrence of radium in the mineral grains (Adler and Perrier 2008) and moisture (e.g., Washington and Rose 1990). Uranium bearing minerals are for example uraninite, zircone, apatite, monazite or zeolite. Moreover, uranium occurs on alterated surfaces of iron and sulphur bearing minerals. Within weathered rocks, weathering products e.g., iron- or manganese-oxides or -hydroxides or clay minerals of alterated feldspar or micro-cracks filled with carbonate or zeolithe can be enriched with uranium (Kemski et al. 1996, Schumann and Gundersen 1996; Wiegand 2001). Grain coatings or cements can act as complexing agents or sorb uranium or radium (Gundersen and Schumann 1989). Organic matter is also commonly enriched with uranium. The average specific ^{238}U activity in carbonate is 23 Bq kg^{-1} and soils have average specific ^{238}U activities of 40 Bq kg^{-1} (Kemski et al. 1996).

Bossus (1984) reported that the radon emanation coefficient increases linearly with increasing specific surface area of the material. Additionally, nanopores, and micro-scopic fractures or fissures can provide pathways for radon emanation (Schumann and Gundersen 1996).

Beside bedrock material and cave-sinter, the cave environment has different sedimentary facies. Near the entrance it is often composed of fine sediments which were transported from the vicinity of the cave by wind and water, coarser clasts which were transported by slope processes, or guano. The areas proximal to the entrance can be subject to surface erosion, weathering or biochemical alteration. Further inside the cave, sediments can be composed of fluvial gravels and sands or fine-grained flood deposits which can be intercalated by speleothems, or colluvial material deposited under vadose conditions.

Radon is a noble gas and therefore chemically inert. Being a heavy gas, it displays a poor intrinsic mobility with diffusion coefficients ranging from of 2.7×10^{-6} m² s^{-1} – 6×10^{-8} m²s^{-1} (Tanner 1964). As ^{222}Rn has a half-life of only 3.82 days, its diffusivity is limited and dependent on the porosity and moisture of the material.

The radon concentration in cave air is strongly dependent on the air circulation and thus the mixing of cave air with ambient atmospheric air. The latter has a negligible radon concentration of < 10 Bq m^{-3}. It has been observed before that radon levels increase with increasing distance from the cave entrance even in smaller caves (Gillmore et al. 2002). Main causes for ventilation are pressure and temperature differences, the drag force from changes of water levels, or harmonic movements which can occur due to compression of air. Changes in the ventilation regime can be caused by changes in pressure and the difference of outside and inside air temperatures. These changes can be seasonal, diurnal or affected by rapid changes of weather conditions. In Postojnska jama it was observed that radon levels are higher in summer than in winter (Kobal et al. 1988). A study by Kies and Massen (1997) about the Moestroff Cave revealed that in summer, radon concentrations were about two times higher in the afternoon than in the morning. However all the processes mentioned above are governed by the specific shape of the cave.

Radon gas accumulates in spaces with impeded air exchange and can reach radioactive equilibrium with the source material if locked in a closed system. Cracks and fissures in caves not only have an influence on ventilation but are a potential source for enhanced migration of radon from other areas. Radon can easily be dissolved in groundwater (Choubey et al. 2003). Being a surface active element, it can be adsorbed at the gas-water interface of a CO_2-micro-bubble and therewith transported e.g., within groundwater (Peirson et al. 1974).

Vaupoti (2010) showed that radon levels in Slovenian show caves vary from cave to cave and from place to place in the same cave. Mean radon levels in the air of Slovenian tourist caves which were obtained with alpha scintillation cells range from 281 Bq m^{-3} (STD ± 362) for the lowest values to 1,118 Bq m^{-3} (STD ± 1583) for the highest values (Kobal et al. 1986). The highest value was measured in Tabor Caves at 5,920 Bq m^{-3} (Kobal et al. 1986). In Slovenian caves not open for public the values range from less than 210 to 7,220 Bq m^{-3} (Vaupoti, 2010). Mean values range from 841 Bq m^{-3} (STD ± 1471) for the lowest measurements to 2,575 Bq m^{-3} (STD ± 2132) for the highest radon concentrations (Vaupoti, 2010).

Jovanovic (1996) showed that radon concentrations in caves deep below the surface showed nearly no variation throughout the year. This is most likely the case for the 230 m deep Lipiška jama. Jovanovic (1996) measured radon concentrations of 310 ± 30 Bq m^{-3} in December, 310 ±30 Bq m^{-3} in March, 1450 ± 90 Bq m^{-3} in July and 1,300 ±80 Bq m^{-3} in September. However, the measuring sites within the cave are not reported but are less than 50 m underground and before the passage "Labirint".

2. Study objects – the caves

Measurements were carried out in September 2012 in Dachstein-Mammuthöhle (Austria) and Mačkovica and Lipiška jama (Slovenia) (Fig. 1–3).

The Dachstein-Mammuthöhle (DMH) formed in the Upper Triassic Dachstein Limestone near Obertraun. The new eastern entrance is at 1,368 m a.s.l. The cave has a total length of 65 km and an elevation difference of 1,208 m. It is made up of older parts which were generated under pheratic conditions and younger parts generated under vadose streams. The measurements were carried out in the old parts of the cave, a mixture of very large hallways, small labyrinths and shafts. Proximal to the entrance autochthonous boulders and breakdown material is frequently found. In the "Kluftgang", boulders are covered with mangenes-oxides. Cave loam is present almost in all parts of the cave which was visited for this study. Cave-sinter, particularly recently generated, is rare. There is permanent ice in the "Feenpalast". Strong ventilation can be felt almost everywhere in the cave. In the younger parts there are many shafts and canyons, many with flowing water. Relative humidity ranged from 60 % near the entrance to 95 % at the end of the "Lehmhalle". The temperature ranged from -1 to 2 °C.

Mačkovica is situated in Lower Cretaceous limestone at the eastern border of Planina Polje near Laze. It is 670 m long and 44 m deep. The entrance is inside a sinkhole at 483 m a.s.l. The cave is predominantly dry but holds a lake with a siphon at its north-western end. The lake level can vary by about 10 m (Habič, 1992). The temperature was 9 °C and relative air humidity 99 %.

Lipiška jama is located between Lipica and Sežana, 9 km NE of Triest. The main entrance, a 14 m shaft, is at an altitude of 397 m a.s.l. The cave is 1,395 m long and 250 m deep and was formed in Upper Cretaceous limestone. In the entrance chamber there are gravel and soil deposits. From there to the "Labirint", the cave features large sinter formations that are white, red or brown in colour. Before the entrance to the "Labirint" there are also fine sediments. The "Labirint" is a very shallow and winding passage. The "Kozinski rov" has less sinter but more loam than the passages before. Scallops and anastomoses at the ceiling suggest a cave formation in phreatic conditions and occasional flooding. A connection of the cave with the underlying water system is presumed. Digging has revealed the "Dvorana Upanja". Relative humidity was between 40 % near the entrance and 80 % in the lowest parts of the cave. The temperature was 11–12 °C.

3. Methods

The AlphaGUARD PQ 2000 PRO radon device from Genitron Instruments GmbH is a continuous active radon sampling sensor with a pulse-counting ionisation chamber which detects radon via alpha spectroscopy. It has a linear response range from 2 Bq m^{-3} to 200 kBq m^{-3}. As the air flows through the ionisation chamber, alpha particles from the radioactive decay of ^{222}Rn, ^{218}Po und ^{214}Po ionize the gas inside, producing a detectable electric current. ^{222}Rn and ^{220}Rn are identified through their respective energies of 5.49 MeV and 5.29 MeV. The AlphaGUARD cannot distinguish between ^{222}Rn and ^{220}Rn (thoron-radioactive daughter product of ^{232}Th), as both energies are similar. The signal generated from the alpha detection is converted to a digital output. Via the DataEXPERT database software, the data were downloaded on a PC and configured into the MSExcel sheet.

The measurement setup consists of an AlphaPUMP and the AlphaGUARD PQ 2000 PRO (both from Genitron Instruments GmbH). Cave air was pumped into the ionisation chamber of the AlphaGUARD. A completely filled 2 l plastic bag which was attached to the other end of the AlphaGUARD indicated that the ionisation chamber was completely filled with cave air. In order to determine only radon, the ionisation chamber was kept closed for a minimum of 11 minutes after it was filled, by connecting the hoses with each other to produce a closed cycle. After five minutes, approx. five half-lives of thoron have passed and only 3 % of its original activity concentration is left. The measurements were run at least another six minutes to generate more values. For the long-term measurement, the hoses were taken off and the AlphaGUARD was put into diffusive mode in which every hour one average value is documented. The AlphaGUARD measures and records simultaneously atmospheric pressure, temperature and humidity with integrated sensors.

CO_2 concentration in the cave air was measured with a handheld DRÄGER Multi Gas Detector. With a manually operated bellows pump, a calibrated 100 ml air sample per stroke is drawn through short-term Dräger Tubes. The indicator inside the tube displays the CO_2 concentration.

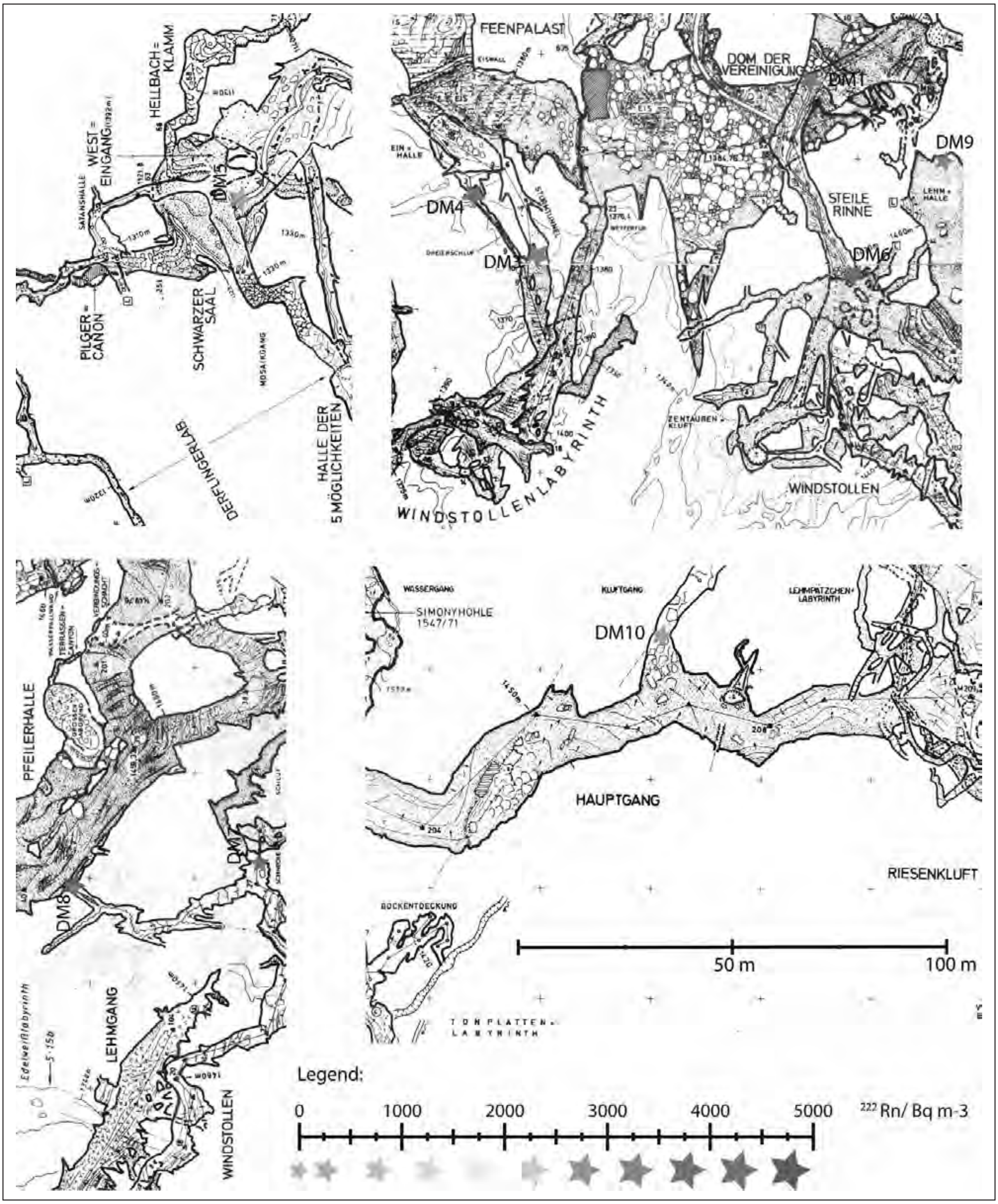

Figure 1. Plan of Dachstein-Mammuthöhle with the measurement locations (Stummer 1980).

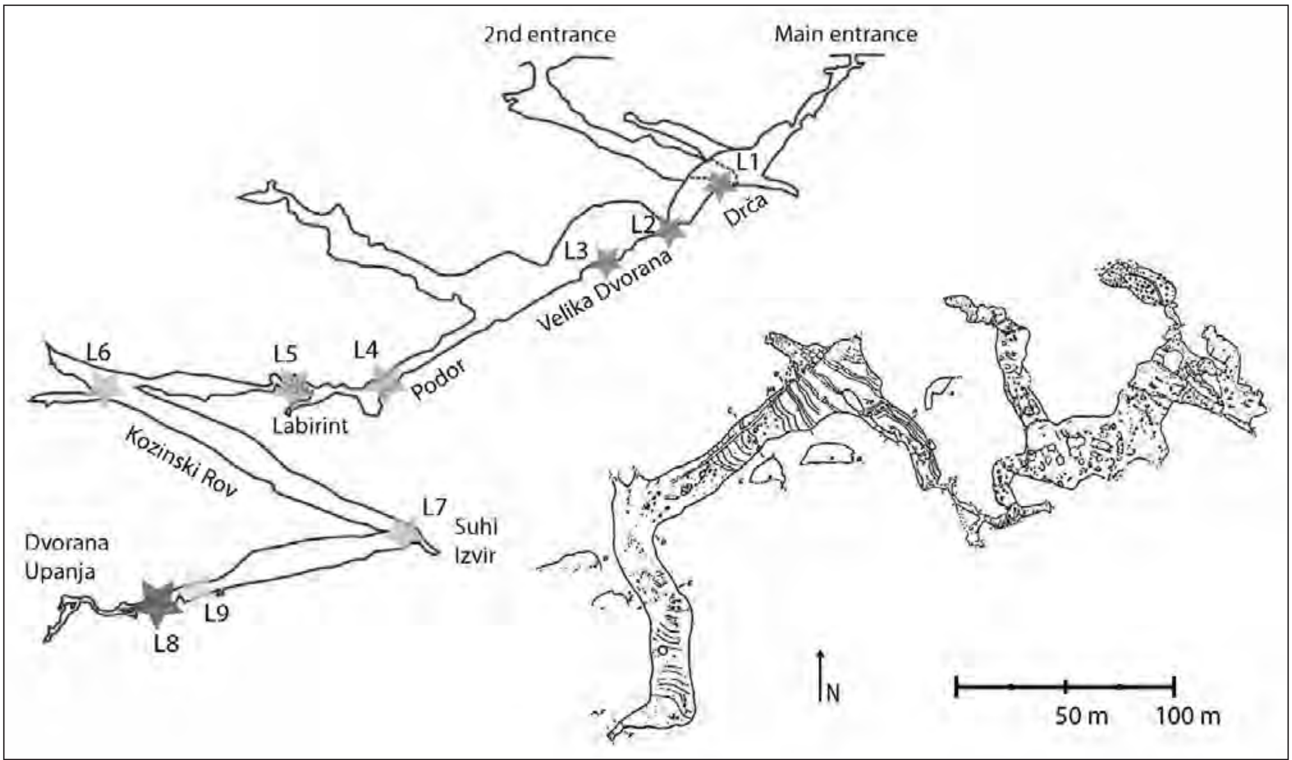

Figure 2. Plan of Lipiška jama with measurement locations (longitudinal cross-section: Jakofčič 2006; ground plan: Dimnice 1977); legend see Fig. 1.

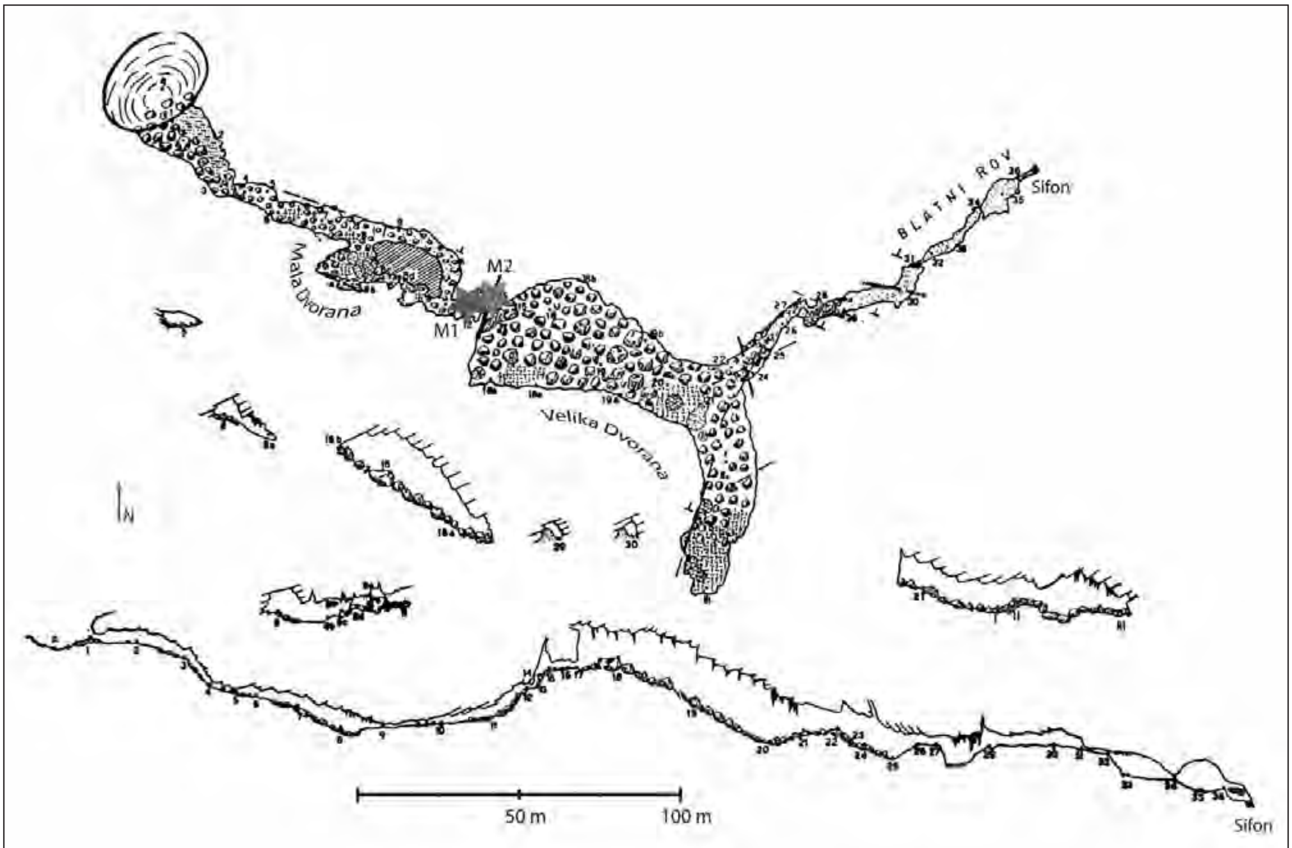

Figure 3. Plan of Mačkovica with measurement locations (Habič 1992); legend see Fig. 1.

4. Results

The DMH measurements are shown in Fig. 1 and Tab. 1. Radon activity concentration in the cave air ranged from undetectable (error bigger than value) in “Kluftgang” (DM10), “Lehmhalle” (DM9) and “Schnecke” (DM7) to 233 ± 44 Bq m^{-3} in the “Sturmtunnel” (DM4). The error of the measurements at the west entrance (DM5), which were repeated later at night, is bigger than their difference.

The measurements from Lipiška jama are shown in Fig. 2 and Tab. 1. The values ranged from 340 ± 145 Bq m^{-3} in the “Drča” (L1) between the two entrances to 3,644 ± 500 Bq m^{-3} in the loamy passage connecting the “Suhi Izvir” with the “Dvorana Upanja” (L8). CO_2 concentrations ranged from 3,000 ppm near the entrance (L1) to 1.5 Vol % in front of the entrance to the loamy passage (L9).

In Mačkovica, measurements were done at two sites, M1 at the end of “Mala Dvorana” and M2 below the entrance to “Velika Dvorana” (Fig. 3, Tab. 1). At site M1 the average radon activity concentration was 4,920 ± 549 Bq m^{-3}. At site M2 the radon level was 4,250 ± 152 Bq m^{-3} and the CO_2 concentration was 15,000 ppm. At this site, a long-term diffusive measurement was run over 32 hours (Fig. 4). In the first hours the values were around 4,000 Bq m^{-3}. Then they constantly dropped down to 3,104 ± 189 Bq m^{-3} until 5 p.m. and stayed around this level until the next morning. The lowest radon activity concentration was measured at 11 p.m. at 2928 ± 549 Bq m^{-3}. During the measurement the air pressure ranged from 969 to 965 mbar (Fig. 4).

The weather during the measurements in Slovenia was controlled by a stable anticyclone. Temperatures for the relevant dates are shown in Tab. 2.

Table 1. Measurements.

Location	^{222}Rn / Bq m^{-3}	CO_2 / ppm	Air pressure / mbar	Rel. Humidity / %	Date	Time
Dachstein-Mammuthöhle						
DM1	206±49		862	74		15:15
DM2	212±139		863	66		15:50
DM3	217±71		862	71		16:05
DM4	233±44		864	83		16:30
DM5a	56±99		863	85		18:00
DM5b	166±53		863	94	26.08.2012	22:30
DM6	86±45		854	92		18:30
DM7	0.02±41		854	93		19:15
DM8	70±59		856	94		19:50
DM9	0.06±47		858	94		20:20
DM10	0.08±36		855	95		20:55
Mačcovica						
M1	4,920±548		969	99	28.08.2012	22:25
M2a	4,250±152	2,000	969	99		22:45
Lipišca jama						
L1	340±145	3,000	979	69		16:00
L2	176±146	4,000	982	77		16:40
L3	362±174		988	71		17:00
L4	2,149±457		988	76		17:25
L5	2,553±157		979	86	30.08.2012	19:30
L6	1,220±237	15,000	990	78		17:45
L7	1,336±390	14,000	995	80		18:05
L8	1,843±138	20,000	997	83		18:25
L9	3,644±500	15,000	991	84		18:45

Table 2. Meteorological record (wetter-online).

Date	Measuring station	Temperature °C	
		Min	Max
28.08.2012	Postojna	8	27
29.08.2012	Postojna	12	28
30.08.2012	Triest	18	31

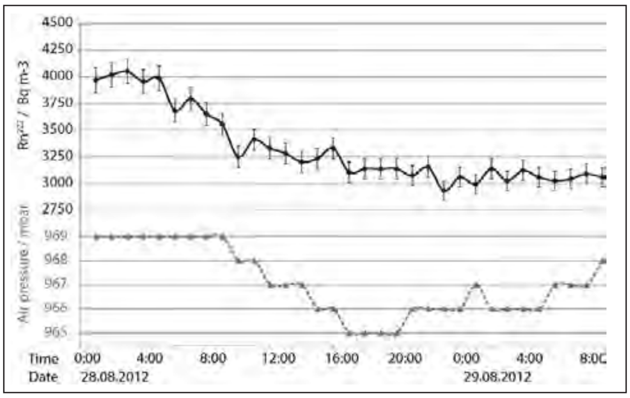

Figure 4. Long-term measurements in Mačkovica.

5. Discussion

DMH revealed the lowest radon activity concentrations in the cave air. Radon levels show no correlation with the distance from the entrance, with cave sediment material or with the narrowness of the passages. The generally low radon concentrations reflect the strong ventilation and connection to outside air. Furthermore it might be possible that the wet cave loam has an influence on a general low exhalation rate of the cave material as water in the pore-space can decrease the exhalation of radon (e.g., Fleischer 1987; Tanner, 1964). Even at the end of the “Lehmhalle”, a dead end, the radon level was very low. A strong ventilation could explain, that even in dry areas, and where boulders were covered by manganese-oxides (DM 10), radon levels were very low.

The measurements in Lipiška jama reveal a general increase of the radon and CO_2 concentration with depth. However it is noticeable that in the narrow passages of the “Labirint”, the radon levels are particularly high. This part of the cave does not contain much fine sediment and is not well ventilated. The parts of the “Kozinski Rov” and the “Suhi Izvir” are loamy but the halls are very large. Low values which were measured here suggest a connection with outside air through fissures. The very high radon level in the artificial passage at the end of the cave reflects the impeded ventilation resulting in radon accumulation. On the other hand, the strong ventilation occurring between the two entrances gives rise to the low radon concentrations in the “Drča”. Local, however unlocatable CO_2 sources and impeded ventilation can give rise to the high CO_2 concentrations in the lower parts of the cave.

The long-term radon measurement in Mačkovica shows no correlation with ambient atmospheric air temperature. It is evident that the radon activity concentration levelled off to a lower value after the first 16 hours. This drop is coherent with a slight drop in pressure. However, even though air pressure rose again, the radon level stayed constant. At the time of the measurement campaign it had not rained for months and water levels were low everywhere. Thus it is unlikely that there was a change in water level in the siphon at the back of the cave, influencing the measurement results. The student group visiting the cave during measurement M1 and M2a and at the beginning of M2b might have affected the air movements.

6. Conclusions

The AlphaGUARD proves to be a suitable device for long- and short-term radon measurements in caves. The highest radon levels were measured in Mačkovica, the smallest of all three caves with the least ventilation. In Lipišca jama, radon levels were also high, but lower values in deeper parts of the cave suggest the existence of unknown pathways, enhancing the air circulation. Variation in moisture or textural and mineralogical properties of the sediments may influence the differences in radon levels in the less ventilated parts of the cave. The measurements carried out by Jovanovic (1996) in Lipiška jama suggest a seasonal variation; this is only evident for the upper parts of the cave. If due to fissures ventilation occurs also in deeper parts of the cave, even here, an annual variation of radon levels could be possible. The mean of the values, measured above the "Labirint" resemble the 1,300 Bq m^{-3} which were measured in September somewhere in the upper part of the cave by Jovanovic (1996). However, as the exact locations are unknown a comparison of the values is not possible.

The long-term measurements in Mačkovica suggest that air temperature outside the cave is not a driving force in ventilating the cave with outside air in summer. The measurements would need to be repeated in winter.

In DMH, even at places where a high emanation rate from rocks, due to e.g., manganese-oxide coatings or dry, fine sediments is assumed, the radon levels were very low. This suggests a strong air circulation and thus frequent mixing of cave air with ambient atmospheric air. The radon levels are too low in order to be used for any study on air circulation within the cave, but on the other hand there is no threat for workers or tourists from radiation.

The measured radon activity concentrations in the cave air are at least one order of magnitude lower than the specific activities of the potential source material. Thus, radioactive equilibrium has not been reached. Reasons are the ventilation or impeded radon exhalation due to moisture or low effective porosity of the material.

Acknowledgments

We would like to thank Juri for the guidance in Lipiška jama and Stephan Höll for the permission to visit DMH. Thanks are also to Dr. Michael Schubert from UFZ Leipzig for lending the measurement equipment.

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ELEMENT AND STABLE ISOTOPE AQUEOUS GEOCHEMISTRY FROM BAYSUN TAU, UZBEKISTAN – TRACING THE SOURCE OF THE DRIPWATER

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Palaeoclimatic information from Central Asia is sparse. The geographical setting in the semi-arid high altitude mountains of Central Asia makes its karst regions hardly accessible. In a suitability study for palaeoclimatic work in the region, we analyzed stable isotopic composition ($\delta^{18}O$ and δD) and major element concentration in water samples collected in August 2012 in the Baysun Tau mountains, SE Uzbekistan.

$\delta^{18}O$ and δD of snow and karst water fall on the Eastern Meteoric Water Line, while rainwater show strong evaporation effects. These preliminary results indicate a dominant moisture source in the arid continental regions west of the Baysun Tau (arid Uzbekistan and Afghanistan), and snowmelt as the major source for infiltration. Dripwater element ratios seem to change in accordance with drip rates, suggesting prior calcite precipitation in the epikarst above the studied cave. We speculate that isotope profiles from stalagmites should be biased towards the wet winter season. We advise robust monitoring of dripwater chemistry as an essential means that allows for accurate interpretation of stalagmite paleoenvironmental records.

1. Introduction

The climatic past of Central Asia, a region where the westerlies and the Indian summer monsoon interact, is of great importance for society. Changes in the intensity and amount of precipitation may have severe repercussions on the water availability in the semi-arid to arid countries of Central Asia. Water availability and its distribution may cause economic stress and societal unrest in the region, even if conflict is not imminent on short time scales (Olsson et al. 2010, Bernauer and Siegfried 2012). Palaeoclimate reconstructions might help to assess the natural variability in precipitation over this vulnerable region.

To date, few palaeoclimatic records have been established and the long-term variability and influencing factors on regional climate remain enigmatic (Huang et al. 2011; Sorrel et al. 2007; Esper et al. 2002). Well-dated high-resolution proxy records are therefore required, as they might give insights into the governing climatic factors and large-scale teleconnections.

The caves in the Baysun Tau mountain range in southern Uzbekistan are the targets for palaeoclimatic studies using stalagmites. Stalagmites can be dated with high precision and accuracy and provide a multitude of geochemical tracers that makes them excellent palaeoclimate archives (Henderson 2006; Fairchild et al. 2006; Fairchild and Treble 2009).

The geological setting prompted speculation that some of the World's deepest caves might be found within the Baysun Tau and speleological expeditions were organized into this hard-to-access region during the 1980s. Unfortunately, political instability brought all speleological work to a halt and only now, after 20 years of inaction, was an international team of Russian, Italian, Spanish, Chinese, and Swiss cavers and researchers able to relaunch investigations there.

As part of the initial screening for the suitability of stalagmites from the Hodja Gur Gur Ata range (Baysun Tau) for palaeoclimatic studies, in 2012 we collected water samples from the Tonnelnaya and Sifonnaya caves and the accessible spring at camp Central, as well as from snow and rain on the plateau. These samples have been analyzed for their elemental and stable isotopic composition.

2. Geographical setting

The Baysun Tau mountain range is located in the southeastern borderland of Uzbekistan, close to Afghanistan and Tajikistan, near 67°E and 38°N (for details, see Tsurikhin et al. in these proceedings). The Hodja Gur Gur Ata chain of the Baysun Tau range consists of a 50–60 km long SW to NE-striking plateau which reaches 3,900 m altitude. Its most prominent feature is a ca. 400 m high vertical SE limestone wall that hosts a multitude of caves. The geologic strata are Cretaceous sandstones and gypsum (upper), and Jurassic limestones (lower). Southern Uzbekistan is characterized by a dry hot summer (Csa) to arid cold steppe (BSk) climate in the Köppen-Geiger classification (Peel et al. 2007). Most of the precipitation is delivered between autumn and spring (Aizen et al. 1996, Sorg et al. 2012; see also Fig. S3 in Cheng et al. 2012), while the summer season receives only very limited rainfall from local thunderstorms.

3. Water analysis – preliminary results

3.1. Elemental composition

Tracing the changes in the elemental composition of the dripwater and linking it to long-term and seasonal variations, and short-term events is an essential prerequisite in understanding the temporal variability of element concentrations in stalagmites and hydrological conditions in the epikarst (Fairchild and Treble 2009). The latter can potentially be used to detect hydrological and atmospheric changes through time.

This first set of drip- and spring water samples collected from Tonnelnaya Cave sets the baseline for future monitoring. All measured concentrations are well within the range of dripwater results reported elsewhere (Musgrove and Banner, 2004; McDonald et al., 2007). The fact that molar element ratios (Mg/Ca and Sr/Ca) increase with lower drip rate (Table 1) points to prior calcite precipitation (PCP). PCP is thought to occur during drier periods (low drip rate), with prolonged degassing of CO_2 and subsequent precipitation of Ca in the epikarst (McDonald et al. 2007). The preferential Ca-removal from the water leads to enrichment of Mg and Sr. A much more frequent sampling is required to understand the seasonal or long-term variations mentioned above, and to characterize the Baysun Tau hydrology.

3.2. Isotopic signature

The stable isotope ratios of oxygen ($\delta^{18}O$) and hydrogen (δD) in rain-, snow-, and dripwater are ideal tracers to understand the source(s) and history of meteoric water. They also help us understand the processes that lead to variations before, during, and after precipitation. Understanding the temporal dynamics of the chemical composition of meteoric water is imperative for the interpretation of isotopic variations in speleothems, which is the goal of palaeoclimatic studies.

We measured water stable isotope ratios on a Picarro L2120 mass spectrometer at ETH Zurich, Switzerland. The vaporization temperature was set to 110 °C and the samples were run in high-resolution mode with multiple injections. The first three injections were rejected to avoid any memory effects.

All cave (drip- and lake water), karst spring, and snow samples from the plateau show relatively depleted isotope ratios, all plotting above the Global Meteoric Water Line (GMWL) (Fig. 1) with the regression ($\delta D=8.43*\delta^{18}O+23.724$), statistically indistinguishable from the Eastern Meteoric Water Line (Clark and Fritz 1997) (Fig. 1). The rainwater samples collected show high values around zero VSMOW, while plotting below the GMWL. Although the number of samples is very limited, we can tentatively interpret the observed behavior. The close correspondence between karst water and the snow samples indicates that snowmelt governs the isotopic composition of the cave water (Clark and Fritz 1997), while rainwater seems to be of negligible influence. The rainwater samples scatter well below the GMWL (with a lower slope of regression), indicating secondary evaporation in the falling raindrops in low-humidity conditions (Clark and Fritz 1997). This is confirmed by direct observations during the rainfall events; very light rain is largely evaporated before even reaching the soil. It seems very unlikely that such low intensity rains contribute to the infiltrating water.

The deuterium excess $d=(\delta D-8*\delta^{18}O)$ can be used as a tracer for the humidity at the source of the moisture. The *d* excess is very high (and the samples plot above the GMWL) if the humidity in the source region is very low (closer to 50% relative humidity, Clark and Fritz, 1997). The observed *d* values, ranging from 18 to 22 are comparable with data reported from Tian Shan glaciers (Aizen et al. 1996). Together with the position close to the EMWL this can be explained by a low-humidity moisture source in arid Eurasia.

Although we clearly need a larger database, we argue that snowmelt during spring and summer is the major water source for cave drips and spring water in the Baysun Tau range. Since most of the annual precipitation is delivered from the arid western regions between autumn and spring, we speculate that the isotopic signal in dripwater (and thus stalagmites) should be biased towards the winter season. To disentangle the seasonal variation of the isotopic composition of the infiltrating water a detailed sampling and monitoring campaign is required.

4. Conclusions

Initial stable isotope and element characterization of waters from the Baysun Tau mountain range in southern Uzbekistan indicates that cave dripwater is influenced mainly by snowmelt. Thus, dripwater and stalagmite stable isotope signatures should be biased towards the wet season (autumn to spring) and should possibly show temperature dependence. Element studies further indicate that drip rates have a strong influence on the composition of the dripwater, with lower drip rates probably leading to enriched Mg and Sr loadings in the water. This can be explained by prior calcite precipitation, which preferentially removes Ca from the solution. A larger dataset is needed before final conclusions can be drawn. Stalagmites from the studies cave in the Baysun Tau should be suitable for palaeoclimatic reconstructions.

Acknowledgements

The Chinese State Key Laboratory of Loess and Quaternary Geology (Grant No. SKLLQG1001) is acknowledged for financial support. We also thank Daniel Montlucon (ETH Zurich) for analyzing the water samples.

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Table 1. Concentration of major elements (in mg/L) and (molar) elemental ratios.

Sampling date	Sample character	Ca (mg/L)	Mg (mg/L)	Sr (mg/L)	Ba (mg/L)	Na (mg/L)	K (mg/L)	Mg/Ca	Sr/Ca (*10^3)
07.08.2012	Camp Central spring	42.669	33.690	0.375	0.053	4.938	1.447	1.302	4.0
10.08.2012	cave lake water	58.870	5.970	0.490	*	—	0.210	0.167	3.8
08.08.2012	very fast drip (>100 drips/min)	68.380	6.090	0.490	*	—	0.220	0.147	3.3
10.08.2012	fast drip	77.480	8.160	0.570	*	1.460	0.320	0.174	3.4
10.08.2012	medium drip	73.330	7.960	0.560	*	—	0.310	0.179	3.5
10.08.2012	slow drip	50.730	8.020	0.510	*	0.660	0.230	0.261	4.6

** Ba concentration was detectable but below the calibration limit. Elemental analysis was performed on ICP-OES (Arcos) at Eawag, Dübendorf, Switzerland.*

Table 2. Stable oxygen and hydrogen isotope ratios of water samples collected in 2012.

Sample ID	Sampling date	Location	Sample character	δ18O (‰ VSMOW)	δD (‰ VSMOW)	d excess
1	08.08.2012	Sifonnaya	Syphon	-9.08	-52.90	19.7
2	10.08.2012	Tonnelnaya	several slow drips	-8.83	-51.98	18.6
3	10.08.2012	Tonnelnaya	medium fast drip	-9.02	-52.74	19.4
4	10.08.2012	Tonnelnaya	very fast drip	-8.85	-52.33	18.4
5	10.08.2012	Tonnelnaya	cave lake	-9.00	-51.93	20.1
7	07.08.2012	Camp Central	karst spring	-9.90	-59.55	19.7
8	08.08.2012	Plateau above Festivalnaya, N38°23.211’, E67°16.692’	snow	-6.14	-27.28	21.8
9	08.08.2012	Plateau above Ulug Begh, 3750m: N38°25.721’, E67°20.100’	snow	-9.74	-56.37	21.6
10	12.08.2012	Baysun Tau	rainwater	-1.19	-3.99	5.5
11	12.08.2012	Baysun Tau	rainwater	-0.74	-0.42	5.5
12	12.08.2012	Baysun Tau	rainwater	0.74	-2.39	-8.3
13	12.08.2012	Baysun Tau	rainwater	2.39	12.96	-6.2

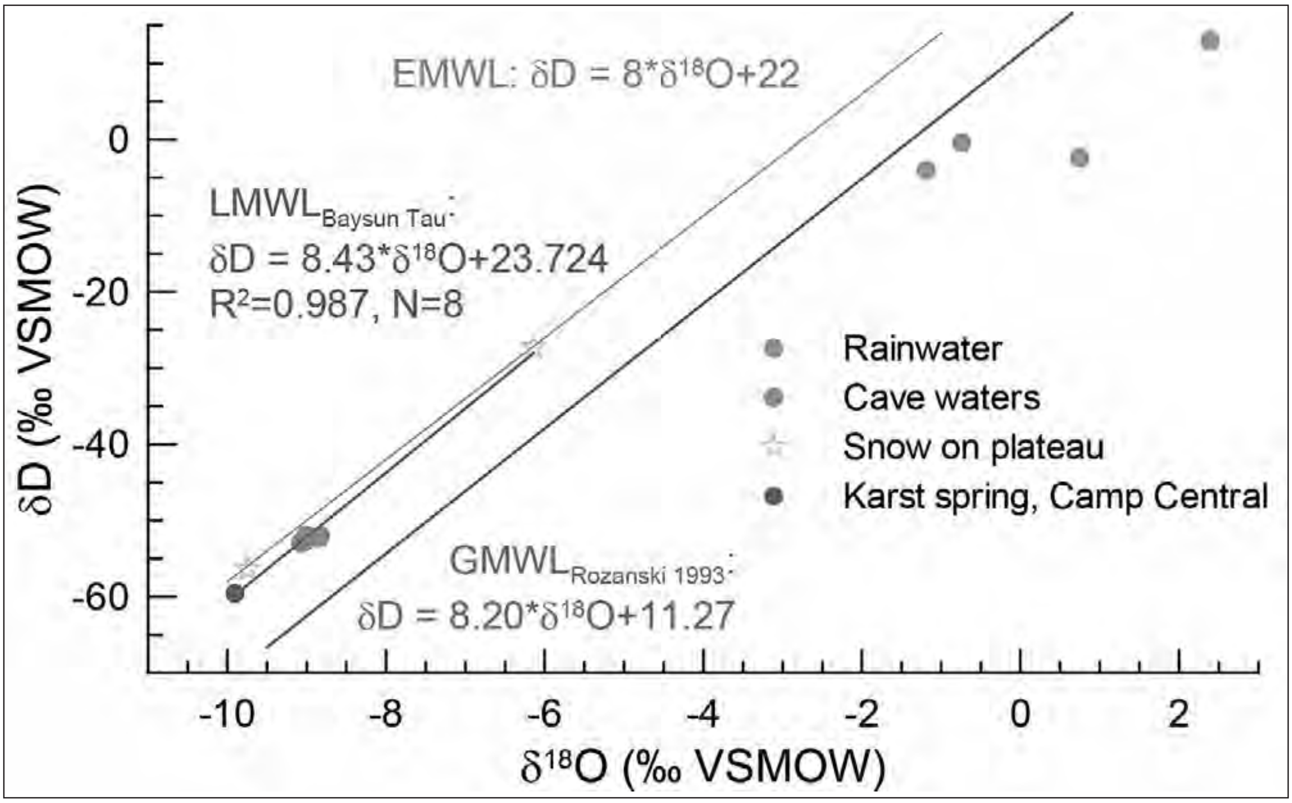

Figure 1. Diagram showing oxygen vs. hydrogen isotope ratios. The GMWL and the EMWL are shown for reference. All Baysun Tau samples, except the rainwaters, are depleted and plot above the GMWL and are indistinguishable from the EMWL. Rainwater samples show clear enrichment by secondary evaporation below cloud base.

HOLOCENE TEMPERATURE FLUCTUATIONS IN CENTRAL EUROPE RECORDED IN STALAGMITE M6 FROM MILANDRE CAVE, SWITZERLAND

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Here we present new high-resolution oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotope records obtained from stalagmite M6 (182 cm) from Milandre Cave in Switzerland. Stalagmite M6 covers the entire Holocene and Younger Dryas and provides the most detailed absolutely-dated temperature-dependent $\delta^{18}O$ record of Central Europe.

Stalagmite M6 was collected in Milandre Cave, located in the Ajoie region of the Swiss Jura Mountains (47°30'N; 7°01'E, 400 m asl), an area that is highly sensible to the North Atlantic climatic variations. The cave developed in the limestone of St.-Ursanne Formation, 30–80 m below the surface. Previous and ongoing studies of the physical and chemical parameters of the cave and drip water allow us to develop a good understanding of the factors that control the $\delta^{18}O$ variation in the M6 stalagmite.

The sample shows no hiatus and annual laminae are visible in its upper part. 26 $^{230}Th/U$-ages were measured with the MC ICPMS technique, using 2 mg powder from well determined layers. Stable isotopes measurements (3,980 samples) were performed at a resolution of 0.5 mm, corresponding to 2–5 year time interval.

To convert $\delta^{18}O$ calcite values into temperature we developed a transfer function by correlating $\delta^{18}O$ calcite values to regional historical temperature reconstructions covering the last 300 years. A variation of 1 ‰ in $\delta^{18}O$ corresponds to an increase of 1 °C in temperature.

We will compare our isotopic and temperature record with other precisely dated climate records on a regional and on a global scale. The timing of Holocene climate changes in response to climate forcing mechanisms (i.e. solar variability, volcanism, internal climate dynamics) will be also discussed.

A MULTIPROXY APPROACH TO RECONSTRUCTING PALEOENVIRONMENTAL CONDITIONS FROM SPELEOTHEMS IN BARBADOS TO ADDRESS GROUNDWATER VULNERABILITY

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Water resources on heavily karstified islands such as Barbados are highly sensitive to shifts in precipitation patterns. To manage water resources most effectively, a solid understanding of regional karst/climate/groundwater interactions is desirable. To this end, we are developing a high-resolution reconstruction of Holocene precipitation and climate variability on the island of Barbados from multiple speleothems. Proxy climate records from speleothem stable oxygen isotope records combined with high-resolution Uranium-series dating will be used on three speleothems collected from two caves on the island. One half of each speleothem was sampled for uranium-series dating, in order to build a chronology of lamina deposition. The other half is being sampled for stable isotope analysis (oxygen and carbon) at a 100-micron resolution. The stalagmite data will be calibrated with a contemporary study of the isotopic signatures of in-situ rainfall, cave dripwater, and recently deposited calcite. In order to improve the proxy reconstruction and explore the usefulness of non-destructive analysis that may complement the isotopic data, speleothem samples were analyzed using a non-destructive large chamber SEM in an attempt to compare lamina growth characteristics and inclusions to the isotopic variability to determine if a relationship can be established between them along a growth axis. Additionally, differences in lamina mineralogy will be derived from minimally destructive Raman spectroscopy. The three datasets, including the stable isotopes, SEM, and Raman data, will be compared at a high-resolution and combined with the U-series dating to develop a chronology of climatic change in the region. The reconstructed paleoprecipitation patterns will be analyzed using time-series analysis, elucidating the role major climate influences play in modulating groundwater recharge from changing precipitation throughout the Late Holocene. The modern precipitation calibration data indicate the climatic conditions operating under the influence of the current atmospheric-oceanic teleconnections impacting the region, which include the ITCZ, El Nino-Southern Oscillation, and the North Atlantic Oscillation. Interaction among these systems can influence the amount of rainfall occurring in the area over periods of decades to centuries. This research will help in managing the karst groundwater resources of Barbados and the Eastern Caribbean in the face of future climate change scenarios.

1. Introduction

Throughout the spring of 2010, the island of Barbados experienced a severe water shortage due to persistent drought conditions. As an isolated island in the Caribbean, water shortages are a very serious problem for the people who live in Barbados. Unlike continental nations, if a small island's limited surface and groundwater resources are depleted, there are few alternative sources and little infrastructure in place for easily importing water from other regions. The impacts of drought induced water shortage are even more pronounced thanks to the relatively small area of the island of Barbados, and the island's karst geology, which allows for rapid drainage and impaction from poor agricultural practices, pollution, and land use changes, exacerbating drought further. Such drought events can be devastating, as water is a precious commodity even during favorable conditions.

Precipitation and water resource issues are not limited to Barbados, as many islands in the Caribbean region face similar problems. Though the islands in the Caribbean Sea are sensitive to significant shifts in precipitation patterns, there are still questions of what and to what extent different climatic features and/or teleconnections have influenced precipitation throughout the Holocene. Barbados lies at the eastern edge of the Caribbean region; however it is actually within the Atlantic Ocean. Barbados's unique situation on the precipice between the Atlantic Ocean and the Caribbean Sea makes it a unique place for recording climate variability, as the island's climate is likely affected by both higher latitude and tropical climate mechanisms. A better understanding of global climate change, as well as local climate variability is essential in assessing potential climatic impacts on water resources in Barbados (Banner et al. 1996). To fully understand how changes in climate could affect Barbados, a long-term paleoclimate record is necessary. Unfortunately paleoclimate records for the island of Barbados are lacking, and the tropics in general have received little attention in terms of paleoclimate reconstructions. While there has been significant research into the geochemical and hydrogeological properties of the Barbadian aquifer, the robust climate data needed to assess the potential future of water resources in the Caribbean is minimal.

The aim of this research is to reconstruct paleoprecipitation patterns affecting Barbados from oxygen, carbon, and hydrogen isotope signatures recorded in cave deposits over the Late Holocene, and identify the driving climatic influences on these patterns to address potential future water resource issues. Having a robust understanding of how interconnected atmospheric-oceanic teleconnections have affected hydrologic patterns in the past is integral in understanding how climate shifts in the future can be expected to affect Barbados' sensitive supply of freshwater, particularly groundwater, which comprises over 90% of the island's main water source.

This information is of direct importance to the Barbados

Water Authority, for managing Barbados' limited water resources more effectively, especially in the face of anthropogenic and natural climate change, growing population and tourism impacts, and rising sea-level. Additionally, the tropics have received far less attention in terms of paleoclimate reconstruction efforts than mid- and high-latitudes, which detracts from a spatially robust vision of regional variations in the climate of the Holocene. The relative lack of long term climate data in the tropics is especially concerning, as many island nations in the tropics are uniquely vulnerable to climate related issues such as sea level rise, coral bleaching, and shifts in marine species habitats. In addition to the applied value of this research it provides a unique opportunity to simultaneously improve the scientific understanding of speleothem ontogeny through mineralogical analysis of sampled proxies, as well as improving non-destructive analytical methodologies for identifying post-depositional sources of error in individual speleothem proxies so that reconstructions can be improved while also preserving samples for reanalysis and posterity. WKU is uniquely equipped through the Advanced Materials Institute, and Non-Destructive Analysis Center, and Biology Department's SEM lab to not only better understand speleothem proxies and assess them for post-depositional alterations, but to develop methods with cutting-edge technologies that are minimally invasive and allow for a multi-proxy approach that leaves samples intact.

2. Geography and Geology

Barbados is the easternmost island in the Caribbean region (Fig. 1), and its climate is shaped by both Caribbean and Atlantic influences. Barbados itself is ~430 mi^2, receives between 1–2 meters of precipitation annually, and is characterized by a tropical climate with distinct wet and dry seasons (Köppen: Am). Barbados experiences a tropical monsoonal climate, which results in the islands wet and dry seasons. The island receives 1.4 meters of rainfall annually, with most of it falling during the wet season (Schomburgk 2001). As an island, the only natural inputs of freshwater to the country are through rainwater. Estimates of Barbados'water resources suggest there is a total of approximately 82 million m^3 of fresh water naturally available on the island. Groundwater refreshed by meteoric waters accounts for 75.9 million m^3 of the total, surface resevoirs account for 5.8 million m^3, and surface streams account for the last 0.5 million m^3 (Schomburgk 2001). Groundwater withdrawals have yet to be thoroughly quantified on Barbados. This makes calculations of overall groundwater flux unreliable. While human use of ground water resources dramatically affects how much groundwater is within the island's karst aquifer at any given time, the total groundwater that can possibly be used is modulated by precipitation.

Barbados is an island dominated by karst. The bedrock at the islands surface is 85% limestone, formed primarily in the Pleistocene through the subaerial exposure and lithification of coral terraces (Donovan and Harper 2005). These terraces have been uplifted as the island is pushed up by sediment scraped off of the sea floor as the South American plate subducts beneath the Caribbean plate. The karst aquifer that has formed in the islands limestone

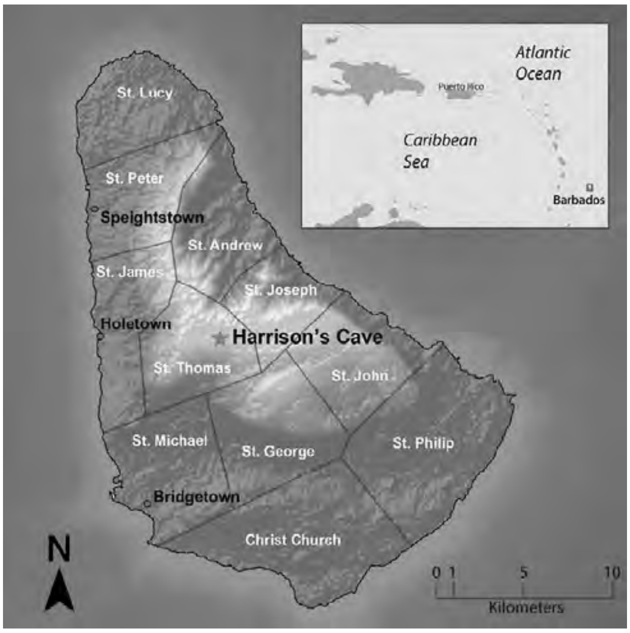

Figure 1. Map of Barbados, with Inset map of the Caribbean Sea. Harrison's Cave is labelled and indicated with a red star.

bedrock not only holds economic importance as the setting for the islands greatest natural attraction (Harrison's Cave), but it is also the source of ~90% of the island's water resources. Our sampling sites are located at Harrison's Cave and Mekkaman Cave, Barbados.

3. Methods

3.1. Precipitation Calibration

In order to understand precipitation fluctuations on Barbados through out the late Holocene, three speleothem samples were collected and prepared for use as isotopic and mineralogical proxies. Speleothem samples were slabbed and polished. One half of each was hand sampled for U/Th series dating, while the other half was milled at high resolution along a transect following the speleothem growth axes at a 100 µm resolution for stable isotope analysis (Fig. 2). The radiogenic isotope samples are used to produce a chronology of speleothem growth. The stable isotope samples are being analyzed for $\delta^{18}O$ and $\delta^{13}C$ isotope ratios. These ratios will be used in conjunction with a modern calibration study currently being undertaken at our sampling site in Barbados to reconstruct past precipitation amounts.

Rainfall amount was measured above Harrison's Cave at ten minute intervals since July 2012 using a Texas Electronics tipping bucket rainguage and an Onset HOBO event logger. Surface temperature and cave temperature/ relative humidity were measured at ten-minute intervals using an Onset HOBO temperature and relative humidity data logger. Drip water and rainwater were collected weekly at Harrison's Cave. Tile plates were installed in Harrison's Cave and Mekkaman Cave to collect modern calcite samples. Calibration of modern precipitation to modern calcite will be used to understand relationships between dripwater, rainwater, and current climate conditions; this information is vital in understanding past climate conditions derived from stalagmite isotope records.

Figure 2. AH-2 (Left) and HC-1 (Right) stalagmites from Barbados. Red line indicates sampling transect.

3.2. Non-destructive Analysis

To extract further paleoenvironmental information from our speleothem proxies, while producing as little damage to the samples as possible, we analyzed them via Raman spectroscopy (RS) and large chamber-scanning electron microscopy (LC-SEM). Analysis was carried out on each instrument by taking transects of data parallel to the stable isotope samples along the speleothem growth axes (Fig. 2). This allows for results to be easily compared with the isotopic analysis and fit easily within the chronology. RS was used to assess the mineralogical composition of speleothem laminae. LC-SEM was used to identify shifts in bulk chemical composition and examine laminae inclusions. The expected results from these methods are several additional data sets that can be compared to our isotopic analysis to explore potential correlations between laminae characteristics and isotopic trends (Railsback 1994).

3.3. Trend Extraction

To make this research valuable in planning and resource management, the precipitation reconstruction will be analyzed for cyclicity via spectral analysis and compared to published reconstructions of oceanic-atmospheric teleconnections that potentially influence precipitation patterns in the region (Ghil et al. 2001). The teleconnections that are likely most involved in modulating Barbadian precipitation patterns include the ITCZ, ENSO, AMO, and the NAO. If specific teleconnections can be identified as heavily influencing precipitation patterns on Barbados, a rudimentary predictive model can be produced that can help guide water resource planning when combined with teleconnection forecasts.

4. Results

Stalagmite sample AH-2 is dominantly monocrystaline, with alternating layers of fluid inclusion rich lamina and dense inclusionless calcite layers. HC-1 is comprised of units of monocrystaline calcite layers with hiatus and extreme event layers interspersed. Extreme event layers contained inclusions of silica sand, and marine invertebrates within a calcite cement (Fig. 3). Monocrystaline layers in HC-1 alternated between dense calcite and inclusion rich lamina as well.

Table 1. Uranium Thorium series dates obtained for HC-1 and AH-2. Dates are before the Common Era, Uranium concentrations are in parts per billion.

	HC-1		AH-2	
	Age	U Conc.	Age	U conc.
Top	183	767.84	459	305.75
	+/- 391	+/- 0.78	+/- 219	+/- 0.25
Bottom	20898	377.33	3002	119.94
	+/- 349	+/- 0.40	+/- 635	+/-0.10

All stalagmites were Pleistocene in age or younger (Table 1). HC-1 is 20,898 ± 349 years old; AH-2 is 3,002 ± 635 years old. Isotopic and mineralogical analysis using the Raman and SEM is underway and will provide three independent techniques to understand the growth dynamics, mineral formation, and changes in precipitation. Variability in the oxygen isotope record is likely caused by the amount effect, given the tropical location, and thus serves as a proxy for rainfall changes throughout the growth periods of the stalagmites.

Between July and December of 2012, 139.5 cm of rain fell at Harrison's Cave (Fig. 4). The average surface temperature was 26.4 °C, while the average cave temperature was 25.9 °C (Fig. 5). The relative humidity at the sampling site remained at a constant 100 % for the entirety of the measurement period. Modern calcite collected at the sampling site in Harrison's Cave displayed a growth rate of around three millimeters per year.

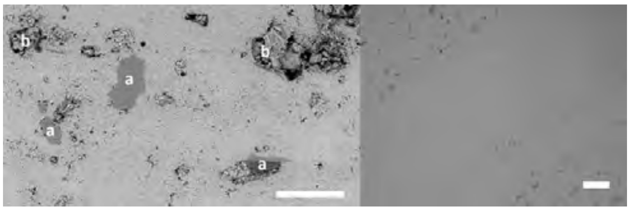

Figure 3. Detrital silica (a) and clay (b) in an extreme event layer in HC-1 (Left). Dense calcite layer (bottom left to top right) between two inclusion rich calcite layers (top left and bottom right) in AH-2 (Right). Scale bars represent 100 μm.

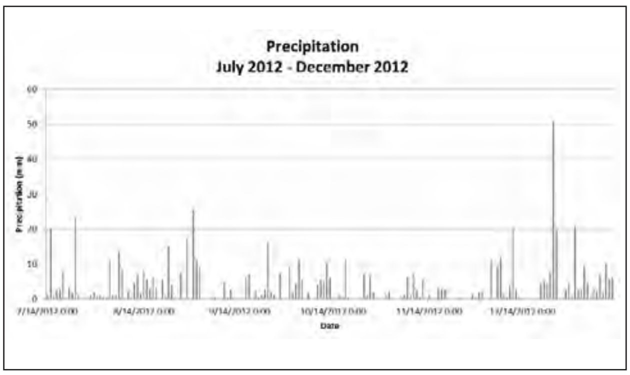

Figure 4. Histogram of Precipitation amount at the surface of Harison's Cave Barbados between July and December 2012.

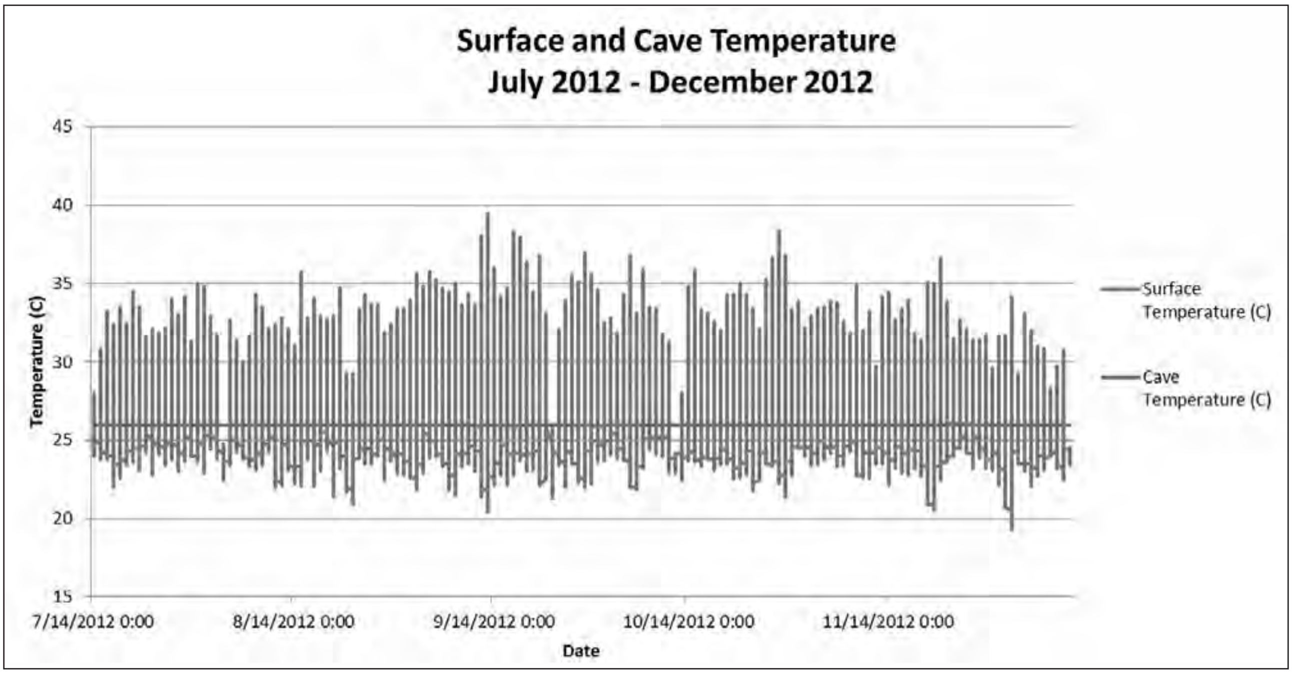

Figure 5. Surface and in-cave temperature at Harrison's Cave Barbados. The average surface and cave temperatures varied by less than half a degree C over the period between July and December 2012.

5. Discussion

This research sheds light on the complexity of eastern Caribbean climate during the late Holocene. Mineralogical analysis of HC-1 shows a unique history of inundation from extreme events since the last glacial maximum, while AH-2 shows several hiatuses in the growth axis, and illustrates flooding events and likely changes in precipitation amount caused by transition from the last glacial period. Further dating and analysis will shed light on the growth rates and trends in precipitation variability.

The mineralogical analysis of HC-1 illustrated the site's vulnerability to the effects of extreme meteorological events through out the Holocene; analysis of AH-2 shows cycles of recharge amount through the late Holocene via shifts between inclusion rich and inclusion free calcite laminae. Contemporary precipitation and temperature analysis confirms that cave temperature is within half a degree C of the average surface temperature and that humidity at the sample site is virtually always 100%. This is testament to the stable nature of the microclimate at the sample site within Harrison's Cave, and reduces the chances that the cave environment adversely affected information obtained from the stalagmite samples.

The interactions between groundwater resources and climate are often complex. The Eastern Caribbean region and the island of Barbados provide a unique place to study a portion of this complexity. When it comes to managing water resources, many factors must be accounted for, including human use and water quality. In understanding how potential ground water amounts change within the context of a dynamic climate, scientists, resource managers, and policy makers have the benefit of a general baseline. From there, further studies that account for fluctuations in water use and demand, as well as analysis of groundwater quality can all be put in context with the natural inputs to the system. As an isolated island, Barbados only natural source of water is precipitation and ultimately their groundwater. It is crucial that the karst aquifer of Barbados be properly managed, especially in the face of anthropogenic climate change.

Acknowledgments

We gratefully acknowledge the National Speleological Society, the Cave Research Foundation, and Western Kentucky University for contrubiting to the funding of this research. We also thank Dr. John Andersland of the Ogden College of Science and Engineering's Electron Microscopy Laboratory for his generous assistance with SEM imaging.

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GENETIC ALGORITHMS AS CORRELATION TOOLS – SPELEOTHEMS STABLE ISOTOPE RECORDS AS AN EXAMPLE

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The isotopic composition of oxygen and carbon in cave speleothems is a valuable source of paleoenvironmental information. The oxygen isotopic composition reflects the mean annual temperature in the cave area and the isotopic composition of the infiltering water. The carbon isotopic composition reflects the stage of development of soil and vegetation type at the surface.

Calcites from cave speleothems can be usually dated by U-series method but these have limitations. One of the most critical is cleanness of the analysed calcite. Any detrital admixture may cause contamination by initial thorium and dating results become unreliable. In such a situation there is a problem with the time scale estimation of the isotopic data.

The oxygen stratigraphy of carbonate marine sediments is based on the correlation of oxygen isotopic sequence from studied profile with the global standard curve. A similar method could be applied to the isotopic profiles obtained from speleothems. In this case any isotopic record can be correlated with a record which has a well defined age profile. Such correlations can be made on the basis of arbitrary decisions by the researcher; however, such procedures may be suffer subjective evaluation. Therefore we decided to develop a tool that will enable the correlation of isotopic profiles.

Speleothems grow with a variable crystallization rate, so similar stretches of time can be represented by deposits of differing thickness. The process of correlation of isotope curves consists of free shifting of data points (in accordance with the rule of superposition) belonging to the record with the undetermined age, relative to the record with the well defined age. Each generated position is evaluated. The best fit is accepted as the true position. Such procedure requires the use of an algorithm, which is able to efficiently search large (almost infinite) sets of possible positions. The genetic algorithm is a tool that can find the optimal solution in a set of large number of solutions. On our poster, we will present the genetic algorithm application for isotopic record correlation. The algorithm constructed was tested on artificial and real data sets (stable isotope records from speleothems).

DIFFERENT TYPES OF LAMINAE IN A FLOWSTONE FROM LA CIGALERE CAVE (PYRENEES, S. FRANCE)

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Due to its potential link with climate and seasonality, speleothem lamination has attracted growing interest in environmental studies. We report here different types of lamination analyzed in a flowstone from a high-altitude cave in the French Pyrenees. The aim of this research is to understand precisely the different mechanisms involved in the formation of the various types of laminae and to evidence the different parameters controlling their scaling, geometry and stacking pattern. While aragonite and calcite form the main part of the flowstone, other minerals have been also identified at different scales (carbonates, oxides and hydroxides, sulfates). Post-depositional diagenesis, in particular aragonite-to-calcite recrystallization may either alter or emphasize the primary lamination. Lamination pattern include: aragonite-calcite first- and second-order laminae, fluorescent laminae and geochemical laminae occurring either in aragonite or in primary calcite. These different types of lamination likely reflect fluctutation in dripwater chemistry and drip rates and thereby, are linked in some way to environmental changes within and outside the cave.

1. Introduction

The occurrence of lamination in speleothems and the idea that these may formed annually dates back from the first half of the 20th century (Allison 1926). Lamination is produced by a repeated variation of a specific character of the spelean precipitate (arrangement and geometry of crystals, geochemical content in trace-elements, mineralogy, UV fluorescence), either in alternating or sequential order.

Four different types of laminations have been evidenced in speleothems, mainly from flowstones and stalagmites: visible or petrographic laminae resulting from textural variations of carbonate minerals, calcite-aragonite couplets, fluorescent laminae, and trace-element laminae (for a review see Fairchild et al 2007; Baker et al. 2008). While all these different types of laminae reflect change in environmental parameters and climate, lamination may correspond either to supra-annual, annual, or even sub-annual cycles. The temporal scale of lamination is of fundamental interest to environmental studies due to its potential link with regional climate and seasonality.

The primary objectives of this project are 1) to characterize the different types of laminae occurring in the studied flowstone; 2) to document their scaling and geometrical relationships and 3) to decipher the environmental parameters controlling the various types of laminae. In the medium term, the overall aim of this work is the precise understanding of the successive mechanisms which produce the various types of laminae and their potential link to climate at different scales.

2. Location and geological setting

La Cigalère Cave is located on the northern side of the Pyrenees, at an altitude of about 1,700 metres (Ariège, S. France). The cave is open into limestones and marbles of Ordovician age. Ore deposits occur in rock formations overlying the cave system and Pb-Zn mining have been working until the middle of the 20th century.

The speleothem presented here corresponds to a flowstone which was sampled close to the porch entrance of the cave.

3. Methods

Following observation of sample slab in reflected light under the binocular, a set of various analytical techniques have been used on thin sections and selected small-sized polished samples to characterize petrography, mineralogy and trace-element content of the various types of laminae and analyze their geometry: optical microscopy, UV-fluorescence microscopy, secondary and backscatterred SEM, X-ray Energy dispersive spectrometry (EDS), XRF-EDS spectrometry and Raman microspectrometry.

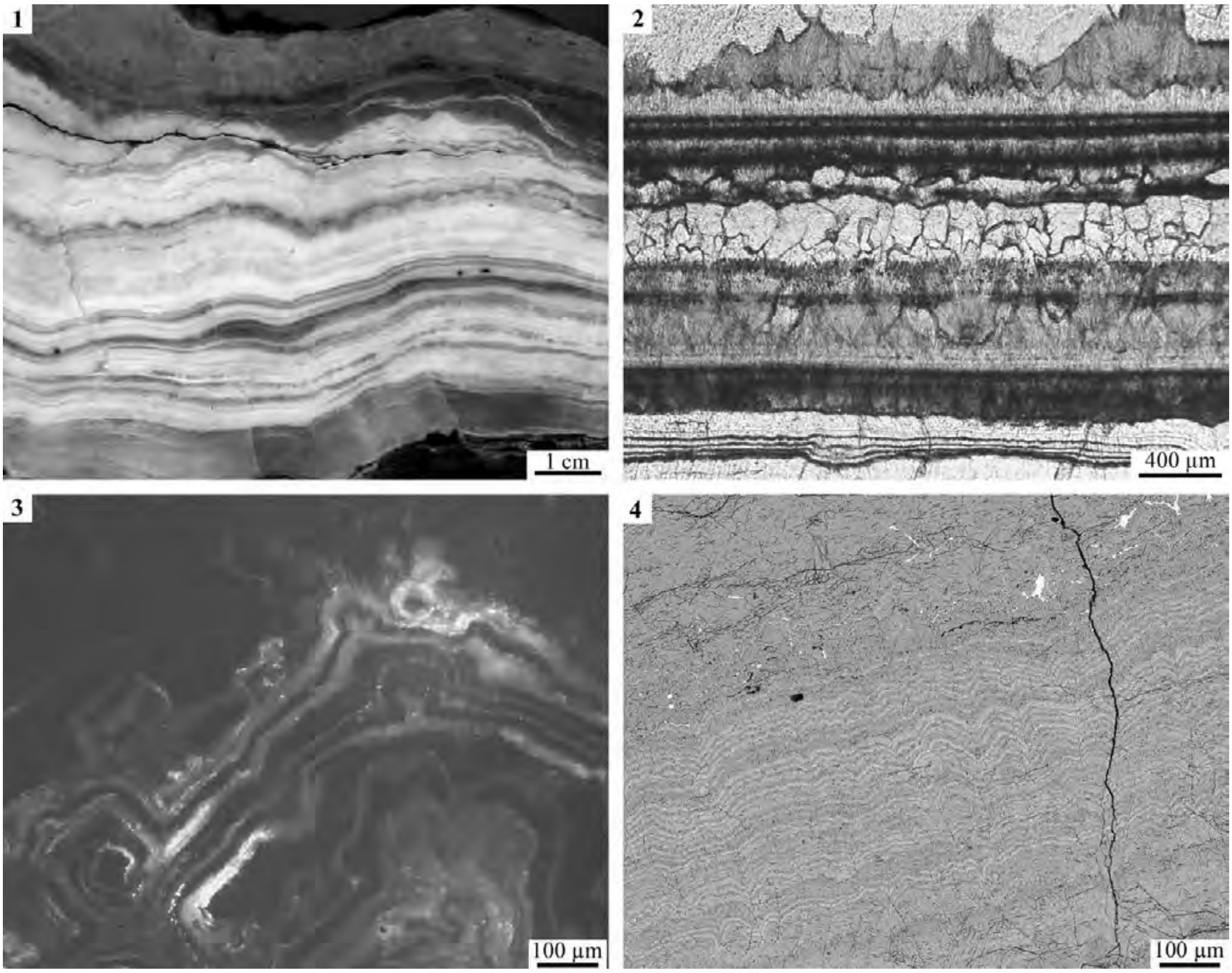
4. Results

4.1. Mineralogy

Identification of minerals has been performed at different scales using optical microscopy and Raman microspectrometry, eventually complemented by EDS micro-analyses. So, far three main types of minerals have been characterized in the flowstone. These are carbonates (aragonite, calcite and smithsonite), oxides and hydroxides of manganese, and low content of sulfates (anhydrite). Aragonite and calcite form the majority of the sample.

4.2. Post-depositional diagenetic modifications

The most obvious diagenetic change is the complete or partial recrystallization of aragonite layers into low-magnesian calcite. As such, diagenesis can potentially



Figures 1–4. 1. First-order mineralogical lamination formed by alternating layers of aragonite (white) and calcite (translucent to brown), polished slab of flowstone. 2. Interlayering of calcite (white) and aragonite (brown and fibrous), second-oder lamination is seen in calcite at the bottom of photograph, the layer at the top corresponds to diagenetic calcite (recrystallization of aragonite), thin section, light microscope, plain-polarized light. 3. Second-order UV-fluorescent lamination in calcite, thin section, light microscope, UV light. 4. Second-order geochemical lamination resulting from variation of Zn content in calcite, SEM backscattered electron detector.

emphasize or strongly alter the primary lamination, or even generate lamination.

4.3. Aragonite – calcite lamination

First-order mineralogical lamination is formed by alternating aragonite and calcite layers, a few mm to 10 mm in thickness (Fig. 1). Within this pattern, a finer-scale (second-order) aragonite-calcite lamination is visible with thin-layers of aragonite occurring in some first-order calcite layers, and thin-layers of calcite occurring in some first-order aragonite layers (Fig. 2).

4.4. Second-order UV-fluorescent lamination

Some calcite layers display fluorescent laminae when excited with UV-light (Fig. 3). Thickness of the alternating fluorescent and non-fluorescent laminae varies between a few to 20 microns.

4.5. Second-order geochemical lamination in aragonite

A sub-micronic scale layering of aragonite fibres is evidenced when slightly etched polished slab-specimens are observed with the SEM. This fine-scale lamination is produced by the stronger effect of etching at preferential levels in neighbouring aragonite crystals. Differential response to slight etching is likely caused by minor variations in geochemical composition.

4.6. Second-order geochemical lamination in calcite

Backscattered SEM imaging clearly show alternating 10-micron thick laminae occurring in some calcite layers. This lamination is caused by variations of the Zn content in calcite (Fig. 4). In some places, the top of these laminated calcite layers is coated by smithsonite or Zn-oxides / hydroxides, sometimes forming also a thin lamina.

4.7. Geometrical relationships between the various types of laminae

Detailed arrangement of the different types of laminations, including overlapping and particular patterns such as sequential order, is currently analysed using imaging and scanning of thin sections at various scales.

5. Conclusions and on-going research

The various types of laminae described in the flowstone of this cave likely reflect variation in dripwater chemistry and drip rates, which are linked in some way to changes of environmental parameters inside and outside the cave. The fact that the studied flowstone was formed close to the porch entrance of the cave may account for its enhanced potential as recorder of climatic fluctuations at various temporal and spatial scales.

On-going research includes precise analysis of the stacking pattern of the different types of laminae, isotopic geochemistry, and U-Th dating of the speleothem, which will help to constrain the timing of lamination, and the precise understanding of the processes which have generated this laminated flowstone.

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CLIMATE SIGNIFICANCES OF SPELEOTHEM δ ^{18}O FROM MONSOONAL CHINA: COMPARISON AND VERIFICATION AMONG STALAGMITE, INSTRUMENTAL AND HISTORICAL RECORDS

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The climatic significance of speleothem δ^{18}O variations in monsoonal China on decadal to annual timescales remains in debate, which prevent its application in climatic parameters reconstruction in the world's largest population country. Here, we analyses an annually layered stalagmite from Xianglong Cave, central China, which contains a seasonal record of δ^{18}O variations that cover a period of 98 years (1912–2009 AD). The annual δ^{18}O record of XL21 shows close similarities with local monsoon precipitation variations, suggesting that speleothem δ^{18}O variations in this area were mainly controlled by monsoon precipitation. Further *in situ* comparison between speleothem and historical records from another cave in this area supports the inverse relationship between speleothem δ^{18}O and precipitation variations. The speleothem δ^{18}O records from central China show anti-phase relationship with the stalagmite δ^{18}O record from India, indicating that the intensity of the Indian monsoon was not the dominant influence on speleothem δ^{18}O in monsoonal China on decadal and centennial timescales during the last 750 years.

1. Introduction

During the past decade, speleothem studies from China have generated great interest among climatologists. Speleothem oxygen isotope (δ^{18}O) records from China extend over a period covering the past 500 ka (e.g., Wang et al. 2001, 2005, 2008; Yuan et al. 2004; Cheng et al. 2009, 2012), and are widely distributed over monsoonal China, from the Xiaobailong (Cai et al. 2006) and Dongge caves in the southwest (Yuan et al. 2004; Wang et al. 2005) to the Sanbao (Wang et al. 2008; Cheng et al. 2009) and Jiuxian caves (Cai et al. 2010a) in the central region, and from Hulu Cave in the east (Wang et al. 2001) to Tianmen Cave on the Tibetan plateau (Cai et al. 2010b). These δ^{18}O records show consistent variations over orbital to sub-orbital timescales, with relatively high values during glacial and stadial periods, but relatively low values during interglacial and interstadial periods, which mirrors changes seen in speleothem δ^{18}O records from low-latitude South America (e.g., Wang et al. 2006; Kanner et al. 2012). The consistent nature of the pattern of variation in speleothem δ^{18}O values indicates that they predominantly reflect changes in the strength of the Asian monsoon on orbital to sub-orbital timescales, which are dominated by the insolation-controlled position of the Intertropical Convergence Zone (ITCZ) (e.g., Yuan et al. 2004; Wang et al. 2006, 2008; Fleitmann et al. 2007; Cheng et al. 2009).

However, the climatic significance of variations in speleothem δ^{18}O in monsoonal China over shorter timescales, such as decadal to annual, remains uncertain (e.g., Tan 2009a; Cai et al. 2010a; Dayem et al. 2010; Pausata et al. 2011). Recently, Dayem et al. (2010) analyzed instrumental measurements of δ^{18}O values in precipitation from stations in the Global Network of Isotopes in Precipitation (GNIP), and found that monthly δ^{18}O values did not correlate well with either local precipitation amounts or local temperature in eastern China. Breitenbach et al. (2010) also found that the monthly δ^{18}O values did not correlate with patterns of temperature and rainfall variation over northeast India, and argued for the importance of the vapor transport distance. However, most of the rainfall δ^{18}O data used by Dayem et al. (2010) covered only short periods and were uncontained, which may preclude a definitive assessment of the relationship between rainfall δ^{18}O and climatic parameters (Sinha et al. 2011). The relationship between rainfall δ^{18}O and climatic parameters may differ when comparing decadal to annual timescales with synoptic timescales. For example, Sinha et al. (2011) observed a significant inverse relationship between stalagmite δ^{18}O series and regional monsoon rainfall records during the past 100 years in northeast India, and suggested that changes to the monsoon precipitation amount were the primary source of δ^{18}O variations in precipitation in this region over decadal timescales. Tan et al. (2011) also found close similarities in the semi-humid region of northern China between a stalagmite δ^{18}O record and nearby precipitation amounts derived from historical documents spanning the past ^{18}60 years, supporting the direct relationship between monsoon precipitation amounts and cave δ^{18}O levels. In particular, the relative impact of variations in monsoon precipitation and intensity over India on speleothem δ^{18}O in monsoonal China (Pausata et al. 2011) has yet to be determined. A way to resolve this problem is directly comparing high resolved speleothem δ^{18}O record with observed meteorological records or other absolute dated proxy records, which contain clear climatic significances.

In this study, we analyses an annually layered stalagmite from Xianglong Cave, central China, which contains a seasonal record of δ^{18}O variations that cover a period of 98 years (1912–2009 AD). By comparing the stalagmite δ^{18}O time series with meteorological records, we provide robust evidence to support the hypothesis that monsoon precipitation controls variations in speleothem δ^{18}O over decadal to annual timescales in this area. This conclusion is further confirmed by in situ comparison between stalagmite and historical records from another cave in this area.

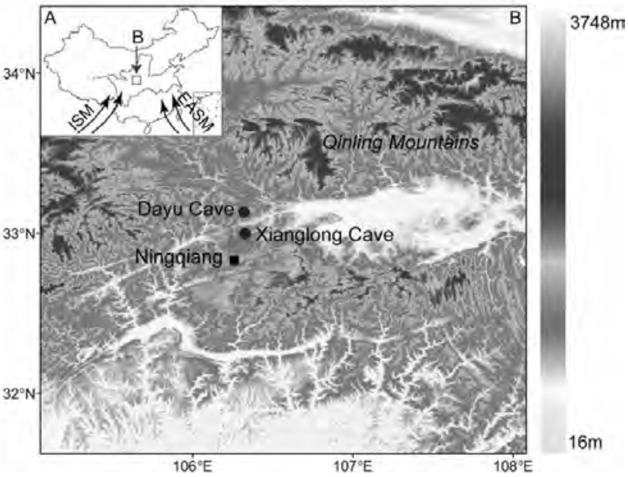

Figure 1. Location of Xianglong Cave and other sites referred to in the text. GTOPO30 data distributed by U.S. Geological Survey's EROS Center (Earth Resources Observation and Science;http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30_info) were used to plot the topographic map. ISM and EASM denote the Indian summer monsoon and the East Asian summer monsoon, respectively.

2. Cave Location, Sampling, and Methods

Xianglong Cave (33°00'N, 106°20'E, 863 m above sea level (asl) at the entrance) is located on the southern flank of the Qinling Mountains, central China, and is strongly affected by the East Asian monsoon system (Liu et al. 2003, Fig. 1). The mean annual temperature and precipitation in this area are 13 °C and 1,100 mm, respectively. Water balance modeling (Thornthwaite 1948; McCabe and Markstrom 2007) indicates that the water surplus develops in this area from April to November, and is at its peak between July and October. Consequently, recharge of the aquifer over Xianglong Cave occurs mainly as a result of summer monsoon precipitation.

Stalagmite XL21 was 4.2 cm in length and was collected about 700 m from the entrance of Xianglong Cave in October 2009. The top of the stalagmite was receiving drips when collected. The vertical stalagmite section showed regular laminae that alternated between a dark, compacted layer (DCL) and a white, porous layer (WPL). The top 3.1 cm of XL21 was aragonite, but the lithology changed to calcite below 3.1 cm. Here, we focus on the uppermost 2.9 cm of XL21. A drill was used to recover subsamples along the growth axis for ^{230}Th dating using inductively coupled plasma-mass spectroscopy (ICP-MS) (Edwards et al. 1987; Shen et al. 2002; Cheng et al. 2009). Visible laminae on the polished surface of the stalagmite were counted. We obtained 582 samples for oxygen and carbon isotope analyses at intervals of 50 µm, using a MicroMill sampling device.

3. Results and Discussion

3.1. Chronology

The uppermost ^{230}Th date obtained from XL21 was 2012 ± 9 AD, confirming that active growth was continuing at the time of collection (Table 1). The high-resolution δ^{18}O record shows 98 cycles, which is consistent with the visible lamina counts and also within the margin of error associated with the ^{230}Th dating (Fig. 2), and this indicates that the DCL–WPL couplets and δ^{18}O cycles are annual. We used the δ^{18}O cycles to develop a chronology for the entire δ^{18}O series obtained from XL21, and found that growth of the top 2.9 cm of the stalagmite occurred between 1912 AD and the present day (October 2009 AD; i.e. the time of sampling). We calculated the arithmetic mean of the annual δ^{18}O cycles to derive an annually resolved δ^{18}O series (Fig. 3). Small errors may be associated with the annual δ^{18}O values because the MicroMill device cannot accurately sample the boundaries of the annual layers. However, these small errors are not significant over a decadal timescale.

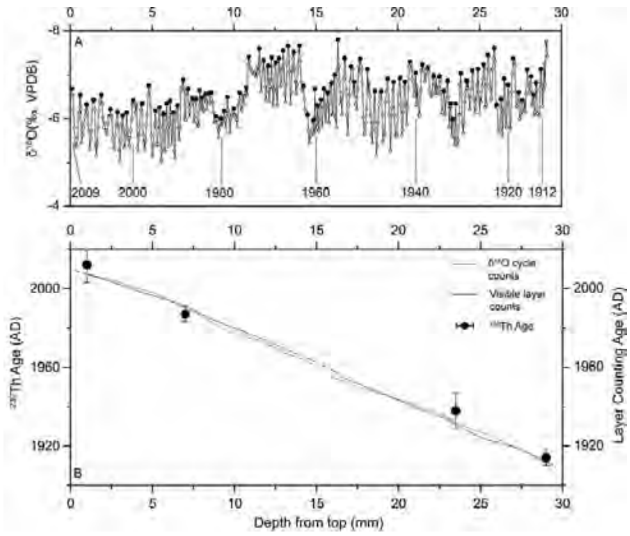

Figure 2. (A) The δ^{18}O time series obtained from contiguous micro-milling at intervals of 50 µm plotted as a function of distance from the top of XL21. (B) Comparison of age models derived from counts of visible annual layers, annual δ^{18}O cycles, and ^{230}Th dates.

3.2. Seasonal variations in stalagmite δ^{18}O values

The cyclic nature of the variations in δ^{18}O values in XL21 indicates a clear seasonal influence. The lower δ^{18}O values correspond to the WPL in XL21, while the higher δ^{18}O values correspond to the DCL. As XL21 was actively growing when it was sampled in October 2009 AD, the uppermost WPL was assumed to have been deposited during the summer of 2009 AD. Monitoring of precipitation outside the cave between June 2010 and June 2011 shows that δ^{18}O values in precipitation are lower during summer and autumn than during winter and spring (Fig. 4). The δ^{18}O value of carbonate sediments deposited on a glass plate (at the site of XL21) between May 2010 and November 2010 AD was –7.00‰, and between December 2010 and March 2011 AD was –6.58‰. This suggests that the lower δ^{18}O values in XL21 represent summer half-years, while the higher δ^{18}O values represent winter half-years, although we

Table 1 U-Th data and 230Th dates for stalagmite XL21.

Sample Number	238U (ppb)	232Th (ppt)	230Th / 232Th (atomic x10-6)	δ234U (measured)	230Th / 238U (activity)	230Th Age (yr) (uncorrected)	230Th Age (yr BP) (corrected)	δ234UInitial (corrected)	230Th Age (yr AD) (corrected)
XL21-1A	4685.2±19.5	4057.0±12.7	3.5±0.2	324.6±4.2	0.00018±0.00001	15±1	-62±9	324.6±4.2	2012±9
XL21-1	3601.0±13.1	807.3±16.4	24.9±1.2	323.9±3.7	0.00034±0.00001	28±1	-37±4	323.9±3.7	1987±4
XL21-2	4507.1±17.7	2517.7±51.3	30.1±0.8	317.4±4.1	0.00102±0.00002	84±2	12±9	317.4±4.1	1938±9
XL21-3	4925.6±13.2	1168.8±23.6	84.9±2.1	322.4±2.7	0.00122±0.00002	101±1	36±4	322.5±2.7	1914±4

Note: Analytical errors are 2s of the mean. Decay constant values are: $\lambda_{230} = 9.1705\times10^{-6}\ y^{-1}$, $\lambda_{234} = 2.82206\times10^{-6}\ y^{-1}$ (Cheng et al., 2009) and $\lambda_{238} = 1.55125\times10^{-10}\ y^{-1}$ (Jaffey et al. 1971). Depths along the growth axes are relative to the top (youngest surface) of the stalagmite.

are unable to assign calendar months to every δ^{18}O data point because of the varying growth rate of XL21 throughout the year.

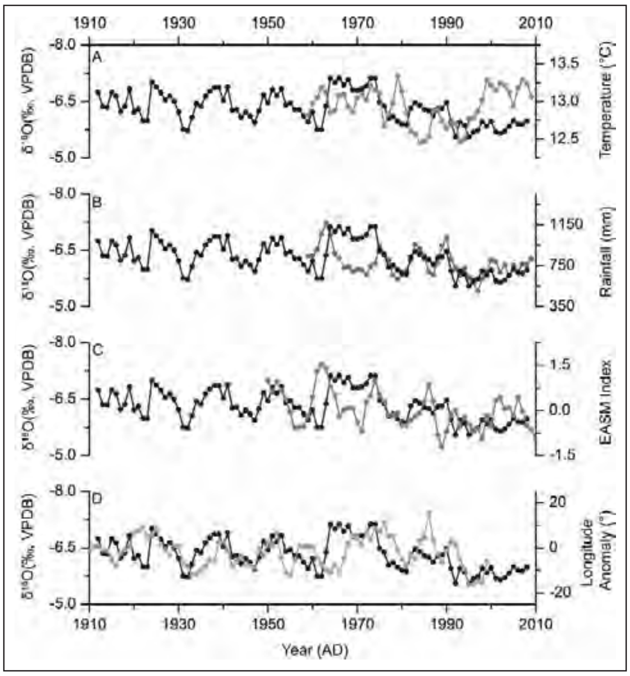

Figure 3. Comparison of the XL21 δ^{18}O record with (A) the observed annual temperature, (B) annual summer monsoon rainfall (excluding the anomalous data from 1981 AD), (C) the East Asian monsoon index (Li and Zeng, 2002), and (D) the east–west shift of the West Pacific Subtropical High (Mu et al. 2001). All series are three-point moving averages, except the XL21 δ^{18}O series.

3.3. Comparison between speleothem δ^{18}O record and instrumental records

To confirm its climatic significance, we compared the XL21 δ^{18}O record with the meteorological precipitation and temperature records from Ningqiang station (32°49'N, 106°15'E, 803 m asl), the meteorological station nearest to Xianglong Cave. If temperature is the dominant control on the δ^{18}O variations recorded in XL21, they would show a positive correlation (Cai et al. 2010a), considering both the temperature dependence of δ^{18}O on precipitation (ca. 0.69‰/°C in high latitudes, Dansgaard 1964), and the temperature dependence of δ^{18}O fractionation in aragonite-water (ca. -0.20‰/°C at 25°C, Kim et al. 2007). However, this inference is not supported by the comparison. For example, temperature decreased between the 1960s and 1980s, but the stalagmite δ^{18}O values increased during this period (Fig. 3). By contrast, the δ^{18}O series show close similarities with monsoon precipitation (June–October) variations. The only exception is in 1981 AD, when the

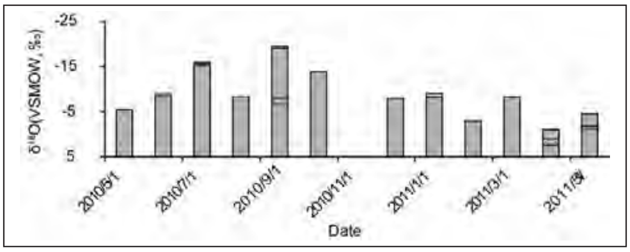

Figure 4. The δ^{18}O values of precipitation at the Xianglong Cave site between June 2010 and June 2011.

monsoon precipitation was abnormally high (more than ca. 230 % of the average). If this data is excluded, the similarities between the two series are more evident (Fig. 3). Lower δ^{18}O values correspond to increased monsoon precipitation, while higher δ^{18}O values correspond to decreased monsoon precipitation. For example, monsoon precipitation follows a decreasing trend from the 1960s to the mid 1990s, and then increases. The stalagmite δ^{18}O values show a corresponding increasing and then decreasing trend. On multi-year to decadal timescales, the lower δ^{18}O values closely follow high monsoon precipitation in the early 1960s and 1980s, while the higher δ^{18}O values reflect low monsoon precipitation in the late 1970s and 1990s. These comparisons indicate an inverse relationship between δ^{18}O variations in precipitation/speleothems and monsoon rainfall amounts in this area, which may be caused by the amount effect. It appears that changes in the moisture source and transport pathways (Breitenbach et al. 2010) had little effect on δ^{18}O variations in precipitation/speleothems, or possibly that the moisture source and transport paths were relatively stable in this area during the study period. However, they may affect δ^{18}O variations in precipitation/speleothems during extremely wet years, such as 1981 AD, and disturb the amount effect. This amount effect, as observed in Xianglong Cave (central China), is also seen in India (e.g., Sinha et al. 2011), southwest China (Tan et al. 2012), and at the northern edge of the Asian summer monsoon area in China (Zhang et al. 2008; Tan et al. 2011). This differs from the relationship seen in southeast China, which may be more strongly affected by changes in the moisture source; i.e. the circulation effect (Tan 2009a; Maher and Thompson 2012).

It is well known that the intensity of the East Asian summer monsoon (EASM) has a significant effect on variations in monsoon precipitation over East Asia (e.g., Ding 1992). In addition to the EASM, the activity of the West Pacific Subtropical High (WPSH) in summer also strongly affects monsoon precipitation over China (e.g., Huang and Sun, 1992; Mu et al. 2001). While the south–north shift of the WPSH is closely related to the intensity of the EASM, the east–west shift is relatively independent (Mu et al. 2001;

Guo et al. 2004). Figure 3 also shows good agreement between the XL21 $\delta^{18}O$ series and the EASM index (Li and Zeng, 2002), as well as the east–west shift of the WPSH (Mu et al. 2001). When the WPSH moves westward, the area containing Xianglong Cave is under the control of the WPSH. Meanwhile, if the EASM is weak, less moisture will be delivered to the area, which reduces the monsoon precipitation and causes enrichment of $\delta^{18}O$ in speleothems. In contrast, when the WPSH moves eastward, convective activity occurs on the western margin of the WPSH, such as the area around Xianglong Cave. If the EASM is strong, more moisture will be delivered, which will increase monsoon precipitation in this area, and result in depleted speleothem $\delta^{18}O$.

3.4. Comparison between speleothem $\delta^{18}O$ record and historical records

Evidence supporting this inverse relationship between the speleothem $\delta^{18}O$ and precipitation variations in this area is also provided by ancient inscriptions inside Dayu Cave, 15 km north of Xianglong Cave. These inscriptions indicate at least 72 visits to the cave, with the earliest visit occurred in 1193 AD. Most of this visits occurred during the Ming (1368–1644 AD) and Qing (1644–1911 AD) Dynasties. Among these inscriptions, six drought events are clearly recorded (Fig. 5). They occurred in 1525 AD (the 4th year of the Emperor Jiajing period, Ming Dynasty), 1596 AD (the 24th year of the Emperor Wanli period, Ming Dynasty), 1707 AD (the 46th year of the Emperor Kangxi period, Qing Dynasty), 1756 AD (the 21st year of the Emperor Qianlong period, Qing Dynasty), and ^{18}91 AD and ^{18}94 AD (the 17th and 20th years, respectively, of the Emperor Guangxu period, Qing Dynasty). Of note, the drought events show good agreement with the speleothem $\delta^{18}O$ record from Dayu Cave (Tan et al. 2009b). When droughts occurred, higher $\delta^{18}O$ values were recorded in the speleothem (Fig. 5). The first *in situ* comparison between stalagmite and historical records further supports the inverse relationship between speleothem $\delta^{18}O$ and precipitation variations in this area.

3.5. Regional differences in stalagmite $\delta^{18}O$ from China and India

The 750-yr speleothem $\delta^{18}O$ record from Dayu Cave show notable decreased values during the Little Ice Age (LIA), which indicates wet conditions during this period (Tan et al. 2009b). The wet LIA climate was also seen in a pollen-reconstructed rainfall record from peat of Dajiu Lake in central China (He et al. 2003). However, the speleothem $\delta^{18}O$ records from Wanxiang (Zhang et al. 2008) and Huangye Cave (Tan et al. 2011) in the north margin of the Asian monsoon show remarkable increased values during the LIA, and the historical record from this area also show remarkable dry climate (Tan et al. 2008). The anti-phase relationship indicates significant regional differences in speleothem $\delta^{18}O$ and precipitation in monsoonal China on centennial timescale.

Recently, Pausata et al. (2011) suggested that reduced precipitation over the Indian basin and the weakening of the Indian monsoon during Heinrich events caused isotopically heavier precipitation over India, and the export of isotopically enriched water vapor to China, resulting in enriched speleothem $\delta^{18}O$ in monsoonal China. Here we test if the variations in speleothem $\delta^{18}O$ in monsoonal China were driven by varying monsoon precipitation over India over shorter timescales. We compared our XL21 $\delta^{18}O$ series with the monsoon rainfall index for the whole of India, which is regarded as the intensity of the Indian monsoon (Parthasarathy et al. 1995), and with the stalagmite $\delta^{18}O$ series from the core monsoon zone of India (Sinha et al. 2011). As shown in Figure 6, the stalagmite $\delta^{18}O$ variations from India resemble the Indian monsoon rainfall variations, indicating a significant amount effect of precipitation oxygen isotope in Indian monsoon region. However, no similarities are observed between the XL21 $\delta^{18}O$ series and the stalagmite $\delta^{18}O$ record from India, or the Indian monsoon rainfall index. In fact, they show anti-phase variations during most of the past 100 years. This inverse relationship between the stalagmite $\delta^{18}O$ records from central China and India also exists on a centennial timescale. As also shown in Figure 6, the stalagmite $\delta^{18}O$ record from Dayu Cave (Tan et al. 2009b) exhibits anti-phase variability with the composited stalagmite $\delta^{18}O$ record from India (Sinha et al. 2011) at a centennial scale over the past 750 years. Xu et al. (2007) found that the precipitation intensity of the East Asian summer monsoon was inversely related to that of the Indian monsoon on decadal to multi-decadal scales during the past 500 years, and suggested that the decadal to multi-decadal variability of ENSO may be responsible for this inverse relationship (Xu et al. 2007, and references therein). Overall, these comparisons suggest that the intensity of the Indian monsoon was not the dominant control on speleothem $\delta^{18}O$ variations in monsoonal China over centennial to decadal timescales.

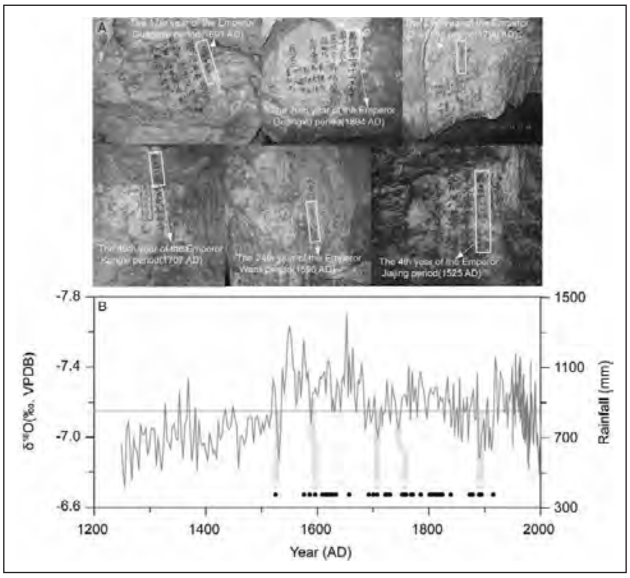

Figure 5.(A) Drought events recorded by ancient inscriptions inside Dayu Cave. The yellow panes indicate the dates of the inscriptions, and the red panes indicate drought records. (B) Comparison between drought events and the speleothem $\delta^{18}O$ record from Dayu Cave. The black dots indicate visits recorded in the cave, and the yellow squares indicate six drought events. The red line represents local monsoon rainfall (Jun.–Oct.).

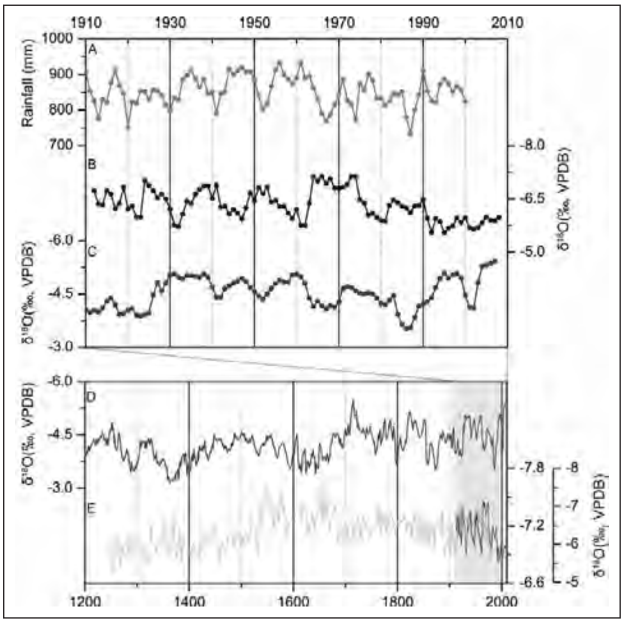

Figure 6.Upper panel shows (A) the Indian monsoon rainfall index (three point moving average, Parthasarathy et al. 1995), (B) the annual XL21 $\delta^{18}O$ record, and (C) the stalagmite $\delta^{18}O$ record from the core monsoon zone of India (Sinha et al. 2011) during the past 100 years. Lower panel compares the speleothem $\delta^{18}O$ records from (D) the core monsoon zone of India (Sinha et al. 2011) and (E) Dayu Cave (Tan et al. 2009b; 15 km north of Xianglong Cave) over the past 750 years.

4. Conclusions

A record of annual variations in $\delta^{18}O$ preserved in stalagmite XL21 from Xianglong Cave, central China, show close similarities with local monsoon precipitation (Jun.–Oct.) variations, suggesting that speleothem $\delta^{18}O$ variations in this area were mainly controlled by variations in the amount of monsoon precipitation. The *in situ* comparison between speleothem and historical records from another cave in this area further supports the inverse relationship between speleothem $\delta^{18}O$ and precipitation variations. The intensity of the EASM, and the activity of the WPSH in summer, control monsoon precipitation, and ultimately control variations in speleothem $\delta^{18}O$ in the study area. The speleothem $\delta^{18}O$ records from central China show anti-phase relationship with the stalagmite $\delta^{18}O$ record from India (Sinha et al. 2011), as well as with the Indian monsoon rainfall index (Parthasarathy et al. 1995), over decadal and centennial timescales during the last 750 years. This indicates that the intensity of the Indian monsoon was not the dominant influence on speleothem $\delta^{18}O$ in monsoonal China on centennial to decadal timescales.

Acknowledgements

This work was supported by the National Science Foundation of China (grant 41001061); Key Program of the Chinese Academy of Sciences (grant KZZD-EW-04-01); National Basic Research Program of China (grant 2013CB955902, 2010CB833405).

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Czech Republic, Brno

July 21–28, 2013

ISBN 978-80-87857-08-3