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S. 03 - Cave deposits
S. 08 - Archaeology and Palaeontology in caves

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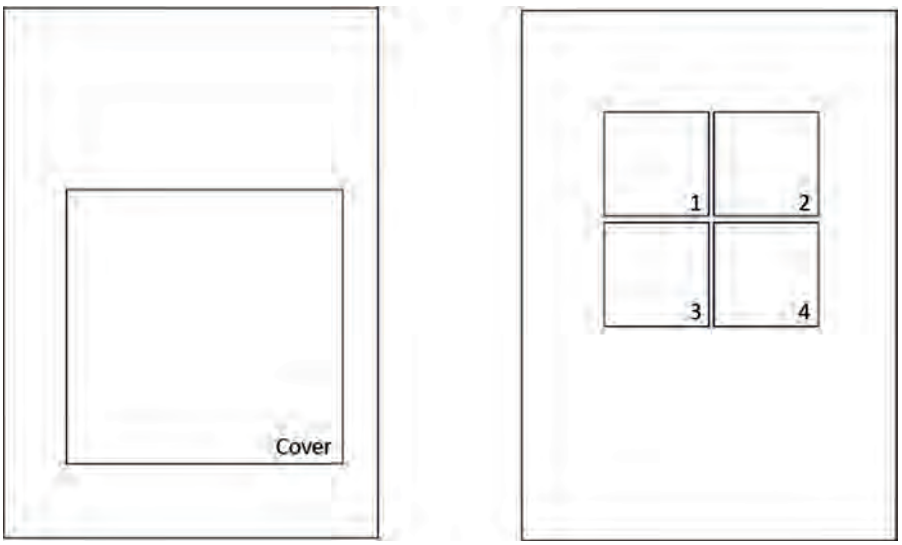

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1 : Butler Cave (Virginie, USA), Reliquat d'un remplissage. Philippe Crochet
2 : Grotte de Lombrives (Ariège, France). Boule de granite allochtone. Philippe Crochet
3 : Grotte du TM71 (Aude, France). Crâne d'ours calcifié. Philippe Crochet
4 : Grotte du Passe Muraille (Ardèche, France), prélèvement d'ossements. Stéphane Jaillet

Photo-frise sur la tranche, réalisée par Philippe Crochet et Annie Guiraud à la grotte de Saint-Marcel d'Ardèche, mai 2022

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INTERNATIONAL YEAR
2021
OF CAVES AND KARST

SYMPOSIUM 03

Cave deposits

Coordination: Carole NEHME (FR/LB) & Sophie VERHEYDEN (BE)

SYMPOSIUM 08

Archaeology and Palaeontology in caves

Coordination: Jean-Baptiste FOURVEL (FR) & Christophe GRIGGO (FR)

Symposium 03

Cave deposits

Cave deposits / Dépôts karstiques

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English

Caves are excellent traps for deposits, that disappear at the surface by continuous weathering. Detrital and organic material give insights on depositional processes in caves and thus on their morphological, hydrological and environmental controls through geological timescales. Chemical deposits and/or speleothems are one of the most versatile and high-resolution continental archives for regional climate. Their main strength is their ability to be precisely dated by U-series radiometric methods. Additionally, quartz or feldspar bearing sediments can be dated by luminescence or cosmogenic radionuclides. Besides informing on climatic parameters, soil and vegetation, cave deposits increase our knowledge in changing earth magnetic field, recurrent events (e.g. earthquakes, volcanism), and anthropogenic perturbations (e.g. deforestation, land use transfer of pollutants to aquifers). The study of the transfer of particles, organics and geochemical signals from the earth surface into and through the cave systems helps to better interpret the archives. Finally, caves host rare minerals that help us understand particular crystallization processes and the effect of microorganisms, but they can also just make us wonder about the immense creativity of nature.
Authors in this symposium investigate many cave deposits, using conventional and innovative methods. Speleothems are studied to reconstruct palaeoclimate and landscape dynamics (Columbu*, Honiat*, Kampolis*, Perrin*, Breitenbach*, Couchoud*b, Kilhavn*, Jaillet*, Verheyden*b, Avellan*, Nehme*), solar cycles (Shopov), talus changes in caves (Dubich*), earthquakes (Martin*) and chemical signatures of palaeo aquifers (Monteserin*), while Pilo* retrieve information from iron-ore cave speleothems. Spotl* identify glacial-age speleothems, while cryogenic cave carbonates are studied by Koltai*, Cleary*, and Martín-Pérez*. Both, Couchoud* and Faulkner & Crae investigate coastal regions through classical and tufa-like speleothems respectively. Monvoisin* give an overview and tips of coring methods, most useful to many of us to preserve cave landscapes. The combination of detrital deposits' investigation and speleothem chronology is a powerful tool to reconstruct both cave speleogenesis and regional palaeogeography as revealed in Ballesteros*, Marinić & Paar, Jagercikova* or Zupan Hajna*. Studies once again demonstrate how caves are useful information 'traps', *archive centers* of the Earth, e.g. the phosphate deposits in France by Lézin* and Puaud* or traces of human occupation by Puaud*b. McFarlane & Lundberg open perspectives in dating guano deposits while Delaby* reveal that cave bioturbations may erase human footprints in less than three months. More specifically, both detrital deposits (Nannoni*, Nogueira*) and speleothems (Pons-Branchu*) can help disentangle anthropogenic vs natural signals.
Mineralogical and crystallographic investigations are well-represented in the session, with increasing knowledge in aragonite to calcite transformation (Martín-García*) and in monocrystalline (De Waele & Forti), moonmilk (Bassel*) or silica deposits (Sauro*). New discoveries are still achieved with Lo Conte* describing strange 'cave coins' or Wisshak* investigating $BaSO_4$ speleothems, Onac* studying minerals of Sardinia, as well as (Tămaş) and (Šarç*) investigating rapidcreekite and cattiite respectively. Finally Verheyden draws a rough synthetic overview on the amount of publications in cave deposits.

: et al.

Français

Les cavités sont d'excellents pièges à dépôts qui tendent à disparaître en surface par l'érosion continue. Les dépôts détritiques et organiques ont la capacité de renseigner sur les processus de sédimentation, conditionnés par la morphologie, l'hydrologie et l'environnement au cours du temps géologique. Les dépôts chimiques et/ou spéléothèmes sont l'une des archives climatiques continentales les plus performantes et précises. Leur principal atout est leur capacité à être datées avec précision par les méthodes radiométriques de la série de l'uranium. Les dépôts riches en quartz ou feldspath, eux, peuvent être datés par luminescence ou radionucléides cosmogéniques. Outre le climat, le sol et la végétation, les dépôts souterrains renseignent sur l'évolution du champ magnétique terrestre, sur les événements (séismes, volcanisme) et les perturbations anthropiques (déforestation, utilisation du sol, pollution). L'étude du transfert de particules, matières organiques et signaux géochimiques de la surface vers et dans la cavité permet de mieux interpréter les archives. Enfin, les cavités contiennent des minéraux rares qui renseignent sur les processus de cristallisation et le rôle des microorganismes, ou qui, tout simplement, nous émerveillent de la créativité de la nature.
Les travaux du symposium concernent des dépôts karstiques variés, et des méthodes conventionnelles et innovantes. Les spéléothèmes sont étudiés pour la reconstruction du paléoclimat et de la dynamique du paysage (Columbu*, Honiat*, Kampolis*, Perrin*,

Breitenbach*, Couchoud*b, Kilhavn*, Jaillet*, Verheyden*b, Avellan*, Nehme*), les cycles solaires (Shopov), l'évolution des éboulis souterrains (Dubich*), les séismes (Martin*) et la géochimie de paléo-aquifères (Monteserin*) ; Pilo* étudie les stalagmites de cavités à minerais de fer. Spotl* identifient les spéléothèmes d'âge glaciaire, tandis que des carbonates cryogéniques sont analysées par Koltai*, Cleary* et Martín-Pérez*. Couchoud* et Faulkner & Crae se focalisent, eux, sur les régions côtières et les formations carbonatées classiques et tufacées. Monvoisin* donne un aperçu des méthodes de carottage, primordial pour préserver les paysages souterrains, et donne des conseils pratiques. L'analyse de dépôts détritiques combinée à la datation de spéléothèmes est intéressante pour reconstruire à la fois la spéléogenèse et la paléogéographie régionale, comme le démontrent bien Ballesteros*, Marinić & Paar, Jagercikova* ou Zupan Hajna*. Une fois de plus, ces études mettent en avant le rôle des cavités comme piège à sédiments, tels des *centres d'archives* de la terre, comme en témoignent les gisements de phosphate (Lézin*, Puaud*) ou les traces d'occupation humaine (Puaud*b). McFarlane & Lundberg ouvrent des perspectives dans la datation de guano tandis que Delaby* montrent des empreintes humaines effacées en moins de trois mois par des bioturbations. Enfin, Nannoni*, Nogueira* et Pons-Branchu* font la distinction entre signaux anthropiques et naturels dans les dépôts alluviaux et les spéléothèmes.
La minéralogie et la cristallographie sont bien représentées dans la session. Les connaissances avancent sur la transformation aragonite-calcite (Martín-García*), les spéléothèmes monocristallins (De Waele & Forti), le mondmilch (Bassel*) ou les dépôts silicatés (Sauro*). De nouvelles découvertes sont encore possibles comme celles de Lo Conte* décrivant des spéléothèmes en forme de pièce, Wisshak* enquêtant sur les spéléothèmes en $BaSO_4$, Onac* étudiant les minéraux en Sardaigne, et celles de Tămaş et Šarç* décrivant la rapidcreekite ou la cattiite). Enfin, Verheyden dresse une synthèse des publications sur les dépôts karstiques.

*: et al.

Water sampling in the Han-sur-Lesse cave, Belgium.
Échantillonnage d'eau dans la grotte de Han-sur-Lesse, Belgique

Internal microstratigraphy and lamination pattern as a tool for deciphering past hydrological conditions: a study case of a Middle Pleistocene stalagmite (Grotte de l'Été, Saône-et-Loire, France)

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Abstract

Stalagmite growth is governed by the water flux, the CO_2 saturation of drip water relative to the cave atmosphere, and temperature. These parameters are inter-related and linked to both climate and site-specific conditions of the karst hydrological dynamics. Petrography and microstratigraphy of speleothems have thus the potential to provide clues for deciphering the relationships between stalagmite fine-scale internal architecture and the hydrological conditions of stalagmite feeding, in particular variability of drip rate which in turn yields important climatic information. We report here on a lower-Middle-Pleistocene calcite stalagmite from the "Grotte de l'Été" (Saône-et-Loire). In our approach, we combine successive morphologies of the stalagmite apex, variations of stalagmite width, nature and occurrence of discontinuities and growth interruptions, facies and lamination characteristics, frequency of laminae, in order to infer their significance in terms of microenvironmental and hydrological changes. The results show that the integration of this information provides a consistent picture of the evolution of the rate of infiltration, its variability, and the state of saturation of the feed water, thus making it possible to reconstitute the history of the hydrology of the seepage site at the time of speleothem deposition.

Résumé

Architecture interne et patron de lamination pour déchiffrer les conditions paléohydrologiques: étude d'une stalagmite du Pléistocène moyen (Grotte de l'Été, Saône-et-Loire, France) La croissance des stalagmites est gouvernée par le débit d'alimentation, la pression partielle de CO_2 de l'eau d'infiltration par rapport à celle de l'air de la cavité, et la température. Ces paramètres sont interdépendants et liés au climat et aux conditions spécifiques du site en termes de dynamique hydrologique. La pétrographie et la microstratigraphie des stalagmites permettent ainsi d'appréhender les relations entre leur architecture interne et les conditions hydrologiques de leur alimentation, en particulier la variabilité du débit d'alimentation, qui à son tour livre des informations importantes sur le paléoclimat. Les travaux présentés ici portent sur une stalagmite calcitique du Pléistocène moyen inférieur de la Grotte de l'Été (Saône-et-Loire). L'approche analytique combine l'évolution de la morphologie sommitale et de la largeur de la concrétion, la nature et l'occurrence des discontinuités et des arrêts de croissance, les caractéristiques des faciès et de la lamination, pour en déduire des informations sur les changements environnementaux et hydrologiques. Les résultats montrent que l'intégration de ces informations constitue une image cohérente de l'évolution du taux d'infiltration, de sa variabilité et de l'état de saturation de l'eau d'alimentation, permettant ainsi de reconstituer l'histoire hydrologique du site d'infiltration au moment de la formation du spéléothème.

1. Introduction

Stalagmite growth is governed by climate at global and regional scales, and site-specific conditions of the karst hydrological dynamics, which in turn constrain the feeding drip conditions of each individual stalagmite. Beside climate, both physical (i.e., conditions of feeding water-flow) and chemical (i.e., geochemistry of groundwater) properties of water feeding speleothems exert strong controls on the crystal precipitates and thereby on petrographic and geochemical characteristics of speleothems. Therefore, reliable interpretation of proxies requires the prior understanding of the relationship between proxy and one or several climate parameters. For this purpose, a widely used method is cave monitoring, which allows present-day site-specific cave parameters to be linked to the external climatic and environmental conditions, as well as the driving factors of carbonate formation to be determined. However, these relationships may evolve through time and their present-day state may differ from those prevailing at the time of speleothem growth. Within the soil-karst-cave system, the groundwater flow feeding speleothems commonly bears two components: a rather diffuse slow long-residence time, high-storage infiltration, and a more rapid fissure-driven, short-residence time, low-storage flow component. Change in the functioning of the karst system can induce significant

changes in the infiltration conditions and in the feeding pattern of stalagmites at any drip site.
Petrography and microstratigraphy of speleothems have the potential to provide clues for deciphering the relationships between stalagmite fine-scale internal architecture and the local conditions of stalagmite feeding, in particular variations of drip rate together with hydrological information about the infiltration conditions and drip rate feeding the stalagmite at the time of its formation. This in turn yields valuable information about the local and regional past climate conditions.
For this study, an integrated approach has been developed for inferring past conditions of speleothem growth and local conditions of hydrological setting. This approach was then applied to a large stalagmite from the Été Cave in the Macônnais region which has been dated back from the lower Middle Pleistocene.

2. Materials and methods

The "Grotte de l'Été" is located in the Macônnais massif, north of Mâcon and two km north of the Azé Caves (Fig. 1), which belong to the same karst system (BARRIQUAND *et al.* 2011, DAUTUN *et al.* 2014). The cave is developed in limestones from the lower-middle Bajocian and Aalenian. "Grotte de l'Été" was discovered in 2014 by speleologists exploring the tunnel drilled in the early 1930's to transport water from the Goulouze source to the village of Saint-Gengoux-de-Scissé. The explored part of "Grotte de l'Été" corresponds to a large-sealed fossil gallery partly filled with coarse detrital and clay sediments, in which a flowstone, bearing the studied stalagmite ÉTÉ 1 was found. The base and top of this speleothem were dated by uranium-thorium and the ages obtained are at the limit of this technique (>400 ka). However, TOMBRET *et al.* (2017) showed that this speleothem probably formed between 500 and 600 ka.
The general methodological approach combines observations of nature and occurrence of discontinuities and growth interruptions, facies and lamination characteristics, successive morphologies of the stalagmite apex, variations of stalagmite widths, frequency of laminae, for inferring their significance in terms of microenvironmental and hydrological changes during speleothem growth. Observations of polished slabs parallel to the general median growth axis were performed with a stereomicroscope. Large thin sections were prepared continuously along the median growth axis of the stalagmite and observed with an optical microscope. Minerals were identified from their optical properties under the transmissive light microscope and from Raman microspectrometry operating with a 535.2 nm exciting line and a spectral window of 130-1800 cm^{-1}.

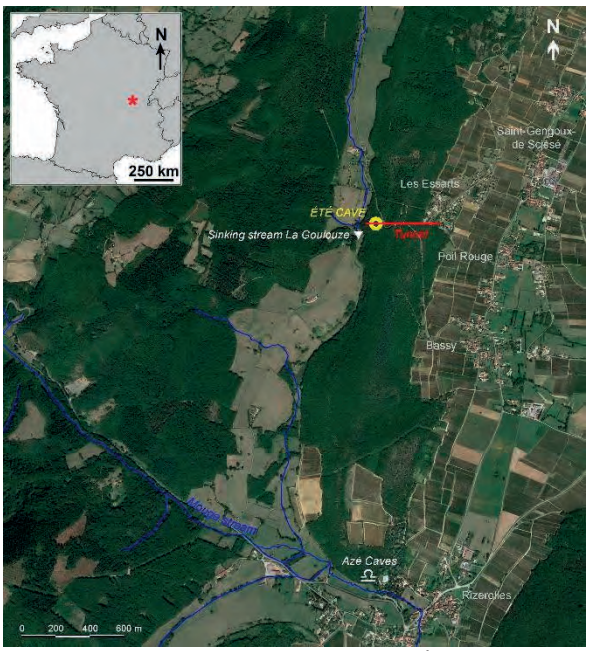

Figure 1: Localisation of the "Grotte de l'Été" *(aerial view Google Earth).*

3. Results

Mineralogy
Mineralogical identifications show that the speleothem is entirely formed by calcite. Small amounts of detrital material, chiefly clay, are included at level of some surfaces of discontinuities.

Facies and lamination
Two main petrofacies, both consisting of columnar calcite, can be easily recognized in the ÉTÉ 1 speleothem (Fig. 2). The compact columnar calcite has a brown-translucent aspect in the polished slabs and a transparent appearance under the optical microscope. The intra- and intercrystalline porosity is very low. The second facies corresponds to an open columnar calcite with high intracrystalline and intercrystallite primary microporosity. The elongated pores likely correspond to ancient and now-empty fluid inclusions. Variations of pore density from one level to the next form the lamination. This open columnar calcite has a rather white or whitish aspect on the polished slab and a more or less dark appearance under the light microscope.

Discontinuities and growth interruptions
Based on typology of discontinuities defined by previous authors (RAILSBACK *et al.* 2013, PERRIN *et al.* 2014, MARTÍN-CHIVELET *et al.* 2017), three main types of surfaces were identified in the studied sample: discontinuities associated with partial dissolution or type E surfaces *sensu* RAILSBACK *et al.* (2013), surfaces marked by a detrital clay deposit, and discontinuities resulting from abrupt facies change. Seven main surfaces of discontinuities (S1-S7) are clearly observed in the speleothem (Fig. 2). They form the boundaries of microstratigraphic units or sub-units.

Growth units
The speleothem displays five successive growth units (Fig. 2). The first two (U1 and U2) correspond to the formation of

flowstone dominated by the brown-translucent columnar fabrics. Units 3 and 4 represent transition phases between flowstone and stalagmite, and unit 5 reflects stalagmite growth. This succession therefore expresses major changes in feeding modes of the speleothem, from a lateral, mainly continuous flow feeding flowstone (units 1 and 2) to a drip-water fed stalagmite (unit 5).

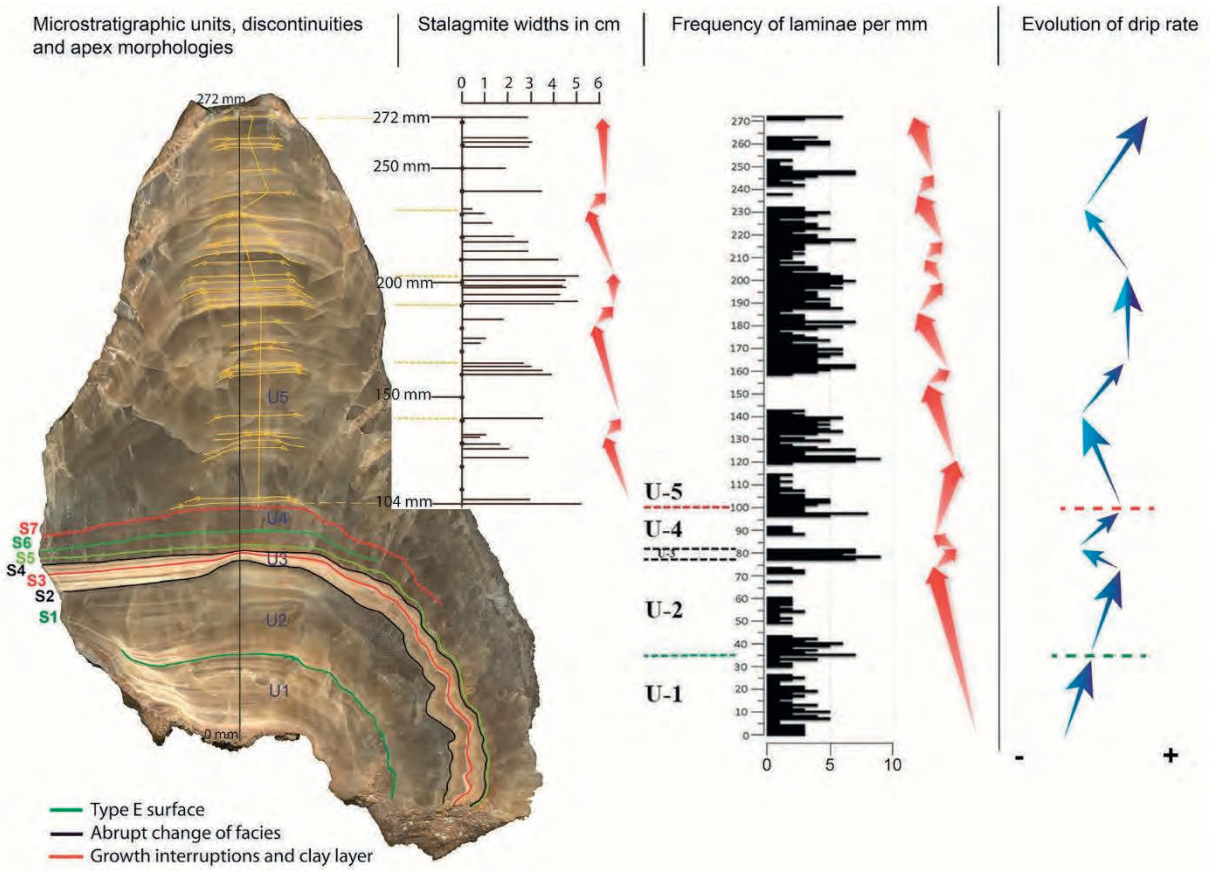

Figure 2: Summary of results obtained from the speleothem ÉTÉ 1 and interpretation in terms of variation of drip rate during speleothem growth. Red arrows denote trends of successive stalagmite width and frequency of laminae per mm, respectively. Blue arrows highlight the inferred evolution of drip rate.

Internal microstratigraphic features

We analyzed in detail some particular architectural speleothem features, which are known to be related to drip rate variability, following methodologies developed by BERTHAUX *et al.* (2002), MUÑOZ-GARCÍA *et al.* (2016), and MARTÍN-CHIVELET *et al.* (2017).

The frequency of laminae per millimeter is relatively low in the two first units (flowstone). It increases with a marked variability in the transition phase (units 3 and 4) and has intermediate and more stable values in the stalagmite phase (unit 5, Fig. 2).

During the stalagmite phase, the apex morphology changes from flat-topped meseta shape to frilled trilobal forms and vice versa. Concomitantly, variations of stalagmite widths show retractional, progradational and aggradational stacking patterns (Fig. 2).

Significance in terms of hydrological changes and drip rate variability

All these features combined provide a coherent picture of the evolution of drip rate, drip rate variability and saturation state of water feeding the speleothem through time.

During the flowstone phase (U1 and U2), the water supply feeding the speleothem was regular and increased successively in both units; enhanced degassing conditions of the thin water film favored the regular growth of compact columnar calcite crystals. The transition phase from flowstone to stalagmite (U3 and U4) corresponds to drastic changes in hydrological conditions characterized by a relatively high variability of water supply to the speleothem ÉTÉ 1. This is shown by abrupt facies changes from compact to open columnar calcite (and vice-versa), by the relatively high frequency of discontinuities (type E surfaces) and growth interruptions, and by the high variability of the number of laminae by thickness unit. During the stalagmite phase (U5), changes of the apex shape and stacking pattern reflect the succession of two decrease-increase cycles in drip water supply, separated by a period of rather constant drip rate (Fig. 2).

4. Conclusion

The speleothem ÉTÉ 1 records the growth of a flowstone which gradually evolves into a large stalagmite as a consequence of change in the source of water feeding the speleothem (i.e., lateral water flow to drip site). Some petrographic and microstratigraphic elements reflect the hydrological history of the speleothem and can be used to infer variability and regularity of water flow feeding the speleothem.

These first results are expected to provide an efficient tool for interpretation of the isotopic and geochemical data in terms of climatic and environmental changes. They also emphasize the value of such integrated approach for documenting hydrological history of drip site, in particular for fossil (e.g., non-still growing) speleothems or those for which *in situ* monitoring could not be undertaken or did not appear relevant.

Acknowledgments

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The Story behind the fluvial deposits in the Caumont chalk caves, France

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Abstract

The particular history of Caumont quarries and caves resulted in the availability of suitable stratigraphical sections of infill to study the cave evolution. In this sense, the stratigraphy of 16 sections were detailed and combined with microscopical observations, XRD analyses and U/Th datings of speleothems. The results helped us define four stratigraphical units. Both units 1 and 2 resulted from the erosion of the cave bedrock before from 300 to 127 ka, while the unit 3 included allochthonous sediments originally from the topographical surface. These sediments were introduced into the system through solution pipes during the Upper Pleistocene. Finally, the muddy unit 4 was deposited under slack-waters conditions. Overall, the infill of Caumont caves recorded the evolution of the karst during the last 300 ka, revealing the efficient connection between the endokarst and the plateau surface after 127 ka.

Résumé

Les dépôts fluviatiles dans les grottes de la craie de Caumont (Normandie, France). Les carrières et les grottes de Caumont présentent la particularité de recéler des remplissages dont la stratigraphie permet de reconstituer l'histoire. Dans ce but, les stratigraphies de 16 sections sont examinées au moyen d'observations microscopiques, d'analyses XRD et de datations U/Th de spéléothèmes. Ainsi, quatre unités stratigraphiques peuvent être identifiées qui permettent de reconstituer l'évolution de ce karst sur les 300.000 dernières années.

1. Introduction

Protected from surface weathering and erosion, cave deposits are superb archives of information on landscape and environmental change. They can provide the evidence required to unravel the evolution of karst systems and regional landscapes over 10^5-10^6 year timescales. However, this requires access to suitable deposits. Often, researchers are only able to access limited parts of any sedimentary deposits, usually those located at the top of detrital sections. The older parts and their internal characteristics often remain hidden unless revealed by natural processes or human excavation. This is especially true for caves formed in Upper Cretaceous Chalk, which are typically formed under paragenetic conditions (FARRANT et SMART, 2011). Most chalk caves are small and sediment filled.

This study documents the caves and their sediments revealed by underground stone extraction at Caumont, in northern France. Here, quarrying for building stone has cut through a network of natural, often sediment-filled cave passages. Caumont caves (Fig. 1) were discovered through the historical underground quarrying that lasted from the medieval period to the 19th century. Between 2018 and 2020, the IDEES Laboratory of the University of Rouen-Normandie conducted the *Archéomaterials, Territoire, Patrimoine* (ATP) project to study the historical underground quarries with the cooperation of the *Comité Régional de Spéléologie de Normandie* (CRSN) of the *Fédération Française de Spéléologie*. Caumont quarries supplied a particular type of high-quality chalk building stone since Gallo-Roman times (Ballesteros et al., 2021). In Caumont, quarrymen mined 12 km of galleries, intercepting active karst conduits filled with cave sediments. Speleologists subsequently explored these caves, often by partially excavating the cave infill (e.g., RODET, 1997; RODET et STAIGRE, 2019), discovering over two kilometers of natural cave passages. The discovery of this complex cave system has made Caumont caves a key site for the speleological community in Normandy (e.g., BEAUFILS, 2018) as no other karst caves in the Chalk areas of northern France rival the large development of Caumont system.

The caves and cave sediments at Caumont were first studied by RODET (1985, 2007, 2010), establishing their origin and development. The present research builds on this earlier work, aiming to reconstruct the regional paleoclimate and paleoenvironment of the Normandy region through the analysis of cave geomorphology and their associated speleothem and detrital deposits. NEHME *et al.* (2020) showed that cave development is linked to the incision of the Seine River over the past million years. Initial cave development was focused on certain low-permeability stratigraphical horizons in the Chalk succession including marl seams (thin clay beds), sheet flints and hardgrounds (mineralized beds that represents past seafloors). Groundwater flow concentration and subsequent mixing dissolution on these horizons, initiated conduit

development (BALLESTEROS *et al.,* 2020). These stratigraphical inception horizons are particularly numerous and well developed in Normandy, compared to southern England, where chalk caves are less common and smaller. Evidence from river terrace deposits and other caves in the Seine Valley suggest Caumont caves were initially formed c. 500-600 ka (NEHME et al., 2020). Uranium-thorium dating of a flowstone from the lowest level of Caumont system gives a minimum age of 301 ± 20 ka BP for base-level lowering and passage abandonment.

The focus of the current research is the reconstruction of the evolution of Caumont cave system from the Chibanian (Middle Pleistocene) to the present and linking this with the fluvial incision. This work combines geomorphological, geological, geochemical, and geochronological techniques to determine the speleogenesis of the system.

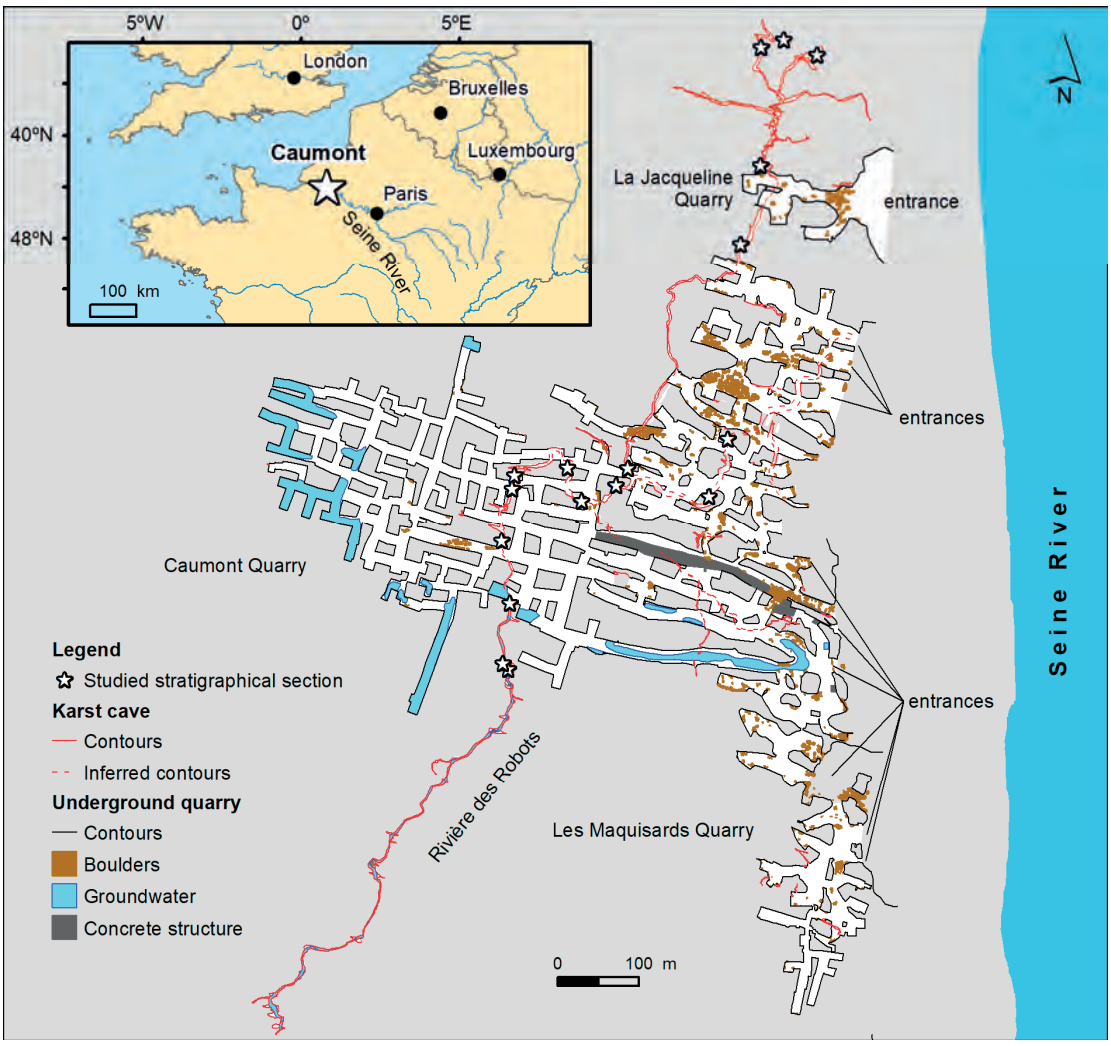

Figure 1: Location of Caumont quarries and caves in Normandy, northern France.

2. Materials and methods

This study used multiple techniques to reconstruct the cave geometry, to describe the mineralogy and texture of the sediments, and to constrain the age of the deposits. Together, the data enabled us to reconstruct a conceptual model of the evolution of the cave and its associated deposits. This work comprised five steps.

Step 1 was to undertake an accurate survey of the cave system and the quarry (Fig. 1) using a distometer laser range finder. The raw survey data was then computed using Compass software to create the georeferenced survey in a geographical information system.

Step 2 was the identification and description of fifteen sediment sections within the caves (Fig. 1). Detailed stratigraphical descriptions (lithology, texture, structure, thickness) helped defining similar sedimentary units between different sections throughout the cave system.

The third step was the analysis of thin sections. Ten thin sections of detrital layers were analyzed using an optical microscope (Leica) to identify the structure and texture of sediments, and to characterize the various minerals and clasts. A specific identification of certain key mineral phases, for example, metamorphic, igneous, and biogenic quartz, helped identifying the sources of the cave sediments.

Phase 4 was the analysis via X-Ray Diffraction (XRD) to identify the clay minerals. The abundance and/or absence of particular clay minerals can be related to the sedimentary

environment and the paleoclimatic context of its deposition. The final step was to constrain the age of the deposits using uranium-series dating. Speleothems located on the top of the sediments or within interbedded layers were dated to constrain the minimal and maximal age of sediment deposition.

3. Preliminary results and interpretations

Field evidence and more detailed observations enabled us to define four distinct and laterally continuous stratigraphical units separated by erosive uniformities. From the bottom to the top, the units are:

Unit 1: up to 0.5 m of dark orange-brown coarse sand to silt, showing up-fining sequences. Erosive channels, cross bedding and ripple lamination are locally present. Thin sections and clast lithology analysis show that the sand grains in Unit 1 are comprised of sub-angular igneous and metamorphic quartz, as well as flint (chert). These characteristics indicate that this unit corresponds to thalweg and channel facies, in which sediments were transported and deposited by streams.

Unit 2: 0.1 to 1 m of brown, frequently massive or thinly laminated silt and clay. The silt is comprised of igneous and metamorphic quartz. The sedimentary characteristics of Unit 2 correspond to active channel deposits associated with streams. A flowstone precipitated on the top of Unit 2, dated to 127 ka, has been partially eroded. The sediments were also eroded, leaving the remaining flowstone perched above the deposits as a false floor. This evidence suggests that Units 1 and 2 were deposited before 127 ka.

Unit 3 overlies units 1 and 2 and comprises 0.1 to 1 m of brownish-yellow silt and fine sand, with interbedded pebbles. These sediments constitute up-fining sequences with small pebbles defining an erosive surface at the bottom. Ripple and parallel lamination are recognized along the sequences, as well as interbedded Clay-with-Flint type deposits. The thin sections indicate that both the silt and sand grains are subangular and exhibit moderate sorting. Most of the grains are composed of metamorphic quartz. Flint, chalk, speleothem fragments and Eocene limestone clasts are also present. The unit is frequently overlain by speleothems. The up-fining sequences, sedimentary structures and clear channel facies indicate that the sediments were deposited in cave streams under high discharge conditions. Such flood events eroded previous speleothems and earlier sediments. The moderate sorting and restricted grain size suggest that much of the sediment was originally derived from the erosion of the Clay-with-Flints and aeolian deposits that cover much of the surrounding Normandy plateau. Here, the Clay-with-flint and aeolian sediments were introduced into the endokarst by debris-flow and collapse processes, probably via dissolution pipes. Two uranium-series dates of flowstone constrain the age of the Unit 3 to between 127 and 10 ka.

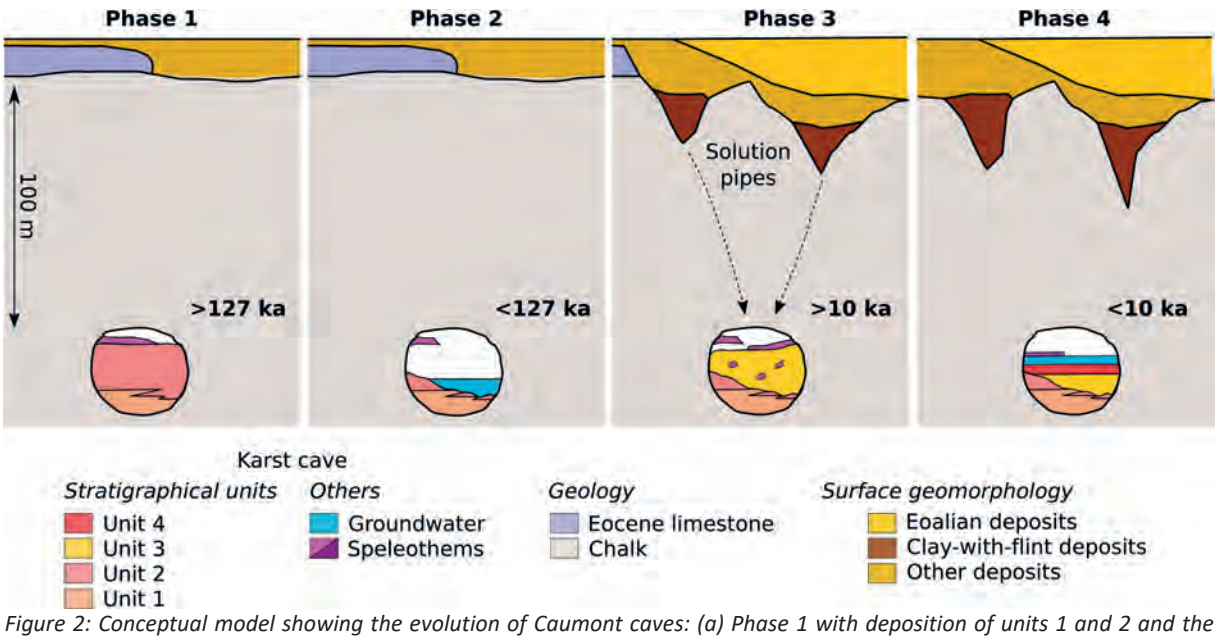

Figure 2: Conceptual model showing the evolution of Caumont caves: (a) Phase 1 with deposition of units 1 and 2 and the precipitation of a flowstone at 127 ka; (b) Phase 2 causing the partial erosion of previous units the flowstone formed 127 ka ago, remaining perched on sediment fills; (c) Phase 3 defined by the deposition of unit 3, involving allogenic sediments and clasts; and (d) phase 4, when cave passages were partially filled by groundwater, triggering the decanting of unit 4.

Unit 4: 5 to 90 cm of brown, sometimes silty massive clay. This unit is deposited directly over the bedrock or on the top of Units 2 and 3. The deposition of Unit 4 is most likely to have occurred in conduits partially or totally filled by water. This ponding is either due to a general water table rise by aggradation at the resurgence, or local ponding within the cave by other deposits, for example a rock-fall, that acted as a dam. A uranium-series dating suggests that the Unit 4 was formed mainly during the Holocene.

The identification of the four stratigraphical units enabled the construction of a preliminary history of the infill of Caumont caves since the Chibanian (Fig. 2). The evolution of the cave deposits can be divided into four phases:

The first phase was the deposition of Units 1 and 2 during the period between the estimated formation of the Caumont caves at c. 500-600 ka (Nehme *et al*., 2020) and 127 ka (Fig. 2). This was most likely during the onset of an interglacial period when underground drainage systems were active. The apparent lack of allochthonous sediments suggests that both units derived mainly from the erosion of the bedrock and autogenic surface deposits, with few if any allogenic inputs from outside the Caumont area. This phase of sedimentation ended with the draining of the cave and deposition of speleothems.

Phase 2 marked a change to erosion, with much of the previous Units 1 and 2 deposits being eroded. The overlying flowstone was locally undermined, causing the partial collapse of the flowstone deposits, the remains of which are preserved in the cave walls and floors (Fig. 2). This phase suggests changes in the drainage (e.g., lowering of the Seine river and sea level, wetter conditions).

The third phase was the deposition of Unit 3 under fluvial conditions during the Upper Pleistocene, sometime between 127 and 10 ka. The provenance of Unit 3 includes allochthonous materials including aeolian deposits and Eocene limestones, indicating a link to the surface (Fig. 2). Fragments of speleothems indicate some reworking of previous deposits.

The final phase prior was the partial erosion of previous deposits and infilling of the conduit by slack-water facies, probably after 10 ka BP (Fig. 2). This may relate to paragenetic sedimentation following base-level rise related to the Holocene sea-level rise and aggradation in the adjacent Seine Valley.

The intersection of the Caumont caves by quarrying and subsequent exploration has led to a reactivation of the conduit and flushing out of some of the sediments, creating the sections observed in this study.

4. Conclusions

The intersection of caves developed in Upper Cretaceous Chalk by quarrying has revealed sediment sections than can be used to decipher the history of cave development. Preliminary results identify four distinct stratigraphical units, deposited since the Chibanian. The initial phase of sedimentation, characterized by the deposition of coarse fluvial sand, silt and pebbles resulting from the erosion of the bedrock, was followed by a period of speleothem deposition. After 127 ka, groundwater floods eroded part of the cave infill. Renewed fluvial activity introduced allogenic sediments from the overlying plateau surface, including Eocene limestone, Clay-with-Flint and aeolian sediments. The final phase involved partial erosion of the sediment and the deposition of a slack-water facies, possibly related to Holocene aggradation of the Seine Valley.

Acknowledgments

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Crystallographic study of moonmilk: any tracers regarding the growing process?

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Abstract

Moonmilk is a common cave deposit extensively studied and well characterized, mainly composed of calcite needles called NFC (Needle Fiber Calcite) measuring few microns large and tens to hundreds of microns long. Nevertheless, one of the key remaining questions is the understanding of the growing process of these crystalline needles and the respective role of physico-chemical and biotic processes is still under debate. In order to address this question, an exhaustive work is performed on moonmilk samples coming from the Leye cave, located in the Vézère Valley (Dordogne, France) and considered as a laboratory cave being representative of the ornated cavities of this geographical area. In this work, synchrotron-based techniques allow the description of moonmilk at the interatomic level, looking for some tracers regarding the biotic or abiotic origin of the needles. Particular attention is given to potential structural and chemical defects as well as organic matter detection. The experiments carried out on three different beamlines at the Synchrotron SOLEIL will be presented and results as well as the issues raised by these analyses will be discussed.

Résumé

Étude cristallographique du mondmilch : à la recherche de traceurs d'une croissance organique ou inorganique. Fréquemment observé sur les parois des grottes, le mondmilch est un spéléothème largement étudié et bien caractérisé. Il s'agit d'un revêtement constitué d'aiguilles de calcite appelées NFC (Needle Fiber Calcite) qui mesurent quelques microns de large et quelques dizaines de microns de longueur. Pourtant, la compréhension des mécanismes de croissance de ces aiguilles cristallines demeure une question clé, et le rôle du processus mis en jeu, soit bioinduit soit purement physico-chimique, fait débat. Afin d'aborder cette question, un travail approfondi est mené sur des échantillons de mondmilch provenant de la grotte de Leye, située dans la vallée de la Vézère (Dordogne, France) et considérée comme une grotte laboratoire représentative des grottes ornées de la région. Dans ce travail, le rayonnement synchrotron permet de décrire le mondmilch à l'échelle interatomique, à la recherche d'éventuels traceurs d'une croissance organique ou inorganique. Une attention particulière est portée aux potentiels défauts structuraux et chimiques ainsi qu'à la détection de matière organique. Les expériences réalisées sur trois lignes distinctes au Synchrotron SOLEIL sont présentées, et les résultats ainsi que les problématiques soulevés par ces analyses sont discutés.

1. Introduction

Ornate walls of Paleolithic caves can be affected by the growth of a calcite coating called moonmilk, leading to conservation issues when it develops on parietal representations CAÑAVERAS *et al.* (1999), CHERVYATSOVA *et al.* (2014). Moonmilk is a common cave deposit extensively studied and well characterized, mainly composed of calcite needles called NFC (Needle Fiber Calcite) measuring few microns large and tens to hundreds of microns long VERRECCHIA & VERRECCHIA (1994). The NFC are presenting various morphologies when observed by Scanning Electron Microscopy (SEM) depending on the presence of epitaxial growth, their surfaces and edges appearance and whether the needles are coupled or not VERRECCHIA & VERRECCHIA (1994), CAILLEAU *et al.* (2009). One of the key remaining questions is the understanding of the growing process of these crystalline needles and the respective role of physico-chemical and biotic processes is still under debate BORSATO *et al.* (2000), CAÑAVERAS *et al.*

(2006). Exhaustive research on cave deposits is performed in a non ornated cave located in the Vézère Valley (Dordogne, France) since 2013 LACANETTE *et al.* (2013), BASSEL (2017), MAURAN *et al.* (2019). This work focuses on the crystallographic study of moonmilk samples with the help of synchrotron-based techniques, looking for some tracers regarding the biotic or abiotic origin of the needles. Moonmilk samples come from the Leye cave (Marquay, Dordogne), representative of the surroundings rock-art caves and thus considered as a laboratory cave. Other samples come from two others non ornated caves situated in the Vézère Valley (Pilier cave and Racine cave) in order to consider the multi-site variability. X-Rays diffraction analyses on bulk samples and on single NFC crystals as well as micro-spectrofluorimetry measurements were realized.

2. Materials and methods

Sample collection was conducted in all the areas presenting moonmilk deposits to ensure the representativeness of such deposits in three caves: Leye, Pilier and Racine (Figs. 1a and b). The analyzes were carried out at the Synchrotron Soleil (L'Orme des Merisiers, Saint-Aubin, France) on three different beamlines. Single crystal diffraction measurements were realized on the PROXIMA 2 beamline at 100 K with the X-ray beam energy set at 18 keV. Each crystal was manually mounted on a loop and put onto the goniometer head (Fig. 1c). Three measurements were done along the growth axis to reveal possible differences. A full set of diffraction spots for 20 needles of moonmilk single crystals were recorded. Diffraction measurements on polycrystalline bulk samples, prepared as cross-sections embedded in resin and polished (Fig. 1d), were done on the DiffAbs beamline at 18 keV. On the DISCO beamline, micro-spectrofluorimetry measurements were performed at the POLYPHEME endstation with an excitation at 270 nm and the spectrometer centered at 430 nm, in order to check the presence of chemical impurities and organic matter. Some powder was scratched off from the raw samples and scanned under the microscope (×40 objective) to select needles with particular features (Fig. 1e). Attention was given to analyse all the different morphologies observed: NFC with smooth edges, with serrated edges, with orthogonal outgrowths, intercepts of two needles and clusters of small crystals. The emission spectra were collected under the same conditions (20 seconds acquisition time per pixel, 0.5 µm spot size, 310 nm-600 nm collection range).

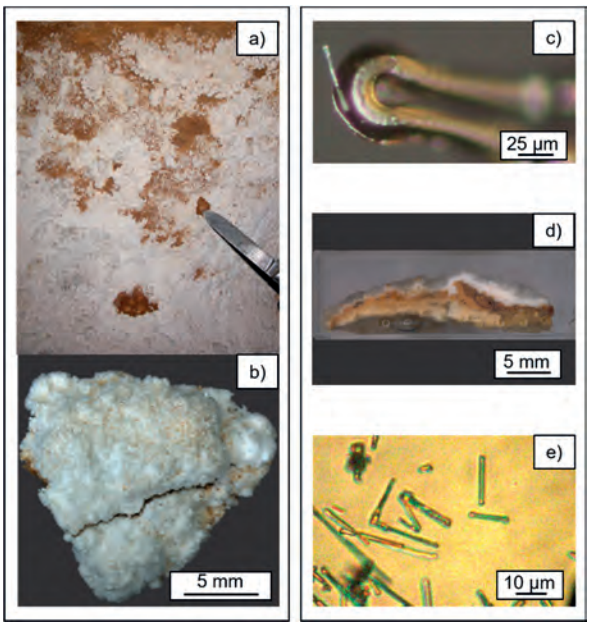

Figure 1: Moonmilk sampling and sample preparation for the synchrotron-based analyses. a) General view of wall covered with moonmilk in the Leye cave and sample localization; b) typical moonmilk sample; c) single NFC mounted on a loop for PROXIMA-2 beamline; d) moonmilk cross-section for DiffAbs beamline; e) NFC powder on a quartz plate observed under the microscope at DISCO beamline.

3. Results

In a general way, for each single needle analysed on PROXIMA 2 beamline, the recorded diffraction spots were very thin and well-defined indicating that the NFC crystals were close to perfect crystals. No particular change was observed, neither between the different measurements on the same NFC, nor between different needles. Nevertheless, a few NFC displayed a splitting or a broadening of the specific Bragg reflection over reciprocal space (see the enlargement of the 0 1 14 node Fig. 2). Moreover, diffuse X-ray scattering signal appears between intensity maxima of the split nodes. Such feature is probably the signature of structural defects that may be stacking faults along the *c*-axis. As expected, the space group of the NFC crystals is the rhombohedral $R\bar{3}c$. However, sometimes, a loss of the three-fold symmetry axis was noted, resulting in the corresponding space group *C2/c*, which is a monoclinic sub-group of the original $R\bar{3}c$ group.

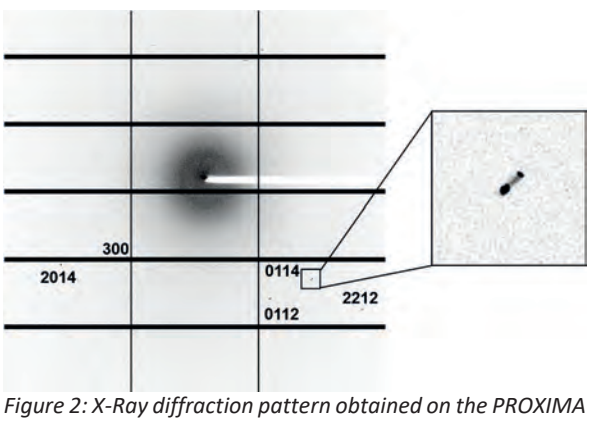

Figure 2: X-Ray diffraction pattern obtained on the PROXIMA 2 beamline for an NFC corresponding to sample GDr_2A from the Leye cave. Observation of diffuse scattering signal around the 0114 reciprocal space node of calcite.

We don't know if such *C2/c* crystal setting corresponds to a post growing phase transition process or to a growth under a space group alternative to the conventional $R\bar{3}c$ one. Nevertheless, it may be related to the presence of stacking faults, which seem to appear along the 3-fold *c*-axis of the $R\bar{3}c$.

Regarding the polycrystalline diffraction measurement on the samples prepared as cross-sections, we run into some experimental difficulties, inherent to the material's characteristics. In fact, the NFC size appeared to be too important compared to the volume probed by the X-ray beam. The right section of the X-ray beam was close to 0.2 mm and according to the beam energy, the value of the penetration depth was of the same order. As written above, the length of a crystal is of a few tens of microns and thus the limited number of irradiated crystals was too low, and we observed spotty Debye-Scherrer rings even using a continuous rotation of the samples (Figs. 3a and 3b). The possibility to perform an accurate line profile analysis in order to extract microstructural characteristics is precluded. However, although it was out of the scope of the initial experiment, since each spot located on the observed rings corresponds to the diffraction of a specific crystal, it was possible then to depict the influence of crystal defects by selecting an indexed spot. Indeed, the reconstruction of some of the 3D reciprocal space maps close to a few reciprocal lattice nodes (RLN) provided insights to the entire scattering signal and showed the presence of diffuse scattering.

Micro-spectrofluorimetry measurements on needles with various morphologies did not highlight significant signal variation, neither along a needle nor between them. The spectra were characterized by a large massif above 400 nm of variable intensity. However, on clusters of small crystals a broad band centered around 335 nm was systematically observed (Figs. 4a and 4b).

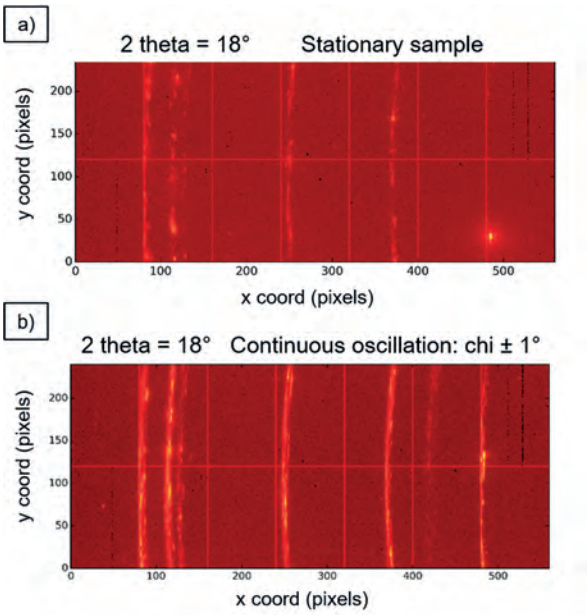

Figure 3: 2D diffraction images recorded on DiffAbs beamline of the bulk sample SdT_11 coming from Leye cave. The Debye-Scherrer rings are spotty. a) without any movement of the sample; b) with continuous oscillation of the sample.

The same band, occasionally also observed at the intercept of two NFC, is supposed to be of organic origin attributed to cell remnants JAMME *et al.* (2013). This signal disappears under beam irradiation, showing that the organic matter deteriorates (Fig. 4c).

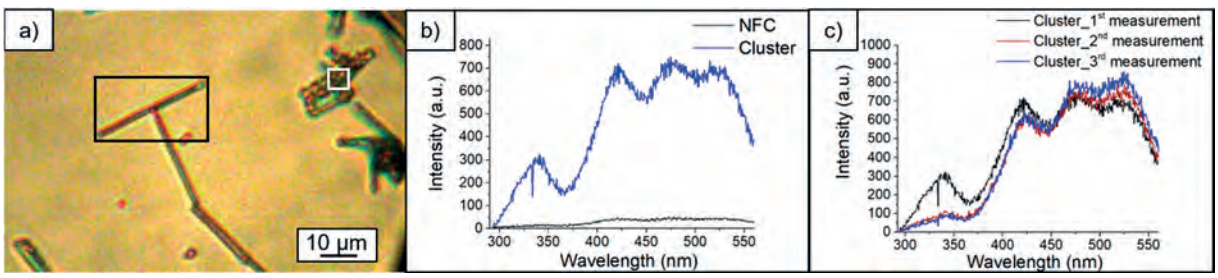

Figure 4: Organic signal detected on DISCO beamline. a) Optical image of the analyzed NFC (black rectangle) and the cluster (white square); b) Comparison between the NFC mean emission spectrum and the cluster mean emission spectrum. For the black rectangle area, the mean spectrum is calculated by selecting only the pixels mapping the NFC; c) Evolution of the organic signal on the cluster with the irradiation.

4. Discussions

The NFC composing moonmilk samples in the three studied caves appeared to be very pure crystals based on the single crystal diffraction measurements. According to the literature, crystals grown by microorganisms in natural environments, are supposed to show more defects than crystals grown by a total abiotic process FAIVRE *et al.* (2005). On the contrary, some organic signal was detected on small aggregates constituting the moonmilk bulk samples as well as at the junction between two NFC. The nature of these clusters has to be precised as no mention about this moonmilk component exists so far. The detection of organic bands is in progress with the aid of Time of Flight – Secondary Ion Mass Spectrometry (ToF-SIMS) analyses, allowing the identification of CNO or CN bonds. Moreover, an additional work is in progress in order to characterize NFC growth conditions. Along a single crystal, the determination

of local chemical variations if detected could indicate some changes during the crystallization process SUGANAWA (2005), STALPORT *et al.* (2005). X-rays fluorescence mapping of single NFC and clusters with a spatial resolution of 150 nm is performed on Nanoscopium beamline. In addition, one aspect highlighted by this study, in particular regarding the polycrystalline diffraction measurement, is the difficulty to analyze the moonmilk samples in their most natural form possible. We chose indeed to minimise the impact of the sample preparation necessary for each beamline and avoid for instance any grinding of the NFC in order to better interpret the collected data and link it more easily with the raw material as present in its natural form.

5. Conclusion

The obtained results do not favour any scenario regarding the NFC crystallization process. Additional analyses need to be undertaken in order to reach to robust conclusions. Finally, when it comes to non-routine analytical methods, as it is the case with synchrotron-based techniques and specifically when applied to natural cave materials, reaching the compromise between adapting the sample to the analytical technique or conversely is a challenging point.

Acknowledgments

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Glacial-interglacial environmental changes recorded in Sarma Cave, Northwestern Caucasus

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Abstract

Although hosting the deepest cave of the world, so far, no speleothem-based proxy records are available from the Caucasus. Using $\delta^{18}O$, $\delta^{13}C$, Sr/Ca and S/Ca ratios from a stalagmite from Sarma Cave we reconstruct environmental changes from the last glacial to the mid Holocene. Stalagmite SAR-12-1 grew during two intervals, first in the Last Glacial Maximum (LGM, 23–21 ka BP), and then the Holocene (8.5–3 ka BP). Stalagmite growth during the LGM indicates absence of permafrost, despite the high elevation of the cave. Petrographic evidence suggests the stalagmite broke repeatedly, with an observed hiatus being unrelated to climatic or flow path characteristics. High Sr/Ca and $\delta^{13}C$ values indicate significant prior calcite precipitation (PCP) and drier conditions during the LGM. The LGM $\delta^{18}O$ signal might be explained by altered precipitation seasonality with increased summer rainfall proportion. Lower $\delta^{13}C$ and Sr/Ca values in the Holocene suggest enhanced soil development and reduced PCP. Holocene $\delta^{18}O$ changes are tentatively linked to moisture source dynamics associated with the westerlies. Our preliminary results suggest that Sarma Cave constitutes a promising archive for reconstructing regional environmental changes.

Résumé

Enregistrements des changements environnementaux inter-glaciaires dans la grotte Samra, nord-ouest du Caucase. Le Caucase est connu pour abriter le gouffre le plus profond au monde (grotte Veryovkina, -2200 m). Pourtant, aucune étude paléoclimatique basée sur l'analyse de spéléothèmes dans cette région n'a été publiée. Une stalagmite récemment prélevée de la grotte de Samra en Géorgie a été datée et analysée ($\delta^{18}O$, $\delta^{13}C$, Sr/Ca et S/Ca), dans l'objectif de reconstruire les changements environnementaux passés de cette région montagneuse. La stalagmite SAR-12-1 s'est développée pendant deux intervalles, d'abord durant le dernier maximum glaciaire (LGM, 23–21 ka BP), puis durant l'Holocène (8,5–3 ka BP). La croissance des stalagmites pendant le LGM indique l'absence de pergélisol, malgré la haute altitude de la cavité. Des valeurs élevées de Sr/Ca et positives de $\delta^{13}C$ indiquent une précipitation antérieure significative de la calcite (PCP) dans la zone vadose et des conditions plus sèches durant le LGM. Le signal $\delta^{18}O$ pendant la période glaciaire peut s'expliquer par une modification de la saisonnalité des précipitations avec une augmentation des précipitations estivales. Des valeurs faibles de Sr/Ca et négative de $\delta^{13}C$ durant l'Holocène suggèrent une meilleure activité bio-pédologique du sol et une réduction du PCP. Les variabilités dans le signal $\delta^{18}O$ au cours de l'Holocène sont provisoirement liées à la dynamique de la source d'humidité associée aux vents d'ouest. Nos résultats préliminaires suggèrent que la grotte de Sarma constitue une archive prometteuse pour la reconstruction des changements climatiques régionaux.

1. Introduction

The west-east oriented Caucasus and its adjacent piedmonts constitute a formidable barrier for northward migrating early humans, but also as a rich habitat for those moving west or east. These characteristics make the Caucasus and the Georgian lowlands a focal point for archaeological research (e.g., PLEURDEAU et al. 2016). Palaeoclimatic studies build the environmental framework into which the archaeological findings must be embedded to grasp the context in which these remains were formed and deposited. Currently, only few detailed and well-dated palaeoenvironmental and palaeoclimatic records are available from this region. Terrestrial archives include pollen-based vegetation reconstructions (CONNOR & KVAVADZE 2009), while sediments from the Black Sea inform on Holocene continental runoff (LAMY et al. 2017) and glacial temperature changes (WEGWERTH et al. 2015).

These reconstructions generally suffer from poor chronological control, thereby limiting our ability to directly link local and regional environmental changes to rapid climatic shifts and human adaptation or mitigation efforts. Under favourable geographical conditions, stalagmites form powerful terrestrial archives from which a range of climatically sensitive proxies can be extracted to reconstruct past environmental dynamics (LACHNIET 2009, FAIRCHILD & BAKER 2012). Despite the importance of detailed regional palaeoclimate reconstructions, and the abundance of caves in the northwest Caucasus and Abkhazia (which hosts the deepest caves worldwide), speleothem-based proxy records have not been reported yet. We present preliminary results from a stalagmite that grew in Sarma Cave and discuss environmental and climatic changes since the LGM. Besides $\delta^{18}O$ and $\delta^{13}C$ ratios we use µXRF-based Sr/Ca and S/Ca ratios to reconstruct hydrological changes and associated shifts in soil conditions above the cave. We evaluate our data in relation to LGM permafrost above Sarma Cave and discuss how multi-proxy data can inform about local moisture conditions. We then test how oxygen isotope ratios reflect regional circulation changes and potential changes in hydrological seasonality, i.e., the relative contribution of winter and summer moisture to the stalagmite isotope signal.

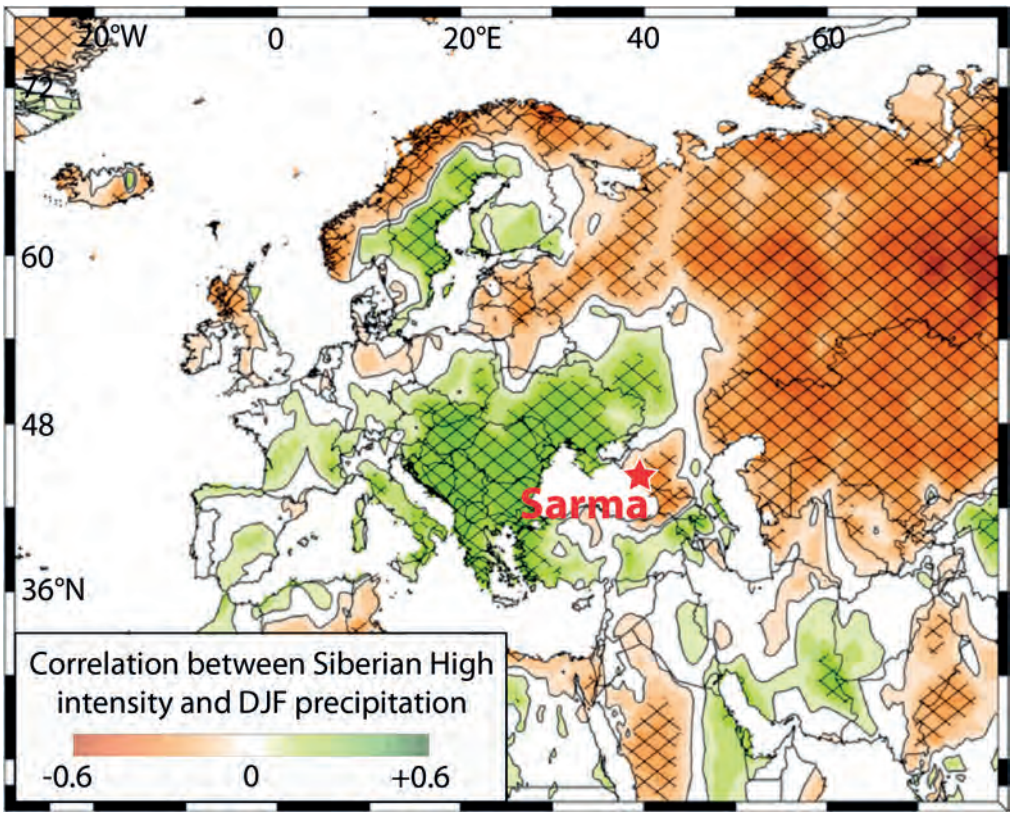

Figure 1: Location of the Arabika karst plateau and Sarma Cave in the northwest Caucasus. The green and brown shading indicates positive and negative correlations between winter (Dec.-Feb.) precipitation and Siberian High index, respectively. Hatching indicates regions with correlations significant at the 95% level. Figure adopted from PERSOIU et al. 2019. The Arabika karst plateau receives significantly less winter precipitation when the Siberian High is particularly strong.

2. Settings, material and methods

A broken stalagmite (SAR-12-1) was recovered in 2010 from ca. 100 m depth from Sarma Cave, located in the Arabika karst plateau in Abkhazia, northwest Caucasus, near the eastern seaboard of the Black Sea (Fig. 1). Reaching a depth of 1830 m Sarma Cave is currently the 3rd deepest cave worldwide. The climate on the plateau can be described as temperate warm, humid alpine, with dry summers and significant cold season precipitation (Csb climate in the Köppen-Geiger classification, PEEL et al. 2007).

The region receives ca. 2260 mm of annual precipitation, and the mean annual air temperature is 14°C (CONNOR & KVAVADZE 2009). The soils on the plateau are poorly developed and thin, which is reflected by the sparse vegetation cover characterised by alpine meadows. Sarma Cave receives most of its moisture from winter snowfall. Drier than normal winters occur when the Siberian High is particularly strong.

Under such conditions, the moisture-bearing westerlies are diverted southward and cold, dry air reaches the karst plateau from the northeast. During summer, strong and sudden thunderstorms can lead to flooding of some cave passages and present a danger to cavers. However, summer rainfall is less significant than winter snowfall.

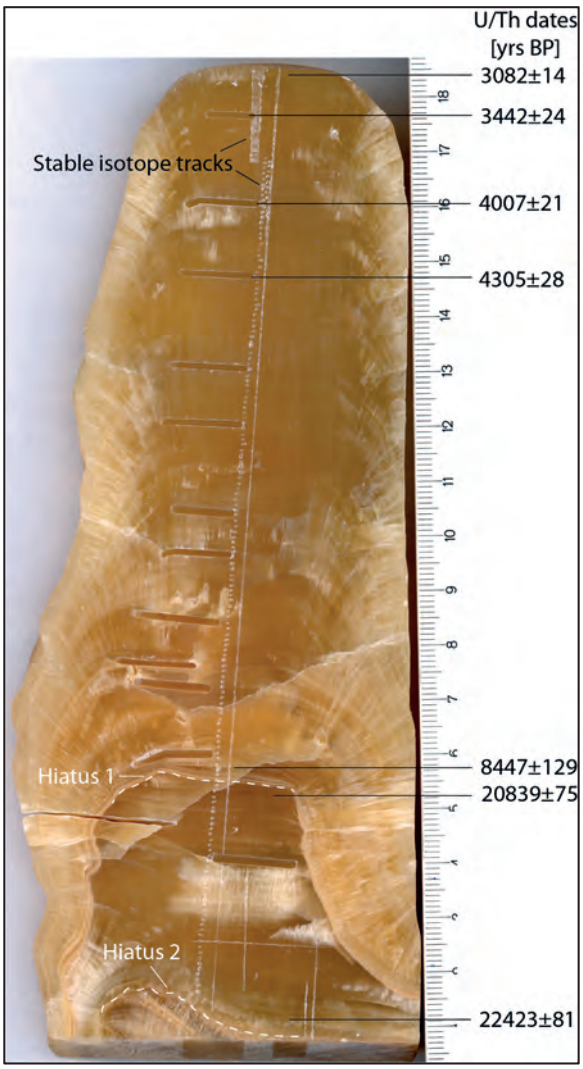

Figure 2: Polished section of stalagmite SAR-12-2 with the U-series samples and stable isotope sampling tracks. Two hiatuses are identified as breakage; the lower one is irrelevant for this study. The µXRF maps (not shown) follow the isotope track.

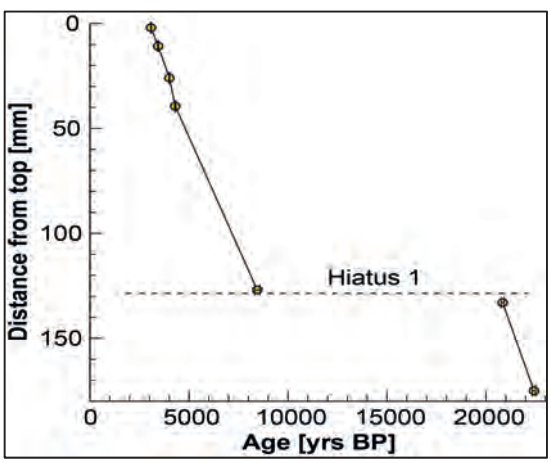

Figure 3: Current age-depth model of SAR-12-1. Similar growth rates are found in the LGM and Holocene. U/Th dates are shown with 2σ uncertainties.

The cave has not been monitored in detail yet but is characterised by ~4-8°C air temperature (RUDKO et al. 2010) and strong ventilation in some passages. The cave is fed by a very small catchment of only a few hectares.

The stalagmite is ~18 cm long and consists of yellowish-brown calcite (Fig. 2). After cutting/polishing two hiatuses are visible in the lower part, with petrographic inspection suggesting breakage, rather than lack of water as the cause of this growth interruption. Hiatus 1 separates the LGM from the Holocene growth interval, while hiatus 2 occurred at the base of the stalagmite sample. Currently, we have no data to constrain the age of hiatus 2. Fifteen samples have been drilled for U/Th dating of which seven have been analysed so far with a ThermoFisher Neptune multi-collector inductively-coupled plasma mass spectrometer in the Xi'an geochronological laboratory. 288 powder samples were manually drilled every 0.1 mm to 1.0 mm for stable isotope analysis and analysed using a IsoPrime 100 mass spectrometer equipped with a Multi-Prep device at the Institute of Earth Environment of the Chinese Academy of Sciences. The external analytical uncertainty of the stable isotope analysis is ~0.08 ‰ for both, $\delta^{18}O$ and $\delta^{13}C$.

High-resolution (50 µm) µXRF maps were constructed using a Bruker M4 Tornado µXRF scanner at the GFZ Potsdam. Only Sr and S were found to have sufficient signal-to-noise ratios and we report only Sr/Ca and S/Ca ratios.

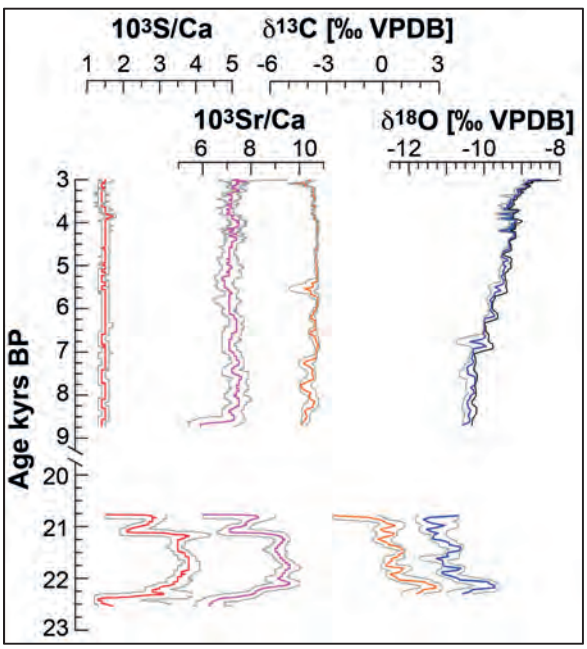

Figure 4: Multi-proxy profiles from SAR-12-1. S/Ca indicates soil conditions, Sr/Ca and $\delta^{13}C$ reflect PCP dynamics, and $\delta^{18}O$ tracks moisture history.

3. Results

Stalagmite SAR-12-1 was deposited between 22 and 20 ka BP (the LGM), while the section above this hiatus covers a large portion of the Holocene period (ca. 8.5 to 3 ka BP) (Fig. 2). U/Th dating indicates similar growth rates (ca. 0.025 mm/a) during LGM and Holocene. Stable carbon isotope ratios vary from -1 to +3 ‰ in the LGM, to -3.5 to -5.5 ‰ during the Holocene. Oxygen stable isotope ratios range from -9.5 to -11.5 ‰ during the LGM and -8.5 to -10.5 ‰ in the Holocene. The temporal resolution of the $\delta^{18}O$ and $\delta^{13}C$ profiles is 5 and 15 years. LGM Sr/Ca ratios vary between 9.5 and ca. 7, while in the Holocene values are rather stable between 6.5 and 7.5. Similarly, S/Ca ratios are much higher during the LGM, with values ranging from 4.5 to 1.5, and virtually stable at ca. 1.5 in the Holocene. The temporal resolution of the Sr/Ca and S/Ca profiles is ca. two years. We observe a strong correlation between $\delta^{18}O$ and $\delta^{13}C$ during the LGM; this relationship breaks down in the Holocene. Similarly, Sr/Ca and S/Ca covary during the LGM.

4. Discussion

Stalagmite SAR-12-1 provides important insights into local and regional environmental and climatic changes since the LGM. The first important information is derived from the fact that the stalagmite grew during the LGM: apparently, the Arabika karst plateau did not cool sufficiently to allow the development of continuous permafrost atop Sarma Cave, which would have precluded infiltration and thereby speleothem deposition (VAKS et *al*. 2020). With current cave air temperature between +4 and +8°C, this suggests only moderate lowering of the mean surface air temperature. Further details on glacial and Holocene conditions can be derived from our multiproxy record (Fig. 4). The S/Ca record indicates reduced sulfur retention potential in the soil during the LGM, whereas Holocene soil development allowed more efficient sulfur retention. The Sr/Ca and $\delta^{13}C$ profiles indicate PCP dynamics in the epikarst and cave. Higher values during the LGM suggest drier conditions, with significant PCP. Improved infiltration and less/absent PCP in the Holocene led to lower Sr/Ca values and reduced kinetic alteration of the $\delta^{13}C$ signal. The $\delta^{18}O$ record reflects more complex moisture changes. Low LGM values suggest increased winter precipitation, deposited during colder winters. The positive trend in the Holocene $\delta^{18}O$ record likely results from a northward shift of the westerlies, reduced winter snowfall, and increased summer rainfall.

5. Conclusions

Sarma Cave gives important insights into local and regional environmental changes in the northwest Caucasus since the LGM. The glacial was likely characterized by increased winter precipitation, but overall drier conditions with absent permafrost and poor soil cover on the Arabika plateau. Holocene conditions improved inasmuch summer rainfall increased, allowing soil development, and winter precipitation became less important (albeit still significant today). The new record thus suggests a change in hydrological seasonality. Current work focusses on likely pan-regional adjustments of the atmospheric circulation, and potential links between the stalagmite's $\delta^{18}O$ signal and moisture source history.

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Bladed stalactites: an unusual occurrence of cryogenic speleothem subtype

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Abstract

Over the past decade, cryogenic cave carbonates have been recognized in several presently or formerly glaciated karst caves. In a majority of these occurrences, they precipitated as loose grains or aggregates with various morphologies and sizes. Based on carbon and oxygen stable isotope analysis, researchers proposed the freezing of water as the driving force behind their genesis. Here, we report on a particular subtype of speleothem (bladed stalactite) identified in Sohodoalele Mici Cave (SW Romania), within a large chamber at the bottom of the entrance shaft. What drew our attention was the presence of calcite blades protruding out and covering the entire surface of stalactites. The observation that during winter these stalactites are enveloped by a thin ice layer guided our study. Stable isotope and U-series analysis were performed on calcite of both the stalactite core and its blades. The higher $\delta^{13}C$ (−3.5 to 0‰) and $\delta^{18}O$ (−1 to 7‰) values found in the blade calcite compared with the inner stalactite's calcite indicate rapid carbon dioxide degassing associated with precipitation during the freezing of water. Two U-series dates indicate that the bladed stalactite formed in the Middle Holocene at 6.4 ± 0.6 and 6.3 ± 3.2 ka.

1. Introduction

Cryogenic cave calcite (CCC) has been documented in a variety of cold environments (HUBBARD & HUBBARD, 1998; ZAK *et al*., 2004; LACELLE *et al*., 2006), but has received relatively little consideration in karst studies. In classic ice caves, CCC form as precipitated grains of varying size (0.1 – 1 cm in diameter) that accumulate on the cave floor (ZAK *et al*., 2018). Other CCC forms have been recognized as aufeis that precipitate in periglacial environments as well as in lakes and the surface of clasts in deglaciated regions (CLARK & LAURIOL, 1992; BLAKE, 2005; LACELLE *et al*., 2006). As accumulated grains, distinction is made by morphology and size, where fine grained CCC powder is the result of the fast-freezing water and coarse-grained CCC cave pearls from the slow freezing of water (ZAK *et al*., 2008). CCC are overwhelmingly recognized as speleothems that occur over different elevation ranges in cave hosting perennial ice deposits at high and mid latitudes.

2. Site and sample description

Sohodoalele Mici Cave is located in the Mehedinți Mountains (SW Romania, Fig. 1A). It is a short (210 m) Y-shaped cavity, accessible only via a 7 m deep shaft. The ventilation regime is seasonal bi-directional; the cold winter air sinks through the entrance along the floor, pushing warmer air along the ceiling and out of the cave, whereas in summer, the direction of air circulation reverses but is limited to the upper part of the entrance shaft.

The cave does not feature a perennial ice block, still, stalactites covered by ice and with a specific boxwork structure were noticed by POVARA & DIACONU (1974).

The bladed stalactite analyzed in this study is 15.1 cm long and a maximum width of 3.8 cm (Fig. 1B). Boxwork calcite has primarily precipitated parallel to the growth axis, although a few occur perpendicular to it. The size of the boxwork ranges from 1 to 4 mm.

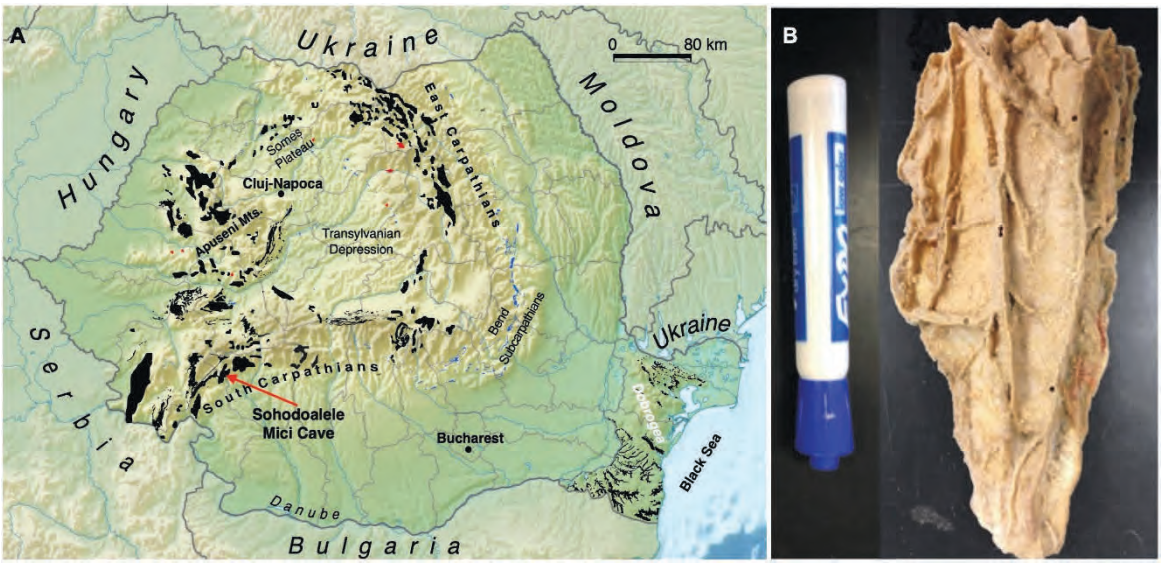

Figure 1: A: Location of the Sohodoalele Mici Cave in SW Romania.
The black areas represent karst on carbonate rocks; B: Image of a bladed stalactite.

3. Methodology

Ninety-two carbonate powders were carefully drilled along and across different layers, on a horizontal and a vertical cross sectional transect, around a single growth layer, and across the boxwork calcite. All these carbonate powders were analyzed for oxygen and carbon isotopic ratios using a Thermo Delta V isotope ratio mass spectrometer at the Stable Isotope Laboratory, School of Geosciences, University of South Florida, USA.

Two samples from both a boxwork and non-boxwork calcite were dated in the Radiogenic Laboratory at the University of New Mexico, in an effort to constrain the timing of stalactite growth.

4. Results and discussion

The isotopic analysis identifies two groups of data: calcite powders from the non-box work have $\delta^{18}O$ and $\delta^{13}C$ values between –7 and –3.5‰ and –9 and –2‰, respectively. In contrast, the boxwork calcite has more positive values for both $\delta^{18}O$ (–3.5 to 0‰) and $\delta^{13}C$ (–1 to 7‰). These results indicate that a freeze-thaw mechanism is the most probable explanation for the morphology of the bladed stalactites. The ^{230}Th dating results indicate that the non-boxwork calcite precipitated at 6.4 ± 0.6 ka BP. However, it was difficult to precisely date the blades due to their high ^{232}Th content. Based on the cross-cutting relationship of the boxwork and non-boxwork calcite, it appears that the boxwork is younger than ~6.4 ka, but from this preliminary investigation it is unclear how long it takes for boxwork to precipitate.

In summary, the high $\delta^{13}C$ and $\delta^{18}O$ values found in the calcite blades confirm for the first time the role of cryogenic processes in the occurrence of boxwork.

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Dating speleothems in Southern Italy (Apulia and Sardinia): palaeoclimate implications and speleogenetic clues

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Abstract

This study reports the results of a comprehensive radiometric dating campaign carried out on 51 speleothems from caves in Apulia and Sardinia during the last ~7 years. Around 230 ages were produced by exploiting the U-Th method. Sampling targeted 5 caves in Apulia and 12 caves in Sardinia. All caves are located ~41˚N (±1˚) latitude, representing an ideal location for the understanding speleothem deposition in relation to past Mediterranean climate. U-Th dates can be used as minimum age for the caves in which they formed, hence providing geochronological constraints on speleogenetic processes. The preliminary results attest that in both regions: 1) there is evidence of speleothem deposition since 600-800 thousand years before present (ka), implying that speleogenesis occurred beforehand. According to cave morphology observations, and in relation to local geology, the formation of most of the explored caves is estimated to have occurred several millions of years before present; 2) speleothem deposition occurred during glacial (last glacial, MIS6, MIS8, MIS10) and interglacial (Holocene, MIS5, MIS7, MIS9, MIS13) stages over the last ~500 ka. This implies that climate during the glacial stages was never too cold and dry to impede speleothem deposition, as has been the case in other parts of Europe.

Résumé

Datations de spéléothèmes dans le Sud de l'Italie (Apulie et Sardaigne) : implications paléoclimatiques et indices spéléogénétiques. Cette étude porte sur les résultats d'une campagne de datation radiométrique menée sur 51 spéléothèmes prélevés pendant les 7 dernières années dans 5 grottes d'Apulie et 12 de Sardaigne. Ces grottes sont situées à proximité du 41 °N, localisation idéale pour comprendre les conditions de formation des spéléothèmes en fonction des climats passés de la Méditerranée. Les dates U-Th peuvent donner un âge minimum pour les grottes dans lesquelles se trouvent les spéléothèmes, contraignant ainsi le cadre géochronologique de la spéléogenèse. Ces résultats préliminaires montrent que dans les deux régions : i) des spéléothèmes se sont formés depuis 600.000 à 800.000 ans, impliquant que les grottes sont plus anciennes. Les observations des formes souterraines en fonction de la géologie locale montrent que la majorité des grottes explorées se sont formés il y a plusieurs millions d'années ; ii) la formation des spéléothèmes s'est faite durant les périodes glaciaires (LGM, MIS 6, MIS 8, MIS 10) et interglaciaires (Holocène, MIS 5, MIS 7, MIS 9, MIS 13) durant les derniers 500.000 ans. Cela implique que le climat durant cette période ne fut jamais trop froid ni trop sec pour empêcher la formation des spéléothèmes, comme cela a été le cas dans d'autres régions d'Europe.

1. Introduction

Dating speleothems provides the twofold opportunity to: 1) understand the relation between cave calcite deposition and past climates (FAIRCHILD & BAKER, 2012); and 2) attribute minimum ages to the caves in which speleothems

formed (SASOWSKY, 1998). Regarding point 1, CaCO3 precipitation is only possible if the precipitation /evapotranspiration (PE) ratio is > 1 at a certain location, and meteoric water is able to percolate into the karst reservoir. Additionally, soils must provide CO2 (and/or bedrock pyrite oxidation must provide H2SO4) to the infiltrating water in order to trigger the dissolution of the bedrock and the consequent precipitation of calcite once the seepage reaches the vadose cave environment (FRISIA & BORSATO, 2010). Accordingly, climate periods that better sustain a regular and continuous deposition of speleothems are those characterized by relatively humid (= abundance of precipitation, i.e., no aridity) and warm (=high soil bioproductivity, i.e., no bare soils) conditions, especially at middle latitudes. Regarding point 2, the age of "voids" can be estimated by dating the deposits they contain. Speleothems often represent the most suitable samples to chronologically constrain cave formation, considering that other datable deposits such as allochthonous sediments and/or dissolution by-products (i.e. alunite and/or dolomite, POLYAK, 1998; POLYAK et al., 2016) are not as common as cave calcite.

Additionally, speleothem dating using the U-Th method has seen remarkable technical improvements in recent times and can be extremely precise (HELLSTROM, 2006; CHENG et al., 2016).

This work presents an extensive U-Th chronological dataset, reporting the age of numerous speleothems sampled in two southern Italian regions: Sardinia and Apulia. The first is an island strategically located at the centre of the western Mediterranean Sea, while the second, comprising the "heel" of the Italian "boot", is representative of the southern portion of the Peninsula. Speleothem-based research has been intense in Italy over the last ~20 years, although it mostly focused on the north of the country (FRISIA et al., 2005; ZANCHETTA et al., 2007; BELLI et al., 2013; REGATTIERI et al, 2019; JOHNSTON et al., 2018; ISOLA et al., 2019; POZZI et al., 2019; DRYSDALE et al., 2020). Accordingly, this work fills the gap of the existing literature by procuring novel information on this underrepresented portion of the territory. It also represents an occasion to explore the environmental conditions favoring speleothem deposition at southern European latitudes with respect to climate change occurring at global scale (i.e., glacial vs interglacial shifts), and provides a preliminary investigation regarding the age of speleogenesis in several cave systems in Sardinia and Apulia

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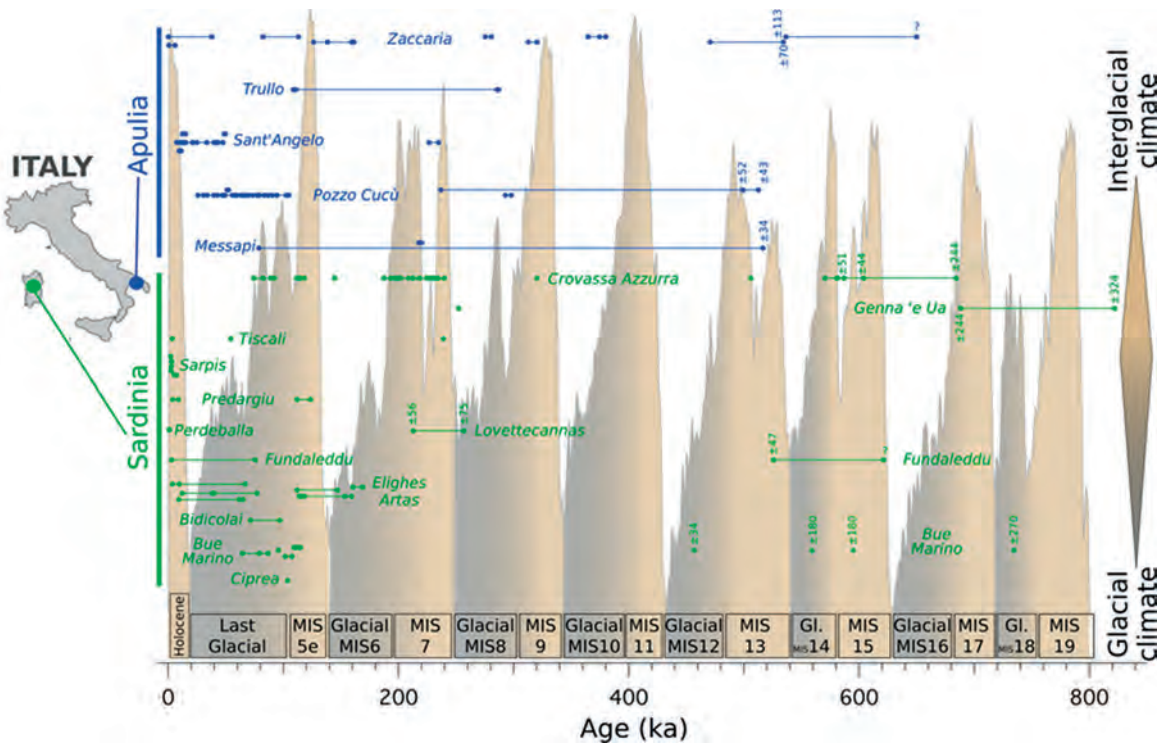

Figure 1: Age distribution of the dated speleothems vs climate variations. Dots indicate the obtained ages, while horizontal lines connect bottom to top of each speleothem. Caves' names are reported in blue (Apulia) and green (Sardinia); numbers indicate age uncertainties only in the case of relatively large errors. Samples marked with "?" did not deliver a precise age because of the method limit. Global stack benthic δ18O curve (LISIECKI & RAYMO, 2005) in the background is here taken as reference for interglacial vs glacial climate changes over the last ~800 ka (scale has been omitted for simplicity). The bottom reports glacial vs interglacial periods referred as Marine Isotope Stages (MIS).

2. Materials and methods

Karst terrains are widespread in both Sardinia and Apulia. In the first region, calcareous rocks outcrop mostly in the central-eastern part and southern-western corner of the island, often forming well recognizable table-topped mountainous morphologies (De Waele et al., 2012). Apulia is instead an extensive karst plateau with relatively small

altitude variations (Parise, 2011). The caves visited during the last ~7 years are Crovassa Azzurra, Bue Marino, Genna e' Ua, Tiscali, Sarpis, Predargiu, Lovettecannas, Perdeballa, Fundaleddu, Elighe Artas, Bidicolai and Ciprea in Sardinia, and Zaccaria, Trullo, Sant'Angelo, Pozzo Cucù and Messapi in Apulia. All caves are located around or below ~41˚N latitude. A total of 51 speleothems were sampled, 21 from Apulia and 30 from Sardinia. For the conservation of the cave environment, only broken speleothems were collected during explorations. All speleothems were dated by the uranium-thorium (U-Th) method, which has a limit of around 600 ka. Dating mostly targeted the bottom and top of each speleothem, in order to evaluate the growth period. However, a few samples were used for proxy-based palaeoclimate research and thus dated with higher resolution (COLUMBU et al., 2020; see these last works for the U-Th method details). Analyses were mostly performed at the School of Earth Sciences of the University of Melbourne, (Australia) and at the Institute of Global Environmental Change of the Xi'an Jiaotong University (China), as well as at the Department of Geosciences of the National Taiwan University (Taiwan).

3. Results

U-Th results attest that almost all speleothems grew during the last ~800 ka (Fig. 1). Because of natural attrition, younger speleothems (i.e. <150 ka) dominate. However, analyses returned several ages at the limit of the U-Th method. For this reason, ages of ~500 ka or older are characterized by a relatively large uncertainty (Fig. 1). In only one case, the precise age was not constrained because of its antiquity, so it has been arbitrarily set at around 600 ka (reported with a "?" in fig. 1). The U-Th ages show that, in both Sardinia and Apulia, carbonate deposition occurred during glacial (last glacial, MIS6, MIS8, MIS10) and interglacial (Holocene, MIS5, MIS7, MIS9, MIS13) climate stages, and possibly even during older glacial/interglacial periods (although the age uncertainties of the older speleothems do not allow a reliable assessment)

4. Discussions and final remarks

This work demonstrates that carbonate deposition at mid- to low European latitudes (i.e., at or below ~41˚N) is efficient during both glacial and interglacial climates. This contrasts with results obtained in western and central Europe, where glacial-age speleothems are extremely rare (LECHLEITNER et al., 2018). In detail, the dating of speleothems from Apulia already suggested that carbonate deposition during the last glacial was continuous, with no significant hiatuses (COLUMBU et al., 2020). The same is likely true also for Sardinian speleothems, as well as those Apulian speleothems where dating was targeted at top and bottom of stalagmites only, with the latter age corresponding to last glacial, MIS6, MIS8 and MIS10 (fig. 1). Continuous speleothem deposition during glacial climate is rather rare even on the Mediterranean side of the Iberian peninsula, which possibly represents the best counterpart with respect to southern Italy. For example, the most representative, but incomplete/intermittent, last glacial speleothem records are from Ejulve and Cueva Victoria Caves in Iberia (PÉREZ-MEJÍAS et al., 2019; BUDSKY et al., 2019); however, none of these speleothems grew during full glacial conditions. In contrast, continuous deposition of speleothems during glacial periods is attested in the eastern side of the Mediterranean basin, in Sofular (BADERTSCHER et al., 2011) and Soreq-Pequiin Caves (BAR-MATTHEWS et al., 2003). From a palaeoclimate/environmental perspective, this work implies that glacial conditions in Sardinia and on the Italian peninsula at least below ~41˚N were milder than continental Europe, in terms of rainfall and average temperature. Specifically, these southern Italian territories were not characterised by enduring periods of glacial aridity, and rainfall was able to efficiently recharge the karst aquifers. Concurrently, average temperatures were higher than northern Italy and Europe, possibly with the same latitudinal temperature gradient existing today.

This work provides the first preliminary chronological constraint for the explored karst systems. In both regions, there is evidence of speleothem deposition since at least ~600 ka, implying that speleogenesis occurred beforehand. Ahead of more detailed studies, geological considerations and morphological observations in caves suggest that all explored karst systems formed in more remote times, possibly several millions of years ago. Regarding Sardinia, the oldest dates belong to Genna e' Ua Cave (~700-800 ka), a fossil cave nowadays found at several hundred meters above the current river stream. In Apulia, the oldest dates belong to Zaccaria Cave (~600 ka), which nowadays lies at around ~120 metres a.s.l. and around 6 km from the modern coastline. It is likely that several million years ago, the local base level was at the same altitude of Genna e' Ua Cave in Sardinia and the palaeo coastline was adjacent to Zaccaria Cave in Apulia. Finally, the case of Crovassa Azzurra Cave in Sardinia is different because morphological observations relate this karst system to hypogenic hydrothermal speleogenesis. Detailed studies have suggested that speleogenetic inception for this cave might even be traced back to the Cambrian (GÁZQUEZ et al., 2018).

This preliminary work confirms speleothem dating as a precious tool for both palaeoclimate/environmental and speleogenetic studies, as long as it is carried out on multiple speleothems from a large number of caves.

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Age constraints on sea level during the last two glacial terminations based on submerged speleothems from New Caledonia

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Abstract

Speleothems from coastal caves are useful sources of sea-level data. Ages from submerged speleothems indicate that the relative sea level was lower than the (corrected) elevation of the speleothem, but there is no certainty that the speleothem was still growing during the transgression. More powerful age constraints could be derived if the speleothem were shown to be growing at the time of submergence. We present preliminary results from submerged speleothems in a coastal cenote at Lifou (New Caledonia), located ~150 m from the current coastline. Daily tidal fluctuations in the cenote suggest a physical connection to the ocean. Two speleothems (AeW-11 and AeW-12) were collected in growth position from -42.0 m and -31.6 m, respectively. A thin (few mm) upper growth phase in AeW-11 dates to ~55 ka. The penultimate growth phase ended at ~135 ka, during Termination II. The tip of AeW-12 is dated at ~11.5 ka, during Termination I. We use trace element mapping to determine if the speleothems were active at the time of drowning, then compare their estimated paleo-elevation with the latest reconstructions of relative sea level.

Résumé

Contraintes chronologiques sur le niveau de la mer pendant les deux dernières terminaisons glaciaires à partir de spéléothèmes immergés de Nouvelle-Calédonie. Les spéléothèmes de grottes côtières sont des sources utiles d'information sur les paléo-niveaux marins. Les âges de spéléothèmes submergés indiquent que le niveau marin relatif était plus bas que le spéléothème (son altitude corrigée), mais il n'y a aucune certitude que le spéléothème était toujours actif lors de la transgression. Des points de contrôles chronologiques plus robustes pourraient être obtenus s'il était possible de démontrer que le spéléothème était en cours de croissance au moment de sa submersion. Nous présentons des résultats préliminaires à partir de spéléothèmes submergés d'un cénote côtier de Lifou (Nouvelle Calédonie), situé à ~150 m du rivage actuel. Les fluctuations tidales journalières dans le cénote suggèrent une connexion physique à l'océan. Deux spéléothèmes ont été collectés dans leur position de croissance à -31,6 m et -42,0 m. Le sommet du premier a été daté à ~11,5 ka, durant la Terminaison glaciaire I, tandis que l'avant-dernière phase de croissance du deuxième s'est terminée vers ~135 ka, pendant la Terminaison II. Nous utilisons la cartographie des éléments traces pour déterminer si les spéléothèmes étaient actifs au moment de leur submersion, puis comparons leur paléo-altitude estimée avec les dernières reconstructions des variations du niveau marin.

1. Introduction

Reconstructions of changes in sea level through glacial terminations are based upon a combination of coastal sea-level archives and oxygen-isotope variations in ocean sediments. These geological sea-level records are largely anchored in time by radiometric dating. Corals are the most widely used of the datable sources of sea-level information, but they are often prone to diagenesis once subaerially exposed, which can affect the accuracy of U-Th ages (SCHOLZ et al., 2004; VILLEMANT & FEUILLET, 2003). Besides, individual species can grow over a relatively wide depth range, making precise paleodepth estimates difficult (e.g., DECHNIK et al. 2017). Although used less frequently, speleothems from coastal caves – stalagmites in particular – have proved to be a useful complementary source of sea-level data because they grow when caves are filled with air and not when they are submerged in sea water or brackish water. Therefore, uranium-thorium ages from the outer surface of a submerged speleothem can provide firm sea-level time-constraints: sea level was necessarily below the tip of the speleothem while it was growing. However, determining if the submersion of the speleothem actually caused its

growth cessation would be a more powerful time constraint, but as far as we are aware, this has yet to be shown in any study employing speleothems as sea-level indicators.

We present preliminary data from two submerged speleothems collected from a coastal cenote (Ani-e-Wee) on the island of Lifou (Loyalty Islands, New Caledonia), in the subtropical western Pacific Ocean (Figure 1). We use trace element patterns to evaluate whether these speleothems were active at the time of submergence and thus capable of yielding more accurate time constraints on paleo sea level.

2. Materials and methods

Lifou is part of the Loyalty islands archipelago, situated east of Grande-Terre, the main island of New Caledonia. The island is an uplifted carbonate platform, measuring 60 km long by 25 km wide, and with a maximum altitude of 104 m asl. Uplift and emergence caused by subduction of the Australia plate under the Pacific plate near the Vanuatu archipelago (BONVALLOT et al., 2012; MAURIZOT and LAFOY, 2004) commenced towards the end of Miocene. The local uplift rate is estimated at approximately 0.13-0.16 m/kyr based on radiometric ages on ~180 ka corals (MARSHALL & LAUNAY, 1978). The platform is strongly karstified as indicated by the lack of surficial runoff and the numerous natural cavities (BOURROUILH, 1972; LIPS et al. 1995).

As with most oceanic islands with significant permeability, Lifou presents at depth a freshwater lens floating on seawater according to Ghysben-Herzberg principle (ORANGE et al. 2008). Ani-e-Wee is a cenote, a water-filled karstic collapse offering an access to the freshwater lens and allowing diving access to the seawater beneath (Fig. 1). It opens into dolomitic limestone on the West coast of the island, 20 m asl, ~150 m inland from the shoreline of Baie du Santal.

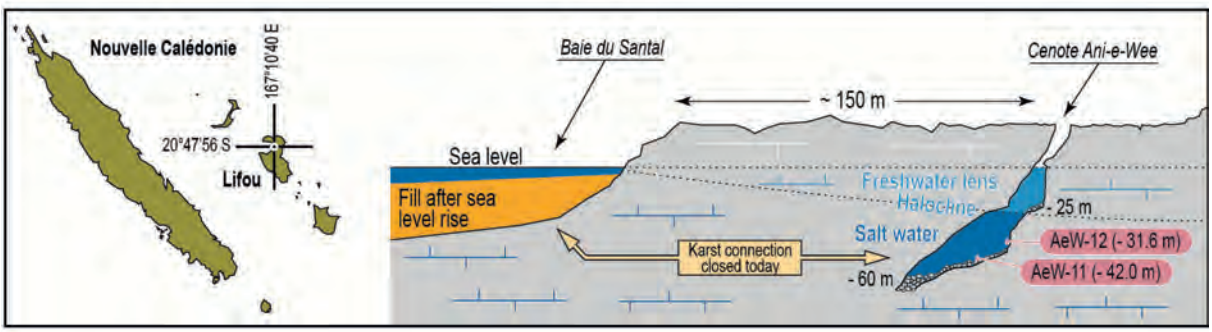

Figure 1: (Left) Location of the Cenote Ani-e-Wee on the island of Lifou, New Caledonia (SW Pacific Ocean). (Right) Cross-section from Baie du Santal (West coast) to the cenote showing the piezometric surface, the freshwater lens and the halocline, and their inferred extension to the sea. The position of the sampled stalagmites is also shown.

It appears as a vast opening on a fault, 30 m long, 15 m wide and 20 m deep (Fig. 1). The water table appears at the base of this vast collapsed entrance, giving access through a flooded pit and a corridor through rock fall to a wide sloping chamber at ~-30 m, which has been explored to -60 m (P. Brunet, pers. com.). An ancient scree slope occupies the chamber, comprising plurimetric blocks and covered in places by more recent rockslides. Many stalactites are visible around -35 m, however stalagmites are less numerous.

Although Ani-e-Wee has no known accessible connection to the open ocean, diurnal tidal changes can be observed. The freshwater lens extends from the water surface to a depth of about -20 m, where it reaches the halocline, which extends to -30 m, after which sea water is reached (LIGNIER et al. 2013). The pH varies abruptly from 8.5 at the surface of the water lens down to 7.8-7.9 at about -8 m then remains stable to a depth of -40 m.

The two speleothems (AeW-11 and AeW-12) were collected in growth position from -42.0 m and -31.6 m respectively (Fig. 1). Both comprise dark compact to light compact and very finely laminated columnar calcite (Fig. 2). They show no visible signs of dissolution despite their long residence time under water, probably due to the fact that they were resting below the halocline.

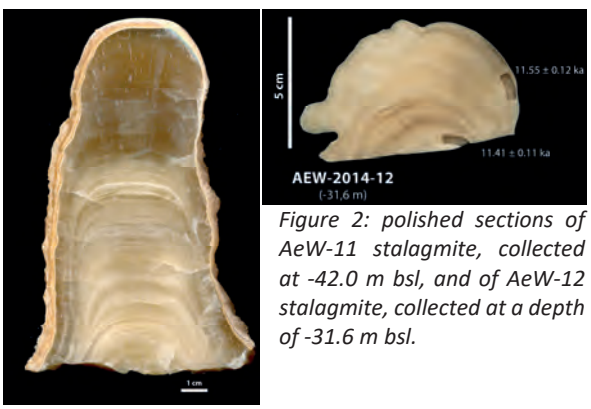

Figure 2: polished sections of AeW-11 stalagmite, collected at -42.0 m bsl, and of AeW-12 stalagmite, collected at a depth of -31.6 m bsl.

Uranium-series dating by MC-ICPMS was undertaken at the School of Earth Science, Univ. of Melbourne, on ~200 mg calcite prisms using the method described by HELLSTROM (2003). In order to determine if AeW-12 was active at the time of submergence, we applied laser-ablation trace-

element mapping over its upper part. We used a RESOlution laser-ablation system coupled to an Agilent quadrupole ICP-MS housed at the School of Earth Sciences at the U. Melbourne. Elemental concentration maps were produced from a grid of 250 parallel raster line scans (104 μm spot, 120 μm spacing). The same mapping will be conducted on AeW-11 in 2021.

The dating and trace element results will be used to evaluate the reliability of the stalagmites as relative sea level (RSL) indicators by comparing their uplift-adjusted sampling positions to relative sea-level curves.

3. Results

The U-Th dating results show that the calcite is low in detrital contaminants and with uranium concentration ranging between 0.1 and 0.4 ppm. AeW-12 apparently grew very quickly (within a couple of centuries) at ~11.5 ka BP.

The taller AeW-11 also grew very quickly, as samples taken at the bottom and top of the main and continuous growth phase returned the statistically identical ages at 2σ: 135 ± 1.7 ka BP. A further growth phase of half a centimetre in thickness, visible after a distinct discontinuity, returned an age of 54.8 ± 0.5 ka.

In order to improve the precision of the speleothem chronologies, new dates are programmed for 2021 using higher precision methods.

Trace-element maps were produced for Ca, B, Pb, Ba, Zn, Cl, Mg, Na, I, U, and Mg. The main purpose of the Ca map (Fig. 3) is to display the exact limit between the stalagmite and the resin in where the section was embedded. Among the other maps, the most striking feature is the significant increases in Mg, U and Na concentrations towards the top (Fig. 3); the other elements do not show any such change.

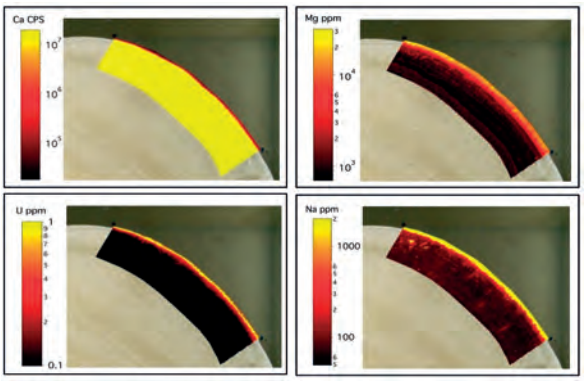

Figure 3: Elemental concentrations of Ca, Mg, U and Na on the top part of AeW-12, showing increased values over the upper few mm. The red band at the top of the Ca map marks the epoxy resin limits.

4. Discussion and Conclusion

The trace element data suggest that AeW-12 speleothem was actively growing at the time it was submerged by the rising freshwater lens. There are at least two lines of evidence to support this. First, the waters of the freshwater lens probably had higher Mg, U and Na concentrations than the drip water that fed the stalagmite due to the longer residence time in the regional karst aquifer. As regional groundwater moves through the karst and becomes exposed to the open atmosphere of the cenote, degassing would promote a shift towards a supersaturated state. This would enable continued calcite growth under subaqueous conditions. Second, the increased concentrations of these elements likely reflect a change in elemental partitioning coefficients as subaerial calcite precipitation is replaced by subaqueous calcite precipitation (DRYSDALE et al., 2019). This has been observed in speleothems from southern Australia, where Mg, U and Na concentrations increase by around a factor of 10 as the speleothem transitions from stalactitic to subaqueous growth (GOULD-WHALEY, 2020). An alternative explanation of the trace element increases in AeW-12 is mineral alteration processes as the speleothem undergoes submergence. Testing these competing hypotheses will be the subject of future investigations using synchrotron X-ray fluorescence. In the meantime, we discuss below the speleothem radiometric age results on the assumption that AeW-12 was active at the time of submergence.

The growth position of both speleothems can be corrected based on uplift rate estimates for Lifou of 14.5 ±1.5 cm/kyr (MARSHALL & LAUNAY, 1978). This returns an adjusted depth of ~-33.3 ± 0.2 m for AeW-12, assuming a top age of 11.5 ka, and of ~-61.6 ±2.2 m for AeW-11, assuming a top age of 135 ka. These estimates must however be treated with caution because of both uncertainties on the speleothem ages (which will be improved with further dating) and the uplift rate estimates, which rely on uncertain sea-level reconstruction and imprecise dating of a single terrace (MARSHALL & LAUNAY, 1978).

Nevertheless, these results can be compared with recent sea-level compilations across glacial Terminations I (LAMBECK et al., 2014) and II (MENVIEL et al. 2019; Fig. 4). The AeW-12 reconstructed position aligns well with relative sea level at the time and supports the notion that it could have been actively growing when it was submerged. AeW-11 grew ~135 ka ago, so the reconstructed position of the speleothem is more sensitive to uncertainties on the uplift rate. Compared with the latest reconstruction available for TII, its position at the time of growth is close, within error, to relative sea level.

Hence, both stalagmites could have been actively growing at the time they were submerged due to sea-level rise. Their top ages could thus be used as a chronological constraint for sea level rise reconstruction in the area, but more robust estimates for uplift rate are needed.

Further dating and geochemical analyses on both speleothems will help reinforcing the argument that they were actively growing at the time of submersion.

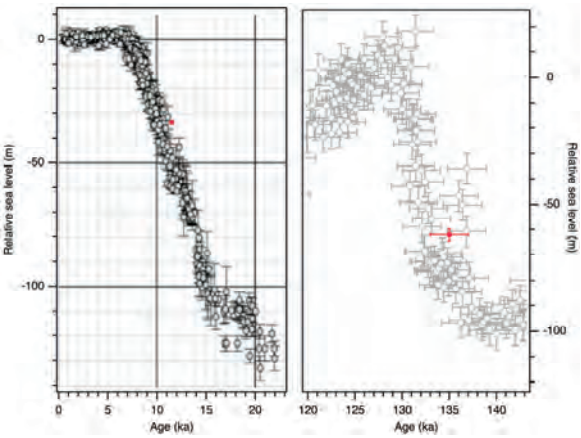

Figure 4: Relative sea level curves for Termination I (left, from LAMBECK et al., 2014) and Termination II (right, from MENVIEL et al., 2019). Age and depth uncertainties are shown by X and Y error bars, respectively. The age and uplift-corrected position of AeW-12 (left) and AeW-11 (right) are shown by the red symbols (where X-error bars are 2σ U-Th age uncertainties and Y-error bars are uplift-correction uncertainties; NB: the error bars are too small for Termination I).

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A Holocene speleothem record of paleoclimate in the northwestern Alps

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Abstract

The western Alps contain few well-dated and highly resolved paleoclimate records to set the context for human occupation and deconvolve palaeoenvironmental data. We present the first regional reconstruction of Holocene palaeoclimate evolution based on four stalagmites from Garde Cavale cave in Les Bauges massif (altitude ~1400 m asl; northwestern French Alps), which receives most of its moisture from the North Atlantic Ocean. Stable isotope records were compiled for each stalagmite, constrained by U-Th dating. Through the Holocene, the speleothem $\delta^{18}O$ record mainly follows an opposite trend to the 45°N summer insolation intensity curve. We suggest that the evolution of local summer insolation through the Holocene influenced the speleothem $\delta^{18}O$ pattern via its impact on both the temperature of precipitation and the seasonality of groundwater recharge. Thus, the relative proportion of summer-to-winter effective precipitation controls the overall $\delta^{18}O$ of the groundwater recharge that feeds the speleothem growth.

1. Introduction

Few paleoclimatic records document the entire Holocene epoch in France, particularly in the Alps. This makes the interpretation of regional palaeoenvironmental data (*e.g.,* erosion patterns, glacial advances and retreats, lake levels, vegetation change) difficult or uncertain because the climate background is poorly constrained.

Speleothems can preserve precisely dated, reliable and continuous paleoclimate reconstructions, in particular using their $\delta^{18}O$ variations, which are strongly climate driven (by temperature and precipitation). In this study, we present a composite high-resolution speleothem time series from Les Bauges massif that preserves a record of climate variations at a subalpine site through the whole Holocene. Our specific focus in this paper is twofold: what are the main drivers of speleothem $\delta^{18}O$ at this site, and what does the long-term pattern of speleothem $\delta^{18}O$ tell us about regional Holocene climate evolution?

2. Materials and methods

Four stalagmites were sampled from the "Précieux" chamber of the Garde-Cavale karstic network, a cave system carved in the Revard plateau (Les Bauges Massif, northern French Alps: 45.64N, 5.98E). The plateau's average altitude is 1400 m a.s.l. and the chamber sits ~50 m below the plateau surface near the village of La Féclaz. The massif is one of the first obstacles of the Alps (after the Massif Central and Mont du Chat) that confront the trajectory of westerly air masses from the North Atlantic Ocean, which carry most of the moisture reaching the site (Fig. 1).

The climate is temperate-subalpine (snowy winters) with a maritime influence (annual precipitation: ~1600 mm/yr). Mean annual temperature is ~6°C (1994-2014; source MétéoFrance). Current vegetation cover is a meadow surrounded by mixed forest.

The Revard plateau is a monocline structure with a gentle eastward dip. Its upper strata comprise hard and massive Cretaceous reef limestone (Urgonian facies) covered in places by Oligocene continental deposits. The Précieux chamber was carved at the interface between Oligocene carbonate-cemented sandstone and underlying conglomerate. Water storage in the sandstone ceiling (about 15 metres thick) buffers surface hydrological extremes and feeds many slow-dripping soda straws. Water draining through rare joints drip more quickly, feeding the growth of a small number of stalagmites. Four of these stalagmites were sampled and analysed. They all show the same type of growth pattern, i.e., candle shape, ca. 10 cm in diameter, made of clean compact columnar calcite, with very fine, flat laminae (Fig. 2).

Stalagmite chronology is based on U-Th dating by multi-collector inductively coupled plasma mass spectrometry (MC-ICPMS) at the University of Melbourne (UoM). Initial samples were ~200 mg prisms detached using a dental air-drill; subsequent analyses were measured on micromilled powder samples (~25 to ~60 mg) to improve spatial resolution of ages. Full details of the dating procedure can be found in HELLSTROM (2003). Age-depth models and associated 95% confidence intervals were generated using a finite positive growth rate algorithm (DRYSDALE *et al.* 2004).

Oxygen and carbon isotope ratios were measured from calcite powders drilled every millimetre along each stalagmite's growth axis using a computer-controlled micromill (lab. EDYTEM, USMB). 'Hendy test' samples were also drilled along several laminae to check for isotopic disequilibrium (HENDY, 1971). Isotopic analyses were run on ~0.7 mg samples using a continuous-flow AP2003 IRMS at the UoM. Results are given in ‰ VPDB with a 1σ uncertainty of 0.1‰ for $\delta^{18}O$ and 0.05‰ for $\delta^{13}C$. No dripping water or active calcite was sampled because the cave was virtually devoid of percolation water at the time of sampling.
Meteorological data for La Féclaz (1993-2019; source: MétéoFrance) and precipitation stable isotope data for the closest GNIP station (Thonon, 1963-2002; ~100 km NNE, alt: 385 m) were used to interpret the speleothem $\delta^{18}O$ data.

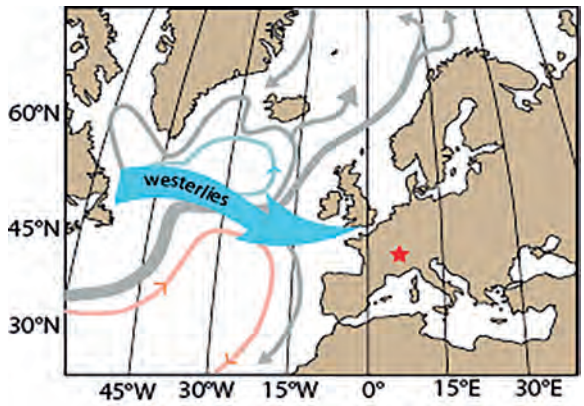

Figure 1: Site location. Most moisture reaching the site comes from North Atlantic frontal systems.

Figure 2: Polished sections of the 4 studied stalagmites.

3. Results

The U-Th results for all 4 stalagmites fall in stratigraphic order within uncertainties. Taken together, the stalagmites cover the whole Holocene epoch (Fig. 3). The dating does not resolve hiatuses associated with the visible growth discontinuities in GC13A. The average resolution of the isotopic measurements is about 9 years for GC9A stalagmite from 8.6 ka, ~15 years for GC9B, ~28 years for GC13B, and ~34 years for GC13A (Fig. 4).
$\delta^{18}O$ values vary from -9.0 to -7.2‰ through the Holocene, and records replicate closely between stalagmites. The absence of significant interference to the isotopic signal due to isotopic disequilibrium is verified further by the Hendy test (HENDY, 1971). Together, this is a strong argument in favour of the speleothem $\delta^{18}O$ being a reliable palaeoclimate proxy.
The Garde-Cavale $\delta^{18}O$ record first shows a rapid increase (~+2‰) out of the Younger Dryas. From ~11.7 to ~8.2 ka, it displays centennial-scale, low-amplitude variations with no long-term trend. At ~8.2 ka, the $\delta^{18}O$ experiences a striking depletion (~-1‰) for a period of about a century before recovery. From ~8 ka to ~0.9 ka, the $\delta^{18}O$ record displays a progressive increase, punctuated by several short-term events (not discussed here). This trend is interrupted by an abrupt $\delta^{18}O$ decrease between ~0.9 and ~0.8 ka (of -1 to -1.2 ‰) before stabilizing at these lower values over the last few centuries.

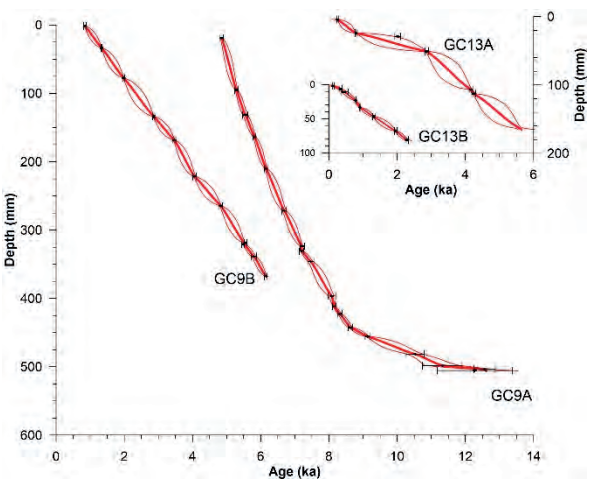

Figure 3: Age-depth models for the 4 stalagmites. The envelope represents the propagated ±2σ error on the age. The dates are represented in black with error bars at 2σ.

4. Discussion

In this contribution, we only consider the long-term, multi-millennial pattern of $\delta^{18}O$ change in the GC speleothems. The main driver of speleothem $\delta^{18}O$ variations through time is changes in rainfall $\delta^{18}O_p$, which depend on vapour source, air-mass trajectory, condensation temperature and rainfall amount (MCDERMOTT, 2004; DANSGAARD, 1964).

At the broadest scale, air-mass trajectories across western Europe are unlikely to have varied considerably over the Holocene, so vapour source has most probably remained the North Atlantic Ocean surface. However, the ocean's isotopic signature has varied, especially during the first half of the Holocene when the final stages of ice-sheet decay released isotopically depleted freshwater. This early-mid Holocene decrease in $\delta^{18}O$ of the vapour source region is not apparent in GC speleothem record.

Rainfall amount can induce significant changes in $\delta^{18}O_p$; it is often associated with tropical speleothems but is also recognised as a significant driver of speleothem $\delta^{18}O$ in the SW Europe-Mediterranean region (COUCHOUD *et al.*, 2009; DOMINGUEZ-VILLARS *et al.*, 2008; DRYSDALE *et al.*, 2004).

However, modern rainfall isotope data from the Thonon GNIP station show a no correlation between $\delta^{18}O_p$ and rainfall amount, allowing us to exclude this parameter as one of the main drivers of GC speleothem $\delta^{18}O$ variations.

Lastly, we need to consider the temperature effect: modern rainfall isotope analysis reveals a significant correlation between $\delta^{18}O_p$ and temperature (r^2=0.95) when comparing the amount-weighed mean $\delta^{18}O$ value by temperature class interval, with a slope of +0.38‰/°C. Given this relationship, if the GC $\delta^{18}O$ record was driven by mean air temperature, high values would be expected during the first half of the Holocene followed by a decrease in values over the second half, consistent with orbitally driven Northern Hemisphere summer insolation (NHSI; MAGNY *et al.*, 2011; MCDERMOTT *et al.*, 2011 and references therein). Instead, the GC long-term Holocene trend is the opposite.

Further, MCDERMOTT *et al.* (2011) compiled oxygen isotope data for well-dated speleothems from Europe to unravel the evolution of $\delta^{18}O$ over the Holocene by longitude. After filtering out high-latitude and high-altitude sites, as well as sites proximal to the Mediterranean Sea, the long-term $\delta^{18}O$ patterns of western European speleothems evolve in the opposite direction to the GC record. This highlights site-related effects controlling the $\delta^{18}O$ in GC speleothems.

We suggest that the seasonality of the groundwater recharge at this site is a key factor in transforming the impacts of orbitally driven local insolation into the GC speleothem $\delta^{18}O$. More specifically, we observe that the GC $\delta^{18}O$ is anti-phased with the NHSI through most of the Holocene (Fig. 4).

The first part of the Holocene experiences high NHSI and weak winter insolation (Fig. 4, A). Based on the strong dependence of $\delta^{18}O_p$ to regional air-temperature, this would imply high summer temperatures lead to high $\delta^{18}O_p$, and low winter temperatures in low $\delta^{18}O_p$. However, high early Holocene summer temperature would also have resulted in high evapotranspiration and a lower contribution of enriched $\delta^{18}O$ waters to the annual karst recharge. This would be further reinforced by dry summers, as suggested by regional proxy-reconstructions (*e.g.,* MAGNY *et al.*, 2011). Overall, karst recharge would have been strongly influenced by winter precipitation, reducing annual $\delta^{18}O_p$ values.

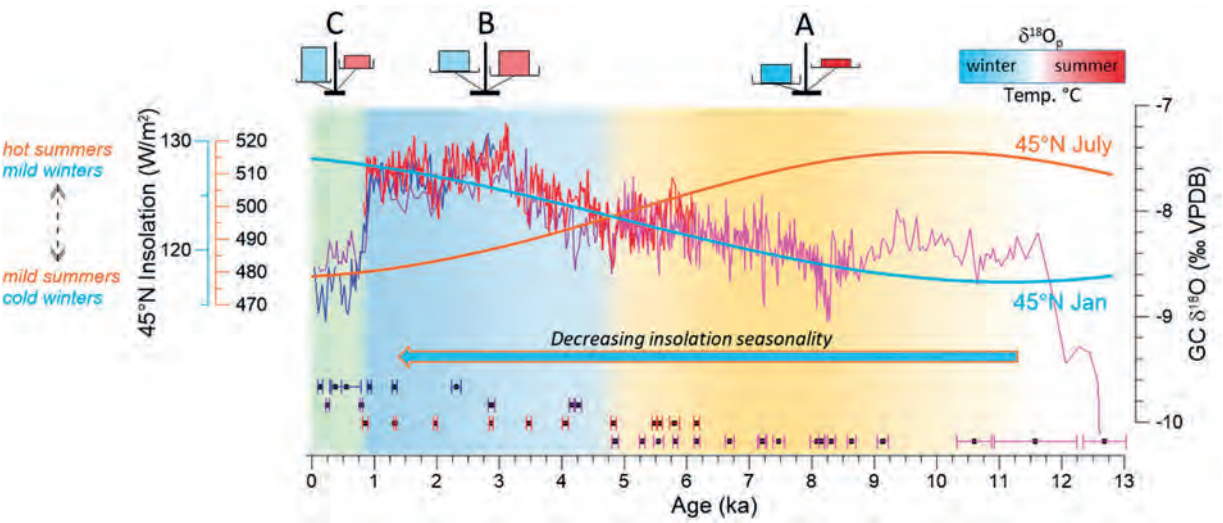

Figure 4: Oxygen stable isotope records of the four stalagmites from Garde-Cavale, compared with the 45°N summer and winter insolation intensity curves. U-Th ages obtained for each stalagmite are represented with their 2σ error bars at the bottom of the graph. A, B and C time zones are defined on the basis of the seasonality of the groundwater recharge and its isotopic signature, temperature dependant (see text).

During the Holocene, the contrast between summer and winter insolation intensity decreases. The second part of the Holocene is thus marked by cooler summers but milder winters (Fig. 4, B). Regional lake records suggest that this period was marked by high cyclonic activity in summer, leading to increased flooding (*e.g.,* WIRTH *et al.*, 2013,

CZYMZIK *et al.*, 2013). Karst water recharge at this time could have been influenced by increased incidence of higher $\delta^{18}O_p$ summer rainfall. In addition, winter precipitation at this time would have produced higher $\delta^{18}O_p$ values than the early Holocene owing to warmer winter temperatures.
Finally, the last ~900 years of the isotopic record show an abrupt negative anomaly (Fig. 4, C) (*ca.* -1.5‰) which cannot be explained by a temperature change at this time. A likely explanation involves anthropic disturbance on the Revard plateau: as people started to settle in this subalpine environment, they cleared the forest for construction, fire and charcoal production, and opened new pastures for cattle. This more open landscape would have enhanced winter recharge due to less canopy interception (reduced sublimation) and a greater susceptibility to repeated snowmelts (VARHOLA *et al.*, 2010). In addition, the lack of overstory vegetation would have enhanced direct evaporation in summer (BRÜMMER *et al.*, 2012). Taken together, this would have favoured a greater winter contribution to the annual recharge budget. Finally, snow regulates infiltration rate better than rain (which is more easily shed by surface run-off), therefore contributing more to the annual groundwater recharge. The altitude of the site, which is prone to snowy winters, thus played a critical role in controlling the $\delta^{18}O$ signal of GC speleothems.

5. Conclusions

We present a new paleoclimate record of the Holocene in the northwestern Alps based on oxygen isotopes from four stalagmites. The observed differences with the long-term trend of existing speleothem records in Western Europe remind us that each cave carries site-specific conditions, producing complex $\delta^{18}O$ signals. The interpretation of these signals requires an independent and cautious approach. We suggest that NHSI strongly influenced the long-term pattern of the GC speleothem $\delta^{18}O$ through the Holocene – as observed in many records – but in an indirect and rarely expounded way. At this sub-alpine site, the NHSI imprint on the isotopic signal was modulated by the seasonality of groundwater recharge.
Finally, the subalpine altitude, which is prone to snowy winters, allows for a particular influence of the snowpack (*vs*. rainwater) on recharge after the clearing of the forest above the cave.

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Bioturbation des alluvions modernes de la grotte de Han

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Résumé

La grotte de Han, site emblématique du Géoparc mondial Unesco Famenne Ardenne, est un système de perte-résurgence par recoupement souterrain de méandre, ici en l'occurrence de la Lesse. Lors des crues, cette rivière passe de quelques centaines de litres à 40 m^3/s. Des alluvions ou limons de crue sont alors déposés en grandes quantités, nécessitant le nettoyage du réseau touristique. Dans les réseaux non touristiques, la surface des alluvions est rajeunie et toutes les traces de fréquentation humaine sont effacées. Lors de visites durant l'été 2020, nous avons observé, dans des galeries situées quelques mètres au-dessus du niveau de la Lesse, que toutes les empreintes de pas des spéléologues avaient disparu. Et pourtant entre deux visites, aucune crue ne nous a été signalée. L'explication tient à la présence de nombreux vers de terre dans les alluvions, qui, par bioturbation et rejet de sol sous forme de déjections (turricules), rendent une surface exempte de trace de passage humain en moins de 3 mois.

Abstract

Bioturbation of modern alluvial deposits in the cave of Han. The Han cave is an emblematic site of the UNESCO World Geopark Famenne Ardenne. It is a karstic resurgence system through an underground network intersecting the meanders of the Lesse river. During floods, the river rises from a few hundred L to 40 m^3/s. Alluvium or flood silt deposits is deposited in large quantities inside the cave, requiring the cleaning of the tourist paths. In paths not open for tourists, the surface of the alluvial deposits is rejuvenated and traces of human frequentation are erased. During summer visits, all footprints left by cavers had disappeared in some galleries located several meters above the level of the Lesse river. And yet, between two visits, no flooding event was reported. The explanation lies in the presence of many earthworms inside the deposits which, through bioturbation and rejection of soil in the form of dejecta (turricles), erase human footprints at the surface in less than 3 months.

1. La grotte de Han-sur-Lesse

La grotte se développe au croisement de la Calestienne, bande de calcaires givetiens qui décrit ici un vaste anticlinal faillé (Quinif et al., 2018) et de la Lesse, rivière épigénétique (fig.2). La Lesse s'engouffre totalement au niveau du gouffre de Belvaux pour réapparaître au niveau du Trou de Han situé sur le bord septentrional de l'anticlinal.

La perte de Belvaux sature à 25 m^3/sec et le Trou d'Enfaule situé en aval peut encore absorber quelques 15 m^3/sec . Aux débits supérieurs, la Lesse déborde dans son ancien cours aérien le long du méandre abandonné de la « Chavée ». La distance perte-résurgence en ligne droite est de 1,1 km, mais la structure géologique explique le développement « semi-circulaire » du réseau selon la stratification/ lithologie de sorte que la rivière souterraine coule sur environ 1850 m dans son parcours le plus bref. Lors des crues, la Lesse envahit le Réseau Sud, parcourant alors plus de 2200 m. La différence de niveau entre perte et résurgence est de 4 m. La rivière souterraine a donc une pente faible (2%). Cela se traduit sous terre par de longues étendues d'eau, des zones noyées et quelques rapides (Égout dans le Réseau Sud, Draperies dans la partie touristique).

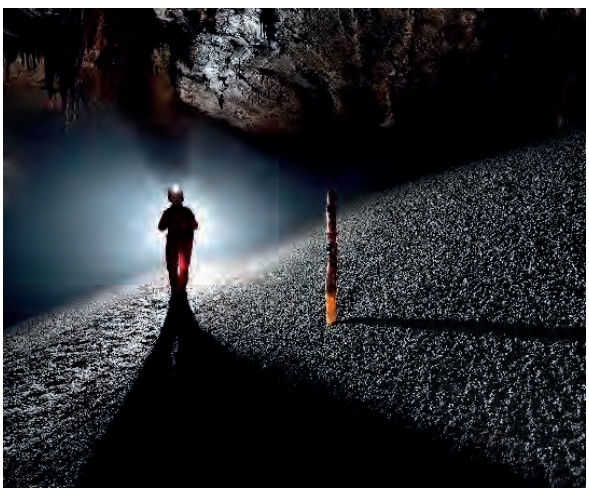

Figure 1 : Réseau Sud, la rugosité de la surface du sédiment est caractéristique d'un sol remanié par des vers de terre (photo Ph. Crochet)

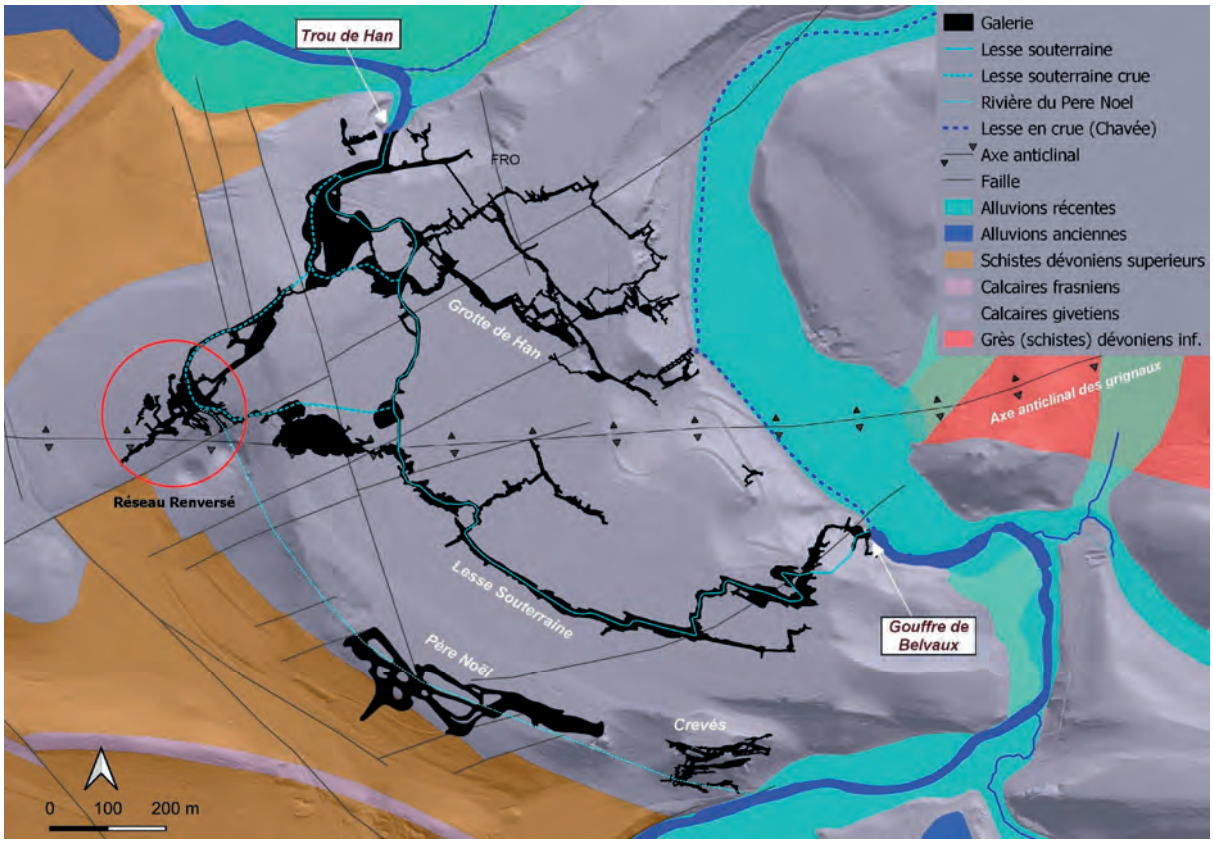

Figure 2 : Réseau de Han en surimposition au relief et à la géologie (source: Service Public de Wallonie). Le réseau se développe au cœur de l'anticlinal dévonien des Grignaux. La Lesse en fonction de son débit emprunte plusieurs parcours.

Une grande partie du cours de la Lesse est alluvionnante, laissant le rôle érosif aux rapides et rétrécissements de galeries. La perte est un impressionnant gouffre noyé plongeant à 45 m de profondeur. Il joue le rôle de filtre : la plupart des matières emportées par la rivière de masse volumique inférieure à 1 g/cm^3 sont bloqués à la surface de l'eau : troncs, végétaux, plastiques, bouteilles…
Lors des crues, toutefois, une quantité de feuilles, brindilles et branchages franchit les zones noyées et est déposée en aval du système, là où les vitesses d'écoulement faiblissent. Ces zones d'alluvionnements couvrent une part non négligeable de la rivière souterraine. On a toujours attribué le rajeunissement des surfaces d'alluvions comme résultant d'un dépôt de crue. Des visites conjointes menées par la Société des Grottes et le Geopark au cours de l'été l'automne 2020 ont trouvé une autre explication.

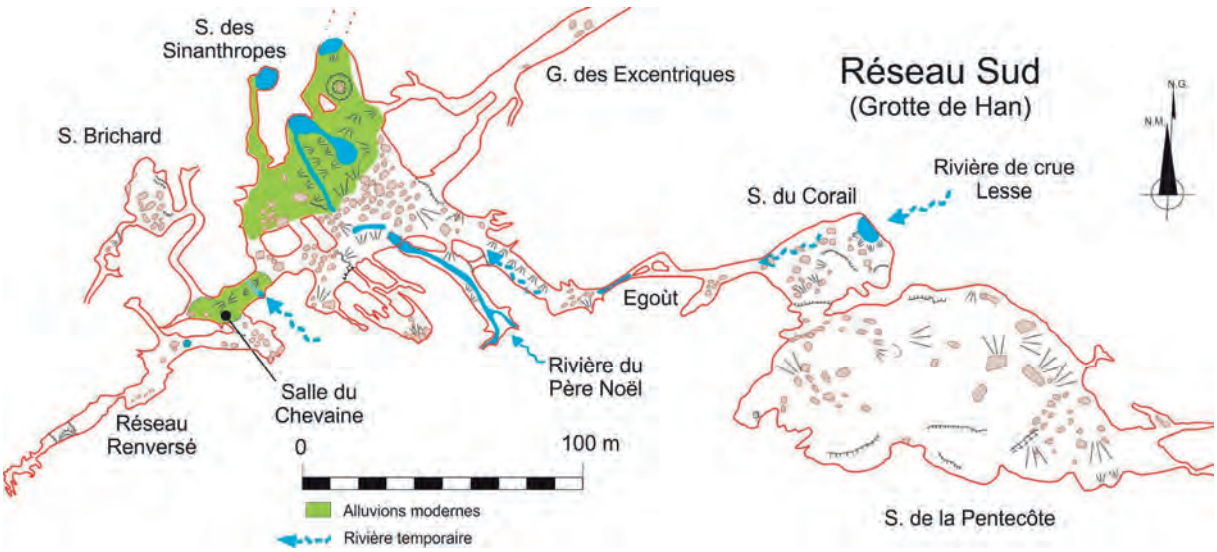

Figure 3 : Plan partiel du Réseau Sud (selon Quinif modifié et digitalisé par Nehme et Delaby) montrant le parcours de la Lesse, de son affluent provenant du Père Noël ainsi que la localisation des alluvions modernes riche en mégadriles.

2. L'observation

Figure 4 : Effacement progressif d'une empreinte deux semaines après le passage du spéléologue.

L'étude présentée ici se focalise sur le réseau Sud, plus particulièrement dans la Salle Chevenne située dans le réseau Renversé (fig. 3). Cette partie est hors du trajet normal des spéléologues. La Lesse n'y coule que lors des fortes précipitations et est toujours dans la zone d'alluvionnement. Cette salle, nommée Salle du Chevenne, en mémoire du gros poisson qui a accompagné nos observations, offre un regard sur la nappe en contact avec la Lesse dans lequel se trouvent piégés les poissons entre deux crues. Lors des précipitations, cette vasque devient émissive.

Une première visite, le 26 juin 2020 effectué essentiellement pour le suivi climatique (T°, CO_2, Radon) du Réseau Sud, avait laissé des traces de pieds et tassements sur la surface des alluvions. Lors de la visite du 6 octobre, 102 jours après, les traces de passages susmentionnées avaient complètement disparu. Or, aucune crue n'a été reporté durant cette période. Les poissons précédemment observés, étaient toujours présents, confirmant ainsi l'absence d'écoulement dans cette partie de la grotte. Par contre, le sol pullule de vers de terre.

Une troisième visite, effectuée le 24 novembre 2020, a permis de réaliser des sondages dans les alluvions, de compter des vers de terre et de prélever une dizaine de spécimens dont l'état de maturité est attesté par la présence d'un clitellum développé. Une cartographie des zones bioturbées est visible sur la figure 3. Elle correspond grosso modo aux surfaces de dépôts se situant à moins de 4 m 50 au-dessus du niveau de la Lesse. Les sondages, nous ont permis de dénombre ~450 individus/m^2. Ce sol peut être considéré comme très riche en vers de terre.

3. Coupe et comptage

Trois sondages de 20 cm de profondeur sont réalisés dans les alluvions, chacun sur une surface de 30x40 cm. Le résultat synthétique des trois sondages est le suivant (fig. 5) :

- le faciès **boule** (3 à 4 cm d'épaisseur). Cette couche superficielle est riche en vers de terre. Ces espèces font 1 à 2 mm de diamètre et jusqu'à 8 cm de long. Leur intense activité de labour transforme le dépôt initial en un amas de déjections (turricules) parfaitement reconnaissable à sa surface rugueuse (fig. 1). Le dépôt argilo-limoneux est fort aérée et riche en matière organique.
- le faciès **chambre** (5 cm d'épaisseur) est plus compact que le faciès **boule** mais de granulométrie identique. Cette couche ocre clair comporte un nombre important de vacuoles parfois avec des vers de terre enroulés sur eux-mêmes. Ces espèces sont donc présents, mais en quantité moindre et surtout moins actifs. ils se logent dans des terriers inférieurs à 1 cm de diamètre, lesquels sont interconnectés par un petit canal millimétrique. En fonction de la localisation sur le profil, deux faciès sont observables :
- la continuité du dépôt « faciès **chambre** », mais dépourvu de vers (voir B' sur le log).A 17 cm de profondeur, ce dépôt devient anaérobie, grisâtre à l'odeur fétide et azoïque (C sur le log)
- un dépôt argilo-silteux, brun-ocre, très compact et collant, correspondant aux alluvions anciennes et observables à différents niveaux du réseau (D sur le log). Ce profil montre donc des dépôts fort bioturbés en surface du log. Ils sont indicateurs d'un taux de sédimentation relativement faible, favorisant ainsi la présence d'endofaune.

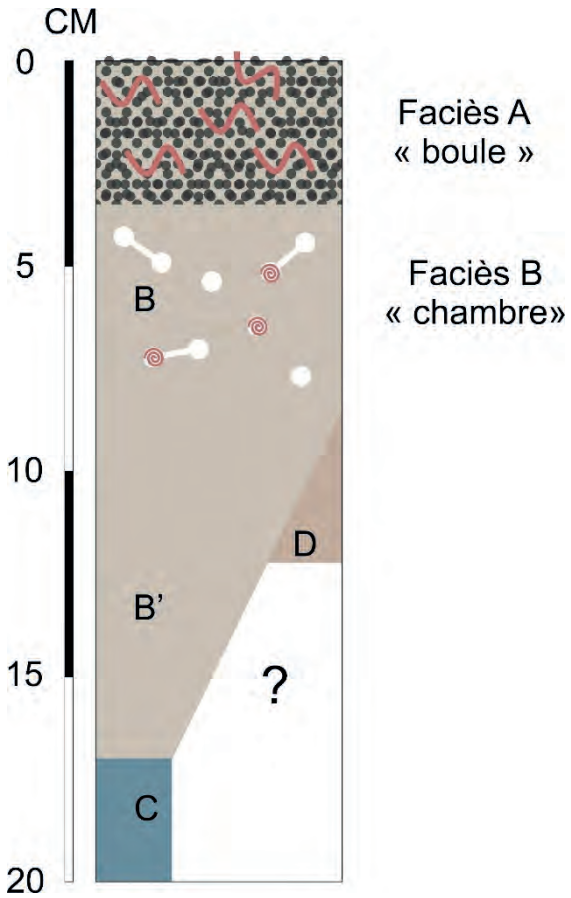

Figure 5 : Log synthétique des trois sondages réalisés dans les dépôts de la salle du Chevenne.

4. Identification

Dix vers de terre (Mégadriles) ont été prélevés dans la zone d'étude et identifiés à l'Institut royal des Sciences naturelles de Belgique (fig. 6). Ils ont été déposés dans les collections de l'IRNSB avec le numéro de catalogue suivant : "I.G. 34441". L'identification a été faite essentiellement sur un spécimen parfaitement mature (clitellum et pores sexuels bien formés) et l'identité des autres spécimens a été confirmée en référence à ce spécimen.

Tous les spécimens appartiennent à la même espèce : *Allolobophora chlorotica* (Savigny, 1826). Un spécimen mature présente un clitellum très développé, tuméfié, ainsi que deux spermatophores (capsules contenant les spermatozoïdes) en provenance d'un partenaire sexuel, fixés sur la partie ventrale, antérieurement au clitellum, ce qui témoigne d'un accouplement récent dans la grotte.

A. chlorotica est souvent numériquement co-dominant avec *Aporrectodea caliginosa* (Savigny, 1826) dans les sols cultivés et les pâturages. Cette espèce est souvent repéré dans les jardins et serres, les bois de prairie ou sous les rondins en décomposition ainsi que dans le compost. Il est également abondant dans les fossés, lits de rivières, entre les racines de plantes, les sols humides organiques ainsi que dans les lacs, les marais avec des débris végétaux en décomposition, les berges de ruisseaux, les plaines estuariennes, les dunes de sable semi-fixes et les grottes (Sims & Gerard 1999). *A. chlorotica* est connu pour ses mœurs ripicoles, pouvant vivre dans des milieux peu organiques (Bouché 1972). Cette espèce occupe une aire de répartition très vaste sur l'ensemble de l'Europe, de l'Asie mineure et dans les zones tempérées d'Amérique (Bouché, 1972).

Figure 6 : Mégadriles au travail

Il s'agit d'un ver de terre « amphibie » qui semble assez enclin à vivre dans des zones inondées, où il est capable d'y vivre une partie de son cycle biologique. Cette espèce n'est pas caractéristique du milieu souterrain mais s'y plaît si les conditions s'y prêtent. Dans ce cas d'étude à Han-sur-Lesse, et pour un milieu aquatique souterrain, on parlera d'une espèce « stygophile ».

5. Conclusion - Rôle dans la géoconservation

Les mœurs ripicoles de cette espèce (mégadrille) la prédisposent à vivre sur les berges alluvionnaires de la grotte de Han, où elle est présente en abondance. Elle se nourrit de matière organique probablement dérivée des végétaux charriés par la rivière durant les crues. Le suivi du niveau d'eau dans la salle du Chevenne montre 3 épisodes de crue susceptibles d'avoir joué ce rôle durant la période allant du 15/12/20 au 8/8/21 (fig. 7). On note que la hauteur d'eau atteinte lors des crues plafonne entre 4 à 4,5 m (crue historique du 15/7/2021) et correspond à la hauteur des alluvions occupées par les mégadriles.

Sous terre, les mégadriles n'ont pas ou peu de prédateurs (ex. oiseau, renard, blaireau, hérisson, sanglier) et ils peuvent se reproduire en quantité.

Ils dégradent la matière organique déposée lors des crues, limitant l'accumulation de vase et ils régénèrent, en quelques mois, la belle surface rugueuse (cf. fig. 1) des alluvions sans trace de fréquentation humaine.

Ils colonisent l'ensemble des alluvions du Réseau Sud, mais sont absents de certaines parties du réseau touristique et en particulier à l'embarcadère (confluence des 2 rivières de crue) ; là, le dépôt est plus grossier, sablo-limoneux à forte charge organique et est dépourvu de vers de terre.

Figure 7 : suivi du niveau de la nappe dans la salle du Chevenne.

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Monocrystalline calcite speleothems: an overview and new insights

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Abstract

Since the early 20th century, monocrystalline calcite soda straws and helictites have been described in the literature. Recent observations have also shown that subaerial macrocrystalline speleothems are much more frequent than earlier thought, often occurring in very stable cave environments where slow epitaxial growth can be favored over long time periods. But it appears that their development can also be controlled by frequent small variations in the depositional system (dissolution-precipitation), as opposed to the stationary (depositional) conditions typical of normal speleothems. Despite these short open system conditions, the paleoclimate signal appears to be preserved in these speleothems. High cave air humidity and CO_2 concentration often appear to be triggering factors.

1. Introduction

Many of the currently known cave minerals occur in the cavern environment as euhedral crystals often displaying a single crystal lattice. It is not so difficult to find large euhedral calcite crystals, or other minerals such as gypsum, halite, barite, or fluorite in caves (HILL & FORTI 1997). Generally, but not always, large crystals have a subaqueous, and often thermal, origin (DUBLYANSKY 1997). The development of single large crystals is always related to the very low supersaturation of the depositing fluids, causing epitaxial growth to prevail over nucleation of new crystals (GARCÍA-RUIZ et al. 2007). This is also why subaerial macrocrystalline speleothems were often regarded as diagenetic forms, where laminated structures were slowly recrystallized (FORD & WILLIAMS 1989). However, already since the early 20th Century, monocrystalline calcite soda straws, helictites and, less frequently, stalactites have been described in the literature (PRINZ 1908, SNYDER 1951, HALLIDAY 1953). Until some decennia ago the single described monocrystalline speleothems were those made of calcite. Only at the end of the 20th and, more frequently, at the beginning of the new millennium, monocrystalline speleothems consisting in other minerals than calcite started to be described: the very first were the halite monocrystalline speleothems (mainly stalactites with a single crystal lattice and a plane-parallel twinning) were described and partially studied (DE WAELE et al. 2009).

Recent observations have also shown that subaerial monocrystalline calcite speleothems are much more frequent than earlier thought (CALAFORRA & FORTI 2019). Monocrystalline calcite speleothems often occur in very stable cave environments characterized by high relative humidity and CO_2 concentration, where slow epitaxial growth can be favored over long time periods. In any case, it was also shown very recently that their development could be triggered by frequent small variations in the depositional system (dissolution-precipitation) as opposed to the stationary (depositional) conditions typical of normal speleothems (FORTI & SPRINGER 2020).

In the present paper the different types of monocrystalline calcite speleothems known at present (fig. 1) are shortly discussed on the basis of their genetic mechanisms.

2. Currently known monocrystalline calcite speleothems

Euhedral crystals notwithstanding, the very first studied monocrystalline speleothems were the calcite soda straws and helictites and triangular microgours (PRINZ 1908, 1909). Later monocrystalline stalactites (ONAC 1996) and triangular columns and stalagmites were also described, even if no genetic explanation for them was given (HILL & FORTI 1997). In any case they were speleothems developing in stationary microclimatic and feeding conditions (GONZALES et al. 1992).

Only in the very last few years, new studies on the influence of non-stationary conditions over the development of some peculiar speleothems (Badino et al. 2016), put in evidence the possibility that monocrystalline calcite speleothems may develop even under such conditions. In particular, in 2017 it was proved that some peculiar spheroidal coralloids and pyramidal stalagmites together with other rare monocrystalline speleothems from the Puerto Princesa Underground River in Palawan (Philippines) developed under non-stationary conditions (CALAFORRA & FORTI 2019). The same was shown in 2019 for the “squared soda straws” of the Dry Cave (West Virginia) (FORTI & SPENCER 2020).

3. Monocrystalline speleothems developing in stationary conditions

Tubular speleothems

Calcite soda straws are surely the most common monocrystalline speleothem: they consist of an elongated cylinder, the diameter of which is always around 5.1 mm (corresponding to that of the equilibrium drop just before detaching from the ceiling). Soda straws are the single monocrystalline speleothems developing even if the energy of crystallization is higher than that allowing only epitaxial growth. Their genesis is controlled by water drops falling from the cave roof and normally the supersaturation reached by the dripping water is high enough to promote the competitive selection among the embryonic crystals instead of the simple epitaxial growth, thus allowing, in a very short space (a couple of millimeters as maximum) to create a monocrystalline structure, with the C axis directed along the vertical, which is the direction of growth of this speleothem (MOORE 1962).

Generally speaking, the thickness of the tubular's external wall is very thin (one millimeter or even less) but it is also possible to see soda straws with thicker walls: in fact, sometimes the inner tube exhibits a diameter quite equal to the capillary feeding fissure within the rock.

The tubular's wall thickness and consequently the diameter of the inner tube, is controlled by the dripping frequency: in fact, high drip rates prevent supersaturation to move from the external surface into the dripping core, thus the calcite deposition only occurs along the outer rim of the falling drop. Decreasing the drip frequency will induce a progressive propagation of the supersaturation within the drop, thus causing a progressive increase of the tubular wall's thickness.

The fact that the tubular lattice is one with the C axis always directed along the vertical becomes evident when the speleothem breaks: in fact, the fracture always occurs along a rhombohedron face, no matter the thickness of the tubular's wall.

Soda straws exhibiting external geometrical shapes distinct from the rounded one (triangular, squared, hexagonal) cannot be considered true tubulars but are instead peculiar stalactites, because their shape is the consequence of a water film flowing over their external surface. They will be discussed in the section of the monocrystalline speleothems developing in non-stationary conditions.

Helictites

Monocrystalline calcite helictites are quite common and were the very first speleothem of this type analyzed in detail (PRINZ 1908). Their external shape is always fully independent from the inner capillary feeding tube because their evolution occurs only if no dripping at all occurs from the speleothem tip (MOORE 1982). Their cross-section can be flat or rounded, or even showing several small protrusions parallel to each other, corresponding to the rhombohedron vertexes. The thickness of the helictites varies from less than 1 up to 2-3 cm and is controlled not only by the evaporation rate of the steady drop present at the tip, but also by the possible water film driven by capillary flow over its external surface.

Sometimes the portion close to the apex has an elongated pyramidal shape with a triangular cross-section, corresponding to the vertex of a calcite rhombohedron &/or scalenohedron (MOORE, 1954).

In any case the supersaturation must be constantly kept to a very low value to allow no other depositional mechanisms besides epitaxial growth to be activated.

Pyramidal stalactites

The external shape of the monocrystalline stalactites is normally pyramidal with a rhombohedral cross-section. The tapering angle of these speleothems is far smaller than that of normal conical stalactites (FORTI & SPRINGER 2020). This occurs because the supersaturation of the water film flowing over their external surface must be very scarce, thus avoiding new nucleation and the consequent evolution of a "normal" conical stalactite as a consequence of the competitive selection of the embryonic crystals (MOORE 1962).

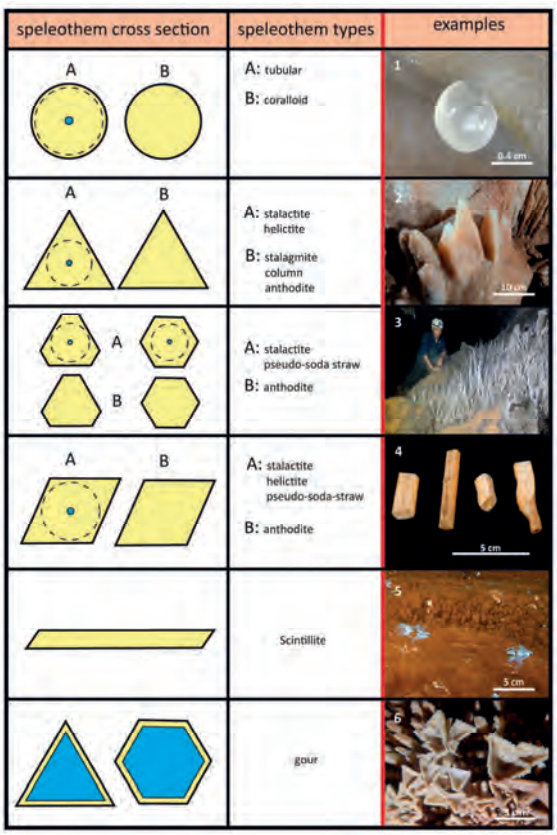

Figure 1: Cross-sections of the currently known monocrystalline calcite speleothems. 1- calcite monocrystal spheroid from PPUR, Palawan (photo M. Vattano); 2- Triangular tapering stalagmites from PPUR (photo Vittorio Crobu); 3- Cave grass anthodites from PPUR (photo Alessio Romeo); 4- "squared soda straw" stalactites from Dry Cave (USA) (photo Paolo Forti); 5- "flattened stars" scintillites from PPUR, Palawan (photo Alessio Romeo); 6- triangular gours from PPUR, Palawan (photo Marco Vattano).

Triangular stalagmites and columns

Triangular stalagmites and columns have been described from different caves (HILL & FORTI 1997). They consist of triangular parallelepipeds, whose elongation axis always corresponds to the C axis of the calcite lattice. Sometimes the stalagmite's top consists of a triangular pyramid, corresponding to the rhombohedral calcite crystal with the C axis coincident with the speleothem's elongation axis, but more often it is partially rounded because of the dripping impact. Both these two monocrystalline speleothems develop in a very stationary environment characterized by an extremely stable environment with high CO_2 and very low evaporation rate. As for most of the monocrystalline speleothems the driving factor is the development exclusively by epitaxial growth.

4. Monocrystalline speleothems developing in non-stationary environments

Only in the past few couple of years it was put in evidence that a few of previously known and some of the newly discovered monocrystalline speleothems develop thanks to non-stationary conditions. Actually at least 5 different such types of speleothems are known, two of which are presently only known from the PPUR karst system in Palawan (Philippines).

Triangular gours

They were among the first monocrystalline speleothems described in the literature (PRINZ 1908) even if, at that time, it was not recognized that their development requires non-stationary environments.

Their evolution is controlled by alternation of short periods of fast slightly undersaturated water supply, which fills the cups and rather long ones of drought during which capillary rise and slow evaporation induce epitaxial growth only on the triangular upper rim of the gours. A striking example of triangular gour is that described from the upper levels of the Puerto Princesa Underground River in Palawan (CALAFORRA & FORTI 2019). It was named "champagne cup" being remarkably similar to a flute glass. Its lower part being a normal monocrystalline helictite, which was transformed into a deep triangular gour due to the presence of a undersaturated dripping impacting its tip during the flashy rainfalls which characterize the Palawan Climate.

Hexagonal, triangular, and squared soda straws

The hexagonal and triangular tubulars were firstly described from the U.S. caves by Snyder (1951) and by Halliday (1953), and later by Basset & Basset (1962).

They were wrongly supposed to be soda straws but their evolution, as that of the squared ones, requires the presence of a water layer flowing along their external surface (FORTI & SPRINGER 2020) therefore they must be considered true stalactites. The absence of any kind of tapering is a clear evidence that slight undersaturation-oversaturation migrates along the whole external surface of these speleothems due to local competition among condensation and evaporation (FORTI & SPRINGER 2020)

Spheroidal coralloids

This peculiar type of coralloids, consisting of a monocrystalline calcite spheroid often with a clearly corroded stalk) was described for the first time from PPUR cave in Palawan (CALAFORRA & FORTI 2019) and its non-stationary origin was immediately recognized.

Their genesis and development were proven to be controlled by the peculiar Palawan climate, which is characterized by strong rainstorms followed by rather long dry periods. Capillary flow is active in both periods giving rise to short periods of slight undersaturation (inducing partial re-dissolution of the coralloid) followed by prolonged slight evaporation which allows only epitaxial growth (CALAFORRA & FORTI 2019).

Pyramidal stalagmites with a triangular base

These stalagmites were hitherto described only from PPUR karst system (CALAFORRA & FORTI 2019). They consist of a monocrystalline lattice with the C axis coincident with the stalagmite axis. The body of the stalagmite is shaped as a scalenohedron crystal, while the tip consists of a perfect rhombohedron. These stalagmites differ from the normal monocrystalline stalagmites by their tapering angle.

As the other just described monocrystalline speleothems of the PPUR karst system, their development is controlled by the peculiar Palawan climate.

In particular, their tapering scalenohedral structure is controlled by the alternation of strong rainstorms with rather long dry periods. In fact, during the few days following the rainstorms dripping may result slightly undersaturated thus allowing partial re-dissolution of the upper part and a slight deposition in the lower part of the stalagmite. At the beginning of the dry periods water present on the floor is driven by capillarity forces to the lower part of the stalagmite, where evaporation allows a further deposition of calcite. Both these two processes are evidently able to induce only a very low supersaturation, which explains why a monocrystalline pyramidal structure develops.

Scintillites

Flowstones, stalactites, and stalagmites, generally called "scintillites", due to their ability to reflect light, have been reported from all over the world (HILL & FORTI 1997). They should be considered a peculiar type of monocrystal speleothem due to the fact that reflection occurs in the presence of large flattened rhombic calcite crystals developed over the external surface of a normal speleothem. Recently, scintillites consisting of extremely large crystals have been reported from PPUR cave (DE VIVO et al. 2017). The development of these flattened calcite megacrystals is the result of local non-stationary conditions, allowing the partial re-dissolution of the external surface of the speleothem during the periods of fast water flow, while the development of the scintillites occurs when dripping is absent and feeding is due to both capillary flow and slow evaporation.

5. Conclusion

Recent observations have shown that subaerial macrocrystalline speleothems are much more frequent than earlier thought, and their development is often controlled by frequent small variations in the depositional system (dissolution-precipitation), which is just the opposite of the stationary conditions typical for the development of normal speleothems. High cave air humidity and CO_2 concentration always appear to be triggering factors for their development.

The observation and the research on monocrystalline speleothems developing in non-stationary conditions is still at the beginning and therefore it is highly probable that in the near future, new speleothem types will be discovered. This seems to be the case of the stalagmite sampled in PPUR during the expedition of 2017 (DE VIVO et al. 2017). Apparently, it is just a "normal" rounded stalagmite with well-defined accretion layers… but it resulted to be also completely monocrystalline. Moreover, preliminary U/Th dates and stable isotope analyses (DE WAELE unprinted data) showed that its internal chronology was unaffected by recrystallization processes.

This means that the process transforming the layered structure of the stalagmite into a monocrystalline one must be quite simultaneous, suggesting a possible (seasonal? or even shorter) alternation of a "normal" evolution (with the development of an accretion layer, characterized by a palisade arrangement of the calcite crystals) with a subsequent recrystallization of this single layer which was transformed into an epitaxial accretion of the stalagmite monocrystalline lattice. In fact, this mechanism alone can ensure that the geochemical characteristics of each layer will be maintained also after the recrystallization. Inside the PPUR karst system this fast alternation is controlled, as already said, by its peculiar climate characterized by short strong rainstorms alternated to long dry periods.

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Apports des stalagmites translatées dans l'étude du fluage d'un éboulis. Application à la grotte Chauvet-Pont d'Arc (Ardèche France)

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Résumé

La grotte Chauvet (Ardèche, France) découverte en 1994 est connue pour ses peintures rupestres, dont certaines datent de 36 000 ans. Leur bon état de conservation a souvent été associé à la fermeture de la grotte par effondrement entre 29 000 et 21 500 ans. L'éboulis polyphasé joue un rôle dans les conditions hygro-climatiques de la cavité et son bon état de conservation. Sa fonction " tampon " d'échangeur de chaleur et d'humidité par rapport aux conditions climatiques extérieures est souvent proposée comme hypothèse. A sa surface, des stalagmites semblent être translatées, ce qui interroge la stabilité de cet éboulis d'entrée dans le temps. Une de ces stalagmites (Chau_stm9), dont la base a été datée à 13 ka, a été étudiée dans ce but. L'analyse pétrographique permet d'identifier différentes phases de croissance, de constater les phénomènes de fluage/décantation de l'éboulis et de situer ces phénomènes dans le temps. Cette étude montre le rôle pertinent des spéléothèmes dans la compréhension de la dynamique post-dépôt de la fermeture des grottes peintes.

Abstract

Contributions of translated stalagmites in the study of the creep of a scree. Application to the Chauvet-Pont d'Arc Cave (Ardèche France). The Chauvet Cave (Ardèche, France) discovered in 1994 is known for its cave paintings, some of which are 36,000 years old. Their good state of conservation has often been associated with the closure of the cave by collapse between 29,000 and 21,500 years ago. Polyphase scree plays a role in the hygro-climatic conditions of the cavity and its good state of preservation. Its "buffer" function as a heat and humidity exchanger in relation to external climatic conditions is often proposed as a hypothesis. On its surface, stalagmites seem to be translated, which questions the stability of this entrance scree over time. One of these stalagmites (Chau_stm9), whose base has been dated at 13 ka has been studied for this purpose. The petrographic analysis makes it possible to identify different growth phases, to note the phenomena of the creep/settling of the scree and to situate these phenomena in time. This study shows the pertinent role of speleothems in understanding the post-deposit dynamics of the closure of painted caves.

1. Introduction

Non directement soumis aux effets de l'érosion extérieure, le milieu souterrain est particulièrement propice à la conservation des objets archéologiques et des biens patrimoniaux. La grotte Chauvet-Pont-d'Arc (Ardèche, France), découverte en 1994, en est un bon exemple. Le très bon état de conservation des peintures, parmi les plus anciennes de l'Humanité, et des archives archéologiques et paléontologiques a rapidement conduit à sa préservation totale et à son inscription au Patrimoine de l'Humanité (UNESCO) (CLOTTES, 1995 ; BAFFIER, 2020). Au-delà du caractère souterrain, la bonne préservation des biens de la grotte Chauvet est associée à l'éboulis qui a colmaté l'entrée préhistorique suite à l'écroulement de pans de l'escarpement surplombant le paléo porche (SADIER et *al*., 2012, 2020). Cet épisode majeur, en obstruant l'entrée, a de fait empêché toutes nouvelles pénétrations humaines ou animales. De plus, sa fonction « tampon » avec les conditions climatiques extérieures est souvent avancée dans les conditions hygro-thermique de la cavité qui sont favorables à la conservation. Compte tenu de ce rôle, il est essentiel de définir les vulnérabilités actuelles et à venir de la zone d'entrée. C'est là un des axes de travail des services de la conservation de la grotte (plan de gestion de la grotte). Une des entrées, retenue pour appréhender les vulnérabilités de l'éboulis est l'approche géomorphologique à haute résolution afin de discriminer son évolution après sa mise en place liée aux écroulements de l'escarpement extérieur entre 29 500 et 21 500 ans (SADIER et *al*., 2012). Au-delà des processus de détente mécanique et de desquamation des parois, à l'origine de nombreux clastes au-dessus de la masse écroulée, on relève la présence de concrétions scellant le sommet de l'éboulis. Parmi ces stalagmites, certaines d'entre elles sont déconnectées de leur point d'alimentation stalactitique et d'autres

présentent des morphologies translatées. Ces observations peuvent indiquer la présence d'un fluage et/ou tassement de l'éboulis au cours de la croissance des spéléothèmes (DELANNOY et *al*., 2010, 2020 ; SADIER et *al*., 2012, 2020 ; GENTY et *al*., 2005, 2020).

2. Stalagmites translatées sur l'éboulis d'entrée et méthodes d'analyse

Pour comprendre l'évolution morphogénique de l'éboulis depuis sa mise en place, la recherche se concentre sur l'étude d'une stalagmite « translatée » prélevée sur la partie sommitale de l'éboulis, Chau_stm9. Cette concrétion, dont la base a été datée à 13 100 ans (GENTY, 2005), constitue un support intéressant pour retracer son évolution et pour analyser l'enregistrement des variations climatiques et géomorphologiques.

En effet, communément analysés à des fins de reconstitutions paléoenvironnementales et paléo-climatiques (PERRETTE, 1999 ; FRISIA et *al*., 2000 ; MCDERMOTT, 2004 ; VERHEYDEN, 2006 ; FAIRCHILD & BAKER 2012), ces proxys environnementaux peuvent également être étudiés d'un point de vue morphologique et ce, afin d'appréhender des évolutions de surfaces topographiques (GILLI et *al*., 1999 ; SADIER et *al*., 2007 ; HAJRI et *al*., 2011). L'évolution des morphologies internes et externes de la stalagmite est appréhendée par les études pétrographique et de tomographie à rayons X. Les indices morphogéniques recueillis guident l'observation fine de la concrétion : modification de texture, réorientation de l'axe de croissance, changement de morphologie des fronts de croissance, identification de lamines poreuses, etc… (Fig. 1).

L'usage de ces deux méthodes a par ailleurs, permis (i) de mettre en évidence des secteurs clés au sein de la concrétion qui seraient liés à des changements d'axe de croissance et (ii) d'interroger par incidence les facteurs pouvant intervenir dans l'évolution de l'éboulis ou de l'alimentation stalactitique. Les données stalagmitiques acquises constituent un support solide de travail pour poser de nouvelles bases d'un scénario d'évolution morphogénique de l'éboulis au cours de la croissance de Chau_stm9 (Fig. 2).

De cette façon, l'analyse d'une stalagmite en provenance de la partie sommitale de l'éboulis, permet de remonter aux conditions environnementales et climatiques ayant régi sa croissance (DRYSDALE et *al*., 2004 ; VERHEYDEN, 2006) et indirectement lesquelles ont pu jouer un rôle dans l'évolution morphogénique de son support de croissance. En parallèle, l'observation et l'interprétation des morphologies de la stalagmite peuvent apporter des renseignements sur l'évolution de la surface topographique de l'éboulis et sur les processus qui en sont à l'origine comme le tassement des matériaux (éboulis, argiles…). À cela, s'ajoute son potentiel de datation donnant la possibilité d'accéder aux temporalités des différentes données acquises.

3. Résultats et Discussions

Les résultats acquis sur la stalagmite translatée Chau_stm9 (Fig. 1) permettent de poser les premières bases de l'évolution morphogénique de l'éboulis d'entrée de la grotte Chauvet tout au long de sa croissance soit sur une période d'environ 13 000 ans. Le scénario proposé permet de poser comme hypothèse forte que la nature translatée de la stalagmite reflète le mouvement de son support de croissance (l'éboulis) et non une évolution ou modification de son alimentation stalactitique.

La figure 1 rassemble l'ensemble des indices morphogéniques liés à l'étude pétrographique de Chau_stm9. Tous ces éléments ont permis de remonter à des facteurs géomorphologiques et/ou environnementaux qui ont conditionné la croissance du spéléothème.

Tout d'abord, l'axe de croissance de la concrétion indique quatre temps de développement distincts arborant chacun un léger décalage progressif sur la gauche. Ces quatre segments sont séparés par trois réorientations de l'axe de croissance. À chaque reprise, la réorientation s'exerce sur la droite entre 1 et 2 cm. Ces indices sous-tendent une évolution morphogénique de l'éboulis et/ou de son alimentation stalactitique tout au long de sa croissance.

Sur la face interne de Chau_stm9, dix phases de croissance ont pu être définies à la suite de modifications à la fois de la texture et des morphologies de fronts de croissance. La variation des morphologies de fronts de croissance au cours des dix stades de développement est bien visible sur la face polie de la concrétion sciée en son centre. Les fronts de croissance sont en grande majorité de morphologies concaves et associées dans la littérature à l'effet « splash » (FAIRCHILD & BAKER, 2012).

Des lamines à forte porosité sont observées à différents endroits sur la face interne de Chau_stm9 bien que majoritairement présentes sur la partie basse de l'échantillon. Leur formation est probablement due à une forte sursaturation et ainsi une précipitation accélérée de la calcite. La formation de ces lamines peut-être rapportée à différents facteurs tels que (i) des phénomènes d'évaporation, a priori fréquents dans les zones d'entrée de grottes, (ii) des périodes de réchauffement à l'origine de l'assèchement du front de croissance ou encore (iii) à la mise en place de phases d'érosion.

La superposition des différents indices morphogéniques décrits (Fig.1) permet de faire ressortir des zones d'intérêts de la stalagmite situées à proximité des trois réorientations de l'axe de croissance. Il est ainsi possible de noter la présence de lamines poreuses et de fronts de croissance concaves dans les secteurs des deux premières réorientations. Leur absence lors de la troisième réorientation suggère d'autres facteurs d'évolution de l'axe de croissance (alimentation stalactitique et/ou variations environnementales). Ces différents secteurs de Chau_stm9 nécessiteraient une analyse plus poussée par l'approche géochimique afin d'étoffer ou non les diverses hypothèses émises.

À partir des données présentées dans la figure 1, il est possible de proposer un scénario d'évolution de l'éboulis d'entrée (Fig. 2). Un fluage lent de l'éboulis a pu être

enregistré à quatre reprises via le décalage progressif de l'axe de croissance de Chau_stm9 et probablement par les autres stalagmites translatées présentes dans la zone d'entrée. Ces périodes de fluage peuvent être liées à des conditions relativement humides indiquées par les fronts de croissance concaves et des morphologies externes (choux-fleurs).

Des périodes de réchauffement ont pu intervenir ponctuellement et entraîner le tassement de l'éboulis par l'assèchement de sa matrice. Ces événements ont pu occasionner le redressement des concrétions et peut-être, la réouverture temporaire et limitée de la cavité, modifiant ainsi les dynamiques aérologiques préexistantes. Ces épisodes se manifestent par la réorientation de l'axe de croissance, reflétant le déplacement du sommet de la stalagmite par rapport à son alimentation stalactitique.

La précipitation des lamines poreuses peut également être rapportée à ces épisodes. Toutefois, leur développement n'est pas toujours suivi d'une réorientation de l'axe de croissance. Cela laisse sous-entendre que ces périodes de réchauffement n'aboutissent pas forcément à un redressement de la stalagmite.

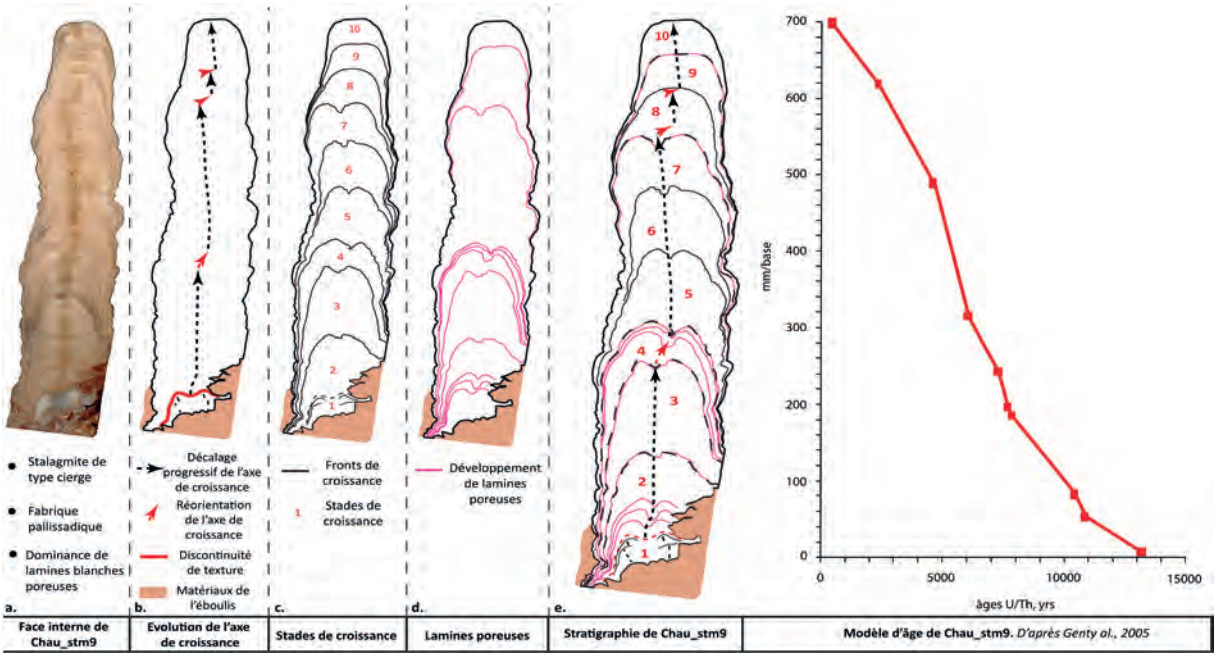

Figure 1 : Synthèse des observations morphogéniques sur la stalagmite translatée Chau-stm9 (grotte Chauvet-Pont d'Arc – France).

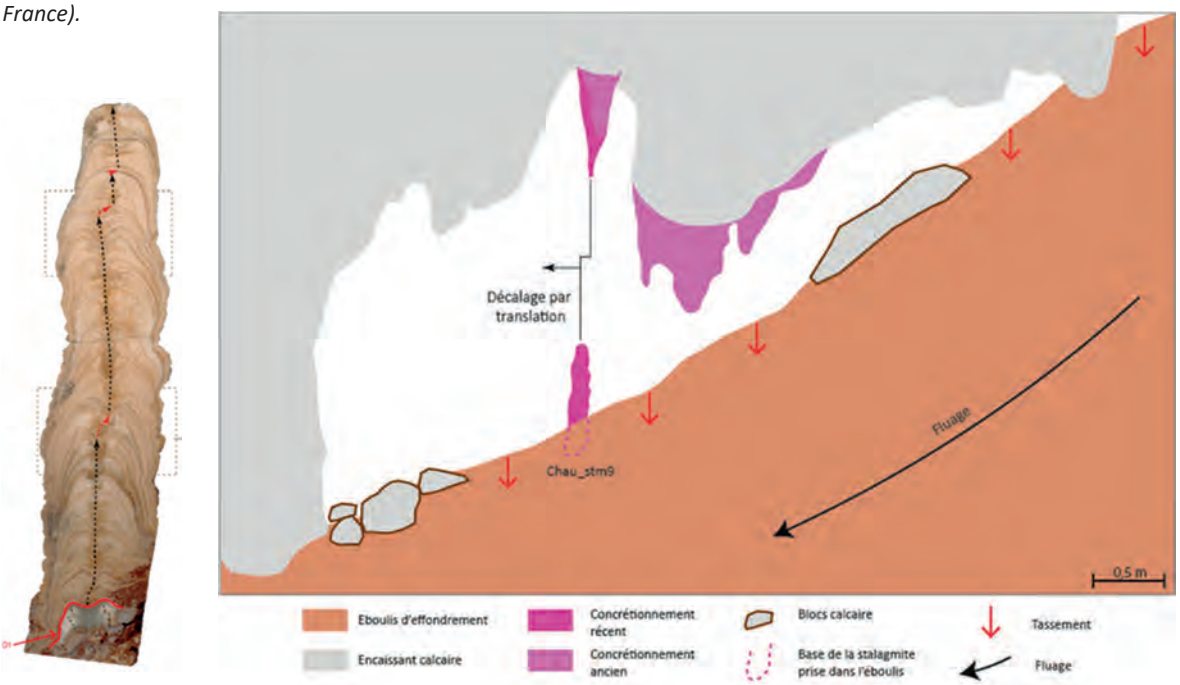

Figure 2 : Proposition de l'évolution morphogénique de l'éboulis selon les données morphogéniques de Chau_stm9.

4. Conclusion

Les variations des morphologies internes et des fronts de croissance reconnues au sein de la stalagmite Chau_stm9 permettent de questionner la stabilité de l'éboulis d'entrée de la grotte Chauvet. Dans le cadre de cette recherche préliminaire, il apparaît que la translation refléterait l'évolution géomorphologique de son support. Poursuivre l'étude de cette concrétion en associant de nouvelles datations avant et après les changements d'axe de croissance permettra de caractériser avec plus de précision l'évolution morphogénique de l'éboulis d'entrée, de les caler dans le temps de l'Holocène et de mieux appréhender les différents facteurs morpho-climatiques qui seraient favorables au fluage de l'éboulis.

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Exotic tufa and speleothem deposits on the calcareous island of Lismore, Argyll, Scotland

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Abstract

Tufa deposits are rare in Scotland. This paper reports deposits of cool freshwater tufa, which are ubiquitous on the calcareous island of Lismore in Loch Linnhe, Argyll. They occur there in several morphological varieties and locations, some being exotic and rarely reported in Britain or more widely. In particular, the tufa commonly occurs in a coastal environment, where it can form distinctive terraced mounds resembling cave gour pools, but with associated plant growth. Many indentations, fracture openings and short, probably hybrid karstic / marine, littoral caves have also formed on raised shore platforms, especially on the west coast of Lismore. These commonly contain stalactites, stalagmites, flowstones or pillars at entrances and in the daylight zone, some appearing remarkably massive. Thin deposits of tufa were also observed on the cliffs of the west coast. Speleothems resembling tufa deposits occur in the daylight zone of some of the larger littoral caves. A single example of a deposit of calcite pearls in the open air in front of a carbonate cliff has morphological and likely genetic affinities to deposits of cave pearls.

1. Introduction

The calcareous island of Lismore lies in Loch Linnhe, SW of Fort William in the Grampian Highlands of Scotland. It is 16 km long, c. 1.6 km wide, reaching 127 m a.s.l. (Fig. 1). The island is beside the Great Glen Fault (GGF) at the western extremity of the Dalradian Supergroup of metamorphic and igneous rocks within the Grampian Terrane (STEPHENSON *et al*., 2013).

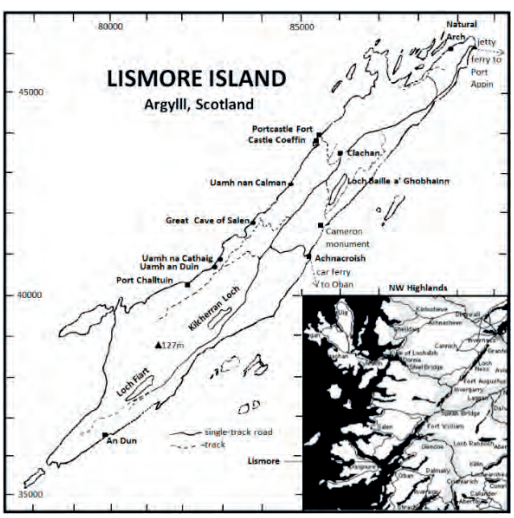

Figure 1: Lismore Island, showing caves and place names.

Comprising the >1 km-thick Lismore Limestone Formation, the island has the longest tract of coastal limestone in northern Scotland. This is a mainly greenschist facies metacarbonate (low grade marble), which deformed in the Ordovician during the Grampian Orogeny. The lithological strike is commonly aligned NE–SW, parallel to island ridges and the GGF. The surviving bedding is commonly vertical or contorted. Dense swarms of vertical igneous dykes up to 3 m wide and of various ages and lithologies intrude the whole outcrop orthogonally, which have created both small ravines and linear stacks (Fig. 2).

Figure 2: A vertical igneous dyke above type D tidal dam deposits on the west coast. Photo by JC.

Some dykes are adjacent to littoral caves, which were first reported on the raised Main Rock Platform at 9–11 m a.s.l. by CORBEL (1957). Littoral caves in marble are rare in Scotland and elsewhere, especially as some on Lismore contain large speleothems. GRAY & IVANOVICH (1988) attempted to date the Platform using calcite deposits from caves and cliff indentations. Most samples were contaminated with detrital thorium, for which Holocene ages were assumed, but one sample yielded an imprecise age of 103.3+28.4/-20.0 ka. This short paper introduces the widespread calcareous deposits on Lismore recorded during a visit by the authors (FAULKNER & CRAE, 2018). Most are in a steep coastal environment, some being exotic and near sea level, whose present tidal range varies throughout the year from 1–4 m.

Lismore glaciation and geomorphology

Lismore was subjected to multiple Quaternary glaciations. Intact surface deposits from pre-Devensian glaciations probably no longer exist, having been overridden at the Last Glacial Maximum (LGM: 27–18 k years ago), but some raised shorelines and littoral caves might have survived that erosion. The island was under a large ice stream occupying Loch Linnhe during the LGM, shown by many far-travelled erratic granite boulders and by depressions that underlie three large inland lakes. Mull to the SW was deglaciated by 17.5±1.0 ka (SMALL *et al*., 2017) and Lismore followed that, perhaps at c. 16 ka. The rarity of other surficial deposits might arise from ice streaming and be partly the result of marine re-working. Being only 55 km SW from the centre of the Scottish ice dome, isostatic depression caused the local sea level to reach a deglacial marine limit c. 40 m a.s.l. This was perhaps during a late readvance before the Lateglacial Interstadial at 14.7 ka (BALLANTYNE & STONE, 2012), after which Lismore remained unglaciated, being then west of the ice margin. However, there are no littoral caves at the 40 m level.

Lismore karst

There are no known inland caves on Lismore, but the island exhibits allogenic underground stream courses ≤300m long, with vertical ranges ≤15m. Other karst springs and seepages are probably risings from autogenic recharge. They are commonly identified by plentiful growths of yellow flag irises and sporadically by fluviatile crust tufa deposits. This superficial karst hydrology probably developed after deglaciation, assisted by open fracture creation or reactivation during isostatic rebound, as proposed in Norwegian marbles (FAULKNER, 2006). Houses and farms extract abundant supplies of fresh water from shallow wells and boreholes that can be 40m deep. These probably resurge invisibly under the sea (CORBEL, 1957). The deeper flow systems also likely follow faults or neotectonic fractures, some of which, together with some dykes, created weaknesses in the bedrock for the formation of the littoral caves. The present climate is damp (>1600mm precipitation per year) and mild, with little winter freezing or snow.

2. Speleothems, travertine and tufa

Speleothem is the term for all cave chemical precipitates. There is some confusion about the definitions of travertine and tufa, especially regarding the extent of biological and hydrothermal influences (LOWE & WALTHAM, 2002; BRASIER, 2011). This paper regards travertine as primarily a hard, non-biological, calcite deposit that forms in the open air in a similar way to a cave speleothem, and tufa as a softer or spongy and porous variety that is biologically assisted by the photosynthetic removal of CO_2 and the use of plants as a platform for deposition, perhaps assisted by cyanobacteria and algal colonies. Calcitic deposits form primarily by degassing of CO_2 from saturated dripwater (FAIRCHILD & BAKER, 2012, who also discussed biological influences) or recharging spring water. More rarely, they form by evaporation in a warm, well-ventilated, cave passage or when spring water meets warmer open air, to create distinctive coralloid precipitates, with a popcorn morphology. Surface deposits commonly form at waterfalls that can build up terraces like gour dams in caves. Warm weather can increase deposition slightly because CO_2 and calcite solubility reduce as temperature increases. Indeed, FORD (1989) pointed out that supersaturation is needed for precipitation, and that might only occur a kilometer downstream, if the spring temperature is low.

Lismore tufa

FAULKNER & BRAZIER (2016) counted only eight known Scottish tufa sites, all inland. Petrifying springs and the hardness of Lismore water were mentioned by CORBEL (1957). Over 70 tufa deposits were recorded there during the authors' visit, some with exotic morphology and locations. Most occur at the coasts, with some even being near the tidal range and many more being subject to sea spray. Only a few references to tufa forming at temperate latitudes near sea level were given by FORD & PEDLEY (1996). Many morphological varieties of tufa have previously been classified (CHAFETZ & FOLK, 1984; PEDLEY, 1990; PENTECOST, 1993). The authors' identifications of tufa on Lismore are broadly based on the classification of autochthonous tufas A–H provided by PENTECOST (1995). They can all be active or inactive or intermittently active at present. The genetic processes and the arising petrology of tufa deposits are discussed in several of the cited references. In advance of similar studies, all the Lismore calcareous surface deposits are treated as tufa, and the quite large speleothems in or near the entrances of the short littoral caves, some being vegetated, are probably biologically-assisted.

No deposits seem to fit the type A, perched springline, morphology exactly. However, many tufa deposits below assumed or relict perched springlines do occur. Several thin white crusts on vertical cliffs were recorded, but only along the west coast and not on any inland cliffs, all within 100m of the sea, with bases from 10–21 m a.s.l. They commonly have a sharp upper limit (Figure 3), suggesting that they are fed along narrow horizontal joints in the bedrock by unseen perched springlines.

One distinctive group of 'speleothems' was observed below an apparently inactive superficial overhanging perched springline on the east coast, in the bank of a small stream just above the sea (Figure 4). Large numbers of cliff 'speleothems' occur just outside cave entrances or in various indentations, from 3–25 m a.s.l., especially on the west coast. These are assumed to have formed below unseen joints in the bedrock (Fig. 5 and 6). Type C, cascade tufa, occurs on both coasts, descending to sea level (Figures 7 and 8). One series of type D, non-tidal dams, are inland, along a small stream. Two remarkable type D tidal dams were observed at 0–8 m a.s.l. That on the east coast is covered in green vegetation with some sea pinks (Fig. 9), below a perched springline nourishing yellow flag irises that does not immediately deposit tufa. The visited site on the west coast comprises a longer and larger feature (Figure 2). Where types C and D tufa reach the sea, they become green in colour. Three inland type E, fluviatile crust, deposits occur along stream beds below springs up to 50 m a.s.l., with three more near the coasts. Type F lacustrine crusts rich in calcifying algae have been separately observed beside one of the marl lakes.

Figure 3: Type A cliff deposits surrounding small holes.

Figure 4: Type A tufa speleothems below inactive perched springline just above the sea on the east coast. Figure for scale.

Figure 5: Type A tufa flowstone beneath a cliff fracture and beside the entrance to the Great Cave of Salen. Photo by JC.

Figure 6: Large type A tufa pillar that partially blocks the entrance to Uamh na Cathaig. Figures for scale.

Figure 7: East coast type C cascade deposit descends to the sea.

FORD (1989, p. 39) and FORD & PEDLEY (1996) confirmed the occurrence of tufa-like speleothems inside many cave entrances in Britain and worldwide. Such deposits are all classified herein as type S internal cave speleothems, in or near the daylight zone on cave floors 10–20 m a.s.l. A few flowstones display a spikey popcorn surface, suggestive of some deposition by evaporation rather than by CO_2 degassing. Some type S deposits appeared to be inactive and sporadically covered in vegetation and not visibly dripping (Figure 10), but others were pristine and bright white, suggesting active precipitation.

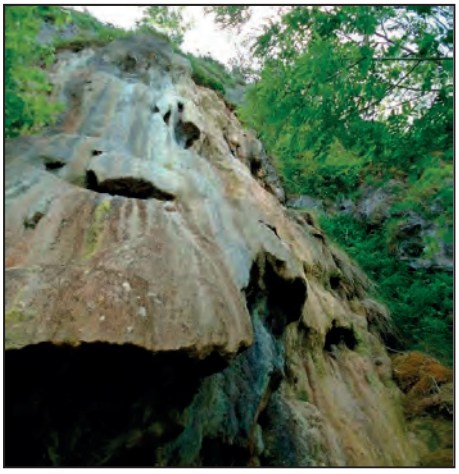

Figure 8: Massive type C cascade, c. 8 m high, overhanging the sea on the west coast. Photo by JC.

Figure 9: Type D vegetated tidal dam tufa with sea pinks.

Figure 10: Vegetated type S speleothems just inside the entrance to a littoral cave at the head of a 10m-deep gorge. Photo by JC.

Figure 11: Two adjacent nests of white calcite pearls in a tiny stream bed on a raised shore platform in front of a marble cliff on the west coast. Boot for scale.

Calcite pearls

Underground cave pearls are well-known, although there is no comprehensive study of their worldwide distribution and characteristics. The occurrence of similar calcite pearls on the ground surface is less well reported. The discovery of

two closely-adjacent nests of rather flat white calcite pearls on the surface of Lismore (Figure 11) is significant for Scotland. They lie in the bed of a tiny intermittent stream that is probably saturated with calcite when it rises from the base of a marble cliff a few meters away.

3. Discussion

Tufa deposits, littoral caves, bedrock orifices and indentations are commonly associated and sporadically near igneous dykes on Lismore. Coastal tufa types C and D are close enough to sea level for marine inundation during high tides and storms. The sheltered location within high mountains and the mild climate appear to prevent them being washed away. Tufa types A, C, D and E occur at 0–10 m a.s.l. and might be related to the present or a previous shoreline. They likely started to form after the LGM: either in the Lateglacial Interstadial after the amelioration of permafrost and the growth of vegetation, perhaps without surviving Younger Dryas periglaciation, or during the Holocene. The active type C, D, and coastal E tufas are rather small, compared with international deposits. This suggests they are in dynamic equilibrium between growth and destruction by the sea or by dissolution following heavy rain, which would send a plume of aggressive water through the fractures.

No coastal tufa, caves, undercuts or conduits were found >25 m a.s.l. This suggests they did not exist at the readvance just prior to 14.7 ka, when a seasonally-frozen sea accelerated coastal erosion and cut the 40 m shoreline. Otherwise, caves and undercuts should be preserved, because the final Lismore deglaciation was at c. 16 ka and sea level has fallen since. Thus, the land probably remained permafrosted immediately prior to 14.7 ka, so that there were no seepage waters and plants to promote calcite deposition as tufa and no karstic dissolution to create conduits, if that was necessary prior to any subsequent enlargement by marine abrasion. Thin type A cliff deposits were only observed close to the NW coast, at ≥10 m a.s.l. This tufa is probably promoted by the evaporation of sea spray borne by the prevailing SW winds. The containing cliffs were eroded back during glaciation, so that the earliest that most high and massive tufas and speleothems could have formed is in the Lateglacial Interstadial. However, the sample with an MIS5 age was collected from a stalactite in a "deep undercut" 19 m a.s.l. It possibly survived if it formed in a littoral cave passage that was mostly removed by glacial erosion before the end of the LGM. Similarly, the massive column in the entrance to Uamh na Cathaig (Figure 6), which is 3 m in diameter and 8 m tall, might have formed at MIS5e inside a paleo cave passage that was later eroded to leave a 5 m-deep gorge that starts about 30 m in front of the existing cave entrance and runs to the sea. Another cave heads a short 10 m-deep gorge (Figure 10). These three sites could be examples of roofless caves, which have rarely been reported in Britain. Other interesting research queries were also discussed by FAULKNER & CRAE (2018).

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Prospecting for Last Interglacial speleothems in Vercors

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Abstract

The Last Interglacial (LIG, ~130–116 ka) was one of the warmest interglacials of the past 800,000 years. Speleothems offer superior age control and a few LIG records are available from the Eastern Alps. In order to prospect for LIG speleothems in the Western Alps, we drilled small diameter cores at the base of stalagmites. In the Vercors, we sampled 27 speleothems in 6 different caves and dated them using the U-Th method. Here, we present the results of these reconnaissance drilling campaigns. Although, to our surprise, we did not identify stalagmites of LIG age, the resulting ages provide useful chronological information on the individual karst settings. Among these 27 ages, 5 are Holocene, the others belong to Marine Isotope Stage 2 (5 samples), 3 (2), 5a (1) and 5c (1), 8 (1), 9 (2), 11 (4), 12 (1), 13 (1) and 4 are beyond the U-Th dating limit. These dates can help to re-assess the age of certain cave conduits and the evolution of this well-documented karst region. In addition, they may serve as a basis for future speleothem-based paleoclimate studies of the Vercors.

Résumé

À la recherche de spéléothèmes du Dernier Interglaciaire dans le Vercors. Le Dernier Interglaciaire (LIG, ~130-116 ka) a été l'un des interglaciaires les plus chauds des 800 000 dernières années. Les spéléothèmes offrent la possibilité d'une excellente chronologie pour cette époque et quelques enregistrements sont disponibles dans les Alpes orientales. Afin de trouver des spéléothèmes LIG dans les Alpes occidentales, nous avons foré des carottes de petit diamètre à leur base. Dans le Vercors, nous avons carotté 27 spéléothèmes dans 6 grottes différentes qui ont ensuite été datés par la méthode U-Th. Nous présentons ici les résultats de ces campagnes de forage de reconnaissance. Bien que, à notre surprise, nous n'ayons pas identifié de stalagmites d'âge LIG, les âges obtenus fournissent des informations chronologiques utiles pour la connaissance du karst. Parmi ces 27 âges, 5 sont holocènes, les autres appartiennent au stade isotopique marin 2 (5 échantillons), 3 (2), 5a (1) et 5c (1), 8 (1), 9 (2), 11 (4), 12 (1), 13 (1) et 4 sont au-delà de la limite de datation U/Th. Ces dates peuvent aider à réévaluer l'âge de certains conduits et l'évolution de ce karst de moyenne montagne. En outre, elles peuvent servir de base pour de futures études paléoclimatiques du Vercors à partir des spéléothèmes.

1. Introduction

The Last Interglacial (LIG ~130–116 ka), equivalent to Marine Isotope Stage (MIS) 5e and considerably warmer than the current interglacial, is a useful test bed for the future course of the Holocene (Anthropocene). In the foreland of the European Alps, the LIG has been studied using pollen preserved in mires and lake sediments. While these records document the succession of tree and other plant species across the LIG, they are very poorly constrained chronologically. Speleothems in caves offer superior age control and a few records are already available from the Austrian Alps (SPÖTL et *al*., 2002; MOSELEY et *al*., 2015) and the Swiss Alps (HÄUSELMANN et *al*., 2015; WILCOX et *al*., 2020). The aim of the project was to find speleothems of LIG ages in the French Alps and thus extend our knowledge about this period across the entire Alps. Mountains are of particular interest for climate science because they are highly sensitive and show higher amplitudes of climate change than surrounding regions (Mountain Research Initiative EDW Working Group, 2015). Site selection was based on previous work on the Vercors

(e.g., AUDRA 1994; DELANNOY, 1997) and discussion with colleagues and local cavers. Criteria of this selection included the availability of high-quality sample material and whether the cave has been characterized previously (including geomorphological observations and speleothems of different age).

Sites description

The four study sites (6 caves) are presented from north to south (Fig. 1). At 1144 m a.s.l. the **Antre de Vénus** is a horizontal cave of 850 m length. It partially intersects the Croix Perrin anticline and at the time of its formation, it drained the vast Méaudre-Autrans depression. It is interpreted as one of the ponors of a vast paleo-poljé and is the witness of a higher base level of the hydrographic network during the Neogene (DELANNOY et *al*., 1998). The Coulmes karst, northwest of the Vercors, is a multi-level cave system that has recorded the landscape evolution since the Neogene. **Pra l'Etang** (1220 m a.s.l., 300 m length) is a cave marking a former higher perched base level. Three samples were taken there. Nearby, at a lower elevation, in the **Gournier system** (572 m a.s.l., 18 km length), an underground river which can be followed up to 680 m a.s.l. Six samples were collected in the first fossil gallery of this cave. Next to it, the **Coufin/Chevaline network** (580 m a.s.l., 32 km length) also hosts two underground rivers. Samples were collected in the so-called "gruyères" sectors. The **Pabro cave** (840 m a.s.l., 100 m length) is a decapitated cave facing the Coulmes karst and perched above the gorges de la Bourne. Six samples were taken in the main room.
Finally, the **Chuats system** was the subject of preliminary investigations. It is an important and recently explored network of 43 km length (LANDRY et *al*., 2019) that comprises 5 known entrances. Three samples were taken from the Chuats II chasm in the sectors near the base of the entrance shafts series. These are the first dated speleothems in this major cave system of the southern Vercors.

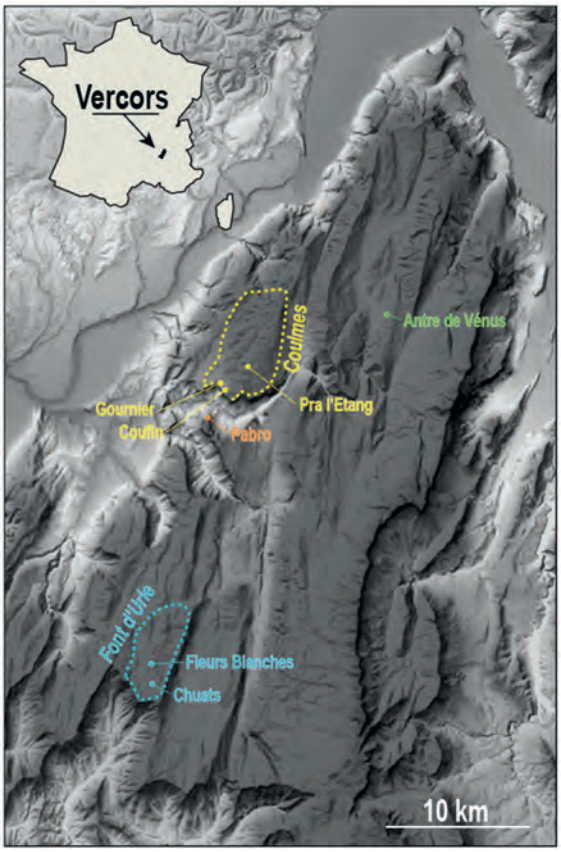

Figure 1: Map of the Vercors region with sampled caves

2. Materials and methods

Figure 2: Sampling of a calcite core in a stalagmite with a hand-held drill and a water flushing unit.

Figure 3: Example of small core pieces used for dating. Both pictures: Serge Caillault

Our sampling approach of taking drill cores instead of entire dripstones minimizes the impact on the cave environment (Fig. 2) (SPÖTL and MATTEY, 2012). In order to search for LIG speleothems, we drilled small-diameter cores (Fig. 3) at the base of 21 speleothems (stalagmite and flowstone) and exclusively retrieved broken stalagmites (6 in total). We targeted the central axis of the stalagmites and sampled the innermost part of each core.

The cores were then cleaned in an ultrasonic bath before being drilled and dated using the U-Th method. Between 30 and 70 mg were analysed at the University of Minnesota and the Xi'an Jiatong University following the same procedure (EDWARDS et al., 1987). All measurements were performed on a ThermoFisher Neptune Plus MC-ICP-MS using the technique described by CHENG et al. (2013).

3. Results

Among the 27 analyzed speleothem samples 5 are Holocene in age, and the others fell into Marine Isotope Stages 2 (5 samples), 3 (2), 5a (1) and 5c (1), 8 (1), 9 (2), 11 (4), 12 (1), 13 (1), while 4 are beyond the U-Th dating limit (older than 650 000 years). The ages are given in year before present (BP) in table 1.

Sample Number	^{238}U (ppb)	^{232}Th (ppt)	^{230}Th / ^{232}Th (atomic x10^{-6})	$\delta^{234}U$* (measured)	^{230}Th / ^{238}U (activity)	^{230}Th Age (yr) (uncorrected)	^{230}Th Age (yr) (corrected)	$\delta^{234}U_{Initial}$** (corrected)	^{230}Th Age (yr BP)*** (corrected)	
ADV-01	259.4 ±0.6	13671 ±275	294 ±6	-30.2 ±2.2	0.938 ±0.004	420669 ±25855	418950 ±25449	-99 ±10	418881	±25449
ADV-02	186.4 ±0.3	13159 ±264	297 ±6	190.0 ±2.0	1.273 ±0.004				Beyond U/Th Limit	
ADV-03-BOT	253.5 ±0.4	2733 ±55	1902 ±38	169.9 ±1.8	1.244 ±0.003				Beyond U/Th Limit	
ADV-04-BOT	115.8 ±0.2	218 ±5	9881 ±229	108.0 ±1.9	1.128 ±0.003	434526 ±18286	434482 ±18281	368 ±20	434413	±18281
COU-01	430.5 ±0.8	1865 ±38	4218 ±85	85.1 ±2.0	1.108 ±0.003	506997 ±33601	506895 ±33573	356 ±35	506826	±33573
COU-02	378.8 ±0.7	5369 ±108	1233 ±25	87.1 ±2.0	1.059 ±0.003	325705 ±6444	325365 ±6429	218 ±6	325296	±6429
COU-03	17.1 ±0.0	150 ±4	1769 ±54	37.5 ±1.9	0.944 ±0.011	251873 ±11203	251634 ±11183	76 ±5	251565	±11183
COU-04	122.1 ±0.2	177974 ±3566	13 ±0	41.8 ±1.9	1.187 ±0.005				Beyond U/Th Limit	
COU-06	108.4 ±0.2	117829 ±2364	16 ±0	46.8 ±2.0	1.042 ±0.005	421933 ±25213	390143 ±30279	141 ±13	390074	±30279
GO-13-Bot	236.7 ±0.3	19251 ±386	38 ±1	356.2 ±2.1	0.190 ±0.001	16324 ±86	14585 ±1234	371 ±3	14517	±1234
GO-14	313.2 ±0.5	12650 ±254	63 ±1	284.8 ±2.2	0.154 ±0.001	13862 ±91	12951 ±651	295 ±2	12883	±651
GO-15	314.5 ±0.5	691 ±14	874 ±18	200.3 ±2.1	0.116 ±0.001	11088 ±66	11035 ±76	207 ±2	10967	±76
GO-16	150.9 ±0.2	11337 ±227	34 ±1	143.5 ±2.1	0.154 ±0.001	15701 ±159	13782 ±1367	149 ±2	13714	±1367
GO-17	107.7 ±0.1	3197 ±64	83 ±2	184.1 ±2.2	0.150 ±0.002	14745 ±192	14018 ±549	192 ±2	13950	±549
GO-18	603.4 ±1.2	155 ±4	8194 ±206	300.1 ±2.3	0.127 ±0.000	11207 ±49	11201 ±50	310 ±2	11133	±50
PLG-01	194.0 ±0.3	4245 ±85	133 ±3	115.1 ±2.1	0.176 ±0.001	18741 ±129	18172 ±423	121 ±2	18103	±423
PLG-03	168.7 ±0.2	697 ±14	350 ±8	103.9 ±2.0	0.088 ±0.001	9012 ±91	8903 ±119	107 ±2	8834	±119
PLG-04	192.6 ±0.4	1734 ±35	56 ±2	-26.5 ±2.1	0.030 ±0.001	3455 ±96	3186 ±214	-27 ±2	3117	±214
PB-19	73.2 ±0.1	448 ±9	979 ±23	41.1 ±2.4	0.363 ±0.005	46662 ±728	46492 ±736	47 ±3	46424	±736
PB-20-Bot	79.2 ±0.1	1291 ±26	433 ±10	66.5 ±2.0	0.429 ±0.004	55717 ±661	55276 ±728	78 ±2	55208	±728
PB-21-Bot	96.2 ±0.1	64 ±3	2179 ±106	34.3 ±2.2	0.088 ±0.002	9642 ±223	9623 ±224	35 ±2	9555	±224
PB-22	106.1 ±0.1	34993 ±701	32 ±1	34.5 ±1.7	0.646 ±0.006	106120 ±1588	96534 ±6960	45 ±2	96466	±6960
PB-23	106.3 ±0.2	9943 ±199	174 ±4	7.5 ±2.3	0.988 ±0.008	416445 ±45062	413750 ±43912	24 ±8	413682	±43912
PB-24	86.8 ±0.1	10496 ±210	134 ±3	6.9 ±2.0	0.985 ±0.008	406405 ±40974	402901 ±39666	21 ±7	402833	±39666
CHU01-TOP	362.7 ±0.4	793 ±16	5227 ±106	275.0 ±1.8	0.693 ±0.002	82559 ±387	82512 ±388	347 ±2	82443	±388
CHU02-BOT	1785.4 ±6.9	298 ±6	98680 ±2111	0.2 ±2.5	0.999 ±0.005	732945			Beyond U/Th Limit	
CHU04-A	487.8 ±0.5	478 ±10	18678 ±382	126.2 ±1.4	1.110 ±0.002	327917 ±4573	327893 ±4572	318 ±5	327824	±4572

Table 1: U-Th dating results. Ages are reported in Year BP; the error is 2 sigma. ADV: Antre de Vénus; COU: Couffin; GO: Gournier; PLG: Pra L'Etang; PB: Pabro; CHU: Chuat

4. Discussion and conclusion

When compared to the deep-sea $\delta^{18}O$ curve based on benthic foraminifera (Fig. 4), the majority of the stalagmites commenced to grow during interglacial periods: 5 are Holocene in age, 2 are from MIS 9, 4 from MIS 11 and 1 from MIS 13. Some ages indicate growth during interstadials. On the other hand, one sample plots at the onset of the Younger Dryas, another sample plots into a glacial (MIS 12) but overlaps within error with the following major interglacial MIS 11 (Fig. 4). Another sample falls into MIS 8 but again its error bar overlaps with an interglacial, MIS 7. Interestingly, we found no speleothems that formed during the LIG.

Regarding the confidence of the dating, the material originating from stalagmites had almost always a higher Uranium concentration and was cleaner (less detrital thorium) than flowstones from the same area in the cave. The high detrital content of the flowstone from the Coufin/Chevaline river were challenging to date and some samples had to be discarded. Samples with a small $^{230}Th/^{232}Th$ atomic ratio (on the order of tens) should be cautiously considered.

We report these new dates to serve as (a) minimum ages for speleogenetic studies of these caves (e.g. to assess the minimum age of certain conduits), and (b) as pilot data for future paleoclimate studies of this part of France. Some of these dates will later be integrated in local studies on these cave systems.

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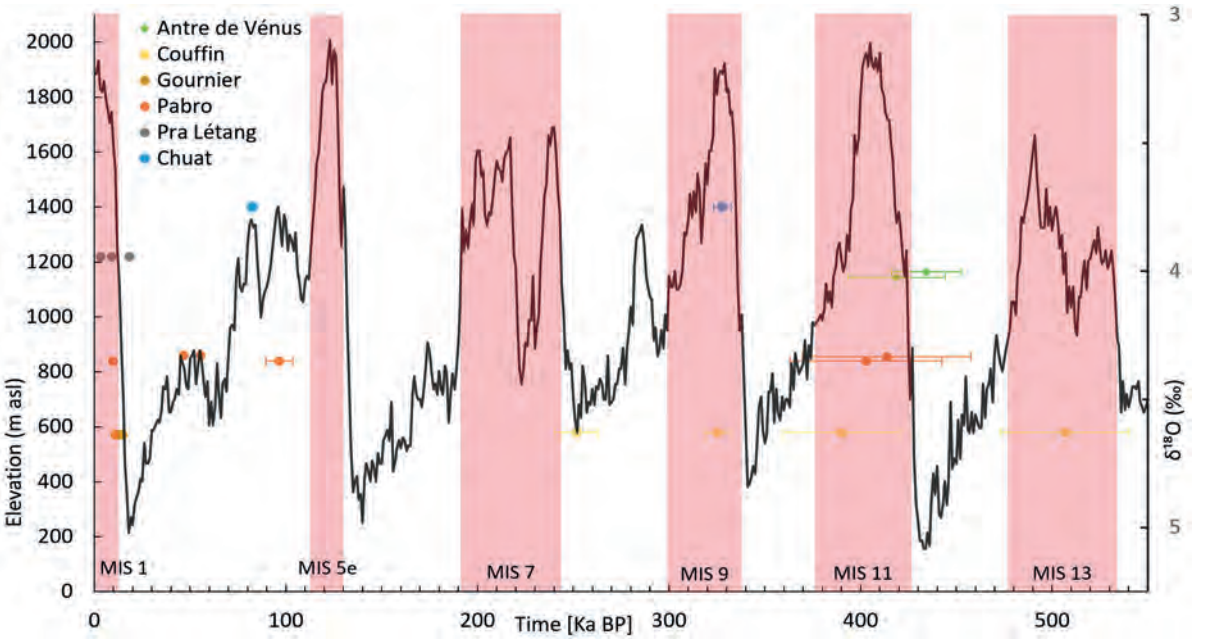

Figure 4: Basal ages with 2 sigma error bars of sampled speleothems from the Vercors arranged according to their approximate elevation (cave entrance), compared to the deep-sea $\delta^{18}O$ curve (LISIECKI and RAYMO, 2005). Interglacials are highlighted in purple.

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Relief and paleoenvironmental conditions during the mid-late Miocene in the French Western Alps (Dévoluy Massif) revealed by Obiou cave deposits

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Abstract

Cave levels at high elevations (2250-2370 m), hosting allochthonous sediments with clear provenance from the Pelvoux External Crystalline Massif were identified in the Obiou mountain, Dévoluy Massif (French Western Alps). These deposits result from burial of alluvial sediments of the paleo-Drac River in Miocene times (burial ages of ca. 10-15 Ma). The Drac River is currently situated 1600 m below the caves, indicating significant post-middle Miocene fluvial incision. The pollen analysis on clay cave infill indicates a humid and warm climate, typical for Western Europe in the mid-late Miocene. It also reveals the presence of dinoflagellate cysts from coastal and lagoon environments suggesting deposition of the clays in the caves when they were close to sea level. These findings indicate uplift of the caves of at least 2000 m since the mid-late Miocene. Furthermore, the pollen assemblage originated from different vegetation belts, in agreement with existing data for mid-late Miocene deposits in the western Alps. The pollen flora includes cool-temperate and boreal trees, suggesting high-elevation source areas for the deposits within the Pelvoux catchment. These data confirm the exceptional character of the Obiou cave deposits that provide new geomorphologic constraints for the evolution of the French Western Alps.

1. Introduction

Cave deposits are a valuable tool to reconstruct past relief and environmental changes, especially in regions where sediments on the surface are not preserved, as is often the case in mountainous areas characterized by efficient erosion. Furthermore, the development of horizontal caves may be linked to paleo-river levels, analogous to alluvial terraces as soon as infill deposits are trapped in karstic systems. The difference with the modern river elevation can be interpreted in terms of fluvial incision, and ultimately in terms of surface uplift when paleo-elevations of caves can be quantified. However, inferring paleo-elevation of caves is generally difficult. One of the means to define a paleo-elevation is to study the pollen assemblages from sediments, as the type of vegetation depends on the mean annual temperature (MAT), which in turn depends on latitude and altitude. The analysis of pollen flora from Paleogene and Neogene foreland-basin sediments provides insights on the evolution of Alpine topography (FAUQUETTE *et al.*, 2015), but such data remains scarce. We employed this method on clay deposits from a high-elevation cave with datable allochthonous infill found in the Obiou (Dévoluy Massif), in order to estimate paleo-elevation and paleoenvironmental conditions during their deposition. These results helped assess the long-term uplift of the Dévoluy Massif.

2. Geological setting and descriptions of the studied caves

The Dévoluy Massif is situated to the west of the Ecrins (Fig. 1), which is part of the Pelvoux External Crystalline Massif (ECM). The Dévoluy is a subalpine karstic massif consisting of Upper Cretaceous limestones folded in a N-S syncline, containing Paleogene foreland-basin sediments (Eocene and Oligocene molasses originated from the Internal Alps). The Dévoluy area comprises some of the oldest caves identified in the French Alps (JAGERCIKOVA *et al.*, 2021).

Allochthonous deposits were recognized in three caves (Baume des Jalabres, Baume du Petit Odieux, Baume du Calvaire) in the Obiou (2789 m), located at an altitude ranging from 2250 to 2370 m asl. Cave deposits include rounded crystalline pebbles (pseudo-spheres and rods), sands and clays, present in some cases as consolidated conglomerates. JAGERCIKOVA *et al.* (2021) determined $^{26}Al/^{10}Be$ and $^{10}Be/^{21}Ne$ burial ages of Jalabres Cave deposits to 15.6 ± 3.8 Ma, which was refined to 10 ± 2 Ma, respectively (by LEMOT (2021). Both burial ages relate the deposition of such conglomerates to mid-Miocene ages. These infills were interpreted as alluvial, originating from the southern Ecrins (Pelvoux ECM). Indeed, the petrographic analysis of the infill showed mostly granites, various metamorphic rocks, sandstones and volcanic clasts (JAGERCIKOVA *et al.*, 2021). The Jalabres Cave preserved magnificent meander morphologies (5-m wide, 30-m high), which indicate an important underground flow. The drainage would correspond to the paleo-Drac River, which has a modern level situated ~1600 m below the studied caves (Fig. 1). The recognition of these cave deposits is important for several reasons: 1) it shows that the Pelvoux basement was already exhumed and being actively eroded since the mid-Miocene; 2) the summit of the Obiou is located currently 400 m above the investigated caves implying that the Dévoluy Massif already had an uplifted landscape during the mid-Miocene with the development of old karst settings; 3) an important fluvial incision of the Drac River (at ~1600 m), related to the surface uplift has occurred since the mid-Miocene. The amount of fluvial incision can be therefore roughly estimated from the elevation difference between the cave levels and the modern river. However, the quantification of surface uplift requires additional information about the paleo-elevation of caves at the time the allochthonous infill was deposited inside the karst systems.

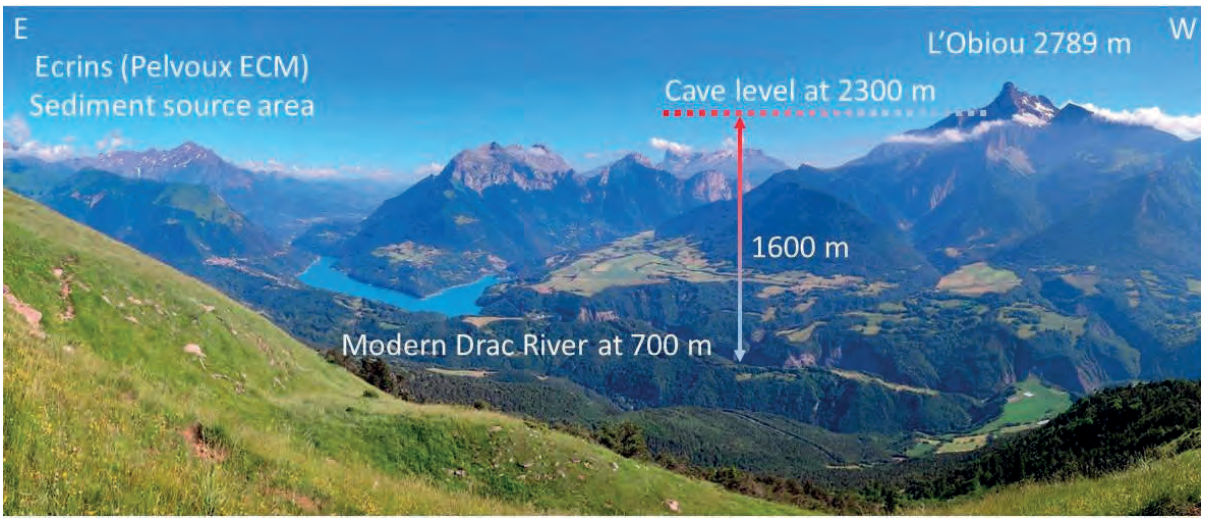

Figure 1: Photograph showing the Obiou and cave level at 2300 m with allochthonous deposits.

3. Methods

In order to better understand the paleoenvironmental conditions during the infill deposition, we performed a palynological analysis on clay deposits from the Petit Odieux Cave (2250 m asl), a horizontal cave almost completely filled with various types of infill. The allochthonous deposits of this cave consist of broken polygenic conglomerates, including crystalline pebbles, limestone blocks, sands and mud clasts, and mica-rich clay infills. Many conglomerates and clays were likely perturbed post-deposition as they are not in stratigraphic position. However, some clay deposits are located in protected spaces inside the cave and show layered structures. This layered clay was sampled for palynological analysis. First, a sample of 60-70 g was processed using the classic method to extract palynomorphs (acid attacks with HCl and HF, heavy liquid $ZnCl_2$) and then sieved at 10 µm. Second, the identification of palynomorphs in the sample was conducted using a microscope at x1000 magnification. Fluorescence light was used in parallel to exclude recent contamination or reworking of palynomorphs. Pollen grains were identified at the genus or family level and classified according to their ecological significance following NIX (1982). The entire residue from the chemical processing was analyzed and provided a total of 102 pollen grains, a number which is relatively low, but significant enough of the vegetation belts with respect to our database of modern pollen floras and their relationship to vegetation in the region. The pollen flora allows the reconstruction of the mean annual temperature (MAT) during the deposition of the cave deposits. This *Climatic Amplitude Method* compares the present-day pollen records distributed worldwide with the identified pollen species in the studied cave deposits. It relies specifically on the relationship between the relative abundance of each individual taxon and climate. The MAT value, together with pollen flora and the vertical shift in the vegetation belts in relation to latitude, is used to quantify the paleo-elevation of a massif (see details of the methods in FAUQUETTE *et al.*, 2015).

4. Results

The clay sample from the Petit Odieux Cave is relatively poor in palynomorphs (see Table 1). The analyzed sample contains 102 pollen grains, 34 spores of Pteridophytes, 206 spores of Bryophytes and 2 dinoflagellate cysts that could be identified. Most of the palynomorphs are well-preserved and they show significant diversity in the vegetation types, with different paleo-ecological implications. The presence of mega-mesothermal plants, with estimated mean annual temperature of ca. 15.4 °C (range: 10–20 °C), indicates warm conditions. Tree pollen of swamp and riparian forests are quite frequent (*Taxodium*-type, *Alnus*, *Carya*, *Liquidambar*, *Zelkova*). The presence of *Osmunda* is consistent with a swampy environment and the abundance of *Pteridophyte* spores, lacking perispores, suggests important runoff conditions. Then, pollen grains of mid-altitude subtropical trees (*Cathaya*, *Sciadopytis*), warm-temperate trees (mostly *Quercus* and *Zelkova*), cool-temperate trees (*Fagus*, *Tsuga*) and boreal trees inhabiting high altitude (*Picea*) were recognized. The presence of such taxa suggests the existence of different vegetation belts in the catchment area (Ecrins sector, Pelvoux ECM). The palynological analysis also revealed the presence of 2 dinoflagellate cysts, *Lingulodinium machaerophorum* and *Pentapharsodinium dalei*; these are coastal to lagoonal species indicating depositional settings close to sea level. The presence of Amaranthaceae and other herbaceous plants is related to coastal environment settings. There is no difference between pollen grains and dinoflagellate cysts under fluorescence light. Therefore, the cysts were not reworked from older deposits and are contemporaneous with the other palynomorphs. Considering the burial age interval (ca. 10-15 Ma), this pollen flora is probably younger than the Mid-Miocene Climatic Optimum (MMCO: 17–14 Ma), because it does not include megathermal (i.e., tropical plants). We thus consider the deposits younger than 14 Ma (mid-late Miocene in age). At that time, the ratio between the altitudinal and latitudinal temperature gradients was supposed to be similar to the present ratio. This implies a relationship in which vegetation belts shift 110 m / one degree of latitude. The reconstructed MAT of 15.4 °C is found today at ~42 °N (i.e., ~2.8° further south of the Obiou). Vegetation belts were therefore shifted ~300 m higher in altitude than the present-day to compensate for higher temperature environments. Nowadays, the spruce (*Picea*) forest develops in the Ecrins from ~1600 m altitude upwards. Based on the MAT reconstruction relationship, this same forest must have developed above ~1900 m during the mid-late Miocene. The estimated basal altitude of the spruce forest ~300 m above its present altitude gives an similar minimum altitude estimate for the mid-late Miocene Pelvoux Massif. In the case the spruce altitudinal belt was complete (as suggested by the significant pollen percentage), the maximum altitude of this forest would then reach ~2600 m, assuming that the amplitude of a vegetation belt is ~700 m).

Subtropical (mega-mesothermal) plants:	
Engelhardia	3
Sequoia-type	8
Taxodium-type	2
Mid-altitude subtropical trees:	
Cathaya	16
Sciadopitys	2
Warm-temperate (mesothermal) trees:	
Alnus	2
Carya	2
Liquidambar	1
Quercus	7
Zelkova	3
Cool-temperate (meso-microthermal) trees:	
Fagus	3
Cedrus	1
Tsuga	1
Boreal (microthermal) trees:	
Picea	11
Trees without signification (cosmopolitan trees):	
Pinus	19
Pinaceae altered pollen grains	9
Cupressus-Juniperus-type	1
Herbaceous plants:	
Amaranthaceae	1
Compositae	3
Cyperaceae	2
Poaceae	4
Rumex	1
Number of identified pollen grains:	102
Pteridophyte spores:	
Osmunda	1
Monolete spores without perispore	15
Trilete Spores	3
Other spores	15
Bryophyte spores:	206
Fungal spores:	12
Dinoflagellate cysts:	
Lingulodinium machaerophorum (coast to lagoon) lllagoonal)	1
Pentapharsodinium dalei (lagoon)	1

Table 1: Result of palynological analysis of a clay sample from the Petit Odieux Cave.

5. Discussion and conclusion

The Dévoluy Massif is the highest Subalpine massif in the French Western Alps, and it was periodically glaciated during the Pleistocene. Mid-late Miocene sediments were hitherto not reported in the Dévoluy Massif. There is thus no

surface equivalent to the allochthonous deposits investigated in the Obiou caves. Therefore, our paleoenvironmental reconstruction based on palynological analysis from cave deposits is a first attempt to infer mid-late Miocene conditions for the Dévoluy Massif and the Southern Ecrins sector. The evidence suggests humid and warmer conditions than nowadays (e.g., presence of subtropical plants), with probable important runoff. These conditions agree with the warm climate well stated in Western Europe during the Miocene by previous works (e.g., SUC *et al*., 2018). Some subtropical taxa like *Cathaya* are now absent from Europe, and they can be found in mountainous regions of Southern China. Our pollen assemblage resembles the Tortonian pollen flora identified in the study of FAUQUETTE *et al*. (2015), from foreland basins located further south. The karst base-level related to the caves would be at low elevation, as suggested by the presence of subtropical trees and probably close to sea-level (e.g., dinoflagellate cysts). Thus, we suggest that these studied caves located presently at high altitudes would be formed close to a coastal plain, which had a low hydraulic gradient and was periodically flooded during the mid-late Miocene. Allochthonous deposits - (pebbles, sands and clays) originated from the Ecrins catchment (Pelvoux ECM) drained by the paleo-Drac River. The pollen assemblage representative of different vegetation belts, suggests a high relief in the Ecrins sector already established since the mid-late Miocene. The presence of *Picea* would suggest an initial elevation of at least 1900 m. This altitude may be even higher in the case of a complete altitudinal belt of *Picea* forest (elevation amplitude of 700 m). Coastal conditions during the mid-late Miocene in the Dévoluy area have not been documented so far, probably due to lack of a sedimentary record. However, mid-late Miocene marine molasses are well-preserved in the Vercors and Bas Dauphiné (KALIFI, 2000). Our findings suggest that there was an extension of this mid-late Miocene sea ~40 km southwards in direction to the Dévoluy region. The Obiou Peak would already have constituted significant topography at that time, standing at least 400 m above the coastal plain and would represent a nascent subalpine massif. Consequently, the paleo-Drac River would have shaped the caves (or at least the Jalabres Cave with its meander), and deposited alluvial infill inside the karstic conduits. At present, the Obiou caves are perched at an altitude range of 2250-2370 m, indicating a significant uplift of at least ~2000 m, since the mid-late Miocene. The mechanisms and timing of such uplift remain yet insufficiently constrained and need to be extensively investigated with additional studies in the future. Our contribution on quantifying and dating the Dévoluy uplift is still a new approach and shows that palynological investigations in cave deposits located in highly erosional environments display a certain potential in deciphering past geodynamics. It will be more robust with additional pollen samples and in combination with other types of investigation on cave deposits.

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Crues holocènes et stalagmites corrodées de l'évent de Foussoubie (Ardèche, France)

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Résumé

En amont des Gorges de l'Ardèche, le système karstique de Foussoubie avec 23 km de développement et un bassin d'alimentation de 14,4 km² se caractérise par un drain dominant alimenté à partir d'une perte unique. Il est caractérisé par des crues importantes affectant une zone épinoyée bien développée. L'exutoire du système (l'Event de Foussoubie) est le siège de mises en charge plurimétriques, commandées par un seuil de déversement au droit du porche d'entrée. Deux stalagmites assez détritiques, ont été datées par la méthode U/Th. Quatre dates ont été obtenues entre 2,05 ± 0,4 ka et 3,95 + 3,07 / - 2,37 ka qui placent l'ensemble de ces croissances dans l'Holocène tardif. L'analyse des sections polies des deux échantillons fait apparaitre plusieurs surfaces d'érosion montrant qu'au cours de cette période des phases de crues intenses (comme c'est le cas actuellement) séparent des phases plus calmes autorisant la croissance des stalagmites. Plusieurs interprétations sont proposées : modification du seuil au niveau du porche, changement géométrique de la perte, évolution du couvert végétal sur le plateau ou dans le bassin d'alimentation.

Abstract

Holocene floods and eroded stalagmites from the Foussoubie Cave (Ardèche, France). Upstream of the Gorges de l'Ardèche, the Foussoubie karstic system, with 23 km of development and a 14.4 km² catchment area, is characterized by a dominant drain with a single sink. It is characterized by significant flooding affecting a well-developed epiphreatic zone. An overflow sill at the entrance porch controls the multi-metric flood in the system's spring (the Foussoubie Event). In the section of the gallery between the downstream siphon and the entrance porch, two detrital stalagmites have been dated by the U/Th method. Four dates were obtained, ranging between 2.05 ± 0.4 ka and 3.95 + 3.07 / - 2.37 ka, which place all these growths in late Holocene. Analysis of the polished sections of the two samples reveals several erosion surfaces, showing that during this period, phases of intense flooding (as is currently the case) separate calmer phases allowed the growth of stalagmites. Several interpretations are proposed: modification of the threshold at the porch, geometric change of the sink, evolution of the vegetation cover on the plateau or in the catchment basin.

1. Introduction

Si les stalagmites sont connues pour être des indicateurs pertinents des variations paléo-environnementales, elles s'avèrent aussi de précieux enregistreurs des crues souterraines. Diverses études ont déjà mis en avant l'enregistrement des crues par les stalagmites, essentiellement par piégeage de sédiments détritiques inter-stratifiés dans les lamines (DASGUPTA et *al*., 2010 ; FRAPPIER et *al*., 2014 ; DENNISTON et *al*., 2017). C'est chaque fois plutôt un enregistrement de paléo-mises en charge avec des circulations lentes d'eaux turbides, qui viennent déposer de minces films détritiques. Lorsque la stalagmite est dans le passage du courant d'eau, ce peut être alors des traces érosives laissées par les flux d'eau et qui affectent les stalagmites elles-mêmes en laissant, dans la structure interne, des surfaces d'érosion. C'est le cas proposé ici à partir de l'exemple du système de Foussoubie. En rive droite des gorges de l'Ardèche, ce système karstique (23 km de développement souterrain, LE ROUX, 1984, fig. 1) est connu pour la violence de ses crues souterraines. Alimentée par un bassin d'alimentation de 14,4 km², la perte unique (la goule), concentre les écoulements dans un drain épinoyé où les mises en charges ont été étudiées et enregistrées sur plusieurs mètres de hauteur (JAILLET *al*., 2012 ; ERGUY et *al*., 2021). A l'aval du système un siphon de 350 m de longueur connait des mises en charges importantes supérieures à 12 m. C'est dans ce tronçon aval que deux stalagmites ont fait l'objet d'une analyse spécifique consistant à les replacer dans leur contexte morphologique, à analyser leurs croissances et à les dater.

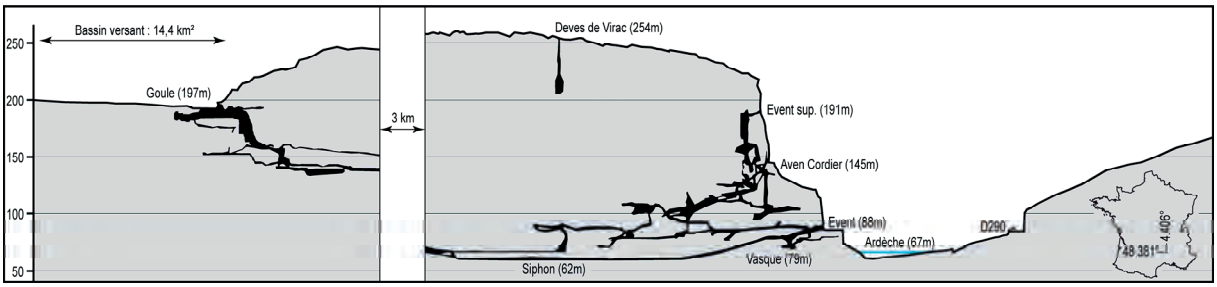

Figure 1 : Le système de Foussoubie en rive droite des gorges de l'Ardèche (23 km) draine un bassin versant de 14,4 km² auquel s'ajoute une alimentation par infiltration. L'évent est l'exutoire temporaire du système.

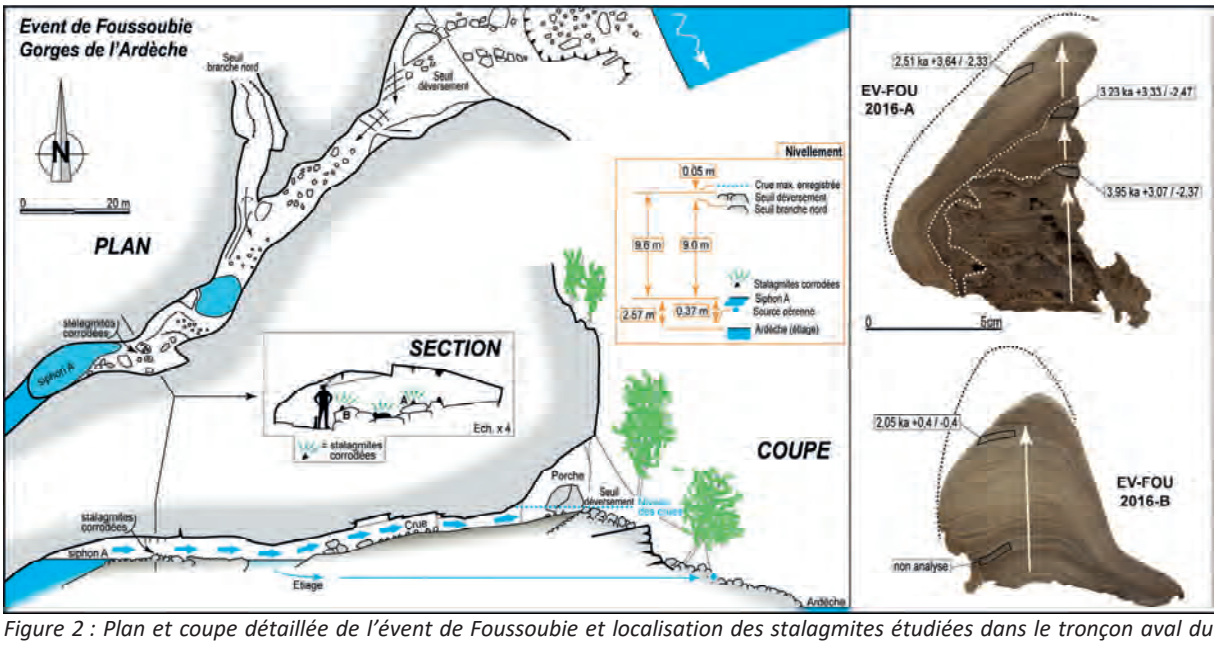

Figure 2 : Plan et coupe détaillée de l'évent de Foussoubie et localisation des stalagmites étudiées dans le tronçon aval du système karstique. Le tronçon de galerie entre le siphon A et le seuil de déversement est le siège de mises en charge récurrentes ennoyant les stalagmites. Les sections polies des stalagmites EV-FOU-2016 A & B montrent les différentes phases d'érosion affectant leur croissance au cours de l'Holocène. Pour EV-FOU-2016-A, des phases de croissances continues sont séparées par des phases de corrosions intenses. La période actuelle est une phase de corrosion.

2. Méthodes : une étude des stalagmites corrodées

L'étude du site a été conduite selon une double approche : (i) topographique et géomorphologique d'une part et (ii) analytique sur les stalagmites d'autres part. Sur place, un relevé topographique de l'évent a été réalisé, en coupe et en plan (fig. 2). Nous avons entrepris un nivellement fin des points clés de déversement des eaux à savoir le siphon A, les seuils, le point d'émergence et l'Ardèche. Ces mesures, réalisées au niveau de chantier, complètent les mesures des hauteurs d'eau réalisées avec des sondes ReefNet au niveau du siphon A. Deux stalagmites corrodées ont été sélectionnées quelques mètres en aval du siphon A (fig. 3). Elles ont connu et connaissent encore des phases érosives majeures. Elles ont été tranchées dans l'axe de la galerie souterraine afin de bien identifier l'alternance des phases érosives et des phases de croissance. Cinq micro-échantillons ont été prélevés et analysés au Laboratoire des Sciences du Climat et de l'Environnement à Gif Sur Yvette. Ils contiennent une fraction importante d'argile rendant leur datation difficile. La technique de préparation mise en œuvre consiste à dissoudre totalement l'échantillon (fractions carbonatée et argileuse). Des échantillons de 100 à 300 mg ont été dissouts en HCl dilué dans des béchers contenant une quantité connue de traceur ^{229}Th ^{233}U ^{236}U. Le résidu argileux non dissout est séparé par centrifugation du surnageant et attaqué par un mélange de HF et HNO_3 concentrés, à chaud pendant une nuit puis évaporé et repris en HCl dilué. Les deux fractions ainsi dissoutes sont mélangées puis traitées classiquement pour une datation suivant un protocole présenté dans PONS-BRANCHU et *al.* 2014. Brièvement, après coprécipitation avec FeOH, les fractions U et Th sont purifiées sur colonne échangeuse d'ions (ici U-TEVA en milieu nitrique). L'analyse est réalisée sur MC-ICPMS Neptune™ +.

3. Résultats : nivellement et mises en charge

Entre le siphon A et le point d'émergence en bordure de l'Ardèche, la dénivellation est de 0,37 m. Celle-ci est à 2,2 m au-dessus du cours de l'Ardèche en étiage. Entre le siphon A et le seuil de débordement au niveau du porche, la dénivellation est de 9,6 m. Ce point commande le moment où l'évent est en crue et déverse par cet orifice temporaire perché (fig. 2). Entre le siphon A et le seuil de débordement au niveau du seuil déversoir en direction de la branche nord et du siphon B, la dénivellation est de 9,01 m. Ce seuil est donc 0,59 m plus bas que le seuil de déversement. Ces éléments altimétriques constituent des seuils clés qui commandent les mises en charge du réseau. Ces mises en charge justement ont été analysées à partir d'un enregistrement des hauteurs d'eau au droit du siphon A, grâce à une sonde ReefNet (période 2011 / 2018). Les données analytiques sont présentées dans un travail spécifique (ERGUY et *al*., 2022) dont nous extrayons les éléments essentiels. Au droit du siphon A, la hauteur maximale enregistrée est 9,65 m, c'est-à-dire 5 cm au-dessus du seuil de déversement. Le siphon C, perché par rapport au siphon A, connaît une mise en charge maximale enregistrée de 8,31 m. Sur la période de 2011 à 2018, il y a en moyenne 47 épisodes par an, de montée des eaux supérieure à 1 m. Les mois qui connaissent le plus de variations sont mars (11), novembre (9), mai (6) et octobre (5). La plupart de ces montées des eaux ne donnent pas lieu à un débordement par le seuil. La moyenne est évaluée à un débordement tous les 3 ans. Enfin, sur les épisodes intenses, la vitesse de montée de l'eau est comprise entre 4 et 6 cm/mn. Si le débit de pointe à la sortie du siphon A est de 7,3 m^3/s (avec évacuation par le seuil), le débit moyen des crues est de l'ordre de 1m^3/s (avec évacuation par l'exutoire en bordure de l'Ardèche par des griffons plus ou moins étagés sur 2m de hauteur). Ces éléments permettent d'évaluer correctement la fréquence et l'intensité des crues subies par les stalagmites étudiées, placées quelques mètres en aval du siphon et donc ennoyées plusieurs dizaines de fois par an.

Figure 3 : Un des ensembles stalagmitiques étudiés présente des marques de corrosion importantes, associées aux crues régulières affectant le système. Le prélèvement de deux stalagmites a permis de réaliser des datations et leur analyse sur section polie.

4. Résultats : Datations et surfaces d'érosion

Les données de concentrations, rapports isotopiques et âges (avant et après correction) sont présentées figure 4. Tous les échantillons analysés présentent des caractéristiques similaires : des concentrations en uranium élevées (plus de 700 ppb), une signature isotopique en uranium appauvrie en ^{234}U ($\delta^{234}U$ négatif) et une contribution importante de thorium détritique, marquée par des teneurs élevées en ^{232}Th et des rapports $^{230}Th/^{232}Th$ faibles (pour l'échantillon de la stalagmite B) ou très faibles (échantillons de la stalagmite A). Les âges déterminés doivent donc être corrigés de cette fraction détritique. Pour l'échantillon B, une correction basée sur un rapport ($^{230}Th/^{232}Th$) de 1,5 ± 50% est appliquée, et les incertitudes propagées, donnant un âge brut de 2,87 (±0,02) ka BP avant correction et 2,05 (±0,43) ka BP après correction. Pour les échantillons de la stalagmite A, le contenu en thorium détritique ne permet pas d'envisager une telle correction avec une composition de la phase détritique prédéterminée. Cependant, ces 3 échantillons étant issus de la même séquence, une correction basée sur la détermination de la valeur de correction permettant de rendre compte de l'ordre stratigraphique est possible (routine STRUTage, ROY BARMAN et *al*., 2016). Pour cette stalagmite, les âges avant correction s'échelonnent entre 33,40 (±0,18) et 16,78 (±0,11) ka BP, avec des inversions stratigraphiques, et après correction entre 2,51 (+3,64/-2,33) et 3,95 (+3,07/-2,37) ka BP. La valeur du rapport de correction déterminée par la routine STRUTage ($^{230}Th/^{232}Th$ = 0,84 ± 0,10) est compatible avec ce qui est attendu pour des argiles.

L'analyse des sections polies a été réalisée sur deux tranches avec un axe de coupe parallèle au flux d'eau. L'échantillon EV-FOU-2016-A présente trois surfaces d'érosion que les dates encadrent partiellement (fig. 2). L'échantillon EV-FOU-2016-B est plus récent et n'offre qu'une surface d'érosion correspondante à la période actuelle. Ces deux échantillons se succédant partiellement, il est possible d'avancer que les deux échantillons enregistrent la chronique suivante : croissance stalagmitique jusqu'au moins 3,95 (+3,07/-2,37) ka BP suivi d'une phase d'érosion importante. Une seconde phase de croissance stalagmitique est identifiée jusqu'au moins 3,23 (+3,33/-2,47) ka BP suivie d'une nouvelle phase d'érosion intense. Une nouvelle phase de croissance s'étend jusqu'au moins 2,51 (+3,64/-2,33) ka BP pour l'échantillon A et 2,05 (+0,4/-0,4) ka BP pour l'échantillon B. Elle est oblitérée par une troisième phase d'érosion toujours active. Sur la base des dates et de l'emboitement des surfaces, il ne semble pas raisonnable de distinguer les dernières phases de croissance qui finalisent les deux échantillons. Au contraire elles sont plus probablement synchrones. Au final, c'est donc ici 3 phases de croissances et 3 phases d'érosion qui sont enregistrées sur une période couvrant les 5 derniers milliers d'années.

Echantillon	[^{238}U] ppm		δ^{234}UM (‰)		(^{230}Th/^{238}U)		(^{230}Th/^{232}Th)		Age brut (ka BP)		Age corrigé (ka BP)		
EV FOU 2016 A1	0,867	0,007	-6,3	±1,1	0,176	±0,0003	0,93	0,002	21,24	±0,07	3,95*	+3,07	-2,37
EV FOU 2016 A2	0,722	0,006	-8,3	±1,0	0,262	±0,0009	0,69	0,002	33,40	±0,18	3,23*	+3,33	-2,47
EV FOU 2016 A3	1,160	±0,010	-65,9	±1,3	0,133	±0,0006	0,76	0,004	16,78	±0,11	2,51*	+3,64	-2,33
EV FOU 2016 B2	0,934	0,008	-36,8	±0,8	0,026	±0,0001	5,26	0,029	2,87	±0,02	2,05	+0,4	-0,4

*Figure 4 : Données de concentrations, de rapports isotopiques et d'âges U/Th. $\delta^{234}U = ([^{234}U/^{238}U] - 1) \times 1000$. Les âges sont exprimés en milliers d'années avant l'année 1950 (ka BP). Les âges * ont été corrigés en utilisant la routine STRUTage (ROY BARMANN et al., 2016). Pour B2, l'âge a été corrigé en utilisant ($^{230}Th/^{232}Th_{det}$) = 1,5 ± 50%.*

5. Conclusions

Il a été possible de montrer que la fréquence des crues affectant le conduit n'est pas une constante. Sur les cinq derniers milliers d'années, des phases calmes, sont séparés par des phases érosives n'autorisant pas cette croissance et affectant les concrétions de manière importante, laissant chaque fois une surface d'érosion caractéristique (fig. 2). La succession des phases d'érosion et des phases de croissance rythme les conditions hydrodynamiques du conduit dont on mesure combien elles évoluent sur des échelles de temps courtes. On a vu que le seuil de déversement est un élément clé du contrôle des mises en charge puisque les crues les plus importantes, celles qui déversent, ne dépassent que de quelques centimètres ce seuil. Il est donc possible d'envisager que la dynamique gravitaire (effondrements) qui affecte le porche, est un élément de contrôle de la variabilité des mises en charge dans la zone aval. Dans cette occurrence, il conviendrait de mieux cerner le rythme de ces effondrements, mais aussi d'expliquer comment après une phase d'effondrement, une évacuation du matériel est suffisante pour expliquer qu'aucune mise en charge ne soit plus possible durant les phases calmes. L'affleurement des calcaires, reconnu de manière peu profonde sous le tablier de bloc ne milite pas pour cette unique explication. Des édifices stalagmitiques identifiés et datés dans la partie amont du réseau montre de même des phases d'érosion alternant avec des phases de croissances (JAILLET et *al*., 2012). Mais les gammes de dates alors reconnues plaçaient ces alternances dans le pléistocène et laissaient donc entendre un contrôle climatique à ces variations. La variabilité de la dimension de la perte (entrée unique des eaux d'infiltration rapide) constitue alors une piste non négligeable pour expliquer l'alternance de phases de croissance et de phases érosives. Le plateau (infiltration lente) comme le bassin versant de la perte (infiltration rapide) sont de même le siège de changements importants de l'occupation de l'espace. On ne peut donc exclure un contrôle lié l'importance du couvert végétale lui-même sous influence climatique et / ou anthropique.

Les stalagmites de l'évent de Foussoubie se retrouvent finalement en position intéressante, au carrefour d'influences variées : (i) locales (dynamique gravitaire du porche et du seuil de déversement), (ii) éloignées mais ponctuelles (dynamique dimensionnelle de la perte à l'amont), (iii) anthropiques (gestion et occupation de l'espace pour le bassin versant et le plateau sus-jacent), (iv) voire climatiques (variabilité à l'échelle du Pléistocène, mais aussi de l'Holocène). Elles enregistrent évidemment une variabilité des conditions hydrodynamiques d'un tronçon de conduit. D'autres analyses permettront de démêler la part des influences externes (hommes, climat) et des contrôles internes (géométrie et seuils dimensionnels) dans cette évolution singulière.

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Climate and environmental changes at the MIS 5a/4 transition in southwestern Peloponnese (S. Greece)

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Abstract

Stalagmite S1 recovered from Selinitsa Cave in SW Peloponnese (Greece) reveals climatic and environmental information for the latest phase of the last interglacial period. The analysis of 182 calcite samples for O and C stable isotopes along the speleothem growth axis sheds light on the hydroclimatic changes that affected the eastern Mediterranean area. The stalagmite spans the time period from 82.5 to 68 ka BP according to eight U-series dating measurements. The stable isotope time series depicts a trend from dry climatic conditions at 82.5 ka to wetter during the Marine Isotope Stage (MIS) 5a and the beginning of MIS 4. A notable environmental change is documented by a stratigraphic hiatus at the bottom of the stalagmite dated at 80.5 ka that appears to coincide with the MIS 5a sea level high stand.

Presentation of the research

Here we present the climatic and sea level record encoded in stalagmite S1 recovered from Selinitsa Cave on the eastern shore of Messiniakos Gulf in SW Peloponnese (Greece). The cave is part of a larger karstic system called ‘‘Selinitsa-Drakos”, which is located 46 km south of Kalamata City. The system comprises Selinitsa and Drakos Underground River caves (PAPADOPOULOU-VRYNIOTI & KAMPOLIS, 2011). It develops in the typical white and grayish, medium bedded, carbonate rocks of Plattenkalk Unit of Upper Senonian - Upper Eocene age. Selinitsa Cave lies mainly above sea level with a minor part being submerged, whereas Drakos Underground River is currently completely underwater (PAPADOPOULOU-VRYNIOTI & KAMPOLIS, 2012). Selinitsa hosts evidence of phreatic origin, yet today the majority of the cave is part of the vadose zone. Selinitsa was once flooded as Drakos nowadays, but due to the tectonic uplift affecting the area, the cave passages are now in the unsaturated zone.

The formation of this karst system is controlled by the regional tectonic activity. The main faults of the area are predominantly NNW-SSE, with a minor secondary E-W direction also present. They have formed mainly during the early Miocene (MARIOLAKOS *et al.*, 1985, 1994), affecting the whole central peninsula of south Peloponnese. Selinitsa Cave develops mainly in a WNW-ESE orientation, with a NNW-SSE to NW-SE trend also evident. The former direction is earlier to Late Pliocene and is due to the clockwise rotation of the western branch of the Aegean Arc since Late Miocene (MERCIER & LALECHOS, 1993). On the other hand, the Drakos cave development trends NE-SW, along a tectonic line, most probably of Mid – Late Pleistocene age (MERCIER & LALECHOS, 1993; PAPADOPOULOU-VRYNIOTI & KAMPOLIS, 2011). The broader area of the system is currently under uplift since the Middle Pleistocene.

The proximity of this cave system close to the Mediterranean Sea makes it attractive for the study of the sea level history and the relevant climatic conditions during the Quaternary. The entrance of Selinitsa Cave is located 18.5 m above present sea level (mapsl) and just 54 m from the Mediterranean Sea (Fig. 1). Therefore, former sea level high stands may have left their imprints on the cave environment.

The 23.5-cm tall S1 was sampled at 615 m from the entrance. We performed eight U-series dating and analyzed 182 calcite powder samples for oxygen and carbon stable isotopes ($\delta^{18}O$ and $\delta^{13}C$) along the growth axis of S1, which spans from 82.5 to 68 ka BP. The $\delta^{18}O$ and $\delta^{13}C$ values vary between –5.42 and –0.14‰ and from –10.83 to –5.47 ‰, respectively. The oxygen isotopic composition of S1 reveals an overall trend from drier conditions at ~82.5 ka to much wetter during the end of MIS 5a and at the onset of MIS 4. We interpreted the $\delta^{13}C$ values to reflect soil biological activity that also suggests changes from drier to wetter climate. Additionally, the presence of a distinct stratigraphic hiatus at the lower part of the stalagmite dated at 80.5 ka is attributed to the MIS 5a sea level high stand. Altogether, this study highlights some important hydro-climatic and environmental changes in the eastern Mediterranean during a less documented time interval.

Figure 1: The entrance (in the middle of the image) and the external environment of Selinitsa Cave.

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The timing and impact of the 8.2 ka event in Europe

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Abstract

The 8.2 ka event is one of the most prominent climate anomalies of the Holocene. There is a general consensus that it was triggered by a sudden outburst of freshwater to the North Atlantic, which caused a slowdown in North Atlantic Deep Water formation. However, its cause, timing, duration and impacts remain debated. Discrepancies in timing and duration of the event in various archives are evident, suggesting poorly constrained chronologies and/or insufficient temporal resolution in the climate proxy records. Furthermore, the event is not clearly preserved in all archives, confounding its climate impact across Europe. To improve our understanding of the climate impact of the 8.2 ka event, we have assembled high-quality published speleothem records from Europe based on the following selection criteria: i) temporal coverage; ii) temporal resolution; and iii) unambiguous proxy interpretation (precipitation/temperature and seasonality). A total of 18 (out of 35) records met these criteria. Their chronologies were standardised using the latest isotope decay constants and applying a common age-modelling technique. Additionally, other high-quality records from ice and lake cores were used to complement the speleothem records and enhance the understanding of regional climate changes across Europe through the 8.2 ka event.

1. Introduction

The 8.2 ka event was a short-lived (~160 year) climate anomaly that occurred in the early Holocene (ALLEY et *al*., 1997; THOMAS et *al*., 2007). The most common explanation for the event is a large outburst of freshwater from the proglacial lakes Agassiz and Ojibway during the final retreat phase of the Laurentide ice sheet (BARBER et *al*., 1999). An alternative cause is a freshwater outburst from the collapsing ice saddle over Hudson Bay (MATERO et *al*., 2017). Whilst the exact cause is still debated, and will not be discussed further here, the volume and routing of freshwater that entered the North Atlantic was sufficient to disrupt the Atlantic Meridional Overturning Circulation (AMOC), which transports heat from the tropics to the Arctic region (BARBER et *al*., 1999; ELLISON et *al*., 2006). The event is clearly captured by the Greenland ice cores. According to the most recent ice core age model (GICC05) and based on the $\delta^{18}O_{ice}$, the event started at 8.25 ka BP and lasted until 8.09 ka BP with a counting uncertainty of 47 years (THOMAS et *al*., 2007). However, its timing and duration in different palaeo-archives across Europe, vary significantly. This inconsistency is usually explained by poorly constrained chronologies. All the reported ages in this paper refer to years before present (BP), where present is AD 1950.

The 8.2 ka event particularly affected the North Atlantic and western Europe, with a general trend of colder and drier conditions (ALLEY & ÁGÚSTDÓTTIR, 2005; ROHLING & PÄLIKE, 2005). Its climatic impact has been detected as far afield as the East Asian and South American monsoon domains (CHENG et *al*, 2009). However, the reported impacts vary, in nature and intensity, and remain unclear even through Europe.

Several reviews of the 8.2 ka event have already been published (ALLEY & ÁGÚSTDÓTTIR, 2005; MORILL et *al*., 2013; ROHLING & PÄLIKE, 2005; WIERSMA & RENSSEN, 2006). The general consensus is that there was a cooling of up to 7 °C in Greenland and of ~1 °C in Europe, whereas precipitation patterns varied across the Northern Hemisphere. The climate state during the early Holocene was quite similar to that of the present. Therefore, the event is one of the closest analogues by which to study the impacts of a future large freshwater discharge to the North Atlantic on regional climate, potentially associated with massive Greenland ice calving under a warming climate.

In this study, we look at the timing, duration and climate impacts of the 8.2 ka event through speleothem archives. We compiled and analysed carefully selected published speleothem proxy records to improve our understanding of the climate impact of the 8.2 ka event in Europe. Additionally, information from other archives (i.e. ice and lake cores) were used to complement the understanding of the climate impacts across Europe.

No.	Site	Type of proxy	Indicator of	Proxy interpretation	8.2 ka event proxy interpretation	Reference
1	NGRIP (Greenland)	ice $\delta^{18}O$	T(a)	Low values: cold	cold	NGRIP (2004); THOMAS et *al*., 2007
2	Pippikin Pot (England)	speleothem $\delta^{18}O$	P(a)	High values: dry	change in isotopic source composition	Unpublished data in: DALEY et *al*., 2011
3	Kaite Cave (Spain)	speleothem $\delta^{18}O$	P(a)	High values: dry	change in isotopic source composition	DOMÍNGUEZ-VILLAR et *al*.,2009; 2017
4	Ammersee (Germany)	ostracod $\delta^{18}O$	P(a)	Low values: cold	change in isotopic source composition	VON GRAFENSTEIN et *al*., 1999
5	Katerloch Cave (Austria)	speleothem $\delta^{18}O$	T(a)	Low values: cold	cold	BOCH et *al*., 2009
6	Scărișoara ice cave (Romania)	ice d-excess	P(w)	High values: dry	change in moisture source (dry Mediterranean air)	PERSOIU et *al*., 2017
7	Kinderlinskaya Cave (Russia)	speleothem $\delta^{18}O$	T(w)	Low values: cold	cold	BAKER et *al*., 2017

Figure 1: List of the selected archives and their interpretation as discussed in this paper. Numbers in the first column correspond to sites located in Fig. 3. T(a): annual temperature variability; P(a): annual precipitation variability; T(w): winter temperature variability; P(w): winter precipitation variability.

2. Materials and methods

We selected speleothem proxy records from Europe and the North Atlantic region that fulfilled three criteria based on temporal coverage, temporal resolution, and interpretation (Fig.1 and Fig. 3): i) The speleothem must have grown continuously from 8.5 to 7.9 ka BP; ii) its record must have a minimum temporal resolution of 30 years per data point to ensure a high enough resolution to capture the event; iii) it must be unambiguously interpreted with discrimination made between winter, summer and annual proxies, whether or not the proxies represent changes in temperature or precipitation, or a change in either moisture-source region or isotopic composition, as clearly indicated by the authors. In some cases, where no season was indicated, we assumed that the proxy was recording an annual signal. If the proxy record was not interpreted, it was excluded from the compilation. The chronology of each of these high-quality records was then standardised: First, the ages were recalculated using the latest U and Th decay constants and applying new detrital thorium ($[^{230}Th/^{232}Th]_{activity}$) correction. Most of the publications assumed a bulk Earth $^{230}Th/^{232}Th$ activity ratio of 0.82±0.41, and these were replaced with a ($[^{230}Th/^{232}Th]_{activity}$) correction of 1.5±1.5 (HELLSTROM, 2006). In cases where the corrections for detrital thorium were based on isochron techniques or stratigraphic constraints specific to the local setting, they were not changed. Following this, the updated ages were used to create a new age-depth model using the *Finite positive growth rate* algorithm (CORRICK et *al*., 2020) to ensure age-modelling consistency. Finally, $\delta^{18}O$ time-series were re-interpolated from these age models. Other archives in this compilation have been used mainly to complement our understanding of the impacts of the 8.2 ka event across Europe, and have not been screened using the same criteria, nor plotted on updated timescales.

No.	1000-yr baseline (‰)	StDev	Event start ±2σ error (yr BP)	Event end ±2σ error (yr BP)	Event duration (yr BP)
1	-34.84	0.45	8250 ± 47	8110 ± 47	140 ± 66
2	-4.75	0.17	8238 ± 30	8129 ± 30	109 ± 42
3	-6.21	0.43	8211 ± 62	8146 ± 62	68 ± 87
4	-10.17	0.36	8240 ± 47	8150 ± 47	90 ± 66
5	-6.11	0.43	8128 ± 211	8003 ±196	125 ± 288
6	7.73	1.41	8264 ± 176	8122 ±231	142 ± 317
7	-12.89	0.20	8250 ± 118	8061 ±122	189 ± 170

Figure 2: Statistics from the selected archives. Numbers in the first column correspond with numbers in Fig. 1. The 1000-yr baseline is the calculated mean from a 1000-yr period preceding the 8.2 ka event (from 9.3 to 8.3 kyr BP). The event start is the first proxy data point with a value lower than the baseline, marked with a red symbol in Fig. 4. The event end is the last proxy data point with a value lower than the baseline, marked with a yellow symbol in Fig. 4. The event duration is calculated from the event start and end mean ages.

3. Results and discussion

The included records in this compilation are shown in Fig. 1 and Fig. 3, with information about the type of proxy used and their inferred climatic response through the 8.2 ka event. Most of the records are concentrated in western and central Europe, with very few in the northern and eastern regions (Fig. 3). A total of 16 speleothem records fulfilled the criteria; only 5 speleothem records are discussed in this paper. The remaining records are still being investigated, due to uncertainties in event identification, hence, they have been excluded from this initial compilation. The 8.2 ka event is generally presented as a cold and dry event in the literature (Fig. 3 and Fig. 4). However, several archives (i.e. Pippikin Pot, Kaite Cave, Ammersee) are interpreted in terms of change in the $\delta^{18}O$ of the moisture source, and other archives do not indicate a clear climate variability through the event (grey symbols, Fig. 3). These differences in reported impacts could be due to various site-specific effects that influence the speleothem $\delta^{18}O$ signal, such as

the precipitation $\delta^{18}O$ response to natural background climate variability, local environmental effects in the epikarst above the cave and the physicochemical conditions inside the cave during speleothem formation.

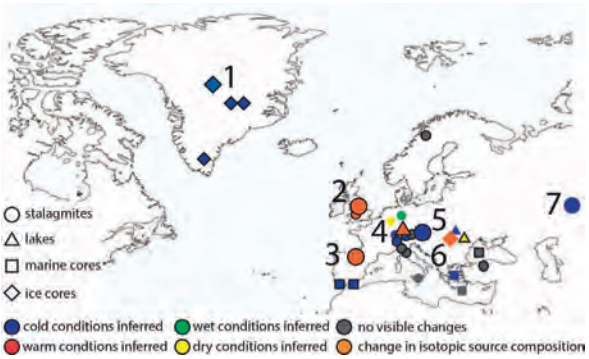

Figure 3: Location of the selected high-quality archives for the 8.2 ka event in Europe. Enlarged symbols represent the archives discussed in detail (numbers refers to the first column, Fig. 1). Smaller symbols represent other archives that meet all the criteria but are still under investigation. Symbols with a black outline represent annual records, and symbols without any outline represent winter records.

In Fig. 4 the palaeo-proxies from the five speleothems and other selected archives (ice and lake cores) are plotted across the early to mid-Holocene (from 6.0 ka BP to 10.0 ka BP). As a first approach to determine the timing and duration of the 8.2 ka event we follow the procedures of event identification from THOMAS et *al*. (2007). A baseline is defined by calculating the mean from a 1000-year period preceding the event, from 9.3 to 8.3 ka BP (Fig. 3). The onset of the event is set to be the first proxy data point of continuously lower values below the baseline (red symbols, Fig. 4). The end of the event is determined by the last proxy data point below the baseline (yellow symbols, Fig. 4). Applying this, the timing for the event onset and end is defined by the first or last proxy data point below the baseline. Hence, the position of the proxy data point of the onset and end (i.e. peak, mid-point) varies in the different archives, most likely due to various resolutions and noise. This approach has its weaknesses and other statistics-based analyses are currently being investigated. However, we targeted the synchrony of the event across Europe performing a *reduced chi-squared test* (also known as the mean square weighted deviation, MSWD) using *Isoplot* for the seven archives in Fig. 4. From this, the error-weighted mean age for the onset of the event is 8238 ± 20 year BP, with a 0.91 probability of fit. The error-weighted mean age for the end of the event is 8128 ± 20 year BP, with a probability of fit of 0.59. Hence, all the starting points for the onset belong to the same population, and the onset of the event appears to be synchronous. The end of the event is also synchronous, but the probability of fit is slightly lower. The duration of the event lasts from 68 to 189 years (Fig. 3); the MSWD test gives an error-weighted mean event duration of 109 ± 29 years, with a probability of fit of 0.80. This is ~40-50 years shorter than the estimated duration of the event in the Greenland ice cores (THOMAS et *al*., 2007). This could be explained by site-specific effects or various resolutions in the different archives, but remains uncertain due to the low number of records included at this point.

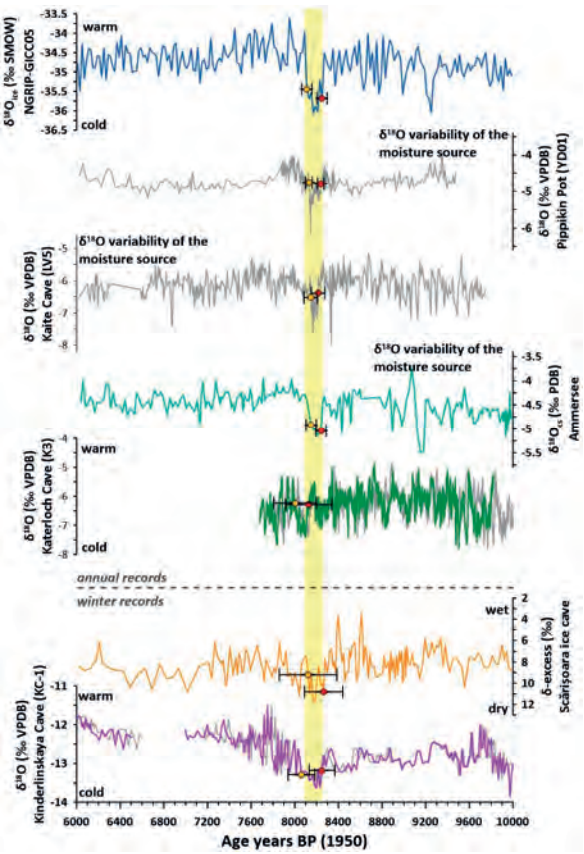

Figure 4. Proxy records from 7 selected archives showing changes through the 8.2 ka event. The records are plotted from top to bottom according to their location, NW Europe to SE Europe, respectively. Red symbols mark the onset of the event, and yellow symbols mark the end of the event, with their age uncertainties (Fig. 2). The yellow shading represents the duration of the event in the NGRIP ice core. Grey shaded signals are the original dataset, before age model adjustment/correction. For references, see Fig. 1.

4. Conclusions

The 8.2 ka event is generally known as a cold and dry event. This brief compilation shows that it is not as straightforward an event as it might seem. Possible unequal seasonal impacts, which in turn might be buffered in the archive records by the large change in the $\delta^{18}O$ of the North Atlantic at the time, and the atmospheric reorganisation during or following the event may have changed the moisture source and/or air-mass trajectories of precipitation reaching the site of each archive. Finally, it appears not to be recorded at all in many archives. More high-resolution records are

needed to fully understand the regional impacts of this event across Europe. According to the records presented here, it appears to be synchronous throughout Europe, starting at 8238 ± 20 year BP and lasting until 8128 ± 20 year BP (i.e. a duration of 109 ± 29 years, which is ~40 to 50 years shorter than its estimated duration from Greenland ice cores).

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Witnesses of former cave glaciation: cryogenic cave carbonates from the Eastern and Southern Alps

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Abstract

Coarse crystalline cryogenic cave carbonates (CCC for short) are secondary carbonate deposits that form via freezing-induced supersaturation of small water bodies within cave ice and are an important indicator of former cave glaciation. Due to their commonly small size CCC have been overlooked in caves compared to other types of speleothems. Our research has shown that about a dozen of currently ice-free caves in the Eastern and Southern Alps contain such deposits. We observed a spectrum of morphologies from skeletal crystals to complex aggregates. CCC vary from a few mm to several centimetres in size. Most commonly they are translucent, white, amber-coloured or dark brown. CCC are likely more common than previously thought and caves in other parts of the Alps are expected to yield such paleo-ice indicators as well.

Résumé

Témoins d'une glaciation ancienne en grotte : les carbonates cryogéniques de grottes des Alpes orientales et méridionales. Les 'Cryogenic Cave Carbonates' cristallins grossiers (CCC ci-après) sont des dépôts calcaires secondaires formé par solidification et super-saturation de poches d'eau liquide emprisonnée dans la glace souterraine ; ce sont d'importants indicateurs de glaciation souterraine passée. A cause de leur rareté et de leur taille pour la plupart modeste, les CCC ont souvent bénéficié d'une attention moindre par rapport à d'autres types de spéléothèmes. Nos recherches montrent qu'une douzaine de sites à présent dépourvus de glace dans les Alpes du Sud et de l'Est contiennent de tels dépôts. Nous observons une large panoplie de morphologies, de cristaux squelettiques jusqu'à des agrégats plus complexes. La taille des CCC varie de quelques millimètres à plusieurs centimètres. Ils sont communément soit translucides, soit de couleur blanche, ambre ou marron foncé. Les CCC sont plus répandus qu'admis auparavant, et il est attendu que de tels indicateurs de glace ancienne soient identifiés à terme dans d'autres secteurs des Alpes.

1. Introduction

Modern ice caves and caves that were glaciated in the past may contain a unique type of speleothem, known as cryogenic cave carbonates. Two types can be differentiated, fine and coarse crystalline (ŽÁK et al., 2018). The former type forms via fast freezing-induced supersaturation of karst water often in ventilated cave passages and is common in modern-day ice caves. On the other hand, the deposition of the coarse crystalline variety requires a stable microclimate and occurs via very slow freezing of small karst water bodies within cave ice when cave air temperatures are slightly below 0°C (ŽÁK et al., 2012). These mineral deposits only form in caves that contain perennial ice deposits. Consequently, the presence of coarse crystalline cryogenic cave carbonates (hereafter CCC) in ice-free caves provides direct evidence of a former cave glaciation.

In the Eastern Alps, the first CCC were found in Großes Almbergloch (Totes Gebirge) by Reinhold Kreuz in 1976. He took a sample of white powder on a breakdown block, looked at it using X-ray diffractometry and optical microscopy, but was unsure about its origin (KREUZ, 1976). A year later, Helmut Traindl and Rudolf Pavuza, unaware of the report by Kreuz, also took a sample of this crystal accumulation which was later identified as CCC (PAVUZA and SPÖTL, 2017).

In the past two decades, CCC have been extensively studied in Central European caves (e.g. ŽÁK et al., 2012), but reports of CCC in the Western Alps (LUETSCHER et al., 2013), Eastern Alps (SPÖTL and CHENG, 2014; PAVUZA and SPÖTL, 2017) and Southern Alps (COLUCCI et al., 2017) are still scarce. Here, we summarize new discoveries in the Eastern and Southern Alps which suggest that CCC may also be widespread in Alpine caves.

2. Methods

We primarily selected caves that hosted perennial cave ice and/or snow/firn as recent as the 20th century and are now unglaciated. These caves often have extended inner, more isolated passages that are not strongly ventilated, making them good candidates for CCC formation. CCC sites were mapped and documented and samples were examined using optical microscopy. Their cryogenic nature was verified using stable carbon and oxygen isotope analyses.

3. New CCC sites in the Eastern and Southern Alps

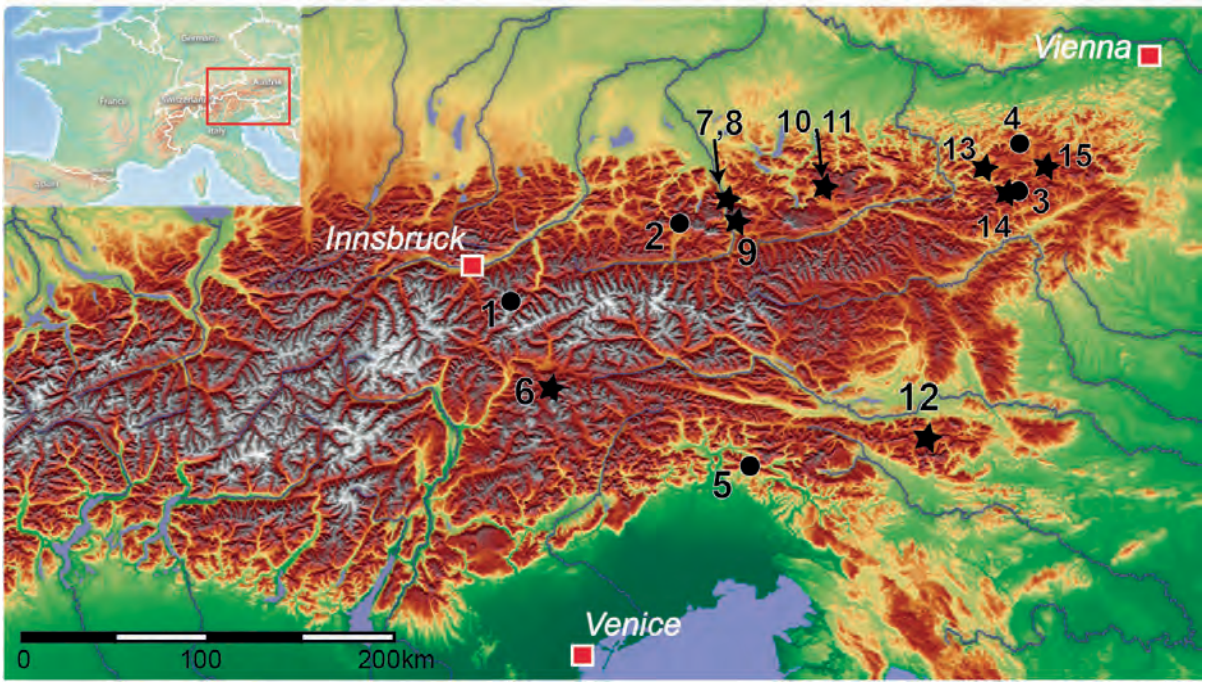

Figure 1: Topographic map of the Eastern and Southern Alps showing the currently known locations of CCC. Black circles mark previously known sites (1-Mitterschneidkar Eishöhle, 2-Glaseishöhle, 3-Potentialschacht, 4-Taubenloch, 5-Leupa ice cave). Black stars refer to newly discovered CCC-bearing caves reported in this study (6-Cioccherloch, 7-Frauenofen, 8-Eisriesenwelt, 9-Eiskogelhöhle, 10-Großes Almbergloch, 11-Almberg Höhlensystem, 12-Obir caves, 13-Hochkarschacht, 14-Speikbodenhöhle, 15-Fledermausschacht). Sources: Wikipedia; Geography name

Our research has shown that about a dozen of currently ice-free caves in the Southern and Eastern Alps contains CCC, some hosting multiple occurrences (Fig. 1). The entrances of these caves are located between 1090 and 2275 m a.s.l. The lowest and highest CCC sites were found at approximately 1054 m (Obir caves) and 2225 m a.s.l. (Cioccherloch), respectively. In most caves, CCC are present as loose crystal assemblages (heaps) either on and partially also beneath breakdown blocks (Fig. 2a), or on the cave floor usually in soft sediment (Fig. 2b). Less frequently, CCC are cemented together. Individual heaps usually cover spots of 0.1 to 2 m in diameter.

Dolomites (Southern Alps)
In 2017 CCC were found in Cioccherloch, for the first time in the Dolomites (Fig 1). They occur close to the end of a descending cave chamber. CCC are amber-coloured and their size varies from a few mm to 2.5 cm (Koltai et al., 2018).

Tennengebirge (Eastern Alps)
CCC were identified in three caves in the Tennengebirge (Fig. 1). In Frauenofen four sites were documented. White and translucent colours are most common, and amber-coloured CCC are also present at one site.

In Eisriesenwelt white skeletal crystals and hemispheres were collected at two sites by cavers back in the 1920s and sent to a museum in Salzburg. We re-visited these sites, identified them as CCC (SPÖTL et al., 2020), and found nine additional sites in inner, ice-free parts of this ca. 40 km-long cave, including aggregates as large as 5 cm.

In 2020 translucent, amber-coloured and dark brown CCC were also discovered in a remote ice-free part of Eiskogelhöhle (Fig. 2b). Individual crystals are up to 3.8 cm in length, the largest of their kind from the Eastern Alps so far.

Figure 2: (a) Typical occurrence of loose white skeletal and amber-coloured rhombohedral CCC on breakdown blocks (red arrows, Großes Almbergloch). (b) Individual amber-coloured and dark brown CCC present on the cave floor in fine-grained sediment (Eiskogel cave). Pen tip for scale.

Totes Gebirge (Eastern Alps)
We re-visited the original site of 1976 in Großes Almbergloch (Fig. 2a) and located six more spots of white and amber-coloured CCC. Raft-like CCC were also documented in-situ on a decaying ice body closer to the entrance in 2018. By 2020 this ice has disappeared.

Located a few hundred meters north of the entrance of Großes Almbergloch, the Almberg Höhlensystem yielded one CCC occurrence, where white crystals resembling those in Großes Almbergloch were found in 2020 by speleologists from the Forschungsgruppe Höhle und Karst Franken.

Northern Karawanks (Eastern Alps)
The Obir caves are situated in the Northern Karawanks (Fig. 1) and comprise several individual caves that are sometimes connected by mining adits. White and translucent CCC are present in two caves, known as the Banane and the Rasslsystem. White and translucent crystals were found at four and six sites, respectively.

Tonion (Eastern Alps)
CCC are present at one site as two distinct heaps, 10 m apart from each other at approximately 250 m beneath the surface in Fledermausschacht, part of Tonion Höhlensystem. The crystals are translucent and amber-coloured and range from a few mm to 1 cm, while larger crystal aggregates are up to 2.5 cm.

Göstlinger Alps (Eastern Alps)
In 2020, white CCC aggregates were found in one of the smaller upper chambers of Hochkarschacht that connects to the main cave via inclined, narrow passages. Some of the white porous crystals are overgrown by dark brown dense calcite that is also of cryogenic origin as indicated by its stable isotope composition. Individual crystal sizes vary from 5 to 10 mm and larger aggregates are up to 1.5 cm.

Hochschwab (Eastern Alps)
Speikbodenhöhle is one of the few caves in the Hochschwab massif (Fig. 1) that has extensive horizontal passages. The upper paleo-phreatic level hosts four CCC occurrences. Heaps of white, translucent, amber-coloured, light and dark brown crystals were documented that are often mixed together.

4. Crystal morphologies

For this short morphological description, we use the terminology of RICHTER et al. (2010, 2013). We observed a wide spectrum of morphologies from skeletal crystals to complex multi-aggregates.

Skeletal crystals and hemispheres are usually translucent or white in colour, while rhombic CCC are amber-coloured, light or dark brown. Beak-like and dumbbell habits of both white and amber-colour are also present. Braided forms are often light brown or white. CCC characterised by a light brown core overgrown by dark brown cryogenic calcite were documented in three caves (Eisriesenwelt, Speikbodenhöhle and Hochkarschacht). These changes in colour and often also in porosity reflect variations in the chemical parameters of the slowly freezing water. Similarly, different crystal habits within an individual heap may reflect (i) changes in water chemistry or (ii) different depositional periods. An example for the latter is Eisriesenwelt, where one CCC site yielded multiple CCC generations, whereby the oldest and youngest CCC formed ca. 73,000 and 12,500 years ago, respectively.

Except for two types of large, cm-size individual amber-coloured and dark brown CCC discovered in Eiskogelhöhle (Fig. 2b), crystal habits in the Alpine caves show similar morphologies as those found in Central European caves (e.g. RICHTER et al., 2010, 2013, 2018; ŽÁK et al., 2012; ORVOŠOVÁ et al., 2014).

5. Conclusion and outlook

CCC are key indicators of former cave glaciation. In the last few years, several new sites have been found in the Eastern Alps and one in the Dolomites, whereby the lowest site is located at 1054 m a.s.l. Often multiple occurrences are present in a cave and in some cases, a range of morphologies can be documented within individual CCC spots. Our study

suggests that these unique and hitherto overlooked speleothems are probably quite common also in caves of the Alps, opening the door to learn more about past times of extensive ice coverage including interior parts of today's ice-free caves.

Acknowledgments

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Les remplissages de la phosphatière de Dams, Quercy (Caylus, Tarn-et-Garonne, France)

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Résumé

Les phosphorites du Quercy, grâce à leur exceptionnel contenu paléontologique, enregistrent, les changements paléoenvironnementaux de quelques 30 Ma autour de la « Grande coupure » de la transition Eocène-Oligocène. Les sédiments piégeant les fossiles ont été peu étudiés et interprétés en regard des contextes géologique et paléoclimatique. Nous proposons une première approche analytique intégrée des sédiments karstiques (sédimentologie, granulométrie, minéralogie, géochimie) des remplissages de la phosphatière de Dams. Ce site montre trois épisodes de dépôt, encadrant la transition Eocène-Oligocène qui se composent de deux fractions principales, l'une détritique, l'autre phosphatée et néoformée. L'apport détritique résulte du transport en masse d'un matériel « sidérolitique » éocène-oligocène présent transitoirement en surface et provenant du remaniement de paléosols latéritiques, formés en amont, directement ou indirectement à partir d'une roche mère cristalline. Le phosphate, précipité sur les parois du karst ou épigénisant les fossiles, livre une signature géochimique marine qui suggère la contribution de l'encaissant carbonaté marin, à la chimie du fluide source. Enfin, les changements climatiques de la Grande Coupure semblent ne se refléter qu'au travers de la dynamique hydrique souterraine enregistrée par les structures, chenaux et fentes de dessiccation, préservées dans les dépôts karstiques.

Abstract

The fillings of the Dams phosphatiere, Quercy (Caylus, Tarn-et-Garonne, France). The « phosphorites du Quercy », thanks to their exceptional paleontological content, record the paleoenvironmental changes over more than 30 Myr encompassing the 'Grande Coupure', at the Eocene-Oligocene transition. The sediments themselves have been little studied and interpreted regarding geological and climatic contexts. We propose here a first integrated analytical approach (sedimentology, granulometry, mineralogy, and geochemistry) of the « phosphorites du Quercy » based on the study of the sedimentary fillings of the DAMS « phosphatière ». This site shows three depositional stages bracketing the « Grande Coupure » event, mainly comprising two parts, one of detrital origin and one of reworked phosphate deposits. The detrital parts result from mass flow infillings of Eocene-Oligocene siderolithic material transitorily lying at the surface and reworked from lateritic paleosols, directly or indirectly developed on upslope crystalline basement rocks. The phosphate, precipitated on cave walls and into bones, yields a REE seawater signature illustrating the marine carbonate host contribution to the chemistry of the source fluid. Finally, climate changes during the «Grande Coupure » seems to be reflected only through hydric sedimentary structures, channels, and mud cracks, preserved in the cave deposits.

1. Introduction

Les phosphatières du Quercy sont des cavités karstiques comblées de dépôts argilo-phosphatés riches en fossiles. Chacune contient un remplissage qui lui est propre et dont la durée de mise en place est estimée à quelques centaines de milliers d'années. Les fossiles extraits des quelques 200 sites reconnus à ce jour, ont permis de reconstituer plus de 30 M.A d'évolution des paysages quercynois de part et d'autre de la transition Eocène-Oligocène (33,9 Ma). Les sédiments eux-mêmes ont été peu étudiés et leur genèse n'a jamais été replacée dans leurs contextes géologique et climatique. L'étude préliminaire présentée ici concerne la phosphatière de Dams (Fig. 1), la seule identifiée, à ce jour, qui conserve trois épisodes de sédimentation bien distincts du point de vue temporel, de part et d'autre de la limite Eocène-Oligocène et permettant l'analyse, dans une même cavité, de sédiments d'âges différents mis en place sous des contextes climatiques particulièrement distincts.

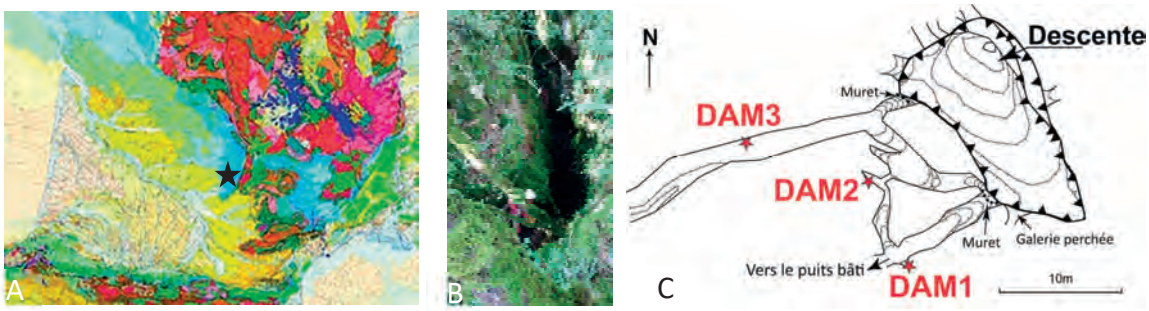

Figure 1 : La phosphatière de Dams. A. Localisation géographique dans le sud du Quercy, à proximité du Massif Central. B. Photo de l'entrée principale de la phosphatière. C. Topographie avec la position des coupes DAMS 1, 2 et 3.

2. Matériel et méthodes

Après le levé stratigraphique et sédimentologique des coupes, l'identification de la source des sédiments et des modalités de dépôt repose sur la minéralogie, la granulométrie et la chimie des échantillons, établies respectivement : par DRX sur la fraction inférieure à 2 µm suivant HOLTZAPFFEL (1985), à l'Université de Mons (Siemens Cristalloflex D5000) et au laboratoire Géosciences Environnement Toulouse (GET ; diffractomètre Bruker D8 Advance du GET), au granulomètre laser LA-950V2 d'Horiba du laboratoire Ecolab de Toulouse, et par spectroscopie de fluorescence X (S2 Ranger de Bruker) au GET.

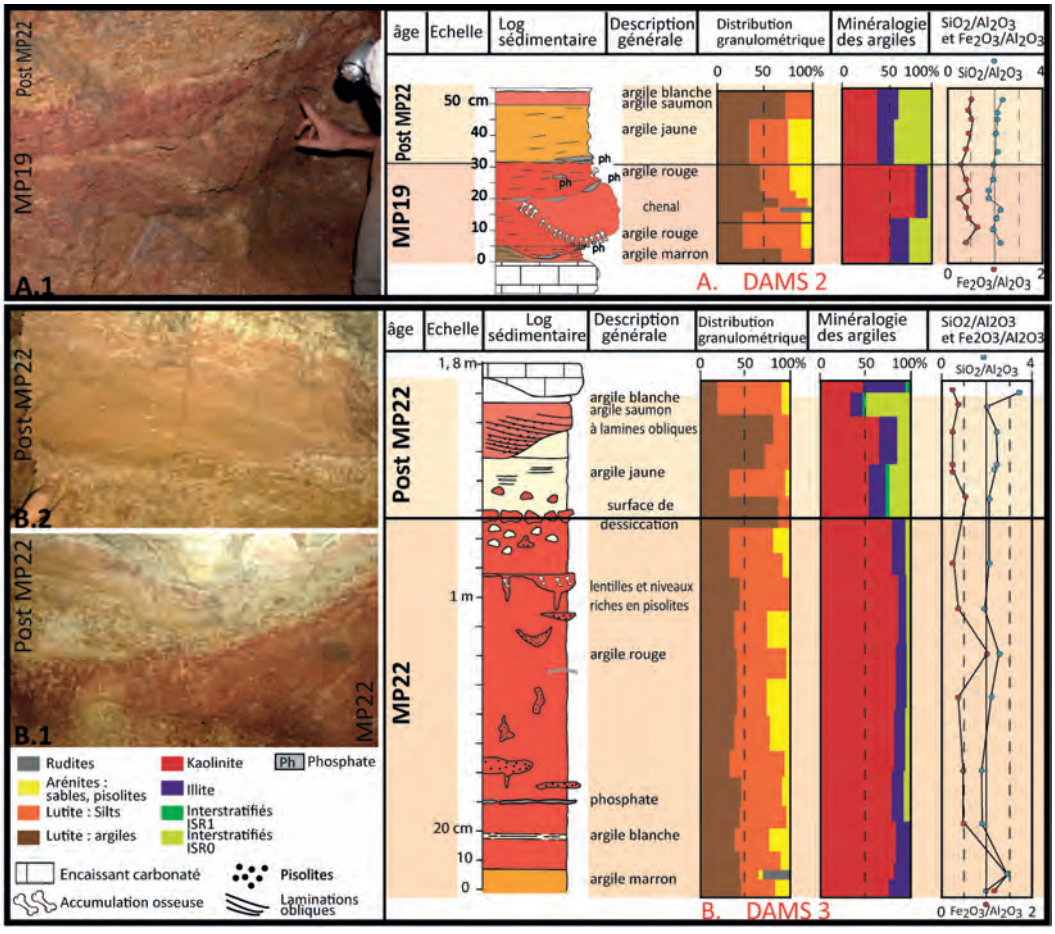

Figure 2 : Illustrations, attributions stratigraphiques, caractérisation sédimentologique, granulométrique, minéralogique et chimique du remplissage DAMS 2 (A) d'âge Eocène supérieur (MP 19) et Oligocène (Post MP22) et du remplissage DAMS 3 (B) d'âge Oligocène inférieur (MP22) et post-MP22. A.1 chenal visible dans le remplissage d'âge MP19 et différence de couleur entre les deux épisodes de remplissages. B.1 différence de couleur entre les deux épisodes de remplissage et illustration de la surface de dessiccation majeure qui les sépare. B.2 lamines obliques visibles dans le remplissage post-MP22.

Pour tracer l'origine du phosphate (e.g., DILL, 1994), les Terres rares (Rare Earth Elements, REE) des composants phosphatés récoltés (Fig.3) ont été analysées. Les concentrations de REE ont été mesurées par ablation laser couplée à un spectromètre de masse (LA-ICPMS) au GET.

Les données ont été traitées à l'aide du logiciel SILLS (GUILLONG *et al.*, 2008) normalisées au PAAS (TAYLOR & MC LENNAN, 1985), et les spectres obtenus comparés à ceux des sédiments détritiques encaissants et à celui d'un échantillon de phosphate marin.

3. Résultats

3.1. Les dépôts détritiques

Les témoins sédimentaires sont préservés localement dans trois galeries qui les connectent (Fig. 1C). Datations biostratigraphiques et similitudes lithologiques conduisent à distinguer trois ensembles de couches. Le premier, datée de l'Eocène supérieur (MP 19 ; 34,4 Ma) a été reconnu dans les coupes DAMS 1 et DAMS 2 (Fig. 1C & 2A). Le second, datée de l'Oligocène inférieur (MP22 ; 30,2 Ma) est identifié dans la coupe DAMS 3 (Fig. 2B). Le troisième, plus récent, mais non datée précisément (post-MP22), clôture les coupes DAMS 2 et 3 (Fig. 2) (Orliac *et al.,* 2019). Les argiles sableuses éocènes et oligocènes, riches en quartz et oxydes de fer (pisolithes de goethite) (Fig. 2) montrent de nettes similitudes : faible variabilité des rapports SiO_2/Al_2O_3 et Fe_22O_3/Al_2O_3. Le cortège argileux est dominé par la kaolinite (~75%) et l'illite (~20%). Ces deux phases de remplissages diffèrent néanmoins. La phase éocène se marque par l'abondance de phosphate notamment sous forme de croûte laminée (DAMS 1) et une remarquable préservation des ossements fossiles dans les chenaux (DAMS 2 ; Fig.2A). La phase oligocène comprend des corps lenticulaires verticaux ou horizontaux remplis de pisolites et de fragments osseux mis en place localement dans des fentes de dessiccation. Les marques d'un épisode de dessiccation majeur sont visibles au sommet de l'unité (Fig. 2B.1). La phase post-MP22 se démarque par un contenu argilo-sableux plus pauvre en oxydes de fer et une couleur jaune à rose, une teneur en quartz plus élevée et une très faible concentration en phosphate, pisolites et os. Le cortège argileux s'enrichit en smectite au détriment de la kaolinite. Des lamines obliques (Fig. 2B.2) sont localement visibles.

La coexistence de 3 à 4 classes granulométriques sans tendance dans tous les niveaux sédimentaires caractérise un sédiment hétérométrique et sans granoclassement.

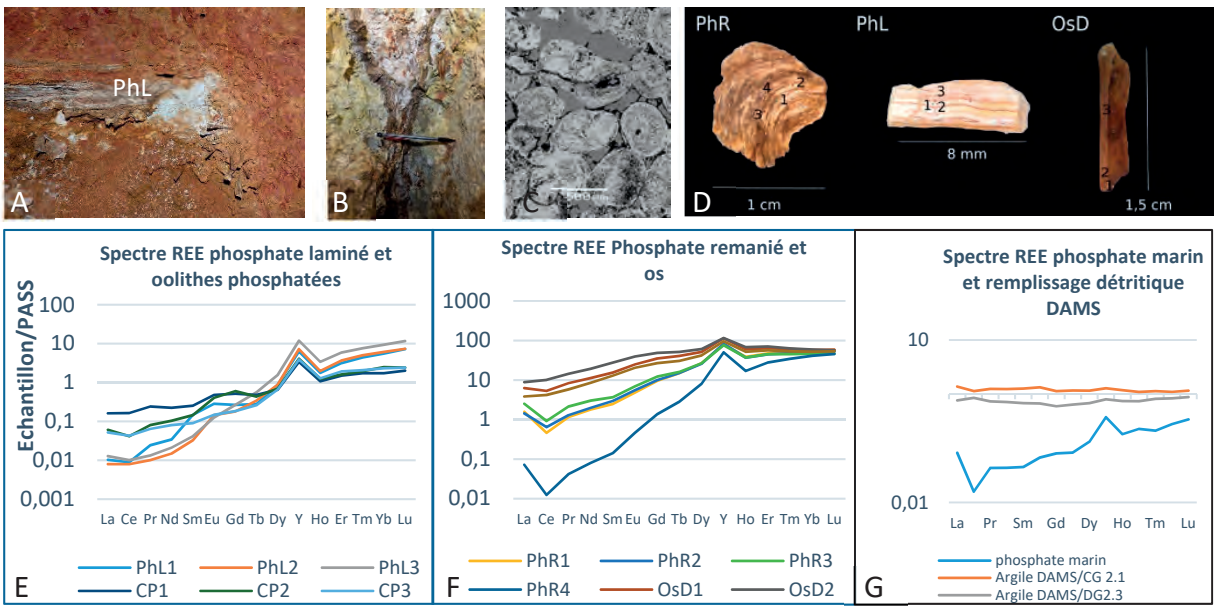

Figure 3 : Les différentes formes de phosphates et leurs spectres REE (terres rares). A. lit de phosphate laminé blanc laiteux (PhL) et ossements, ***B.*** *croûte phosphatée marron qui recouvre les parois du calcaire encaissant, C. oolites phosphatées épigénisées dans la roche encaissante (CP),* ***D.*** *Nodule de croûte phosphatée laminée remaniée qui compose ponctuellement le remplissage sédimentaire argileux (PhR) et ossements (OsD). E et F spectre de REE de tous les échantillons de phosphates. G. spectre de REE d'un échantillon de phosphate marin et de deux échantillons de sédiments détritiques de Dams.*

3.2 Les dépôts phosphatés

Différentes formes de phosphate coexistent à DAMS : lit de phosphate laminé (Figs. 3A, D: PhL), nodule de croûte phosphatée remaniée (Fig. 3D : PhR), encroutement tapissant les parois du calcaire encaissant (Fig. 3B), oolithes de la roche encaissante épigénisées (Fig. 3C: CP), et ossements (Fig. 3D: OsD). Malgré cette diversité de forme et d'origine (précipitation directe versus épigénie), tous ces habitus donnent des spectres de REE très proches, caractérisés par une anomalie négative plus ou moins marquée en Ce, une anomalie positive en Y et un enrichissement significatif en Terres Rares lourdes (Figs 3E & F). Ces motifs sont similaires à celui de l'échantillon de phosphate marin, tandis qu'ils contrastent nettement de ceux de la fraction détritique encaissante qui ne révèlent aucun fractionnement (i.e. spectres « plats » ; Fig. 3G).

4. Interprétation et Discussion

L'analyse sédimentologique, minéralogique et chimique des dépôts détritiques de Dams confirme que la formation sidérolithique Eocène-Oligocène riche en argiles rouges, quartz et pisolithes (GOURDON-PLATEL *et al*., 2000), et affleurant localement sur le plateau calcaire quercynois, est la source du matériel détritique accumulé dans le karst. Il s'agit de fersialsols remaniés formés sous climat tropical. Ces altérites sont issues de l'intense altération indirecte (sédiment détritique) ou directe (sur le socle) des roches cristallines du Massif Central. Les altérites accumulées dans la phosphatière de Dams ont été transportées en masse par des fluides très visqueux comme en témoigne l'absence de classement et de tri granulométrique. La présence de chenaux et de laminations obliques dans les remplissages indique que le transport tractif joue également un rôle à l'Eocène sup. et post-MP22 suggérant un ennoyage des cavités au cours de ces deux périodes. Dans les sédiments oligocènes, les structures de dessiccation indiquent une importante phase d'aridité. Ainsi, malgré de nettes similitudes lithologiques entre les différents dépôts sédimentaires qui suggèrent une source commune, les divergences observées, en termes de concentration en phosphate, de structure et d'assemblages argileux (kaolinite versus smectite) témoignent d'un contrôle climatique et notamment l'instauration d'un climat plus aride à l'Oligocène inférieur.

Les principales phases minérales phosphatées des karsts sont la fluoroapatite et l'hydroxyapatite dont dérivent des paragénèses alumineuses secondaires à crandallite et perhamite (BILLAUD, 1982). Les spectres de Terres Rares des différents éléments phosphatés de Dams sont typiques de l'eau de mer (e.g., BOHLAR et al., 2004) et suggèrent une origine marine du fluide source. Une telle signature géochimique, en contradiction avec le contexte environnemental continental de la période de phosphatisation, impliquerait la contribution de l'encaissant carbonaté, d'origine marine, sur la chimie du fluide source. Cette hypothèse est confortée par le contexte géologique de formation et de mise à la surface des cavités karstiques à l'origine des phosphatières. ASTRUC et al. (1998) évaluent à 500m l'épaisseur de formations jurassico-crétacées à dominante carbonatée soustraite par altération chimique. Si l'origine marine du phosphore demande encore à être mieux documentée, il apparaît que la dissolution, même partielle, de ces carbonates constitue une source suffisante de calcium et de REE pour former l'apatite. En outre, la préservation exceptionnelle d'ossements, de graines, d'insectes, ainsi que la présence d'organismes momifiés plaident également en faveur de processus de phosphatisation rapides et probablement continus.

5. Conclusion

L'approche multidisciplinaire présentée dans cette étude éclaire d'un jour nouveau le remplissage sédimentaire de la phosphatière de Dams. D'une part, il semble que le contenu sédimentaire à savoir des fersialsols ou « sidérolithique » remaniés aient enregistré les variations hydrologiques ayant eu lieu à proximité de la transition Eocène-Oligocène. D'autre part, la phosphatisation qui a affecté le karst, trouverait son origine dans la dissolution de l'encaissant calcaire mésozoïque, comme en attestent les spectres de Terre Rares typiquement marins.

Remerciements

Ces travaux s'intègrent dans le projet de recherche "Deadender", financé par l'Agence Nationale de la Recherche (ANR) dont la coordinatrice scientifique est Maeva Orliac.

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Mineralogical curiosities: The “lapis specularis” coins of the Re Tiberio gypsum cave (Italy)

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Abstract

In 2020 a new peculiar gypsum monocrystal structure was observed in the main gallery of the Re Tiberio gypsum cave (Emilia Romagna Region, Italy), close to its entrance. The new forms consist of a small, extremely flat cylinders (less than 1 cm in diameter and 1 mm in height), which make them remarkably similar to true coins. They were piled one over the other in a small cup just below a narrow fracture filled by clay. The morphological study of the crystals together with that of the fracture, inside which they developed, allowed the definition of their genetic mechanism, which was controlled by two main factors: steric hindrance and epitaxial growth.

Résumé

Des curiosités minéralogiques : les médailles *lapis specularis* de la grotte de gypse de Re Tiberio (Italie). En 2020, une nouvelle structure monocristalline très particulière de gypse a été observée dans la galerie principale de la grotte de gypse de Re Tiberio en Émilie-Romagne, près de l’entrée. Ces formes nouvelles consistent en de petits cylindres très plats (moins d’1 cm de diamètre et 1 mm de haut), ce qui les fait ressembler à de véritables pièces de monnaie. Ils étaient empilés les uns sur les autres dans une petite cupule juste en-dessous d’une fracture étroite remplie d’argile. L’étude morphologique de ces cristaux et de la fracture dans laquelle ils se sont développés permet de préciser le mécanisme de leur formation contrôlée par deux principaux facteurs : la croissance cristalline et l’empêchement stérique.

1. Introduction

Peculiar euhedral gypsum crystals were recently observed within the Re Tiberio cave (Emilia-Romagna Region, Italy). They are extremely flat cylinders making them very similar to gypsum coins. These gypsum crystals are perfectly transparent (like those called “*lapis specularis*” by the Romans) with a diameter ranging between 2 e 3 cm and a thickness from less than 1 up to 2,5 mm (Fig. 1).
The detailed analysis of the area helped define the boundary conditions required for the development of these peculiar crystals, which had hitherto not been observed in any other cave of the world.

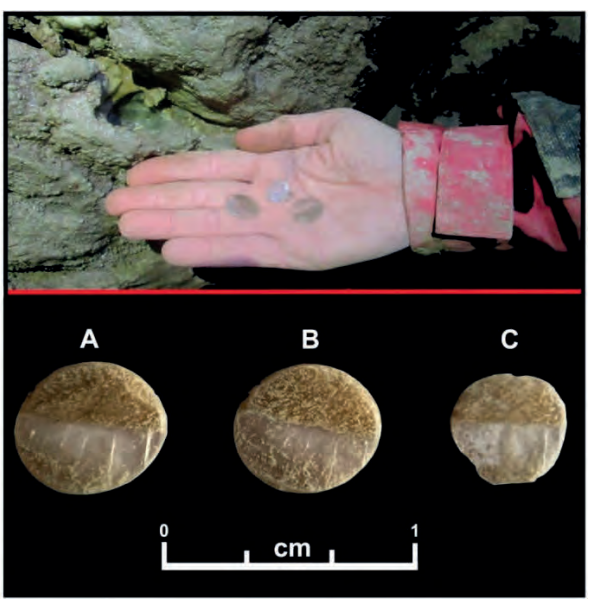

Figure 1: Re Tiberio cave: the 3 “lapis specularis coins” just taken at the foot of the subhorizontal fracture where they developed; B: close up view of the coins (A: Φ 16,5-18 mm, B: Φ 16x17 mm, C: Φ 14x14 mm): all of them show just below one half of their upper flat surface the presence of a thin layer of small undefined grains, while in the other half the impurities are far less and extremely close to the external surface. (Photo M. Ercolani).

2. The mechanism for the genesis and evolution of the "coins"

The "*lapis specularis*" coins grew within a small open subhorizontal crack located close to a dripping of meteoric seeping water, which is sometime slightly undersaturated with respect to gypsum and consequently able to deposit a thin crust of calcite. Droplets originated by the splash of the dripping water maintain constantly wet the mud filling the crack. During the period of scarce or even absent rainfalls, the slow evaporation of the water trapped within the crack induces a slight supersaturation with respect $CaSO_4 \cdot 2H_2O$, leading to the formation of secondary gypsum.
But the very low energy of crystallization only allows the enlargement of an already existing crystal via bidimensional accretion, rather than new nucleation, a tridimensional mechanism.
In the meantime, the presence of the clay and silt infilling, hindering the development of euhedral crystals, enhance that of lens shaped ones, which are proved to be the most common forms in such contest (FORTI & LUCCI 2016, FORTI 2017).
But why, only in this small fracture, do peculiar crystals (flattened cylinders similar to true coins) develop instead of the "normal" lens-shaped ones?
The single possibility is that the vertical development of the lens-shaped crystal cannot proceed anymore, and that, consequently, the further deposition of gypsum only occurs around its circumference.

As already evidenced for the cubic cave pearls (HILL & FORTI 1997, FORTI & PENSABENE 1989a,b), the single growing mechanism which may cause the development of the gypsum coins is the steric hindrance, which becomes active when the vertical dimension of lens shaped crystal becomes equal to that of the subhorizontal crack (Fig. 2A). Then the crystal is progressively obliged to modify its shape until it becomes a perfect cylinder (Fig. 2B), which, from then on, can only increase its diameter (Fig. 2C).
Even in contact each other and with the crack walls, the different "coins" do not merge due to several concurring factors: among them the presence of clay in between their contact planes and the transient undersaturation occurring during the relative fast water flow during the rainfalls.
Clay particles mechanically avoid crystalline subcritical gypsum particles to stick on the external surface of the coins, thus acting as a "barrier" in between the two gypsum surfaces. Moreover, these particles being free from each other can move back and forth during the wetting and drying cycles, thus they exert some abrasion on the external surfaces of gypsum cylinders.

Anyway, beside these two hindering factors, another makes the merging of two different coins practically impossible: the energy of crystallization, which is, as mentioned above, always extremely low, thus only allowing epitaxial growth. This process is bidimensional; therefore, the crystal lattice grows maintaining the original structure and orientation. Thus twinning &/or growth penetration-crystals cannot develop because they need a higher crystallization energy.
Obviously, the crystal lattice of any gypsum monocrystals is always the same, but its spatial orientation may be different. Statistically this is much more probable than a perfect overlapping of the separate structures thus explaining why two eventually superimposed coins cannot merge to form a single bigger cylinder.
In fact, the different crystal lattice spatial orientation of the piled coins prevents epitaxial accretion to act simultaneously over the two planes in contact and transforming the two coins into one.

But why did the coins pile themselves in the depression just below the crack where they originally developed?
The progressive widening of the crack towards the open space suggests that steric hindrance is still the driving factor. In fact, due to the progressive increase of their diameter, the coins will meet the walls earlier, the closer they are to the inner part of the crack.
This will force a slow, progressive, displacement of the coins towards the exterior, movement which is in turn enhanced by the lubricant presence of the plastic clay.
This process will continue until the coins, extruded over a half from the crack, will fall and accumulates one over the other in the underlying depression (Fig. 3).

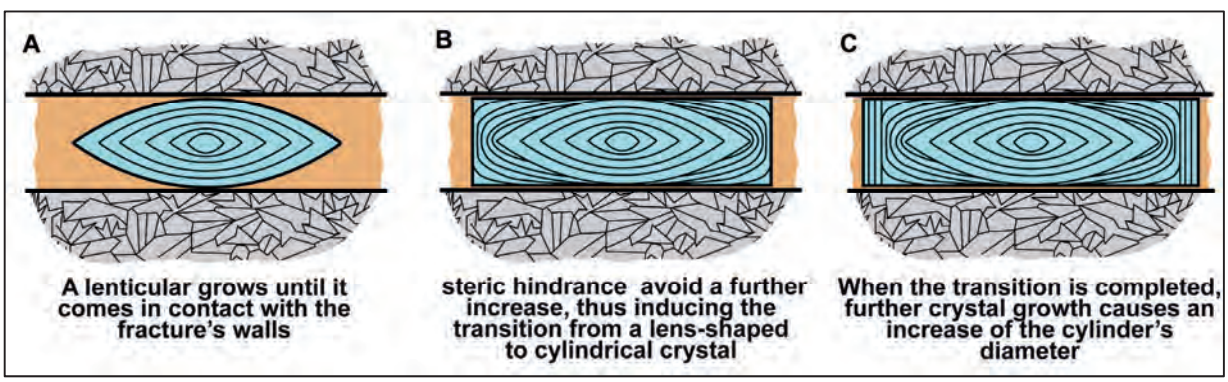

Figure 2: Steric hindrance effect on the lenticular shape of the gypsum crystal (A), which progressively transforms into a cylinder of the same diameter (B), then enlarging it (C).

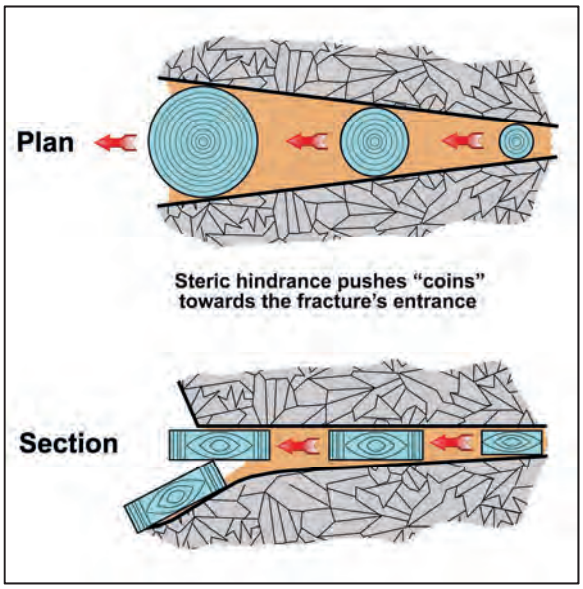

Figure 3: Sketch of coins' migration within the fracture which is controlled by the steric hindrance.

Finally, an explanation is required for the subdivision of the upper surface of all the three coins into two parts (v. Fig. 1, bottom), the first of which shows a high number of very small pale brown to grey inclusions, which were sealed in the gypsum lattice just rather at the end of the accretion process.

The other side of the coins exhibits very few inclusions only, which always restricted to the very outer crown.

The extreme closeness of the pale brown grains to the outer surface of the coins suggests that the inclusion occurred when the development of the monocrystals was nearly completed.

This hypothesis is supported by the with the fact the sealing of the mud and clay grains could not start before the coins were partially pushed out of the fracture. In fact, it is well known and documented that the all the euhedral gypsum crystals, even if developed within clay interbeds, are quite free from solid inclusions and this because the epitaxial growth avoid their incorporation within the crystal lattice. But a further evidence exists that strengthens the hypothesis that incorporation started only after the coins' partial "emersion" from the crack. The boundary between the transparent and the opaque areas is always rectilinear, suggesting that it was coincident with the outer edge of the crack.

Starting from this evidence it is reasonable to think that the last step in the evolution of the coins was controlled by the recurring presence of splash droplets induced by the dripping which feeds the small cup, just below the crack, just after the strong rainfalls.

In fact, the dripping impact, beside supplying the droplets which can land over the upper side of the coins when partially exposed in the open space (Fig. 3 A), have enough energy to mobilize not only silt and clay grains but also small fragments of calcite and/or gypsum.

The evaporation starts just after the cessation of dripping, but its rate is very low, as it was during all the process of development of the coins inside the crack. Thus, supersaturation will cause only the gypsum deposition via

When these droplets land over the exposed surface of the coin, they leave the carried impurities (Fig. 3 B). Moreover, these droplets were probably still undersaturated as a consequence of the fast seepage after strong rainfalls, such that they could dissolve, even slightly, the surface of the crystals on which they landed.

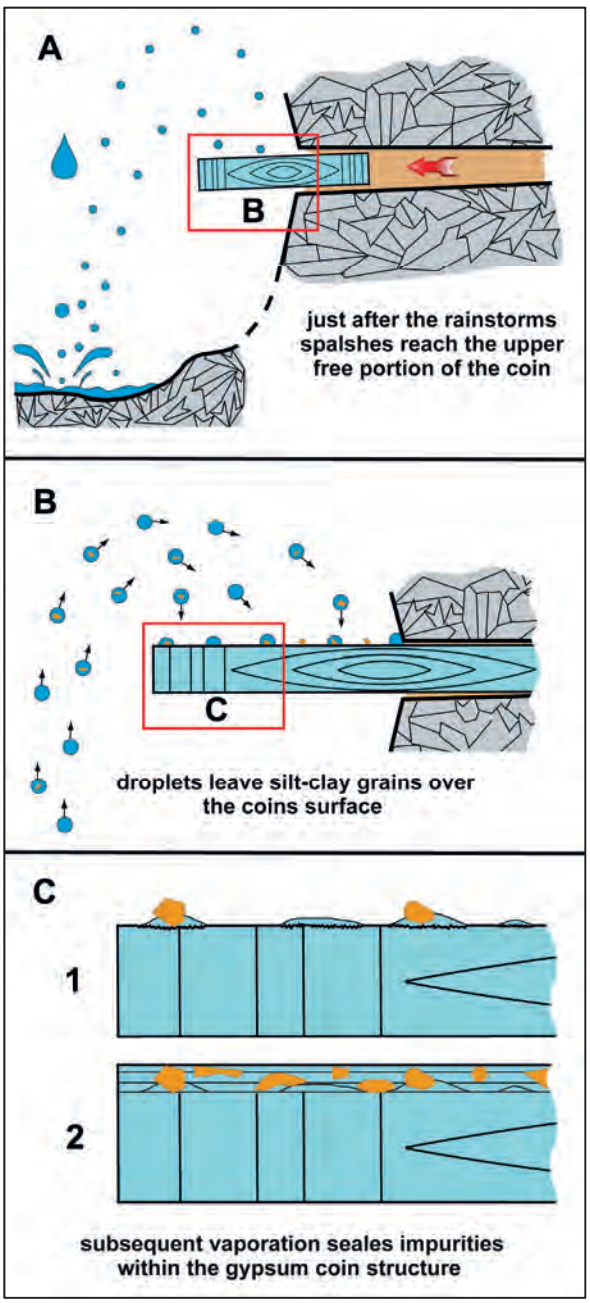

Figure 4: Droplets generated by dripping impact on the cave floor reach the coins' exposed upper surface where small impurity grains are deposited (A). Then evaporation induces gypsum deposition which seals impurities within the coin (B). Several subsequent deposition-evaporation cycles totally bury the grains within the crystal structure (C).

epitaxial growth, which in turn allows the impurity grains to be sealed linked to the coins' surface (3C1)

The alternation of several rainy periods, with consequent development of splash droplets, to dry periods, with gypsum

deposition by evaporation, causes the progressive inclusion of the impurity grains within the crystal lattice (C2).
Thanks to this mechanism the whole external surface of the coins, still consisting of a single crystal, remains completely flat and homogeneous, but the color of the portion over the impurities is quite different, because the transparency of gypsum makes them visible.

Finally, it should be noted that impurity grains are far less numerous in the other parts of the coins, thus suggesting that their fall from the crack occurred recently.

3. Conclusions

The detailed analysis of the area in which the "*lapis specularis*" coins developed allowed the definition the two controlling factors ruling their genesis and evolution: energy of crystallization and steric hindrance.
Finally, before they were completely extruded from the fracture, the splash droplets brought impurity grains over the free portion of their upper surface, where they were later sealed within the crystal lattice. After the complete extrusion and accumulation in the depression below the crack, the accumulation of foreign grains may have started to affect the whole coin upper surface, but it is evident that this process started only a brief time before the coins were observed and studied.
In conclusion the processes which led to the development of these very peculiar gypsum coins was rather complex and this explains why these gypsum crystals were never seen before.

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Significance and comparison of sediments in Northern Velebit deep caves, Dinaric karst, Croatia

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Abstract

When they are well-preserved, cave detrital infills can be very useful for the determination of climate conditions and sedimentation processes that were present at the time of their deposition. In this research, two caves, located in the Northern Velebit National Park and named Nedam and Ledena jama respectively, were chosen for the analysis of their infill. Nedam recently became Croatia's fourth deepest shaft of 1226 m deep. In Nedam, rock samples were systematically taken to construct a geological profile. Ledena jama shaft is 536 m deep and located in a paleo-glacier valley. The shaft is characterized by the presence of permanent ice between 50 and 160 m depth. Nedam is located on steeper and more inaccessible karstic settings. The entrances of Nedam and Ledena shafts are at different altitudes and combined with different geomorphological settings (paleo glacier valley vs. steep karst), suggest that possible differences in the studied detrital infill may be present. The analysis made on the rock samples and cave detrital infill were the determination of mineralogical composition: i) identification of clay minerals by X-ray diffraction analysis, ii) separation of light and heavy mineral fraction, iii) thin sections preparation and iv) identification and characterization. From these analyzes, we can deduce the provenance and sedimentation processes of the detrital infill, and the environmental and climate conditions during the deposition.

1. Introduction

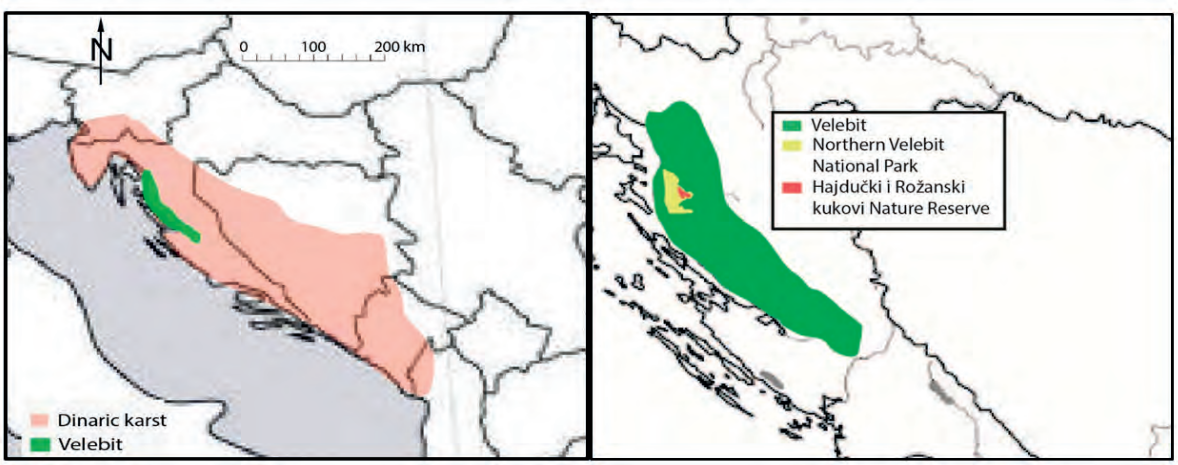

Figure 1: One the left: Map of SE Europe with the position of Dinaric karst area and Velebit Mt. On the right: Map of Croatia with the position of Velebit Mt., Northern Velebit National Park and Hajdučki i Rožanski kukovi Nature Reserve

The Croatian coast consists of mountains belonging to the External Dinarides and the Adriatic Carbonate Platform. The External Dinarides have a specific relief so-called ˝the Dinaric Karst˝ in which a multitude of karst forms have been formed. The longest mountain range in Croatia is Velebit mountain (145 km) and is also a part of the External Dinarides with NW-SE strike direction (Fig. 1). North Velebit is a 30 km long and up to 30 km wide mountainous region that extends from the Vratnik mountain pass in the north and to the Veliki Alan mountain pass in the south and its highest parts reach almost 1700 m. The North Velebit is also a territory of a national park (Northern Velebit National Park) due to its preserved biodiversity and fascinating karstified terrain. In this region, The natural reserve of Hajdučki i Rožanski kukovi shows isolated groups of ledges, cliffs and rocky peaks with deep sinkholes between them (Fig. 1). Most

of the North Velebit region is comprised of Jurassic limestone and dolostone characteristic of Paleogene ˝Jelar breccias˝ (Velebit breccias) and Triassic dolostone clastic and carbonate deposits (VELIĆ *et al.,* 1974). Cretaceous and Quaternary deposits are also present but in small areas. Jurassic limestones are most often rich in fossils of algae, gastropods, bivalves, etc. The remains of dinosaurs and reptiles were not reported in this area (SOKAČ *et al.*, 1976). Jurassic limestone bedrock is widespread, with the presence of dolostone, usually alternating with limestone. Paleogene ˝Jelar breccias˝ are the second most widespread lithologies of this region, characterized as heterogeneous carbonate breccias with Middle Jurassic to Paleogene fragments, which overlie the Jurassic limestone nonconformably (HERAK & BAHUN, 1979). The genesis of the breccia is connected to local tectonic disturbances, epeirogenic movement and erosion. The thickness of breccia deposits is approximately 300 m, which is visible at the entrances of pits formed in Jelar breccias. All four Croatian shafts deeper than 1000 m are located in the North Velebit region, which makes it one of the most important regions for speleological research in Croatia (Fig. 2). The shafts chosen for this research are Nedam and Ledena jama. Nedam is located in Hajdučki i Rožanski kukovi nature reserve, its entrance opening at altitude of 1420 m and depth of 1226 m. The terrain around Nedam is very steep, inaccessible and karstified. The morphology of the shaft is different from other deep shafts in North Velebit – it is built as a tangle of narrow meanders, verticals with plain and wide walls.

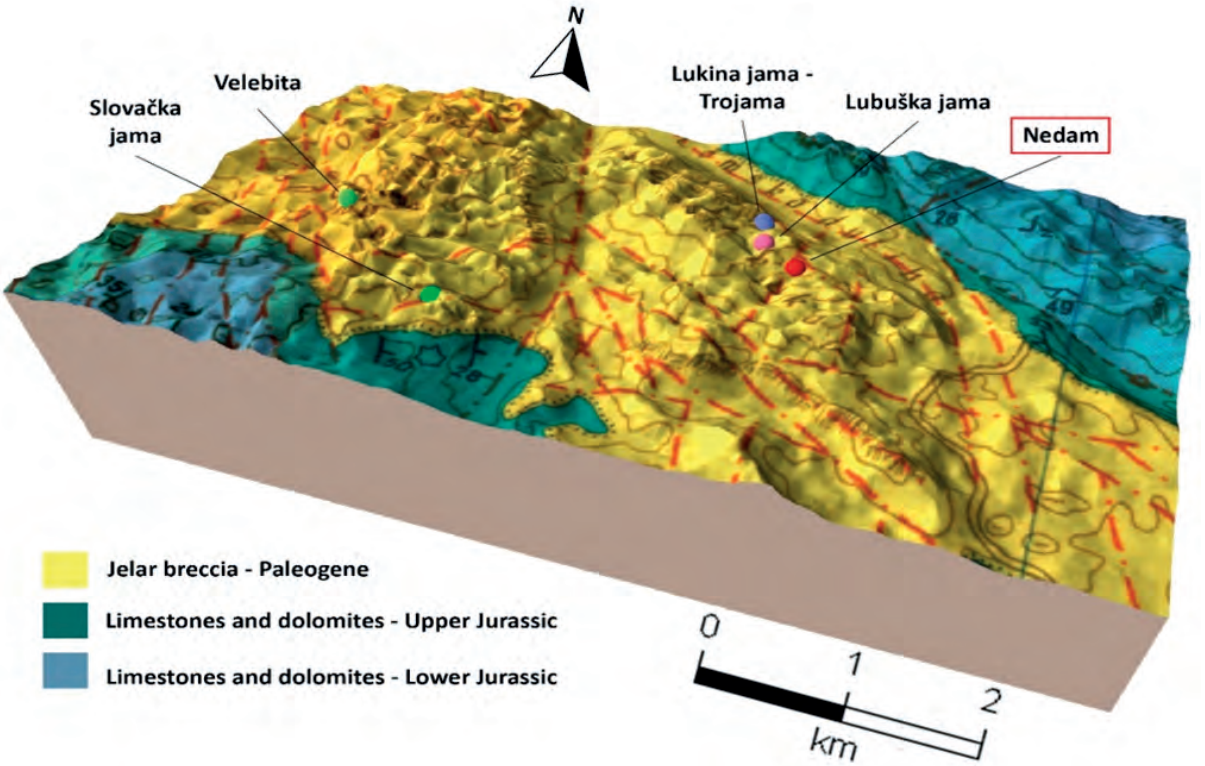

Figure 2: 3D model of the surface with entrances of the shafts deeper than 1000m. In the Hajdučki i Rožanski kukovi area, Northern Velebit, with a geological map of the overlay.

At the bottom, the cave splits into two branches, one of which leads to a sump that re-emerges into an air-filled section, which is still under exploration. The other channel ends in a room which is a few meters deeper than the sump. Ledena jama is a shaft and its entrance is at 1235 m a.s.l., located in a paleo-glacier valley called Lomska duliba. Lomska duliba extends in the WNW – ESE direction, is 7 km long and less than 1 km wide. Lomska duliba is a valley enlarged by glaciers during the Pleistocene (BOGNAR *et al.*, 1991). Ledena jama is located in the middle of Lomska duliba and is significant for its ice deposit, which is present at a depth of 50 to 160 m. The total depth is 536 m, but due to ice, it is very dangerous and rarely visited.

2. Materials and methods

Approximately 500 grammes per detrital sample and fist-size rocks samples were collected. In the Ledena jama only at depth of 50 m (where the ice layer begins) – one rock sample and one detrital infill sample. In the Nedam pit, 20 rock samples (TN1, TN2, etc.) were collected based on observations of changes in lithology, and 8 detrital samples were collected where present (SN1, SN2, etc.). All rock samples from both shafts were first macroscopically examined and selected ones were then made into thin sections. Rock and detrital samples from both shafts were crushed to a powder and analyzed using X-ray diffraction (XRD) as a ˝whole rock˝ (WR). In detrital samples (9 in total) the amount and

proportion of each grain size fraction was determined with wet sieving using 7 sieves with mesh sizes from 4 mm to 0.063 mm. All particles smaller than 0.063 mm went into a large container as a suspension. Grain size fraction in suspensions were determined using a sedigraph. The fraction from 0.125 mm to 0.063 mm of four detrital samples was further used for separation of light and heavy mineral fraction. The four samples chosen for heavy fraction analysis (one from the Ledena jama and three from the Nedam pit) were selected depending on the physical characteristics and depth of the sampling site. Separation of heavy minerals is based on density difference (minerals with a density > 2.9 g/cm^3 belong to the heavy fraction and those with lower density belong to the light fraction) and liquids of known densities were used for its implementation (in this research sodium polytungstate (SPT) was used). Samples were immersed in SPT and centrifuged to separate fractions. Thin sections were made from the isolated heavy fractions and analyzed using a polarizing microscope. In each sample the proportions of transparent and opaque minerals were determined, and 300 transparent mineral grains were determined using the ˝ribbon counting˝ method. For clay analysis in sediments, previously WR and randomly oriented mounts were analyzed first using XRD. For making oriented mounts, particles less than 2 µm in diameter, were separated using centrifuge, dripped on slides as suspension, air-dried and analyzed on XRD. The samples were then saturated with ethylene glycol (EG), to identify the swelling clay minerals, heated on 400℃ and 550℃. After all these steps, samples were analyzed using XRD (STARKEY *et al.*, 1984).

3. Results

Results of heavy mineral analysis of detrital samples are presented in Table 1. Clay mineral analysis showed resemblance between multiple samples. Samples SN2 and SN3 pointed out the presence of very specific hydroxy-interlayered vermiculite, together with gibbsite and kaolinite. All the other samples only contain chlorite, kaolinite, illite and gibbsite. XRD analysis of all rock samples from both pits indicate that calcite is the principal mineral. Depending on different microfossils and microstructures present in samples, determined age and lithology of rocks from the entrance to the bottom of the pit are Eocene-Oligocene Velebit breccia, Upper Jurassic limestones and dolomites, Middle Jurassic limestones and carbonate breccia without any index fossils (Fig. 3).

	SN2(%)	SN6(%)	SN8(%)	LT4(%)
Opaque	76	58	80	60
Transp.	24	42	20	40
Zircon	39.3	5	37	10.7
Rutile	27	1.7	6	2.7
Tourmaline	13.3	2	5.3	1.6
Clinopyrox.	0	55.3	12.7	39
Clinozoisite	3.7	2.7	10	4.3
Apatite	1.3	13.7	7.3	8

Table 1 : Results of heavy mineral fraction analysis showing opaque and transparent grains ratio and main transparent minerals present in each detrital sample.

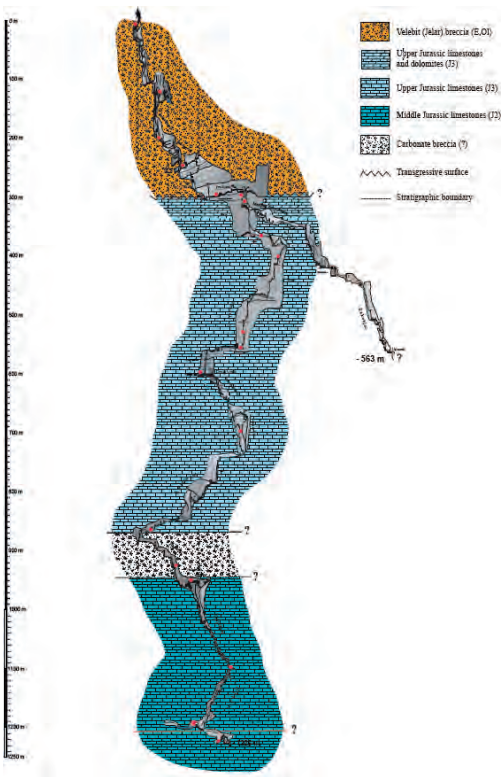

Figure 3: Geological profile of Nedam pit showing the sampling points and the bedrock lithology at different depths.

4. Discussion

Upper and Lower Jurassic rocks on Velebit mountain are characterized as layered limestones and dolostones. All rock samples analyzed with XRD were limestones, with almost no signs of dolostones. Thin sections of rock samples could show some tectonic structures, as we observed macroscopically, but they still need to be analyzed in further detail. Zircon is one of the most abundant minerals in the heavy mineral fraction and one of ZRT group mineral. Such mineral is very stable, difficult to weather, not easy to abrade physically and that is why it often concentrates in deposits (WENK & BULAKH, 2016). Zircon is usually present as accessory mineral in eruptive rocks such as granite and syenite (BERMANEC & SLOVENAC, 2003). Rutile has similar physical characteristics as zircon – hard to weather, a typical mineral in different kinds of deposits and very stable. It occurs in metamorphic rocks (amphibolite, gneiss, slate), and silicium rich intrusive rocks (andesite, granitoids). Tourmaline is mostly pneumatolytic mineral with

many variations in its composition (BERMANEC & SLOVENAC, 2003). The closest areas with igneous and metamorphic lithologies are at the middle part of Velebit mountain, the Alps or the Pannonian basin. Differences in clay minerals present among the samples can refer to a different paleoclimate and environmental conditions at the time of their deposition. As it is well known, glacial cycles that affected the area of Velebit mountain must have had some influence on the development of caves, the weathering of rocks on the surface and the deposition of detrital deposits

5. Conclusion

Based on the mineral composition of analyzed detrital deposits, we can determine more specifically, that their primary source are igneous and metamorphic rocks, probably from the surrounding areas (middle Velebit, Alps, Pannonian basin) and they are by no means of local origin. They are probably transported by eolian, fluvial or glacial processes. We can also assume that the deposits of the SN2 and SN8 samples and those of the SN6 and LT4 samples have different origins and probably different yielded material. These data can be of great use in the interpretation of the speleogenesis of these caves, especially for the Nedam shaft. Further ongoing analysis will give more details and information that are useful for the interpretation of the speleogenesis of this karstic area.

Acknowledgements

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Candlestick stalagmites, a tool to better understand the influence of past earthquakes on natural caves

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Abstract

Candlestick stalagmites exhibit resonance in the frequency-band of regional earthquake ground motions. An earthquake can break such elongated structures if the ground movement is strong enough. Therefore, the existence of intact stalagmites in caves would indicates that a certain level of ground movement has not been exceeded since they exist. Field surveys were carried out in the Han-sur-Lesse Cave (Belgian Ardennes) to estimate the eigenfrequencies of stalagmites of different sizes and shapes (e.g., Minaret Stalagmite, “Verviétois” gallery) and to explore their reactions to external events such as quarry blasts or earthquakes. The eigenfrequencies of the stalagmites are obtained from direct measurements of ambient seismic noise caused by human activities, microseisms, etc. Seismic sensors were placed on the stalagmites and on the nearby cave floor as well as at various other locations inside and outside the cave. Noise and transient events (e.g., quarry blasts) were recorded during weeks of continuous measurements. 3D laser scans of the stalagmites and Finite Element Modelling allowed constraining the link between their complex shape and their eigenfrequencies.

Résumé

Stalagmites cierges, un moyen de mieux comprendre l'influence des séismes passés dans les grottes naturelles. Certaines stalagmites cierges peuvent entrer en résonances dans la bande de fréquences des mouvements du sol des séismes régionaux. Si celui-ci est suffisamment puissant, les stalagmites peuvent se briser. Dès lors, l’existence de stalagmites intactes dans les grottes indique qu'un certain niveau de mouvement du sol n'a pas été dépassé depuis qu'elles existent. Des études ont été menées dans la grotte de Han-sur-Lesse (Ardennes belges) pour estimer les fréquences propres de stalagmites de différentes tailles et formes (ex : Stalagmite du Minaret, Galerie Verviétois) et pour étudier leurs réactions aux événements transitoire tels que les tirs de carrière ou les tremblements de terre. Les fréquences propres des stalagmites sont obtenues à partir de l’enregistrement du bruit sismique causés par les activités humaines, les microséismes, etc. Grâce aux capteurs sismiques placés sur les stalagmites, sur le sol de la grotte et à l'extérieur de celle-ci, le bruit sismique et les événements transitoires ont été enregistrés sans interruption pendant plusieurs semaines. Les scans laser 3D des stalagmites et la modélisation par éléments finis ont permis de contraindre le lien entre leur forme complexe et leurs fréquences propres.

1. Introduction

Since the 1990s, broken or deformed speleothems have been used as indicators of paleoearthquakes (BECKER *et al.* 2006, for a review) and the usefulness of broken speleothems has been proven to date ceiling collapses and therefore date certain paleoearthquakes (CAMELBEECK *et al.* 2018). However, numerical models and physical experiments pointed out the limits of the link between these deformations and earthquakes (CADORIN *et al.* 2001; LACAVE *et al.* 2004) but did not consider all possible imperfections and weaknesses in the body of the speleothems. Finally, in many cases, it is difficult to prove that the speleothem deformations are linked to seismic events because other phenomena such as frost, ground instability, floods ... can produce similar effects (e.g., BECKER *et al.* 2006). To avoid these uncertainties, the study of intact speleothems was favored. The absence of breaks places an upper limit on the ground motion (e.g., GRIBOVSZKI *et al.* 2017) that a specific site may have encountered. These ground motion levels are directly comparable to results of seismic hazard evaluation and of earthquakes ground motion modelling (as for precariously balanced rocks or archaeological objects (BRUNE 1996; SCHWEPPE *et al.* 2017)). Structures can resonate and break at a lower acceleration than predicted, if the ground motions are in the same frequency band as the eigenfrequency of the structure (<20 Hz). The natural frequency and damping factor of the speleothems are fundamental parameters in the study of the response of stalagmites to seismic motion.

Eigenfrequency studies have been conducted with laser or seismic sensors either following a slightly excitation of the stalagmite using a finger or a rubber hammer (LACAVE *et al.* 2000, 2004; GRIBOVSZKI *et al.* 2017, 2018; BOTTELIN *et al.* 2020), or from the ambient seismic noise (i.e., the permanent vibration of the ground surface with different origins depending on the frequency band such as human activities, microseisms, local weather conditions) over a period of 22 days (MARTIN *et al.* 2020). These studies have shown the link between eigenfrequency and the shape of stalagmites (by modeling, 3D scanning, etc.) or the impact of the connection of the stalagmite to the base rock.

This article presents the results obtained during the acquisition campaigns carried out in the Han-sur-Lesse cave (Belgium). The elements that may have an impact on the motion perceived in the cave compared to the surface are presented, namely: eigenfrequencies studies, motion decrease or increase in cave and stalagmites and, the records of external events (earthquakes, quarry blasts).

2. Material and methods

These investigations were made in the karstic system of Han-sur-Lesse, situated in the SSE of Belgium. It is an underground cut-off meander of the Lesse River in the Givetian limestone (Figure 1). From a seismicity point of view, the Han-sur-Lesse cave is situated at a distance of 50–60 km from the Lower Rhine Embayment, which is the most seismically active area in northwestern Europe. However, the closest seismic activity instead comes from the eastern part of the Ardennes at a distance of 30 km (e.g., Verviers: Mw ~6.0, 18 September 1692). In the cave, important roof collapses or slope movement near the river have been linked to regional earthquakes (CAMELBEECK *et al.* 2018).

The study of candlestick stalagmites is currently performed in the “Verviétois” gallery (highlighted in orange on Figure 1) and the first results exploited mainly focus on the "Minaret" stalagmite (red star on Figure 1). The depth of this gallery varies from 60 to 80 m from the ground surface, with the Minaret in the deepest part. The study of the seismic response of the cave is carried out in the tourist part of the cave (yellow dots on Figure 1 indicating the location of seismic sensors), which has among others deeper dry parts (90-100m from the surface), Lesse river crossing areas, rooms of various size and of shapes, different substrates...

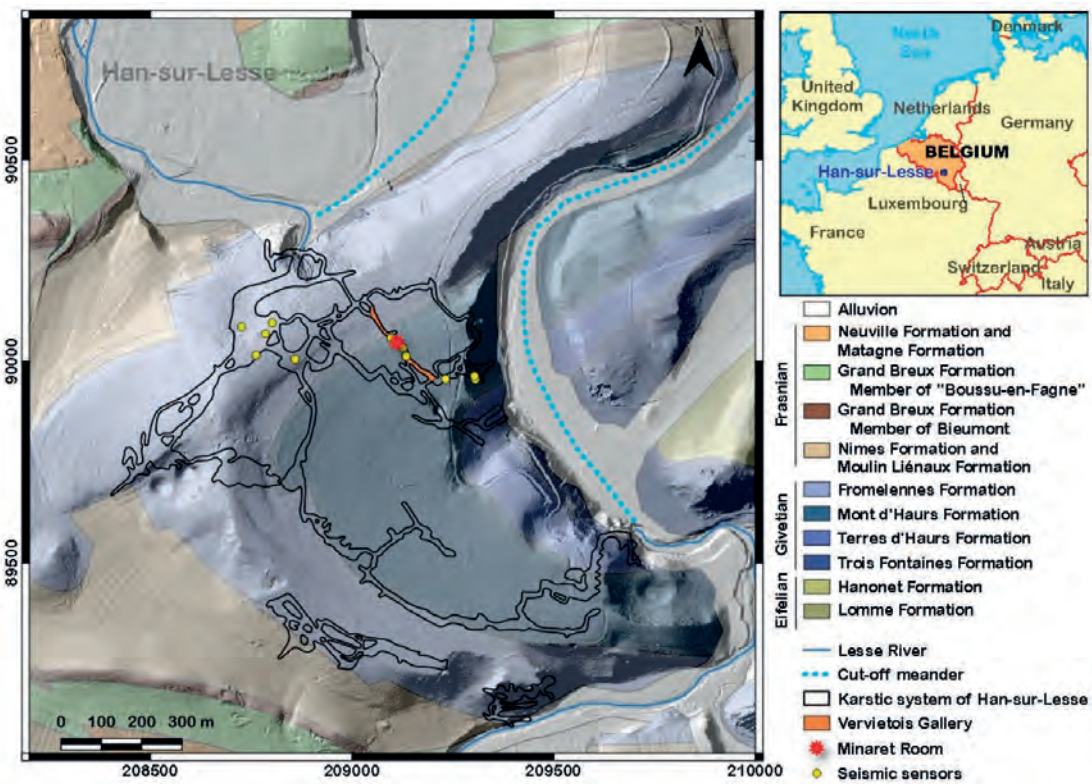

Figure 1: Geological map of the Karstic system of Han-sur-Lesse (Belgian Lambert 1972, in m). The Han-sur-Lesse cave is formed within the Givetian limestone formations (in blue). The cut-off meander (light blue dotted line) can be observed in the alluvial formation (white). The surrounding Eifelian and Frasnian formations are made by shales. The location of the Minaret room is shown by a red star. The “Verviétois” gallery is in orange and the seismic sensors in yellow. This map is based on the new geological map of Wallonia, the Digital Elevation Model (LIDAR) of Wallonia from the Service Public de Wallonie and MARTIN et al. (2020)

Three-components seismic sensors (Smartsolo, Dynamic Technologies – DTCC) were placed on candlestick stalagmites to study their eigenfrequencies and their reaction to external stresses. (see figure 2, bottom left corner). At the same time, sensors were installed at the bottom of the stalagmite, in the centre of the room (if possible) and at the surface (outside the cave). In addition, twenty vertical one-component seismic sensors were placed at the surface and in the cave for 1 month (see figure 2) in rooms of different sizes, shapes, depths, and substrates in order to study the seismic response of the cave.

In parallel with the seismic data, a FARO Focus 3D infrared phase scanner was used to perform a 3D scan of the room of the Minaret and the stalagmites present in this area to capture the shape of the stalagmites and to deduce the possible impact of this on the frequency or the reaction to earthquakes.

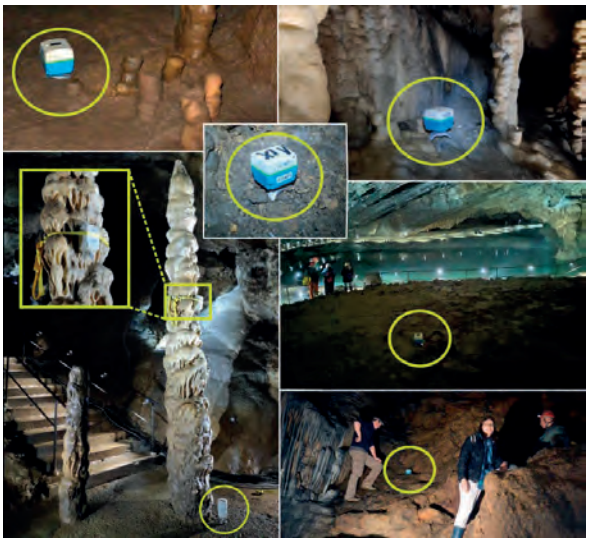

Figure 2: Example of seismic sensors in Han-sur-Lesse cave

3. Results

The ambient seismic noise makes it possible to identify the natural frequencies of the candlestick stalagmites present in the cave (Figure 3 (1)). For example, the natural frequencies of the Minaret have been found at 12.2 Hz and 15.2 Hz for the first mode shape. These two frequencies have perpendicular polarization directions (N52E and N142E). The same results were obtained by modelling based on a subsampled point cloud of the 3D laser scan.

Changes in amplitude due to anthropogenic noise were also observed in ambient seismic noise, even in the upper part of the cave (e.g., Minaret room, "Verviétois" Gallery). They are higher during daytime than at night and on weekdays compared to the weekend. They are also more important at the surface than in the cave except for the Minaret. The stalagmite motions are larger compared to the motions measured at its base (21 or 13 times for X and Y components) and at the surface outside the cave (14 or 4 times, respectively).

The use of continuous recording of seismic data also allowed the recording of seismic events such as teleseisms with important magnitude (e.g., MW >6: Turkey, China, Russia, Bering Sea, Caribbean Sea earthquakes). Their frequency bands are usually lower than 2Hz. Quarry blasts have been recorded from the nearby Rochefort quarry in particular (8 km distant); here, the frequency bands are then higher (~2Hz-60Hz). Those frequencies correspond to the eigenfrequencies of the Minaret. The motion recorded on the Minaret clearly shows this event (Figure 3 (2)).

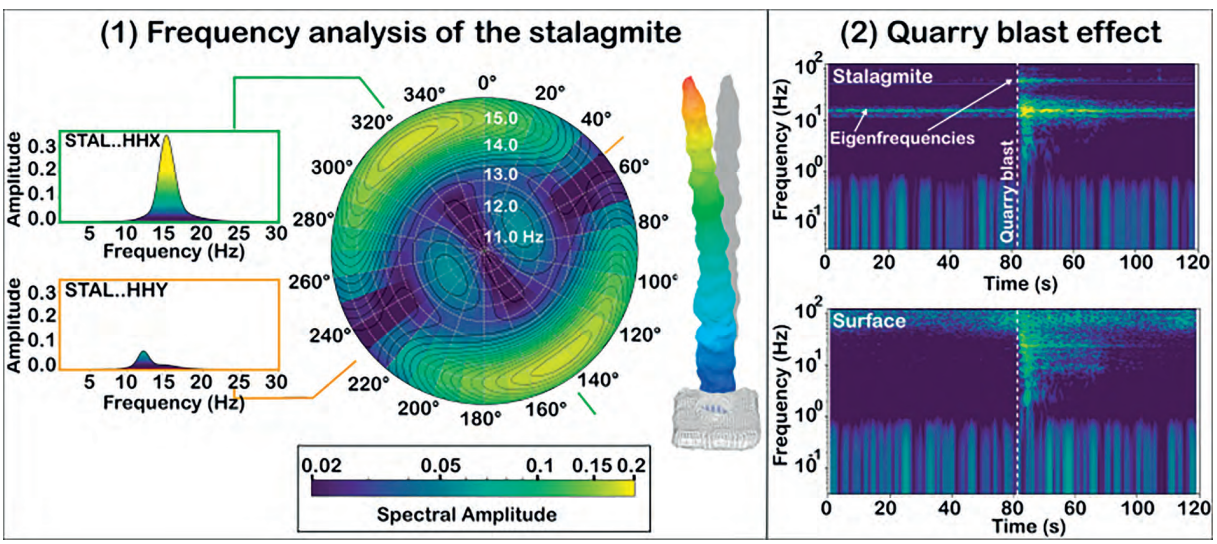

Figure 3: Results obtain with seismic data: (1) Polar spectral plot of the data measured with the sensor on the Minaret stalagmite (STAL). On the left, the spectra of the horizontal directions HHX (N142°E) and HHY (N52°E). On the right, the first type of mode shape of the Minaret stalagmite; the maximal total modal displacement is in red.
(2) Spectrogram of quarry blast event of Rochefort quarry on stalagmite and surface for the horizontal.

4. Discussion and conclusion

The use of ambient seismic noise in natural underground environments showed promising results, mainly to better understand the influence of past earthquakes on stalagmites.

First, the lower eigenfrequencies of the stalagmites could be extracted from the data, thus providing a fundamental parameter in the study of the response of the stalagmites to seismic motion. The use of long-time windows increases the resolution. The model output based on 3D laser scan data shows a good consistency with measured frequencies. The results also highlight the influence of the stalagmite shape and heterogeneities on eigenfrequencies (e.g., by explaining the split frequencies by ellipsoidal cross-section). The small differences between measurements and modelling might be caused by uncertainty on mechanical properties of the stalagmite, heterogeneity in their distribution and the influence of the sensor weight during the measurements which has only a slight influence in the case of the Minaret. These observations can help the study of very fragile candlestick stalagmites, which requires a careful use of adequate seismic sensors, whose installation would be risky.

Second, even if an amplitude decrease of the ground motion amplitudes is observed between the surface and the cave, as it is generally described, the motions recorded on the stalagmite are strongly amplified with respect to the surface motions (4-14 times) or on the ground in the cave. This observation brings strong implications for any seismic hazard validation based on speleothems.

Third, the use of continuous measurements over a long time period gives the opportunity to capture external events over a large frequency band. For example, records show that the Rochefort quarry blasts excite the Minaret's eigenfrequency. This information is encouraging for studies conducted on more slender stalagmites, with lower eigenfrequencies which might be more easily excited by an earthquake.

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Complex behavior of speleothems during transformation of aragonite to calcite

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Abstract

Aragonite speleothems are increasingly being used as high-resolution climate proxies; however, aragonite is unstable and susceptible to diagenetic transformation into calcite leading to mineralogical, textural and geochemical alterations. This study combines stable isotope geochemistry and U-series dating with petrological observations and EMPA elemental analyses to characterize a stalagmite that shows primary aragonite diagenetically altered and with reverse ages. Characterization and interpretation of the chemistry of the waters from which the aragonite precipitated, and of the ones that subsequently formed the calcite, indicates that both polymorphs formed from the same fluids. These fluids hydrochemically evolved from an "aragonite mode" to a "calcite mode" along a diagenetic path within the sample. The results show that during transformation the system stayed close in one of the stages, and open in the other with the same textural result. These results highlight the complex behavior of speleothems during diagenesis and the impact on the geochemical information of the primary and secondary phases, and thus the importance of petrological and geochemical characterization of speleothems for paleoclimatic studies.

1. Introduction

Speleothem-based studies targeted to decipher past climate events and the rates at which they occur rely on accurate dating (DRYSDALE *et al.,* 2009; ST PIERRE *et al*., 2009). Diagenetic transformation of speleothems composed of unstable phases, such as Mg-rich calcites and aragonite, can alter the chemical properties of the deposit and it is critical for the accuracy of dating. In most cases, transformation from a precursor to a stable phase is clearly indicated by changes in the fabric of the speleothem (FRISIA, 1996; WOO & CHOI, 2006; MARTÍN-GARCÍA *et al.*, 2009; FRISIA, 2015). There is, however, the possibility that topotactic diagenetic transformations preserve the initial precursor fabric (BAJO et al., 2016), or that the transformation itself proceeds through crystalline defects and initiates at the core, rather than in the outer layer of the stalagmite (cf. FRISIA *et al*., 2002). This last case is particularly important, because the ages of the transformed phase may not mark the occurrence of mineral transformation, but rather other diagenetic phenomena such as U (or Th) leaching that could indicate that there has been remobilization of other chemical species as well, and transformed aragonite to calcite speleothems should be treated with caution.

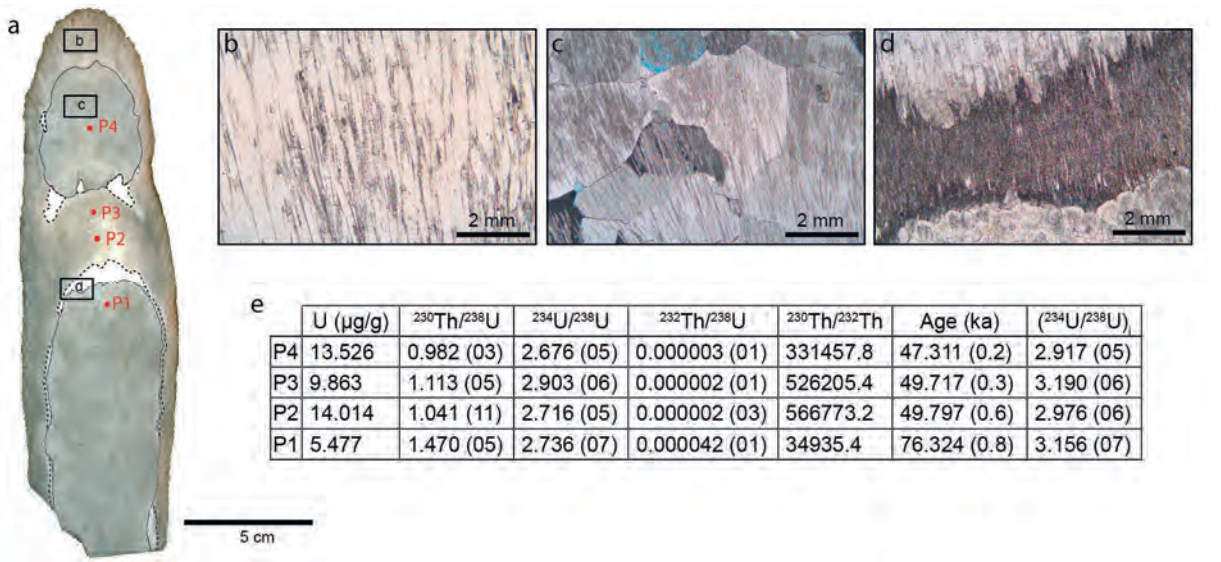
In this study we analyzed a stalagmite from Castañar Cave clearly affected by diagenesis, characterized by a mosaic calcite core and aragonite cortex, to understand, first the carbonate diagenetic processes, secondly the effects of diagenesis on the geochemical behavior of the different elements and stable isotope values, and finally the impact that this behavior has on the age data.

2. Materials and methods

The candle-shaped stalagmite was sampled at -20 m from the surface on a flowstone that connects this gallery with a lower chamber. It is 21 cm long, with a diameter of 5 cm and composed of aragonite and calcite. When collected in situ, the stalagmite was not fed by dripping. Scanning Electron Microscope (SEM) observations and Electron Microprobe an analyses (EMPA) (quantitative concentrations of Ca^{2+}, Mg^{2+}, Sr^{2+}, Fe^{2+}, Mn^{2+} and Ba^{2+}) were carried out at the National Center of Electron Microscopy (ICTS-CNME) in Madrid. Mineralogical characterization of samples was performed by X-ray diffraction at the Faculty of Geology, UCM, Madrid and, finally, 73 powder samples for stable isotopes were collected along a transversal profile from the core to the surface at increments of 0.25 mm. Powders were then analyzed on a continuous-flow isotope ratio mass spectrometer at the Dep. of Earth Sciences, UoN, Australia. Conventional acid-digestion was carried out by using the analytical protocols outlined in DRYSDALE *et al. (*2009). U/Th dating done by multi-collector ICP-MS at the School of Earth Sciences of the University of Melbourne using the procedure described by HELLSTROM (2003).

3. Results

The stalagmite architecture consists of fabrics composed of diverse mixtures of aragonite and calcite (Fig. 1a). Aragonite fabric forms the outermost part of the speleothem as a continuous rim, plus an internal zone resembling the same shape as the modern tip (Fig. 1b). The crystals are transparent columnar crystals, from 2 to 8 mm long. Calcite has been observed in the core part of the stalagmite as mosaics of two distinct size-groups with aragonite relicts inside (30-50%). The relicts can be observed within the calcite crystals passing from one crystal to the adjacent following the direction of the aragonites at the rim (Fig. 1c). Microcrystalline aragonite is composed by a mesh of crystals of less than 4 µm (Fig. 1d) that occur as patches in the boundary between the aragonite and the secondary calcite. Formation and transformation of the minerals occurred in a sequence: 1. aragonite formation followed by 2. calcite nucleation and partial transformation of the aragonite and 3. microcrystalline aragonite that probably formed soon after that of calcite. These three phases repeat twice along the stalagmite length. Sr^{2+}, Fe^{2+}, Mn^{2+} and Ba^{2+} carbonate values are near zero in all of the mineralogies and textures analyzed (Fig. 2). The amount of Mg^{2+} distinguishes aragonite from calcite: while all aragonite textures have circa 0% mol $MgCO_3$, mean % mol $MgCO_3$ for the large calcite crystals is 0.12, reaching up to 1.07 in the smaller crystals. The stable isotopes analyses (Fig. 2) show that values of $\delta^{13}C$ in the bigger calcites range from -7.95 to -7.59‰ VPDB and for $\delta^{18}O$ from -4.80 to -5.80‰ VSMOW. As the profile approaches the small calcite crystals near the aragonite rim, values in $\delta^{13}C$ decrease to the lightest isotope value of -10.03‰ VPDB whereas $\delta^{18}O$ remains constant. In the aragonite rim, both $\delta^{13}C$ and $\delta^{18}O$ values are heavier than in the calcites, particularly with $\delta^{13}C$, which reaches up to -6.04‰ VPDB. U-series dating was carried out including all the fabrics identified by optical microscopy (Fig. 1e). The results show a reverse dating in point 1, corresponding to secondary calcite mosaic. It shows an age of 76 ± 0.8 ka, older than the aragonite dated in points 2 and 3 that give the very similar ages in stratigraphical order of 49.7 ± 0.3 ka and 49.7 ± 0.6 ka. The calcite mosaic sampled in point 5 shows an age of 47.3 ± 0.2 ka, in stratigraphic order with the rest of the ages.



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	U (µg/g)	$^{230}Th/^{238}U$	$^{234}U/^{238}U$	$^{232}Th/^{238}U$	$^{230}Th/^{232}Th$	Age (ka)	$(^{234}U/^{238}U)_i$
P4	13.526	0.982 (03)	2.676 (05)	0.000003 (01)	331457.8	47.311 (0.2)	2.917 (05)
P3	9.863	1.113 (05)	2.903 (06)	0.000002 (01)	526205.4	49.717 (0.3)	3.190 (06)
P2	14.014	1.041 (11)	2.716 (05)	0.000002 (03)	566773.2	49.797 (0.6)	2.976 (06)
P1	5.477	1.470 (05)	2.736 (07)	0.000042 (01)	34935.4	76.324 (0.8)	3.156 (07)

Figure 1: a) Architecture of the stalagmite. P1 to P4 are the dating points. b) Columnar aragonites. Ppl. c) Calcite mosaic with aragonite relics. Cpl. d) Microcrystalline aragonite between primary aragonite (top) and secondary calcite mosaic (bottom). Ppl. e) U–Th activity ratio and age of 4 points. Numbers in round brackets are fully propagated 95% uncertainties considering long-term reproducibility of powdered std. Age is calculated using equation 1 of HELLSTROM (2006).

4. Discussion

Controlling factors for aragonite precipitation in cave systems are complex, documented to depend on the interaction between pH, Mg/Ca ratio in the parent waters, saturation index (SI), and the drip site characteristics within a single cave (de CHOUDENS-SÁNCHEZ & GONZÁLEZ, 2009; WASSENBURG *et al.,* 2012). In present day Castañar cave, waters are slightly supersaturated for both minerals, SI_{ar} is 0.27 and SI_{cc} is 0.47. Concentration of Mg in the waters is circa 40.0 mg/l, and the Mg/Ca = 0.48-1.0, which is related to long residence in dolomite host rock (SÁNCHEZ-MORAL *et al.,* 2006). The Mg/Ca ratio threshold for aragonite formation is 1.2 (BAJO *et al.,* 2016), which is not reached in Castañar Cave waters. Considering that development of aragonite elongated columnar morphologies has been related to constant drip rates, relatively low super-saturations and Mg/Ca ≥ 0.3 in the dripwaters (FRISIA & BORSATO, 2010), and considering the relatively high growth rates calculated for Castañar aragonite speleothems ~140 mm/ka (MARTÍN-GARCÍA, 2012), it is likely that primary aragonite precipitation in the cave is mainly due to high CO_2

degassing rates, which also generated high growth rates, with the Mg/Ca ratio being a secondary factor.

Observations of thin sections show that the calcite crystals bear large amounts (≤50%) of aragonite relicts, undoubtedly a proof of its secondary origin. SEM observations show rhombohedral microcrystals of calcite growing on the aragonite elongated c face being probably the first stage of transformation. Subsequently these crystals continued growing and engulfed aragonite fibers. FRISIA *et al*. (2002) and similarly WOO & CHOI (2006) described the transformation as induced by the presence of prior calcite crystals among aragonite needles, favoring the nucleation of diagenetic calcite. As the transformation process occurred only in inner parts of the stalagmite nucleation sites are difficult to determine and probably simultaneously at different sites. Fluid must have migrated from the speleothem surface to diagenetic sites through microporosity/permeability of the aragonite crystals. In this scenario, any small change in the physicochemical composition of the fluids that are in the limit between aragonite and calcite, would lead to a change in mineral precipitation. A higher saturation index with respect to calcite, or a lower Mg/Ca ratio could lead to the nucleation of calcites. Data obtained suggests that the transformation can occur without the addition of external waters to the system, thus precipitating calcite from the same fluids from which aragonite precipitated in the first place, after a complex diagenetic evolution. Fluids would precipitate aragonite, which extracts Ca from the system, increasing the Mg/Ca ratio and decreasing the SI_{ar}. In this scenario, theoretically, calcite would be unlikely to precipitate due to the Mg/Ca ratio value, probably above the threshold of aragonite (1.2). However, RODRÍGUEZ-BERRIGUETE *et al*. (2018) showed that in travertines formed from cool meteoric waters with Mg/Ca between 2.0 and 10.0 mol/mol, aragonite precipitates near the spring, at high degassing rates, while calcite starts to form downstream in less turbulent conditions. Analogously, absence of degassing processes in pores this speleothem would trigger precipitation of calcite. Low variation of the large calcite crystals and the aragonite isotopic values supports the idea of both minerals precipitating from the same or very similar solution. Microscopy observations suggest that the small calcite crystals are the last phase to form in the transformation process and their lighter values in $\delta^{13}C$ corroborate the hypothesis of the evolving fluids, as well as their highest Mg^{2+} content inherited from this evolved fluid. In this case, even if cave waters where continuously in an "aragonite mode", the fluids inside the speleothem could have change to "calcite mode", so the transformation could have started in the inner parts at the same time as aragonite was still precipitating on the surface.

Data obtained shows an anomalous age in P1 (Fig. 1a, e) corresponding to the secondary calcite mosaic which shows older ages than expected. Looking at the U concentration, the closest primary aragonite dated point is P2, with 14 µg/g. Comparison of this value with the 5.5 µg/g found in secondary calcites of P1 indicates that there has been U-loss. According to reports, during recrystallization from aragonite to calcite the system behaves as semi-closed or open, with a redistribution of the large uranyl anion, unable to incorporate easily into calcite, with the consequent loss of U yielding false older ages (assuming that Th is immobile and there is no detrital contamination) (ORTEGA *et al*., 2005; LACHNIET *et al*., 2012). Point number 5 corresponds to a calcite mosaic as well, so a similar situation as with that of

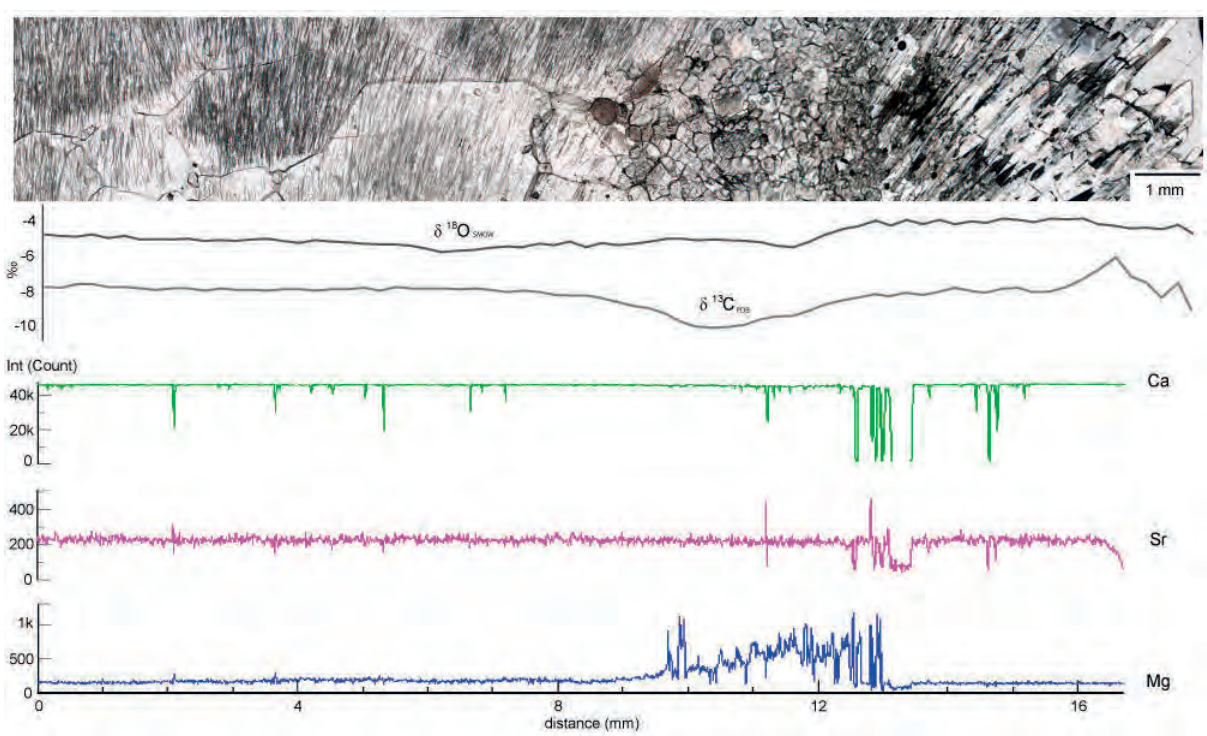

Figure 2: Oxygen and carbon stable isotope records, and Ca, Mg and Sr contents of the stalagmite in a profile perpendicular to the growth axis. Small calcite mosaic presents the lightest $\delta^{13}C$ and the highest contents of Mg.

point 1 would be expected. However, it seems that no U was lost, because the U content of the calcites (13.9 µg/g) is similar to the initial values of aragonite. In this case, during the transformation process the system remained closed, with an inheritance from the precursor mineral as described by DOMÍNGUEZ-VILLAR *et al.,* 2017.

5. Conclusions

The precipitation of aragonite was mainly controlled by CO_2 degassing rates with low discharge rates, indicated by the crystal morphology. The primary aragonite was transformed into calcite in the core, far from the speleothem surface. This implies the presence of a fluid in the pore system of the aragonite columnar crystals. According to the geochemical results, this fluid could have been the same as the aragonite-forming fluid but evolved diagenetically. In this case, it cannot be assured that aragonite and calcite formed under different climate conditions, but differences are due to geochemical evolution of the fluid inside the speleothem.

The sample shows two recrystallized areas yielding the same texture but one has older ages than expected and the other is in stratigraphic agreement with the rest of the ages. According to the U/Th geochemistry, during recrystallization of the first area, the system behaved as open/semi-closed while it remained closed during the transformation of the other area.

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Precipitation of cryogenic calcite, aragonite, and lansfordite in Snežna jama, Slovenia

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Abstract

In Snežna jama, Slovenia (entrance = 1514 m a.s.l.), fine cryogenic cave carbonates (CCC_{fine}) occur associated with the permanent and seasonal ice bodies present near the cave entrance. These deposits consist of detached flakes, 50 to 200 µm in diameter and around 20 µm thick, composed of calcite and smaller amounts of aragonite and lansfordite ($MgCO_3 \bullet 5H_2O$). CryoSEM examinations of CCC_{fine} particles growing on ice have shown spherical mineral precipitates resembling vaterite, indicating that vaterite probably forms as a transitional (precursor) phase of calcite. CCC_{fine} apparently form rapidly in highly ventilated areas by segregation of solutes during freezing of solutions that are rich in calcium and magnesium bicarbonate, or/and by degassing and evaporation processes. We aim to reconstruct the relative influence of all these processes on the genesis and mineralogical evolution of CCC_{fine} by monitoring the cave environmental conditions and performing chemical and petrographic analyses of these actively forming minerals.

1. Introduction

Cryogenic cave carbonates (CCC) are loose mineral accumulations that form by the freezing of water containing dissolved salts on seasonal and permanent ice bodies in caves (ŽÁK *et al.,* 2018). Two main types are differentiated by grain size and formation mechanisms: 1) Coarse cryogenic carbonate (CCC_{coarse}) particles can be up to 40 mm in diameter, and precipitate slowly under closed-system conditions by the progressive freezing of water pools in iced caves. They are important paleoclimatic indicators because their presence in currently ice-free caves provides a clear indication of former permafrost conditions (LUETSCHER *et al.* 2013); 2) Fine cryogenic carbonate (CCC_{fine}) particles are usually smaller than 1 mm and form by fast freezing of thin films of water, evaporation and CO_2 degassing in highly ventilated areas near cave entrances. They display a wide variety of calcite crystal habits including pseudomorphs of previous metastable phases such as ikaite or vaterite (LACELLE *et al.,* 2009; ŽÁK *et al.*, 2018). Thus, CCC_{fine}, which actively forms during winter in many high-altitude caves, offers an opportunity to study early formation and transformation of carbonates in natural environments.

In Snežna jama, Slovenia, CCC_{fine} are precipitating *in situ* on the surface of ice stalagmites, stalactites, and an ice lake near the cave entrance. To decipher their mode of formation we have monitored the environmental conditions prevailing in the iced part of the cave and performed geochemical and petrographic analysis of samples collected and examined under both cryogenic and room temperature conditions.

2. Material and methods

Snežna jama is a 1600 m long cave located at 1514 m a.s.l. in the Kamnik- Savinja Alps, Slovenia. Developed in Triassic limestone and dolostone, it consists of a nearly horizontal main passage, cut by several vadose vertical shafts (ZUPAN-HAJNA *et al.,* 2008) In winter, a strong cold air current is established between the entrance and the first shaft (150 m from the cave entrance). In this area there is a permanent frozen lake (25 m long, 15 m wide, and up to 10 m deep) formed by accumulation of snow, frozen vadose inflow from a small chimney and the cold conditions provided by the winter airflow (MIHEVC 2018).

Ice stalactites, stalagmites and columns form every winter along the entrance passage until the first shaft, and also in a higher perpendicular chamber that was discovered after the level of the ice lake dropped in the last few years. Frost activity in these areas has also caused severe damage on flowstone and host rock and cryoturbation of the sediments. CCC_{fine} occur as very thin coatings on the surface of ice stalagmites (Fig. 1) along the traces left by dripping water. In the warmer season, when ice stalagmites disappear, these carbonate coatings accumulate as fine powders on the cave floor. On the ice lake, CCC_{fine} form milky layers that can be entrapped under new ice, or transported and accumulated in small ponds when the ice melts. Floor powder accumulations were sampled during the summer, while in winter, chips of ice with CCC_{fine} were collected with a scalpel and transported to the lab in frozen state.

Mineral composition of CCC_{fine} powders was analyzed by X-ray diffraction using a Bruker D2 PHASER diffractometer at the Karst Research Institute ZRC SAZU. $\delta^{13}C$ and $\delta^{18}O$ stable isotope ratios were analyzed at Universidad Autónoma de Madrid using a ThermoFisher Scientific Gasbench II connected to a Thermo Delta V Advantage isotope ratio mass spectrometer in continuous flow mode.

Samples were examined with a JEOL JSM-IT100 Scanning Electron Microscope (SEM) equipped with an Energy Dispersive X-ray Spectroscopy (EDS) detector (ZRC SAZU). Ice chips with CCC_{fine} were mounted on specially adapted

SEM holders previously cooled in liquid nitrogen and examined under a SEM using in-chamber low-vacuum sublimation of ice fragments. Observations of frozen samples were carried out in backscattered electron mode (BES) under low vacuum (40 Pa) at an accelerating voltage of 15 kV and a working distance of 10 mm. Dry powders were gold coated and analyzed under high vacuum in secondary electron mode (SED) at 10 to 15 kV and a working distance of 10 mm.

Cave air temperature and humidity were continuously recorded by Lascar data loggers installed at the ice lake and in the higher chamber (2019 onward). Cave air CO_2 concentrations were measured seasonally using a handheld Vaisala GM70 meter with a GMP222 probe (measuring range 0–10,000 ppm). A Kestrel 5500 weather meter was used to measure the speed of air currents entering the cave during winter.

3. Results

At the higher chamber, temperature oscillates between −4°C and 0.5°C and the average annual temperature is −0.2°C. Temperature at the ice lake is much more variable because it is directly influenced by air currents in the cave. The average temperature there is −0.8°C, with summer temperatures up to +2°C and minimum values down to −9°C occurring between January and March. Humidity is very stable and near saturation during summer, but decreases significantly when temperatures drop, to values down to 76%. In January 2020, we measured the wind speed at the passage connecting the entrance shaft with the ice lake chamber, which reached a maximum value of 2.4 m/s. The lowest air CO_2 concentration measured was 330 ppm in January 2019 and the maximum 610 ppm in July 2021.

Figure 1: Ice stalagmites on the floor of Snežna jama. Arrow indicates accumulations of CCC_{fine} on the ice surface.

Fine cryogenic carbonates occur as detached flaky particles that form thin whitish crusts on the ice surface (Fig. 1). Flakes are 50 to 200 µm in diameter and around 20 µm thick, similar in morphology to cave rafts. They have a flat outer side and drusy crystals on the inner side, often showing rosette morphologies. According to XRD analysis, the collected powders are mainly composed of calcite with smaller amounts of aragonite. One sample also contained significant amount of lansfordite, a hydrated magnesium carbonate ($MgCO_3 \bullet 5H_2O$) (Fig. 2). Other minerals present in very small amounts are dolomite and quartz.

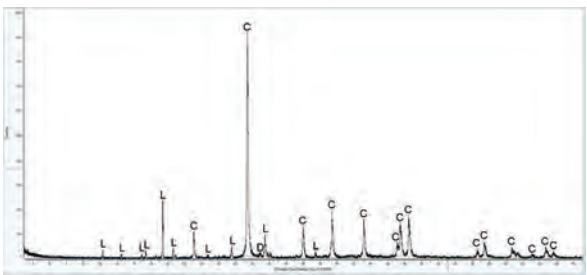

Figure 2: Diffractogram of a CCC_{fine} sample containing calcite and lansfordite, and possible traces of dolomite.

The drusy sides of the carbonate flakes display a wide variety of crystal habits under SEM (Fig. 3). The most common are rhombohedra, from relatively simple single crystals to complex morphologies consisting of stacked rhombohedra interpreted as calcite (Fig.3A, B). Occasionally, CCC_{fine} particles are formed by needle-like crystals (Fig. 3C), which show comparatively less Mg than the rhombohedral ones, and probably correspond to aragonite. Lansfordite crystals are tabular or hexagonal and have desiccation cracks (Fig. 3D). Frozen CCC_{fine} samples observed in situ on ice consisted of small smooth spheres, 1-5 µm in diameter, resembling vaterite, a metastable $CaCO_3$ polymorph (Fig. 3E). Samples obtained after melting and drying in the lab showed similar spheroidal $CaCO_3$ crystals of different sizes coexisting with euhedral rhombohedral calcite (Fig. 3F).

$\delta^{13}C$ and $\delta^{18}O$ isotopic analyses were performed only in samples collected during the summer. Preliminary data show values typical of CCC fine (ŽÁK *et al.,* 2018), with positive $\delta^{13}C$ values (from 0.34‰ to 6.81‰ VPDB) that show higher variability than the $\delta^{18}O$ (from −4.34‰ to −6.24‰ VPDB) (Fig. 4).

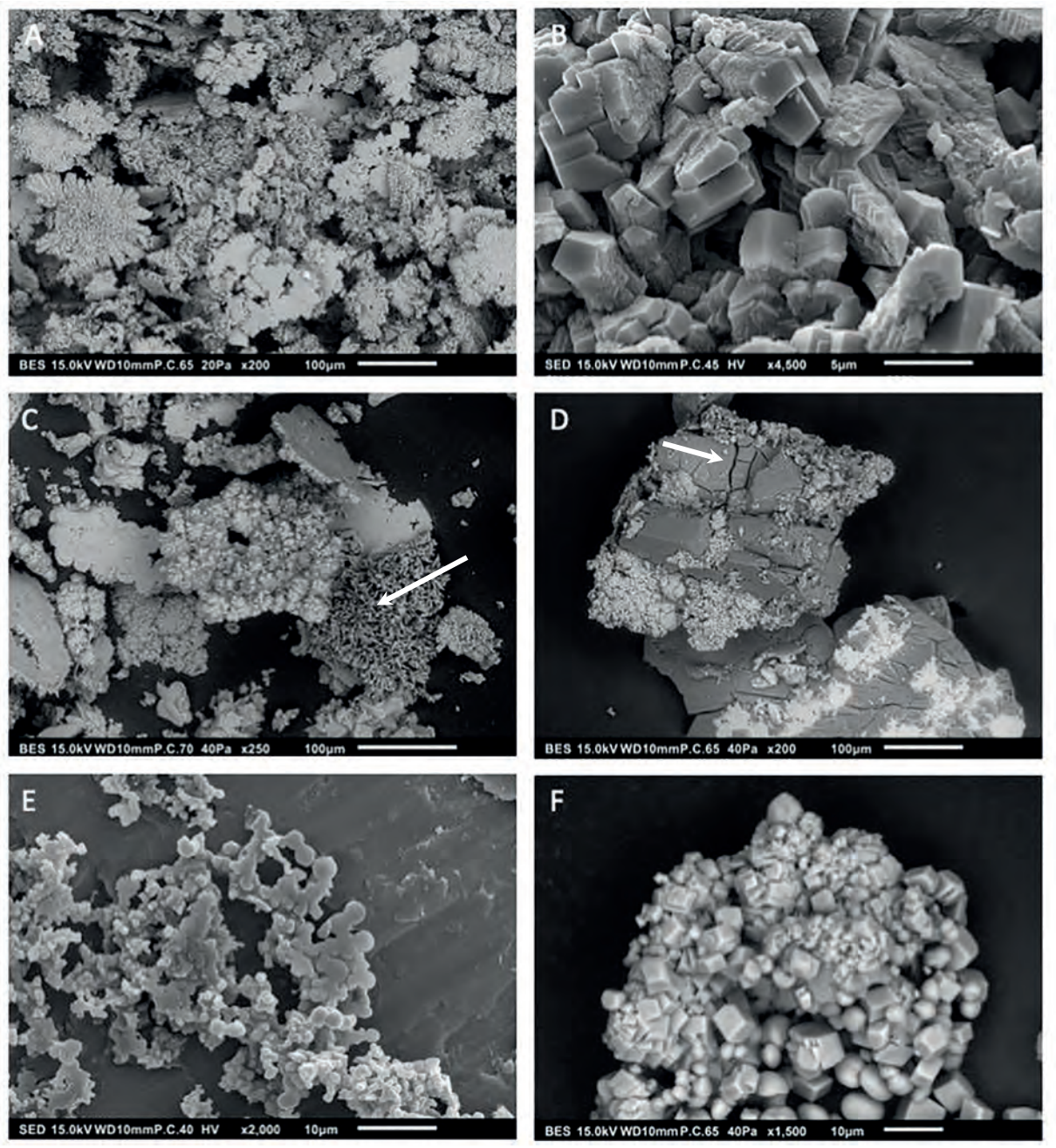

Figure 3: Different crystal habits of CCC_{fine} observed under SEM. A: Aggregate of CCC_{fine} particles showing a typical raft morphology, with one side flat. Backscattered electron (shadow) imaging mode (BES). B: Rhombohedral calcite crystals Secondary electron mode (SED). C: Flakes of CCC_{fine} of different morphology. The arrow indicates needle-like crystals that probably correspond to aragonite (BES). D: particle formed by lansfordite (darker grey) and $CaCO_3$ (lighter grey) crystals. Arrow is showing desiccation cracks in the lansfordite crystal (BES). E: Spheroidal $CaCO_3$ crystals resembling vaterite from a sample of CCC_{fine} examined under a SEM using in-chamber low-vacuum sublimation of ice fragments. The sample was later gold-coated and observed in high vacuum to obtain this image (SED). F: Spheroidal $CaCO_3$ crystals coexisting with very euhedral rhombohedral calcite in a sample of cave ice that was observed at room temperature, after melting and drying in the lab (BES).

4. Discussion and future work

The environmental conditions near the entrance of Snežna jama, with temperatures around or below 0°C all year round, are suitable for the formation of ice and therefore, in the presence of mineralised waters, of cryogenic carbonates. Typically, CCC_{fine} form by segregation of solutes during freezing, but other processes such as CO_2 degassing and evaporation caused by the strong air currents can contribute considerably to mineral precipitation.

The occurrence of aragonite and lansfordite, in addition to the more common calcite, is probably caused by the presence of Mg^{2+} in the water, due to dissolution of the dolostone host rock. Formation of these minerals may be related to a sequential precipitation from waters enriched in Mg due to the prior precipitation of calcite, which would preferentially remove Ca from solution. BAZAROVA *et al.* (2016) explained the formation of lansfordite by a similar mechanism, where the removal of Ca by prior precipitation of ikaite provided favorable conditions for the crystallization of magnesium minerals. Different Mg/Ca ratios in the dripping waters caused by heterogeneities in the host rock could also control the formation of aragonite and lansfordite in specific areas of the cave.

CryoSEM observations of spheres resembling vaterite in frozen samples and coexistence of these spheres with small rhombohedral crystals in lab-melted samples suggests that the studied CCC_{fine} initially precipitate as the metastable $CaCO_3$ vaterite and then rapidly transform into calcite in the presence of liquid water, as previously interpreted by LACELLE *et al*. (2009), who also performed SEM of CCC under cryogenic conditions. These findings demonstrate the complexity of processes affecting the mineralogy and chemistry of carbonates in cold cave environments, where the primary features can be strongly affected by early post-depositional mineral transformations.

The isotopic composition of CCC_{fine} in Snežna jama shows a wide range of $\delta^{13}C$ values, which probably reflects variable influence of freezing versus CO_2 degassing processes in the precipitation of the CCC. However, because all the samples analyzed here were collected in summer, variability could also represent different extent of diagenetic processes.

In the future, we will perform detailed analyses of *in situ* CCC_{fine} forming in different parts of the cave and in different seasons to unravel the relative influence of all the identified processes in the genesis of CCC_{fine}. In this way, CCC_{fine} could be used as a tool to identify former changes that took place at the entrance of iced caves, such as a complete sealing of the cave entrance by snow, which would preclude the formation of strong air currents that cause CO_2 degassing.

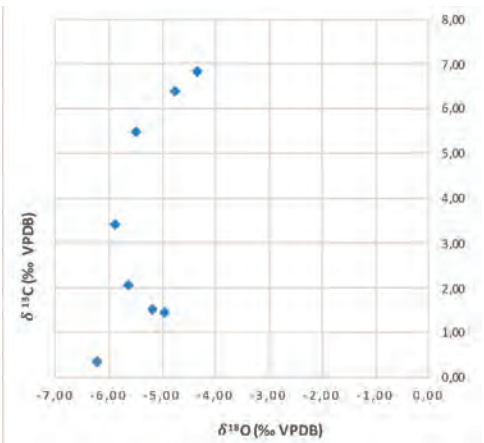

Figure 4: Stable carbon and oxygen isotope ratios of CCC_{fine} from Snežna jama

Acknowledgments

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Potential cosmogenic $^{10}Be/^{36}Cl$ dating of fossil guano deposits

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Abstract

Recently, there has been renewed interest in sub-fossil bat guano deposits as paleo-archives and repositories. Effective protocols for radiocarbon dating guano samples < 50 ka in age have been developed. However, many subfossil guano deposits of archeological and paleoecological interest exceed the radiocarbon age limit, and no alternative radiometric dating options are currently available. Clastic cave sediments have effectively been dated using the age-dependent changes in relative concentrations of cosmogenically-derived isotopes ^{10}Be and ^{26}Al, but this technique is geochemically unsuited to guano. Here, we test the potential of a novel method for guano: coupled ^{10}Be and ^{36}Cl. Preliminary results demonstrate that measurable quantities of these isotopes are bound to the chitin matrix of ancient insectivorous guano, are immobile in the stratigraphic column, and that the ratio of these isotopes shifts with time over deca-millenial timescales. We further demonstrate appropriate change in isotopic ratio in a small number of independently dated guanos. The half-lives of $3.01 \pm 0.02 \times 10^5$ years for ^{36}Cl and $1.387 \pm 0.012 \times 10^6$ years for ^{10}Be imply a change in ratio of ~25% over 125,000 years, opening the possibility of dating fossil guanos well beyond the radiocarbon limit.

Résumé

L'utilisation des cosmogènes $^{10}Be/^{36}Cl$ pour dater les guanos fossiles. On a redécouvert récemment l'intérêt des dépôts de guanos de chauves-souris comme archives environnementales. Des protocoles ont été développés pour des datations radiocarbones d'échantillons de guanos jusqu'à 50.000 ans. Or certains dépôts de guanos subfossiles qui présentent un intérêt archéologique et paléoclimatique dépassent cet âge limite et aucune alternative radiométrique n'est actuellement disponible. Des sédiments clastiques prélevés dans les grottes ont été datés en se fondant sur l'évolution des concentrations d'isotopes dérivés des cosmogènes ^{10}Be et ^{26}Al, mais cette technique n'est pas adaptée à la géochimie du guano. Ici, nous testons la possibilité d'une nouvelle méthode couplant ^{10}Be et ^{36}Cl.Les premiers résultats montrent que les quantités mesurables de ces isotopes sont contenues dans la chitine des insectes échantillonnée dans les guanos ; et qu'elles conservent la même place dans la colonne stratigraphique. La demi-vie du ^{36}Cl étant de $3{,}01 \pm 0{,}02 \times 10^5$ ans et celle du ^{10}Be de $1{,}387 \pm 0{,}012 \times 10^6$ ans, cela implique un changement dans le rapport d'environ 25 % pour 125.000 ans, ce qui ouvre la possibilité de dater des guanos fossiles au-delà de la limite des méthodes radiocarbone.

1. Introduction

In the past few years, there has been renewed interest in ancient bat (and, in SE Asia, cave-dwelling swiftlet – *Collocallia sp.*) guano deposits as paleo-archives and repositories (CLEARY & ONAC, 2020). These deposits can be as much as 10 m in thickness, and under suitable environmental conditions may preserve intact insect chitin for tens of thousands of years (WURSTER *et al.,* 2010). Exhaustive work by WURSTER *et al.* (2009) has now established effective protocols for radiocarbon dating guano samples < 50 ka in age. However, many subfossil guano deposits of archeological and paleoecological interest exceed the radiocarbon finite-age limit, and no alternative radiometric dating options in this age range are currently available. Clastic cave sediments have effectively been dated using the age-dependent changes in relative concentrations of cosmogenically-derived isotopes ^{10}Be and ^{26}Al but this technique is geochemically unsuited to guano. JOHNSTON *et al*. (2010) report on coupled ^{14}C and ^{36}Cl analyses of a Holocene guano, but encountered difficulties with the latter, apparently because they used bulk guano samples in which most of the chlorine was likely to have derived from percolating fluids. Here, we present exploratory data on the use of coupled ^{10}Be and ^{36}Cl cosmogenically-derived isotope ratios with the potential for absolute dating of ancient bat and swiftlet guano deposits considerably beyond the range of carbon dating.

Cosmogenic ^{10}Be (created in Earth's atmosphere by high energy cosmic particles, rained out, and incorporated into surface materials) is typically present in organic matter at concentrations of 10^6-10^{10} atoms ^{10}Be/g organic matter (WILLENBRING & BLANCKENBURG, 2010) Our own ICPMS measurements of total Be in bat guanos have yielded values in the range of 0.1-0.8 ppm, which translates to 10^6-10^7 atoms ^{10}Be/g guano. Total chlorine levels in fossil and subfossil bat guanos are quite high. JOHNSTON *et al.* (2010) report total chlorine concentrations of 4000-5000 ppm, and ^{36}Cl values of 1.7- 4.7 x 10^{11} atoms/g in Holocene fossil bat guano from Romania. However, only a small, but still

significant, amount of Cl is matrix-bound and resists the acid and alkali washes that remove mobile Cl.

Since the zero-age concentration of both ^{10}Be and ^{36}Cl would be unknown in an ancient guano accumulation, we have used the age-dependent change in relative concentrations of these isotopes. Since bats and swiftlets of the same species often frequent the same locations today, we can use modern guano samples to establish a zero age isotope ratio for these accumulations. Correlation with Late Pleistocene ^{14}C-dated guano from the site can be used to establish the validity of the technique

Half-lives of 3.01 ± 0.02 x 10^5 years for ^{36}Cl and 1.39 ± 0.01 x 10^6 years for ^{10}Be (KORSCHINEK *et al.,* 2010) imply a potential change in ratio of ~25% over 125,000 years.

Figure 1: Sequence of old guano deposits in Niah Great Cave, Sarawak, Borneo

2. Materials and methods

Guano samples were collected from Niah Cave, Niah Cave National Park, Sarawak, Malaysia (Fig. 1), under permit from the Forestry Department (99.JHS.NCCD.600-7.2.107). Samples were analyzed for ^{10}Be and ^{36}Cl at the Rare Isotope Measurement Laboratory, Purdue University, Indiana. Accelerator mass spectrometer radiocarbon analyses were performed by Beta Analytic, Miami, Florida.

Samples were pretreated with acid, alkali, and chloroform/methanol washes as per WURSTER (2009). Splits were prepared for ^{14}C (1 gram) and ^{10}Be and ^{36}Cl. For Be and Cl analysis, paired 6-gram splits were ashed at 900° C and dissolved in sulfuric/nitric and hydrofluoric acids in Teflon crucibles. After addition of a stable Cl isotope spike, Be and Cl were selectively precipitated with a Be carrier and barium nitrate. Final separation of chlorine from sulfate was by ion exchange chromatography.

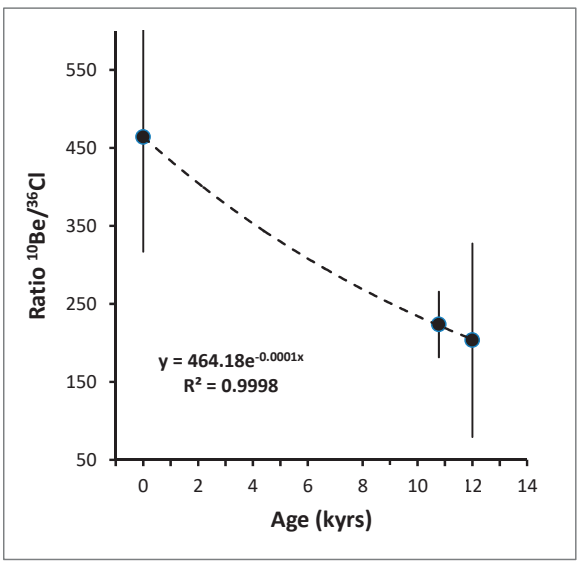

Figure 2: Change in ratio of $^{10}Be/B_{total}$ and $^{36}Cl/Cl_{total}$ over time.

3. Results

Isotopic measurements are shown in Table (Fig. 3), and the plot of $^{10}Be/B_{total}$ and $^{36}Cl/Cl_{total}$ against time (Fig. 2) shows an excellent correlation.

Age	$^{36}Cl/Cl_{total}$	$^{10}Be/B_{total}$	$^{10}Be:Be/^{36}Cl:Cl$
0	5.54E-15	2.57E-12	463.90
10780	2.65E-15	5.92E-13	223.40
12000	1.64E-15	3.34E-13	203.23

Figure 3: ^{14}C ages and isotopic ratios.

4. Discussion and Conclusion

This proof-of-principle analysis has demonstrated that measurable quantities of chitin-bound ^{10}Be and ^{36}Cl can be recovered from ancient guano deposits. Furthermore, the change in isotope ratio with time is highly correlated with known age derived from accelerator mass spectrometry radiocarbon dating over at least 12,000 years. Further analyses will be required to demonstrate the relationship out to the radiocarbon finite-age limit of ~45 ka. Currently, nothing is known about the retention or selective leaching of ^{10}Be and ^{36}Cl from ancient bat guanos. However, in dry guano accumulations, the original structure of the chitin fragments is retained over the full span of the ^{14}C timescale. Thus, there is reason to suppose that an intact, matrix-bound ^{10}Be and ^{36}Cl record may be retained. If this is the case, then, by combining a radiometrically dated sequence with established techniques of recovering environmental ^{13}C records from bat guanos (c.f. WURSTER *et al.*, 2008; 2010; CLEARY & ONAC, 2020), there is a potential, using this novel dating method of coupled ^{10}Be and ^{36}Cl, to examine environmental histories beyond the radiocarbon dating limit.

Acknowledgments

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Reconstructing the isotopic composition ($\delta^{18}O$ and δD) of paleo-aquifer water from gypsum crystals of the Giant Geode of Pulpí (SE Spain)

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Abstract

The Giant Geode of Pulpí (Almería, SE Spain) hosts the largest (up to 2 m in length) subaqueous crystals of selenite gypsum ($CaSO_4 \cdot 2H_2O$) discovered in Europe. We investigate the stable isotopes of hydration water in gypsum from the Sierra del Aguilón, where the Geode is located, to reconstruct the $\delta^{18}O$ and δD of the paleo-aquifer. In a $\delta^{18}O/\delta D$ plot, most results are aligned with the Local Meteoric Water Line, suggesting that the original solution consisted of meteoric water that recharged the aquifer during the period of subaqueous formation of the crystals, while the contributions of other water sources (e.g. sea water) were insignificant. The isotopic variability observed between gypsum from different locations in the Sierra del Aguilón is probably related to changes in the isotopic composition of the paleo-aquifer. This variability resulted from fluctuations in the $\delta^{18}O$ and δD of rainwater in this region, in response to climatic oscillations that were recorded eventually by the hydration water of gypsum. Our study suggests that gypsum hydration water in subaqueous selenite records the isotopic composition of the aquifer in which the crystals formed and can be used as a paleoclimatic proxy.

1. Introduction

The Giant Geode of Pulpí (Pulpí, Almería, SE Spain) is one of the few examples of a cavity which surfaces are completely covered with large euhedral selenite crystals ($CaSO_4 \cdot 2H_2O$) (CALAFORRA et al., 2001; GARCÍA-GUINEA et al., 2002). The Geode was discovered in 1999 within the Mina Rica of Pulpí by mineral collectors and due to its spectacular characteristics has become an important touristic and scientific attraction.

Figure 1: Gypsum crystals of the Giant Geod of Puplí (A and C) and location of the Mina Rica mine(B); Photos: Victor Ferrer.

At current, the Giant Geode of Pulpí is the only gypsum geode open to the public globally. During the last 20 years, the Geode has been subject to several studies directed to evaluate the impact of visitors on its microclimate and the potential degradation of its fragile gypsum crystals (FERNÁNDEZ-CORTÉS, 2005). Up to date, some investigations have addressed the mechanisms that led to the formation of these massive selenite crystals, which are up to 2 m long (CALAFORRA et al., 2001; GARCÍA-GUINEA et al., 2002; CANALS et al., 2019).

Most investigations on gypsum speleothems elsewhere have focussed on their formation mechanisms (CALAFORRA & FORTI, 1994; GARCÍA-GUINEA et al., 2002; BERNABEI et al., 2007, amongst others). More recently, subaerial gypsum speleothems have been proposed as paleoclimatic archives (CALAFORRA et al., 2008; GÁZQUEZ et al., 2011; GÁZQUEZ et al., 2017a) and stable isotopes in gypsum hydration water as a new proxy for paleoclimate research (GÁZQUEZ et al., 2020).

In this study, we investigate the potential of stable isotopes ($\delta^{18}O$ and δD) of gypsum hydration water in subaqueous selenite to reconstruct the isotopic composition of the groundwater from which it crystallized. Specifically, we evaluate the possible usage of the stable isotopes of gypsum from the mining district of Mina Rica, where the Giant Geode is located, for future paleoclimate reconstructions.

2. Geological setting

The Geode of Pulpí is located within the abandoned mine 'Mina Rica' of Pilar de Jaravía (Pulpí, Almería) (Fig.1), in the Alpujárride complex at the eastern part of the Betic mountain Range. The cavity was discovered inside an old Ag-Pb-Fe mine is 10.7 m^3 in volume, 8 m long, 1.8 m wide and 1.7 m high (FERNÁNDEZ-CORTÉS, 2005) and lays at the depth of 97 m a.s.l in the Triassic dolomites of the Sierra del Aguilón (CALAFORRA et al., 2001). Miocene volcanic events generated sulfide ores that derived later in oxy-hydroxide and sulfate mineralizations. The mineralization sequence from the host rock to the geode core comprises dolomite-siderite-Fe-Mn oxy-hydroxides-celestine and eventually gypsum (GARCÍA-GUINEA et al., 2002). Silver, lead and iron were extracted from the Mina Rica mine during the first part of the XXth century. In addition to the giant gypsum crystals, the mine hosts numerous minerals that include pyrite, galena, chalcopyrite, epsomite, siderite and celestine, among others.

3. Materials and methods

Forty gypsum samples from the Mina Rica mine and from its surroundings were investigated for stable isotopes of gypsum hydration water. The samples were collected at different heights ranging from 156 to 196 m a.s.l. outside of the mine and from 93 to 128 m a.s.l. inside the mine.

The isotopic analyses of gypsum hydration water were conducted at University of Almería using a Heat Induction Module (IM-CRDS, Picarro©) coupled to a Cavity Ringdown Spectrometer (CRDS, Picarro© L2140i). The $\delta^{18}O$ and δD values of the water vapor released after heating the powdered samples to 250ºC were standardized to the Vienna Standard Mean Ocean Water (V-SMOW). Calibration was conducted by analysing four gypsum standards, which were previously calibrated against liquid water using the cryogenic extraction method by GÁZQUEZ *et al*. (2015). Each sample was analyzed 3-4 times and precision (1SD) was better than 0.1‰ for $\delta^{18}O$ and 0.6‰ for δD. The isotopic composition of the gypsum mother water was calculated by using the isotope fractionation factor at 25ºC (1.0034 for $\alpha^{18}O_{gypsum\text{-}water}$ and 0.981 for $\alpha D_{gypsum\text{-}water}$; GÁZQUEZ *et al.,* 2017b). These fractionation factors, specially $\alpha^{18}O_{gypsum\text{-}water}$, are very insensitive to temperature.

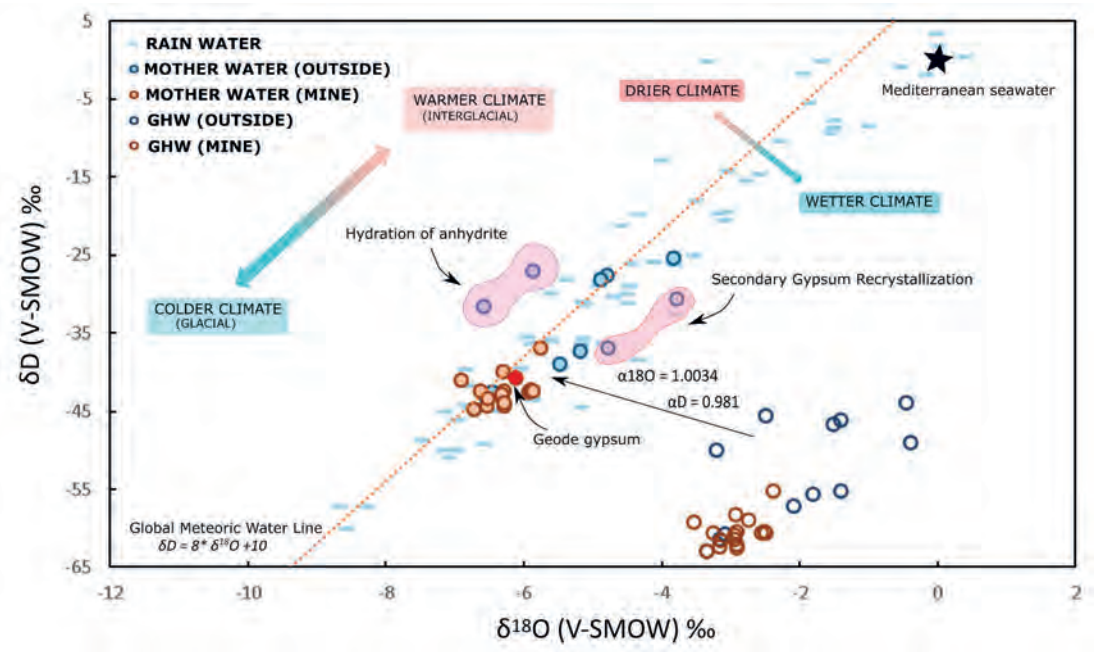

Figure 2: $\delta^{18}O$ and δD of gypsum hydration water (GHW) and calculated paleo-aquifer water (mother water) in Sierra del Aguilón at the time of gypsum formation. $\delta^{18}O$ and δD of paleo-aquifer water were obtained by applying known isotope fractionation factors which are almost insensitive to temperature ($\alpha^{18}O_{gypsum\text{-}water}$ =1.0034 and $\alpha^{18}D_{gypsum\text{-}water}$=0.981)(GÁZQUEZ et al. 2017a). Climatic parameters could affect the isotopic composition of infiltration water to the aquifer of Sierra del Aguilón during the gypsum formation, including changes in atmospheric temperature and humidity.

4. Results

Considering the entire dataset, the $\delta^{18}O_{gypsum}$ values of gypsum hydration water ranged from -0,4 to -3,5‰ and δD_{gypsum} did from -34,5 to -62,9‰. After applying the isotope fractionation factors, we found that the $\delta^{18}O$ values of the original water (hereafter $\delta^{18}O_{aquifer}$) from which gypsum precipitated ranged from -3,9 to -6,9‰ and was between -22,4 and -62,1‰ for δD (hereafter $\delta D_{aquifer}$).

The isotopic composition of the gypsum hydration water of samples from the mine surroundings ranged from -0,4 to -3,3‰ (-2,0 ± 0,2‰) for $\delta^{18}O_{gypsum}$ and from -45,6 to -62,9‰ (-52,8 ± 0,7‰) for δD_{gypsum}; then, the $\delta^{18}O_{aquifer}$ and $\delta D_{aquifer}$ of the original water ranged from -3,9 to -6-6‰ (-5,4± 0,2‰) and from -25,4 to -44,7‰ (-34,5± 0,7‰) respectively. The d-

excess values of the formation water ranged from -0.4 to 21.1‰ (8,8 ± 0.6‰).

The $\delta^{18}O_{gypsum}$ values of the samples from inside the mine ranged from -2.4 to -3.5‰ (-2.9 ± 0.1‰) and from -55.2 to -62.1‰ (-60.5±0.5‰) for δD_{gypsum}; then, the $\delta^{18}O_{aquifer}$ ranged from -5.8 to -6.9‰ (-6.5±0.1‰) and $\delta D_{aquifer}$ did from -36.9 to -44.8‰ (-4.,3 ± 0.5‰). The d-excess values of the paleo-aquifer range from 4.6 to 14.3‰ (8.1 ±0.6‰). In particular, the sample, taken from the Giant Geode, crystallized from a solution with a $\delta^{18}O_{aquifer}$ of -6.1‰, $\delta D_{aquifer}$ of -40.7‰ and a d-excess of 8.3‰.

The d-excess values of original solutions reconstructed from the outside samples can be clustered into three groups (Figure 2): samples with relatively low d-excess values (n=2; -0.4‰ and 1.3‰); samples with relatively high d-excess values (n=2; 19.9 and 21.1‰) and the rest of the samples that show d-excess values ranging from 4.2 to 11.0‰ (n=36, 7.2 ± 0.6‰).

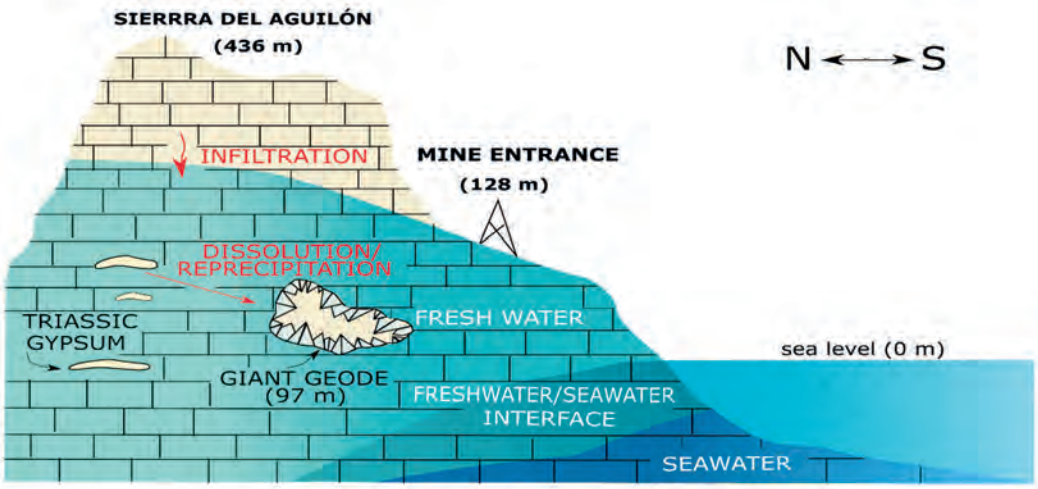

Figure 3: Genetic model proposed for the Giant Geode of Pulpí. The sea level was placed below the goede level and the water source from which the gypsum crystals formed was meteoric water that infiltrated into the quifer. Dissolution of Triassic gypsum, together with oxidation of polymetallic oxides was the main source of sulfate to the solution. noted that the scale is exaggerated for a better display.

5. Discussion

In the present study we reconstruct the isotopic composition of the paleo-aquifer of Sierra del Aguilón, where the Giant Geode of Pulpí is hosted, using stable isotopes of gypsum hydration water. We compared our results with modern stable isotopes of modern rainwater in the region (GÁZQUEZ et al., 2017a). Previous studies on sulfur and oxygen isotopes in gypsum sulfate indicated that dissolution of Triassic gypsum hosted in the Sierra del Aguilón formation is the most likely source of sulfate for the precipitation of selenite (GARCÍA-GUINEA et al., 2002; CANALS et al., 2019). These investigations also suggested that the aquifer hosted relatively cold (20-25°C) and low salinity water during the formation of the Giant Geode.

As observed in Fig. 2, the $\delta^{18}O_{aquifer}$ and $\delta D_{aquifer}$ data pairs are aligned with the modern rainwater values in this region. This suggests that seawater (with $\delta^{18}O$~ 0‰ and δD~0‰) or water from deeper magmatic/metamorphic processes (usually with higher $\delta^{18}O$) did not contribute significantly to the solution from which gypsum formed. In contrast, most gypsum crystals recorded the isotopic composition of the meteoric water that recharged the paleo-aquifer of Sierra del Aguilón at the time of mineral precipitation. Indirectly, these results indicate that when the Geode formed, the sea level was at a similar or a lower position than at present (Fig. 3). Otherwise, seawater would have influenced the solution by increasing salinity and isotopic values, which is not seen in our results. The possible presence of thermal water at deeper levels did not significantly influence the precipitation of gypsum, but it did control previous stages of barite, celestine and Fe oxides precipitation (CANALS et al., 2019).

Importantly, some of the samples (n=4) collected from outside the mine are significantly distanced from the meteoric water line. This can be attributed to several processes during the formation of gypsum. The lower d-excess values of the mother water (i.e. -0.4 and 1.3‰) correspond to crusts composed of microcrystalline gypsum taken from outside and probably formed as a result of gypsum recrystallization from evaporated water in subaerial conditions. Evaporated waters generally show higher $\delta^{18}O$ and δD values and lower d-excess than non-evaporated waters and fall on a line with a slope less than 8. Precipitation of secondary gypsum probably occurred in recent times, when materials were exposed to weathering because of the mining activity. The higher d-excess values of the mother water (19.9 and 21.1‰) are much higher than the mean of modern meteoric waters in this region (~10‰) and correspond with samples taken from cracks of the carbonate host rock. These results probably indicate that these microcrystalline gypsum veins formed as a result of hydration of anhydrite. This process generally results in gypsum hydration water with higher d-excess values (CHEN *et al.*, 2016) that could have occurred in the Sierra del Aguilón during some periods.

The isotopic variability observed between the distinct groups of samples from Mina Rica can be attributed to changes in the aquifer isotopic composition during the different phases of gypsum precipitation in Sierra del Aguilón. These changes were most likely controlled by fluctuations in the isotopic composition of rainwater in this region as a result of long-term variations in atmospheric temperature and relative humidity.

Although the ages of the Mina Rica gypsum deposits are still unknown, we hypothesize that the range of isotopic compositions observed could be explained by variations in the isotopic composition of rainwater between glacial and interglacial periods. Lower $\delta^{18}O$ and δD values, like those observed in samples taken at lower elevations (inside the mine), are expected during glacial (colder) periods, while higher isotopic values of the aquifer, as recorded by the samples from higher elevations (outside the mine) would reflect infiltration of rainwater during interglacial (warmer) period. Therefore, we suggest that the hydrochemical conditions of the paleo-aquifer may not have been the same at different times of gypsum precipitation.

6. Conclusions

The $\delta^{18}O$ and δD analyses of gypsum hydration water of samples from Mina Rica show that the massive gypsum crystals of the Giant Geode of Pulpí precipitated from meteoric water that infiltrated in the aquifer of Sierra del Aguilón at the time of gypsum precipitation. Thus, the Geode formed within the freshwater lens of the coastal aquifer of Sierra del Aguilón. These results rule out previous hypotheses that considered the contribution of marine or magmatic waters. Likely, gypsum crystals of distinct ages formed from waters with significantly different isotopic compositions. We conclude that selenite gypsum crystals of Mina Rica registered changes in the isotopic composition of the groundwater, with potential paleoclimatic implications.

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Techniques de carottages sur calcite souterraine. Enjeux et méthodes.

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Résumé

Le développement de techniques analytiques permettant d'étudier des échantillons de calcite souterraine (datations U/Th, U/Pb, analyses chimiques et isotopiques, morphoscopie…) amène à multiplier les prélèvements d'échantillons sous terre. Cependant le souci de conservation du milieu souterrain, les enjeux d'un impact paysager limité, la nécessité d'une documentation efficace du prélèvement sont autant d'éléments qui militent pour le développement de techniques de carottage adaptées. Ces techniques, présentées ici, couvrent trois types d'échantillonnage : (i) diamètre 4 à 10 mm, longueur 65/80 mm adapté aux bases de stalagmites ; (ii) diamètre 28 à 32 mm, longueur 30 cm à 1 m adapté aux petits planchers et bases de stalagmites ; (iii) diamètre 80 à 112 mm, longueur 0,3 à 2 m adapté aux planchers et coulées stalagmitiques. Un groupe d'études techniques du réseau de métiers CNRS « Milieux Souterrains et Karsts » propose ici une synthèse des retours d'expérience et de tests menés sur le terrain. Les contraintes du carottage (grotte protégée), d'accessibilité au site (karst profond), d'extraction (conditionnement) en fonction du type d'échantillonnage et de leur documentation sont discutées. L'objectif final est de proposer un guide méthodologique adapté aux différents enjeux et situations rencontrées sous terre.

Abstract

Core drilling techniques on subterranean calcite. Issues and methods. Several analytical techniques are available to study underground calcite samples (U/Th, U/Pb dating, chemical and isotopic analyses, morphoscopy...). This leads to an increase of the number of samples taken from the caves. However, the conservation of the underground environment, a limited landscape impact and efficient documentation of the sampling are all elements that militate in favour of the development of adapted coring techniques. These techniques, presented here, cover three types of sampling: (i) diameter 4 to 10 mm, length 65/80 mm adapted to stalagmite bases; (ii) diameter 28 to 32 mm, length 0.3 to 1 m adapted to small floors and stalagmite bases; (iii) diameter 80 to 112 mm, length 0.3 to 2 m adapted to stalagmite floors and flowstones. A technical study group of the CNRS "*Milieux Souterrains et Karsts*" trade network offers here a synthesis of feedback and tests carried out in the field. The constraints of coring (protected cave), site accessibility (deep karst), extraction (conditioning) according to the type of sampling and their documentation are discussed. The final objective is to propose a methodological guide adapted to the different issues and situations encountered underground.

1. Introduction

Les analyses d'échantillons de calcite souterraine sont de plus en plus utilisées pour travailler sur des sujets majeurs comme les datations absolues (U/Th, U/Pb), les analyses chimiques fines de traces et ultra-traces et les analyses isotopiques permettant de discriminer les différentes sources d'éléments chimiques et leur histoire géologique ou climatique. Une partie de ces applications est tournée vers les grottes ornées à haute valeur patrimoniale ou vers les études paléoclimatologiques, mais également vers des études plus expérimentales sur l'histoire de ces cavités et de leur développement. Les carottages sont un moyen fiable de réaliser les échantillonnages. Il est possible de travailler avec de petits carottiers, légers et adaptés aux prélèvements de parois sensibles (grottes ornées) ou en karst profond (portage important). Très peu d'articles et de documentations techniques traitent des carottages souterrains à part l'article de SPÖTL & MATTEY (2012).

Un groupe d'études techniques du réseau de métiers CNRS « Milieux Souterrains et Karsts » propose ici une première synthèse de retours d'expérience et de tests menés sur le terrain prenant en compte les contraintes du carottage (cavités sensibles), d'accessibilité au site (karst profond), d'extraction des carottes (conditionnement) en fonction du type d'échantillonnage et de leur documentation.

2. Des techniques adaptées à différents enjeux de conservation

Les contraintes d'accès aux sites de travail, l'image donnée par des scientifiques prélevant et cassant des concrétions, l'impact visuel des dégradations de concrétions et l'importance patrimoniale de parois ornées imposent une réflexion spécifique. Le groupe d'études techniques s'est donné pour objectif d'avoir cette approche globale incluant ces questions de conservation.

Figure 1 : Différents types de matériels utilisés (couronnes diamantées (4 à 112 mm), rallonges, têtes d'injection).

Parmi ces enjeux, la détermination de l'âge des voiles de calcite scellant l'art pariétal est sujet à discussions (PONS-BRANCHU *et al.*, 2014 ; VALLADAS *et al.*, 2017 ; PONS-BRANCHU *et al.*, 2020). Sur ces sites, il n'est souvent pas envisageable de prélever des échantillons complets de parois ou de concrétions. Il importe cependant de pouvoir prélever suffisamment profond pour recueillir toutes les couches de dépôts à étudier. L'utilisation de micro-carottiers est alors plus adaptée. Il est également possible de forer encore plus fin, avec un système de dremmell ou une perceuse avec une mèche de 1-2 mm, mais l'absence de système de carottage et la dureté de la calcite ne facilitent pas ces échantillonnages. On ne récupère alors que la poudre sans possibilité de distinction exacte de l'échantillon. Cette technique sera préférentiellement utilisée pour micro-échantillonner les carottes de retour au laboratoire. Dans le domaine de la paléoclimatologie, les échantillons prélevés doivent recouvrir des périodes différentes et les analyses des isotopes de l'Oxygène et du Carbone permettent par exemple de reconstituer les conditions environnementales au moment de leurs dépôts.

Figure 2 : Mise en œuvre d'un perforateur sur accus avec carottier 32 mm (ici deux rallonges) et refroidissement à eau (grotte Pallas 3, Ardèche). Photo S. Jaillet.

3. Des techniques adaptées à différents usages

Le groupe d'études techniques du réseau de métiers CNRS « Milieux Souterrains et Karsts » travaille sur un large éventail de carottiers et de modèles de perforateurs adaptés aux carottiers (fig. 1). Les diamètres internes des carottiers vont de 4 mm à 112 mm, pour des longueurs entre 65 mm et 400 mm, avec parfois des rallonges permettant d'atteindre 1 m de profondeur. Tous les carottiers sont dotés de couronnes diamantées. Ils sont connectés à des perforateurs portatifs de tailles et de puissances variables et adaptées. Les perforateurs ne sont jamais utilisés en mode percussion. Pour les petits carottages (4 à 10 mm), un perforateur léger (ex : Bosch GBH 18V EC) ou une visseuse (ex : Makita DDF484 18V) sont utilisés. Un perforateur plus puissant (ex : Hilti TE-6A 36V ou Bosch GBH 18V) est mis en œuvre pour les carottages moyens (28 à 40 mm) (fig. 2) et un carotteur nécessitant une alimentation électrique extérieure (ex : Hilti-DD100 220V) est nécessaire pour les plus gros diamètres (80 à 112 mm). Les contraintes majeures des carottages sont (i) ne pas casser ou bloquer le carottier pendant le forage, (ii) extraire la carotte de calcite en un minimum de morceaux, (iii) la sortir du carottier et (iv) parfois pouvoir l'orienter afin de retrouver sa position initiale une fois extraite. Tous les prélèvements par carottage se font nécessairement avec injection d'eau pour deux raisons : (i) évacuation des boues de forage, (ii) évitement de l'échauffement, pour éviter d'user prématurément ou de casser la couronne diamantée, voire d'avoir des conséquences importantes sur les échantillons (datations U/Th/He notamment). La tête de la couronne diamantée, d'un diamètre légèrement supérieur, permet de maintenir un espace entre carottier et paroi pour la remontée de l'eau et des boues. Un opérateur est dévolu

uniquement à cette gestion de l'eau. Dans certains sites, pour éviter des contaminations, des eaux du commerce sont utilisées. Souvent, utiliser l'eau de la grotte (rivière ou mieux piégée dans un gour) permet de résoudre le problème. Lors d'un atelier dédié à ces méthodes, nous avons testé 3 ensembles de matériels adaptés aux situations rencontrées.

Pour les prélèvements de petit diamètre (4 à 10 mm interne), la profondeur d'investigation permet d'atteindre 80 mm sans difficulté particulière (fig. 3). Les problèmes rencontrés sont l'amorce du forage (impliquant qu'un opérateur tienne la tête au début du travail). Sur les très petits diamètres, la carotte se fragmente et remonte dans la tête d'injection, gênant la possibilité de reconstituer correctement la carotte. Le dosage de l'injection d'eau (pouvant être réalisé avec un pulvérisateur ou une bouteille PET) doit être fait avec soin. La pression sur l'outil doit être adaptée. Ces éléments militent pour une formation de l'opérateur surtout pour des sites à forts enjeux patrimoniaux.

Figure 3 : Carottage de petit diamètre (ici 4 mm intérieur) mis en œuvre avec une visseuse et un pulvérisateur de jardin (Aven d'Orgnac, Ardèche). Photo S. Jaillet.

Les tests réalisés sur diamètre moyen (28 à 40 mm) se sont révélés concluants. Sans colonne de guidage et avec deux rallonges, en 32 mm, il est assez aisé d'atteindre 1 m de profondeur (fig. 2). Les principaux problèmes rencontrés sont de casser les tronçons de carottes à la base du carottage et d'extraire la carotte. Cette difficulté augmente à chaque ajout d'une rallonge. Une longue tige métallique rigide peut être utile pour casser la carotte. Aspirer dans le tuyau d'injection d'eau peut parfois permettre de maintenir la carotte dans le carottier dans la phase d'extraction. Notons qu'à partir de ces diamètres, la consommation d'eau devient importante (au moins 10 litres pour 1 m de carotte).

L'utilisation de diamètres plus importants (80 mm ou plus) implique le recours à une colonne de guidage fixée au sol (gougeons ou scellement) (fig. 4). La méthode permet d'ajouter plusieurs rallonges et d'envisager des carottages de plus de 2 m (QUINIF, 1991). L'impact visuel et environnemental, le recours à un matériel plus lourd, la nécessité d'utiliser le 220 V, milite pour limiter ces opérations à des cas particuliers (analyse morphologique des lamines par exemple, demandant une largeur minimale de la carotte).

Figure 4 : Carottier 80 mm sur colonne de guidage et refroidissement à eau, ici mis en œuvre sur une grosse stalagmite couchée (Aven d'Orgnac, Ardèche). Photo P. Crochet.

4. Prélever pour analyser, communiquer, échanger

La question de l'impact visuel est importante et suscite d'autres réflexions. En effet les spéléothèmes participent à l'esthétique de la grotte. Il est donc indispensable d'accompagner chaque prélèvement d'une réflexion préliminaire sur l'intérêt de l'échantillonnage, le choix de la zone retenue et l'impact visuel final. En premier lieu, pourquoi prélever sur ce point ? Quelles analyses seront faites sur l'échantillon et à quelles questions scientifiques cela permettra de répondre ? Comment organiser la restitution des données et comment intégrer les résultats

dans les bases de données qui se mettent en place ? Ces questions sont de plus en plus d'actualité dans la communauté scientifique, à l'heure d'un développement croissant des échanges de données (CNRS, 2020).
L'impact visuel peut être limité avec plusieurs approches potentielles. Doit-on cacher le prélèvement ? Si oui, il n'est pas impossible de boucher le trou avec des matériaux inertes, le temps et les écoulements recouvriront la cicatrice rapidement si la concrétion est encore active. Il est également possible d'envisager de montrer explicitement le trou en documentant le travail, par exemple avec une pancarte expliquant pourquoi, par qui et quand ce prélèvement a été réalisé. Ces messages peuvent avoir deux effets : (i) ne pas laisser les visiteurs devant un trou sans explication et (ii) sensibiliser aux questionnements scientifiques et aux modes de travail. Une troisième possibilité est de reproduire un fac-similé du prélèvement, lorsque la concrétion entière a été prélevée, mais cette possibilité n'est plus d'usage si l'on se limite à un carottage plutôt qu'un prélèvement de la concrétion complète.

Conclusions

À travers cette note préliminaire, nous avons voulu présenter les premiers résultats de ce groupe de travail sur les carottages sur calcite au sein du réseau de métiers MSK du CNRS.

Ces premiers tests montrent que le diamètre 4 mm est délicat à mettre en œuvre et doit sans doute être réservé à des enjeux particuliers. Le diamètre 10 mm permet, avec une visseuse et une bouteille PET, d'avoir un matériel simple, polyvalent et efficace (poids total 3 kg), notamment pour des datations prospectives. L'utilisation de carottiers de 32 mm avec un perforateur 18, 24 ou 36 V permet d'atteindre aisément 1 m de profondeur dans des conditions satisfaisantes, là encore avec un encombrement raisonnable (poids total 7 kg). Il est toutefois important d'avoir un perforateur (ou une visseuse) avec un couple de serrage de bonne qualité (minimum 40 N/m) et des batteries de fort ampérage, pour l'autonomie. Parmi les différents modèles de têtes diamantées que nous avons testés, la société ODS (Saint-Leu-la-Forêt, 95) a démontré la performance de ses couronnes diamantées sur mesure, notamment sur des forages avec rallonges.

Loin de limiter ces réflexions à des aspects techniques, nous souhaitons les élargir à des problématiques plus vastes qui sont celles des enjeux de conservations des milieux souterrains et à la question du partage des données. La seconde phase de ce travail sera donc de confronter, au cours d'un atelier thématique à venir, les différents utilisateurs de spéléothèmes. L'objectif sera de comparer les avantages et inconvénients des différentes techniques utilisées et utilisables, puis de former et sensibiliser les débutants aux questions posées. À plus long terme, l'objectif final de ce travail sera de proposer un guide méthodologique adapté aux différents enjeux et situations rencontrées sous terre.

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Natural and anthropogenic cave sediments: the example of the Apuan Alps (Central Italy)

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Abstract

The Apuan Alps represent an important karst area of Central Italy characterized by large karst systems fed mainly through autogenic recharge. For this reason, cave sediments are not abundant and are usually associated with allogenic recharge through sink holes. An important source of cave sediments is currently represented by the carbonate powder produced during the quarrying of the famous "Carrara" marble. This material has a grain-size ranging from fine sands to silt that can be transported by meteoric waters into karstic network as a very fluid slurry through fissures and cavities crosscut by quarries. Samples of sediments have been collected in some caves and springs fed by the major Apuan karst systems. Composition, grain-size, and morphological features of these sediments have been compared with those of the anthropogenic carbonate powder. Marble slurries and spring sediments show some differences in their mineralogical compositions: the former deposits are composed mainly by calcite grains, whereas the latter show variable proportions of calcite, dolomite, and silicates particles.

1. Introduction

Carbonate aquifers are extremely vulnerable to contamination due to the presence of fast infiltration flow paths such as solutional-enlarged fracture and cavities (WORTHINGTON et al., 2000). Moreover, the yield of these aquifers is not constant neither in time nor in space because of the high heterogeneity and anisotropy of permeability (BAKALOWICZ, 2005). Human activities can potentially damage karst aquifers, including quarrying. The Apuan Alps is a mountain range famous for the extraction of the precious "Carrara" white marble. These mountains are made up of both metamorphosed and non-metamorphosed carbonate rocks arranged in different tectonic units (CARMIGNANI *et al.*, 2006, CONTI et al., 1993). The structural setting and the lithological heterogeneities determined complex hydrodynamic behaviors of the local karst aquifers which represent an important drinking water supply for the coastal urban areas (PICCINI *et al.,* 2019). Quarries are widespread in the metamorphosed sectors of the mountain range (Fig. 1). Large marble blocks are extracted by sawing the rock with belt, wire and chain saws. The powder produced during extraction and squaring of the blocks is collected and disposed in repositories but a significant fraction of it infiltrates before it is removed during sawing operations, representing a pollutant that can propagate into the karst systems through enlarged fractures when precipitations occur. The input of this contaminant in the groundwater systems changes the physical and mineralogical properties of transported sediments and causes episodic increases of turbidity in karst springs during heavy rains and floods (DRYSDALE et al., 2001). This work proposes the Apuan Alps as a case study to characterize the impact of this physical pollutant on sediments transported and stored in karst aquifers. With this aim, the features of sediments collected in caves and karst springs presumably contaminated by the marble slurry are presented and discussed.

2. Hydrogeological setting, materials and methods

An extensive network of karstic cavities has developed in the metamorphosed carbonate units of the Apuan Alps, with a total length of more than 325 km (DOVERI *et al.,* 2019). The major carbonate aquifer consists of a succession made up of dolostone, dolomitic marble, marble, and cherty meta-limestone. The carbonate aquifer is laterally and vertically confined by impermeable basement rocks (schists) and clastic sedimentary covers. The metamorphosed carbonate succession is arranged in contiguous but distinct drainage systems. Most of the springs fed by the metamorphic aquifers have very irregular regimes, typical of vadose and epiphreatic flow systems (DOVERI *et al.,* 2019). The sampling sites were chosen to study the mineralogical, morphological and grain size characteristics of the anthropogenic marble powder, the cave deposits, and the spring sediments. Samples were collected in some of the quarries where the marble powder is produced. Care was taken to collect samples of powder produced with different sawing techniques. Cave sediments were sampled in vadose passages (active and relict ones) of the Monte Corchia cave. This is one of the most extensive caves in Italy (length of about 65 km). Samples were also collected at some of the

major springs variably contaminated by the marble slurry (Fig. 1). Cave sediment samples mainly transported in phreatic conditions were collected close to the outlet and grouped with the spring samples. 1 dm^3 of sediment was collected in a LDPE bag at each site using a Teflon spoon. The samples were dried, passed through a 2.8 mm sieve to remove impurities. The fraction passing a 0.25 mm sieve was analyzed with XRD, SEM-EDX and an automated optical microscope for grain size analysis.

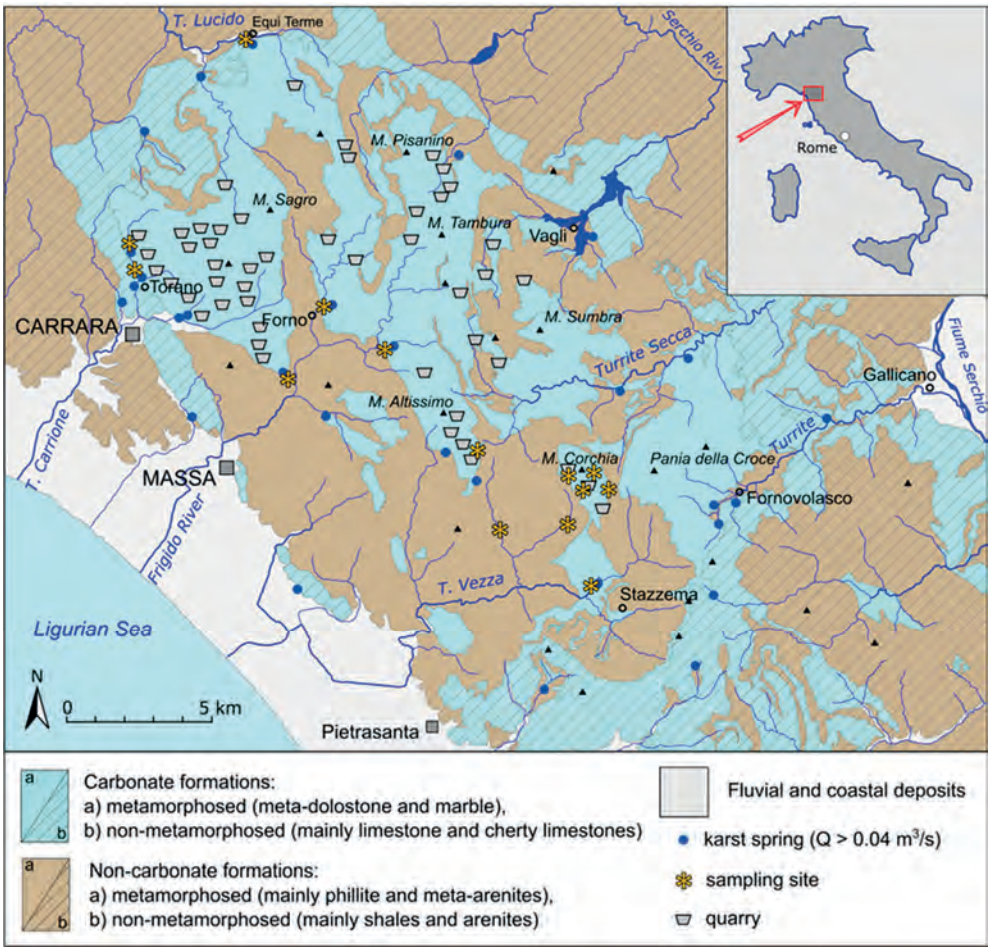

Figure 1: Simplified hydrogeological map of the Apuan Alps (modified after PICCINI et al., 2019).

3. Results

In order to measure the granulometric composition of the samples by optical methods, we removed the sediment fraction that had a diameter larger than 0.25 mm (grain size $\phi = 1$). The marble slurry has a grain size distribution of a silt with variable amounts of fine sands. Spring and cave deposits have a mean grain size of a fine sand, with variable amounts of silt, whereas the clay fraction is volumetrically irrelevant in all the sediments. The XRD analyses revealed that the marble powder has a mineralogical composition totally or predominantly composed by calcite. SEM micro-morphometric analyses showed that the particles composing the marble powder have angular contours and no signs of chemical alteration (Fig. 2a). Cave and spring deposits are mostly made up of calcite grains with variable proportion of dolomite and silicates, in particular quartz, muscovite (and albite in some cases). The highest concentrations of silicates are found in the spring samples. Dolomite is frequent in cave samples. Calcite and dolomite grains show different superficial morphologies. In particular, some calcite grains and most of the dolomite grains show irregular surfaces caused by dissolution phenomena (Fig. 2b). However, angular calcite grains with no evidence of dissolution are also present in all cave and spring samples, except than in cave sediments collected in ancient relict passages (Fig. 2c).

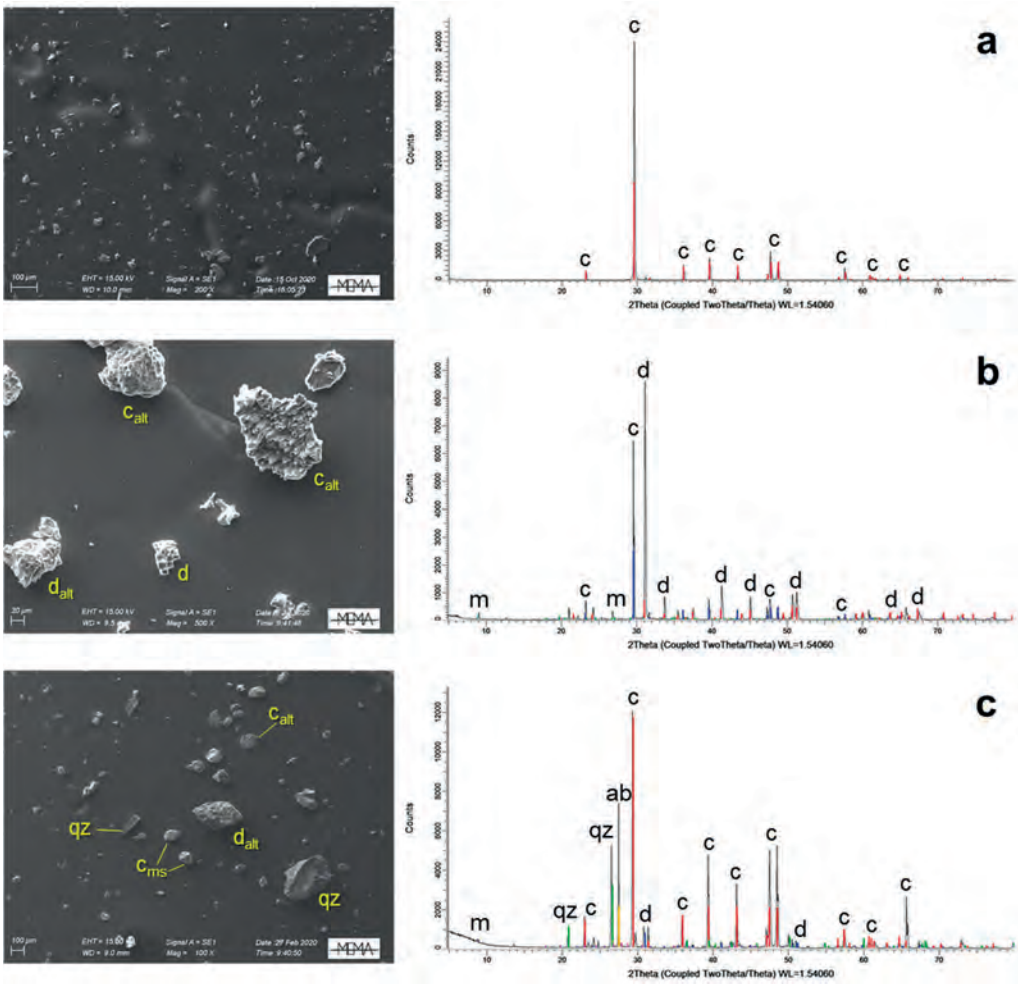

Figure 2: Examples of SEM pictures (left) and diffractograms (right) for a marble powder sample (a), a cave sediment (b), and a spring sample (c). Labels on SEM pictures: c_{ms} = particle of marble slurry (calcite), c_{alt} = weathered calcite, d = dolomite, d_{alt} = weathered dolomite, qz = quartz. Labels on diffractograms: c =calcite, d = dolomite, m = muscovite, qz = quartz, ab = albite.

4. Discussion

The mineralogical composition of the cave and karst spring sediments depends upon the geology of the catchments feeding their internal drainage systems. Calcite, dolomite, and silicate grains are the main constituents, and can be produced by the natural weathering and physical degradation of the rocks outcropping in the study sites. In particular, dolomite particles are produced by the partial dissolution of the dolostone occurring in the epikarst, forming a fine dolomitic sand that can be easily mobilized by the percolating waters. The vadose cave samples from Monte Corchia cave have variable proportions of dolomite grains because dolostone outcrops only in specific sectors of the system so that sediment supply can be either calcic/siliciclastic or a mixture of the three mineral groups (Fig. 3a). However, some samples collected in cave sectors that develop mainly in the dolomitic portions of the aquifer contain a relevant and unexpected amount of calcite grains. Therefore, these samples could be the evidence of marble powder contamination originated from quarries. As expected, major springs have the highest concentrations of silicates because their catchments embrace also relevant sectors of non-carbonate rocks.

A closer observation at specific grain size intervals is useful to highlight differences between the marble slurry and the natural to variably contaminated sediments. It appears that the marble slurry is finer than the karst sediments, although covering a wide dimensional range (Fig. 3b). Marble powder samples are very dispersed in grain size because they were produced with different sawing methods and did not undergo transport. There are no clear differences in grain size between the springs and the cave sediments (Fig. 3b). It is worth to mention that a fine silt fraction is absent in springs that have recently experienced clear episodes of contamination by marble powder. This can be addressed either to 1) the fact that it is not volumetrically relevant independently from other factors or, 2) although it represents a significant volume fraction, it cannot be found because it easily washed away as suspended load during floods, or 3) it was already deposited upstream of the sampling site.

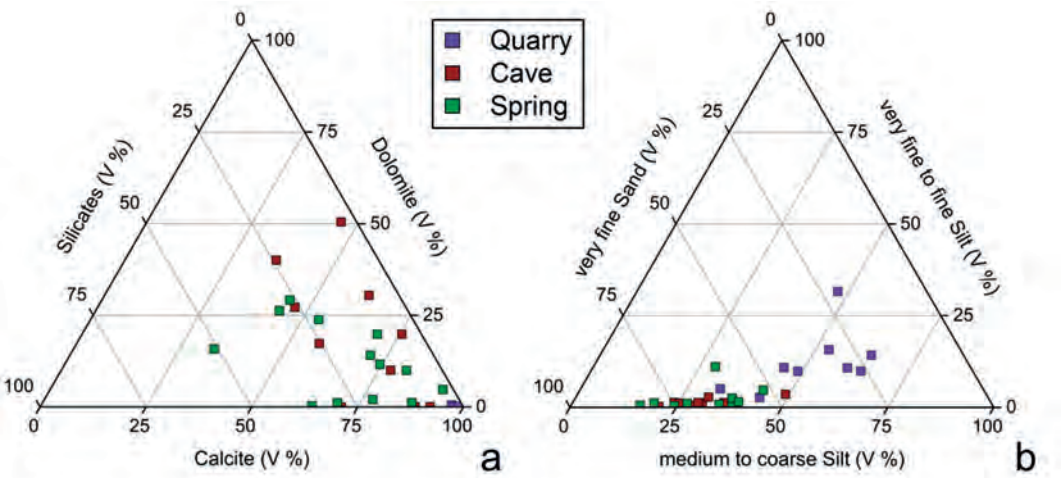

Figure 3: Ternary diagram of the mineralogical composition (a), and of the grain size distribution (b) relative to the very fine to fine silt (ϕ = 6 – 8, µm = 15.63 – 3.9) – medium to coarse silt (ϕ = 4 – 6, µm = 62.5 – 15.63) - very fine sand (ϕ = 3 – 4, µm = 125 – 62.5) interval of the sediments, both expressed in volume percentage.

5. Conclusion

This study confirms a homogeneous calcite composition for the anthropogenic marble powder, whereas cave and spring deposits are mineralogically more heterogeneous, although calcite is always the prevalent constituent. For this reason, the occurrence of calcite alone is not indicative of contamination, but the comparison of mineralogical and textural features and a detailed knowledge of the local geology were useful to recognize the presence of the marble slurry in the Apuan karst systems. Grain size analysis of specific fractions showed that this contaminant is generally finer and less sorted respect to the karst groundwater sediments because the deposition of the latter depends on the hydrodynamic conditions through the systems. The extreme temporal and spatial variability of the hydrodynamic behavior of these systems justify the heterogeneity of the morphological and compositional characteristics of cave and spring sediments, even for a single system.

In conclusion, marble slurry does not influence much the grain size distribution of cave and spring sediments, except than for a few, very contaminated samples. However it increases the amount of anthropogenic calcite grains, whose morphology is characterized by the absence of dissolution features differently from those produced by natural weathering processes.

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Climate Variability reconstructed from La Cueva Chica speleothems: implication for Megafauna and Human settlements in South Patagonia, Chile

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Abstract

Investigating new palaeoclimate records is of major importance for evaluating the impact of past forcing factors on the evolution of ecosystems as well as megafauna, and human dispersal, especially in Southern Patagonia (Chile) where few records are available. The Cueva Chica, located in the Cerro Benitez (Ultima Esperanza) is partially filled with postglacial deposits that preserve the oldest palaeontological evidence of palaeofauna in the region and is sealed by calcite flowstones. The study relies on a 40 cm long flowstone core S6 and stalagmite S8. The samples were radiometrically (U-Th & ^{14}C) dated to build an age-depth model for the proxy series (stable isotopes, chemical composition). The objectives of this work are to: i) reconstruct past climate variations from geochemical analyses, and ii) assess the palaeoclimatic context of megafauna extinction and human settlements in the area. Core S6 grew discontinuously from 13 to 1 ka with several possible hiatuses. Sample S8 grew from 6.8 to 5.8 ka and at *ca.* 1.2 ka. The results show a change from a wet phase prior to the Holocene to a drier phase during the mid-Holocene likely related to the westerlies dynamics in the Southern Hemisphere. Based on these results, we further discuss the possible implications of climate changes on the megafauna extinction in the area.

Résumé

Variabilité climatique reconstituée à partir des spéléothèmes de La Cueva Chica : implication pour la mégafaune et les établissements humains dans le sud de la Patagonie, au Chili. L'étude des enregistrements paléoclimatiques est d'une importance majeure pour évaluer l'impact des forçages passés sur l'évolution des écosystèmes, la mégafaune et la dispersion humaine, en particulier dans le sud de la Patagonie (Chili), où peu d'archives naturelles carbonatées sont disponibles. La Cueva Chica, située dans le Cerro Benitez (Ultima Esperanza) est partiellement remplie de dépôts postglaciaires livrant parmi les plus anciens vestiges de paléofaune dans cette région. Ces dépôts sont scellés par un plancher de calcite. L'étude repose sur les datations Uranium-Thorium et l'analyse pétrographique et isotopique de la carotte S6 (40 cm de long) prélevé du plancher et de la stalagmite S8. Cette étude a pour objectifs de: i) reconstituer les variations climatiques passées à partir des analyses géochimiques, et ii) évaluer le contexte paléoclimatique de l'extinction de la mégafaune ainsi que des premiers établissements humains dans la région. La carotte S6 couvre une période allant 13 à 1 ka BP, marqués par plusieurs hiatus. La stalagmite S8 couvre une plus courte période, de 6,8 à 5,8 ka et *ca.* 1,2 ka. Les résultats montrent un changement climatique avec une phase humide et chaude de 13 à 9 ka et une phase plus sèche de 8,5 à 5,8 ka, et un retour vers un climat plus humide de 3,0 à 2,5 et *ca.* 1,2 ka. Sur la base de ces résultats, les implications possibles des changements climatiques sur l'extinction de la mégafaune dans la région seront discutées.

1. Introduction

Studying new palaeoclimate records is of major importance for evaluating the impact of past forcing drivers on the evolution of ecosystems and extinction of megafauna, especially in Southern Patagonia where few records are available. The Cerro Benitez (Ultima Esperanza) hosts more than 13 caves and rockshelters with the oldest

palaeontological evidence of palaeofauna in the region (MARTIN et *al.,* 2013; 2015). Two caves (Cueva Lago Sofía 1; Cueva del Medio) host two of the oldest archaeological records of Patagonia, dated between 13.6 and 10.6 ka cal BP, while Cueva Chica hosts the oldest paleontological record of the region, a *Lama gracilis* astragale dated 18,500-17,930 cal BP. The famous Cueva del Milodón comprises the paleontological remains of the extinct ground-sloth *Mylodon*. Cueva Chica is a 73 m long cave located in the southeastern part of Cerro Benitez and comprises the earliest known megafaunal occupation (*e.g. Lama gracilis*) at *ca.*16 ka cal BP. The Cerro Benitez was fully covered by a piedmont ice lobe during the last glacial at *ca.*40 ka. After several glacier retreats and advances from 30 ka to 18 ka, the caves of the Cerro Benitez, including Cueva Chica, were open and partially sediment filled (TODISCO et *al.,* 2018). Underground galleries were then occupied by megafauna as evidenced by fossil remnants in the cave deposits. We investigated La Cueva Chica as the cave comprises laminated deposits partially sealed with a thick calcite flowstone (Fig. 1). As no stalagmites are preserved in the cave, a 40 cm core was drilled in the flowstone at the end of the cave (Fig. 1C). The calcite core S6 and the stalagmite S8 were radiometrically dated (U-Th,^{14}C). Petrographical and geochemical analyses (δ^{18}O, δ^{13}C, chemical composition), combined with monitoring data were used to reconstruct a high-resolution paleoclimate record spanning the Holocene and assess the palaeoclimatic context of megafauna extinction and first human settlements in this area.

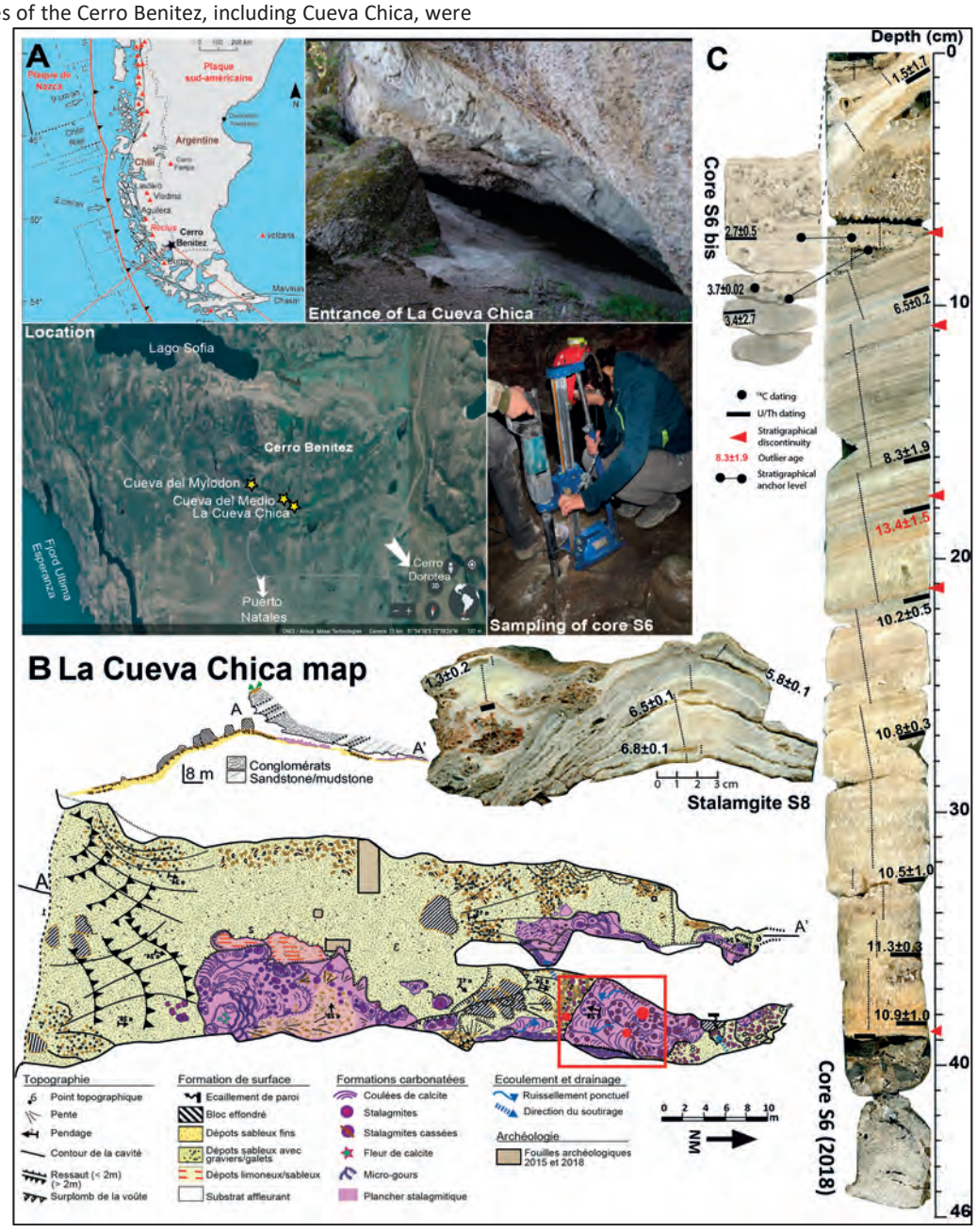

Figure 1: Location of Cerro Benitez and Cueva Chica in SW Patagonia, Chile (A). The map of La Cueva Chica shows the location of the samples (B). The image of stalagmite S8, and cores S6 and S6bis highlights dating points and potential discontinuities. The ages are reported in BP 1950.

2. Materials and methods

Both cores S6 and S6bis were sampled using a Makita drill. The cores and stalagmite S8 were cut along their growth axes and polished using 120–4000 µm silicon carbide sandpaper. 16 ages were obtained on a Nu Instruments MC-ICPMS at the Geochemistry Laboratory, Earth Science Department, University of Melbourne (Australia) using an internally standardized parallel ion-counter procedure and calibrated against the HU-1 secular equilibrium standard following the procedures of Hellstrom (2003). Correction for detrital Th content was applied using initial activity ratios of detrital thorium ($^{230}Th/^{232}Th)_I$ of 0.93 ±0.73. the ^{14}C date was obtained through the analysis of 10 mg of charcoal sampled on core S6bis. A stratigraphical correspondence combined with U-Th dates from core S6bis permits the inclusion of the radiocarbon date into the age model.

12 thin sections of 80-100 µm thick were prepared at the department for Sediment and Isotope Geology, Ruhr University Bochum, Germany. A preliminary petrographic analysis was conducted with a Leica optical microscope to determine the stratigraphical characteristics of core S6 (e.g., fabric, structure, inclusions, discontinuities/hiatuses).

381 stable isotope samples were taken along the growth axis of core S8 (Fig. 1) for $\delta^{13}C$ and $\delta^{18}O$ measurements. Samples were also drilled along the stalagmite growth axis at 1 mm resolution using a Merchantek Micromill mounted on a Leica microscope. The samples were analysed using either a Nu Carb carbonate device coupled to a Nu Perspective mass spectrometer (MS) at the Vrije Universiteit Brussel or a Thermo Gasbench II connected to a Thermo MAT253plus MS in continuous flow mode at the Sediment and Isotope Geology department, Rhur University Bochum, Germany.

Preliminary monitoring data were collected with loggers continuously measuring temperature both outside and inside the cave. Additionally, 16 seepage and water samples were collected from La Chica cave and nearby caves, springs and lakes in December, 2016, 2017, and 2018 for $\delta^{18}O$ and δD measurements in hermetically sealed glass bottles. Isotope measurements were performed at Vrije Universiteit Brussel on a Picarro L2130-i analyzer using cavity ringdown spectroscopy (CRDS). The sensitivity of the proxies to hydrological changes and prior carbonate precipitation (PCP) is further tested with indicators using µXRF element data. The S6 core was scanned using the Bruker M4 Tornado µXRF scanner at the GFZ-Potsdam, Germany to determine relative concentrations of Sr and S (Sr/Ca; S/Ca).

With this on-going study, further dating points will be analyzed to refine the age model and plotted later against the stable isotopes and XRF element records. A detailed petrographic analysis is ongoing to determine growth stops. At this stage, only a linear age model is interpolated between the dated levels in order to reconstruct a preliminary paleoclimatic time series.

3. Results

Flowstone S6 grew discontinuously from *ca.*13 ka to *ca.*1 ka with several possible hiatuses at *ca.*10 ka, from 5.7 to 3.0 ka and 2.5 to 1.8 ka (interpolated ages). Sample S8 grew from 6.8 to 5.8 ka and at *ca.*1.2 ka. Several hiatuses are found between 29 and 70 mm, at 80-, 218- and 385-mm depth (Fig.2).

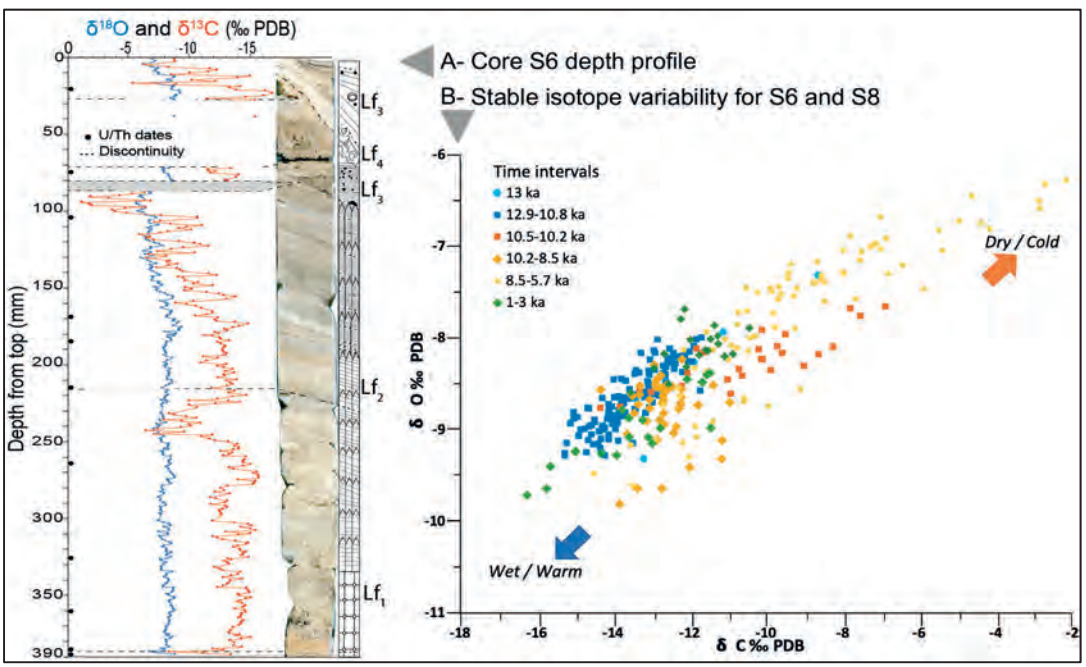

Figure 2: Stable isotope measurements on both S6 and S8 samples. ***A.*** *Stable isotope depth profile measured along the S6 core with the lithofacies legend and* ***B.*** *Stable isotopes variability for S6 and S8 plotted against a linear age model.*

Petrographic analysis of thin sections shows that core S6 is mainly composed of columnar calcite, which ranges from poorly-to-well laminated to massive, often with a persistent detrital and allochthonous component and other impurities. Based on clastic content, fabrics, visual appearance, and colour of the calcite, four lithofacies are defined in core S6 from the base to the top (Fig. 2): lithofacies Lf_1 is rich in clastic material and characterised by yellowish calcite with a poorly laminated and more porous structure imbedded in a microgour structure. Low but significant content of oxides, rutile and calcite fragments (micrite, sparite) fill the voids between the calcite crystals comparing to other levels. Lithofacies Lf_2 is composed of compact, elongated columnar calcite with highly laminated structure. Few empty voids are reported comparing to Lf_1. The basal part of Lf_2 shows few impurities and more, well recognizable, fluid inclusions. The upper part of Lf_2 shows more impurities and higher number of hiatuses. Lithofacies Lf_3 is less-clearly laminated but comprises the highest amount of impurities, minerals, bones fragments and remains of organic material in the entire record. Oxides, rutiles, pyroclasts are the most common minerals preserved in this part. Lithofacies Lf_4 is not laminated but rather a primary subaqueous calcite formed in a sub-aqueous environment. Stable isotopes analyzed at sub-centennial resolution show a 3 ‰ range for $\delta^{18}O$, and more than 14‰ for $\delta^{13}C$. These changes; mostly in carbon, are likely caused by kinetic fractionation and prior calcite precipitation (PCP), controlled by changes in moisture availability and cave air humidity. The $\delta^{13}C$ record varies closely in-phase with the $\delta^{18}O$ record but with different degrees of compression (*vs* distance) for the same oscillations (Fig. 2). The sensitivity of the proxies to hydrological changes and PCP is further tested with Sr/Ca acquired by µXRF element scanning. The Sr/Ca record is consistent with the $\delta^{18}O$ profile showing an anti-phase correlation. The basal part of core S6 up to 176 cm depth shows low Sr/Ca ratios with more negative $\delta^{18}O$ values. The mid and upper parts of the core (from 176 cm to 86 cm, and from 27 cm to the top) show higher Sr/Ca ratios and more positive $\delta^{18}O$ values.

4. Discussion & conclusions

The multiproxy record from La Cueva Chica suggests a wet phase from *ca.*13 to 9 ka, likely related to strong southern westerlies, preceded by a short dry/cold spell at *ca.*13 ka. This wet phase was followed by colder/drier conditions from 8.5 to 5.8 ka, likely related to weaker westerlies, especially during the mid-Holocene. High precipitation and strong westerlies prevailed from 3.0 to 2.5 ka and during Medieval times. Our paleoclimate record implies that the presence of extensive megafauna, the development of *Nothofagus* forest and human arrival (METCALF et al., 2016), all occurred during a climatically favorable wet/warm period *ca.* 13 to 9 ka, after the Antarctic Cold Reversal (ACR). However, the deterioration of the vegetation cover at the Cerro Benitez coinciding with high $\delta^{13}C$ values excursions was initiated since *ca.*11 ka. Previous studies suggest an extinction of major megafauna species (e.g. *Mylodon, Smilodon, Panthera onca meembrina*) during this wet/warm period. Such climate-driven changes likely reduced open ecosystem environment and may have led to local decline of herbivore populations. Later cooling/drying at *ca.*9 ka may have contributed to the disappearance of other mammal species along with human activities. Finally, a charcoal layer dated at *ca.*4 ka in core S6 indicates possible human activities inside La Cueva Chica, well after the megafauna' extinction. The speleothems S6, S6bis and S8 from La Cueva Chica provide a new palaeoclimate record from high-latitude Southern Patagonia (Chile). The constructed time series span most of the Pleistocene-Holocene transition and the Holocene period. This preliminary work reports several proxy records (stable isotopes; chemical composition). Additional U-Th dating will refine the age model. Petrographic, monitoring and statistical analyses will be completed to assess the consistency of the proxy time series and the significance of the reconstruction at regional scale.

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Fluvial depositional systems: morphoscopic analysis of sediments in dry valleys in central Brazil

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Abstract

Dry valleys with sediments are typical features of the karst landscape associated with the geological context in central Brazil. This research aims to characterize the fluvial deposits considering data from morphoscopic analysis that evaluated the circularity and size of the grains that constitute the sedimentary units. The morphoscopy allowed the characterization of the average circularity of the samples as well as the averages referring to the size of the grains. With the obtained data, we observed that the diameter of the grains in general has the same behavior, but there are some samples that presented a higher average in relation to the others. This situation may be linked to the area of origin and transport capacity of the rivers. However, the circularity showed high values, close to 1, and constant. This characteristic was attributed to the source areas that are known to present such types of sediments due to aeolian and fluvial origin.

1. Introduction

The karst region of northeastern Goiás in central Brazil is linked to the San Franciscana basin with different geological groups such as the Bambuí, Areado, Urucuia and Chapadão Formation. The Bambuí Group (Neoproterozoic) has formations with occurrences of carbonate rocks such as the Lagoa do Jacaré Formation. The Areado Group sits in angular erosive unconformity over the Bambuí and Santa Fé Group. Its sedimentation is typical of complete alluvial systems associated with fluvial, lacustrine environments and aeolian dune fields. The Urucuia Group (Neocretaceous) supports the top of the Serra Geral de Goiás plateau and is composed of sandstones. Finally, the Chapadão Formation (Cenozoic) also corresponds to unconsolidated sandy covers (CAMPOS & DARDENNE, 1997; CRUZ, 2012a; DARDENNE, 1978; BERBERT-BORN & TRINDADE, 2003).

The region has geomorphological characteristics associated with the erosion process of the Serra Geral de Goiás plateau escarpment (CAMPOS & DARDENNE, 1997; CRUZ, 2012a; DARDENNE, 1978; MOTTA, 2003). In this context, several typical features of karstic environments emerge, such as cave systems, dolines, sinkholes, resurgences and dry valleys (CALDEIRA et al., 2021; FERREIRA, 2020; HUSSAIN et al., 2020; BERBERT-BORN; TRINDADE, 2003). The latter (dry valleys) can protect sedimentary packages that act as natural 'geofiles' for studies of the most varied approaches, including climatic, anthropogenic geological, in addition to understanding the evolution and dynamics of fluvio-karstic systems (KOŠUTNIK, 2007; MONOD *et al.*, 2006; ÖZTÜRK, 2020; PETROVIĆ *et al.,* 2016; TIRLA *et al.,* 2016). The characterization of these depositional systems involves the realization of physical analyzes of the sediments, such as grain morphoscopy, which comprises the analysis of the diameter and circularity of the grains. Grain size can be one of the indicators of the type of deposition. While the degree of circularity indicates the type and intensity of transport, reworking, time and the distance from the source area of the lithological matrix (HENRIQUES & VALADÃO, 2017; SUGUIO, 1973). Thus, some variations can be established in the depositional systems of fluvial deposits. Therefore, the purpose of this study is to characterize the fluvial deposits based on morphoscopic analysis of the sediments in abandoned dry valleys.

2. Materials and methods

This study was carried out based on four main steps. The first phase included a theoretical-methodological survey, characterization of the study region as well as a topographic survey to identify the study areas, based on visual interpretation of satellite images (world Imagery, Earth) image of a digital elevation model (DEM) of the SRTM

(Shuttle Radar Topography Mission) project, both acquired from the United States Geological Survey (USGS - https://earthexplorer.usgs.gov/) and the preparation of altitude and slope maps. In the second phase, faciological descriptions and collection of samples were carried out on the field and were sent for laboratory analysis. Thirdly, morphoscopy was performed at the ACILWEBER analytical laboratory, using the Bettersizer S3PLUS equipment and applying the Fraunhofer analysis method - Image, which consists of six steps: 1. Entering the sample data; 2. Measuring the white value; 3. Adding the sample directly to the analytical container, with agitation at 1600rpm and ultrasound (50W); 4. Activating the cameras (0.5x and 10x) for greater analytical range; 5. Waiting for 2 minutes to collect images; 6. After analysis, generating reports for particle size and circularity.

The analysis consists of measuring the longest, shortest and intermediate pebbles in the grain, calculating the index for its shape (approaching a sphere, a disk or a rod). The profiles studied were Pedras (Profile 1, Figure 1), Funil (Profiles 2a and 2b) and Extrema (Profile 3). The distribution of the 28 analyzed samples was chosen regarding the depositional strata in each profile analyzed, totalizing 28 samples (Figure 1). Finally, the fourth stage involved the interpretation of the data.

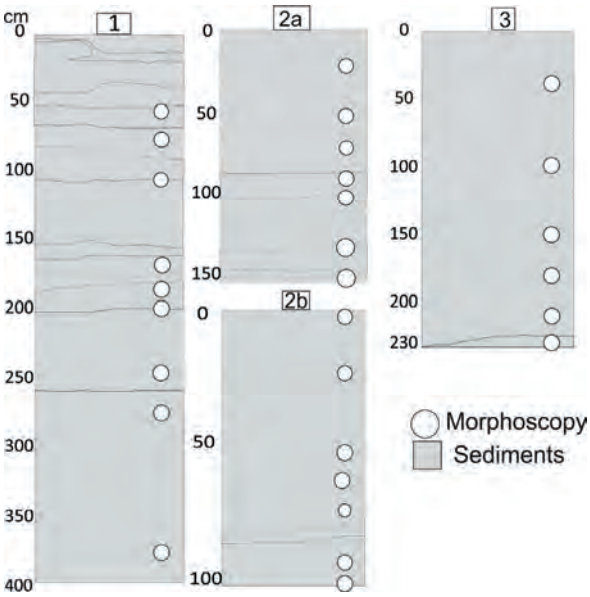

Figure 1: Distribution of samples in Profile 1 (Pedras), Profile 2/a-b (Funil) and Profile 3 (Extrema)

3. Results

In the studied dry valleys, four profiles were analyzed, and present a variety of sediment types. The Pedras succession (Profile 1) showed a deposition of essentially sandy materials with rounded and sub-rounded pebbles in addition to sparse coal fragments. The stratification of the layers is plane-parallel. In the upper strata, closer to the surface, more clayey deposits are observed, also including technogenic (anthropic influencer) deposits from nearby limestone extraction areas. The morphoscopy analysis showed that most grains have a diameter below 25 µm, reaching 80 µm at 170 cm depth and almost 100 µm at 60 cm depth. The Pedras profile in general showed a circularity index higher than 0.8, with a significantly lower circularity index at 200 cm and 380 cm depth in the profile.
Both profiles of the Funil depositional system (2a and 2b) have different deposit layers, the profile 2a present, a small sandy layer at the base, a thick stratum of calcareous tufa mixed with a high silt fraction and a porous wavy crust rich in molluscs fossils. At the top of the profile, a silty clay material seals the underlying layers. Profile 2b, however, is composed of two main sedimentary units, one essentially sandy at the base and the second is composed of silty clay layers. Regarding the morphoscopy analysis of this profile, the second largest diameters were found close to the surface (~20 cm in depth). The circularity index was higher than 0.8 in all the samples of the profile. However, in profile 2b, a variation of the circularity index is noticed towards the base with a significant increase in the lower part.

Profile 3 (Extrema) presents three main deposit units from base to top: angular blocks of limestone and sandy material at the base, sandy sediments with fragments of coal, and finally, the sandy layers with organic material.

The Profile 3 shows a considerable increase in the grains diameter close to the surface (40 cm) and in the middle of the profile, (180 cm in depth) while in the rest of the profile, grain diameter remains low, less than 10um. The circularity is higher than 0.7, with a decreasing trend towards the base.

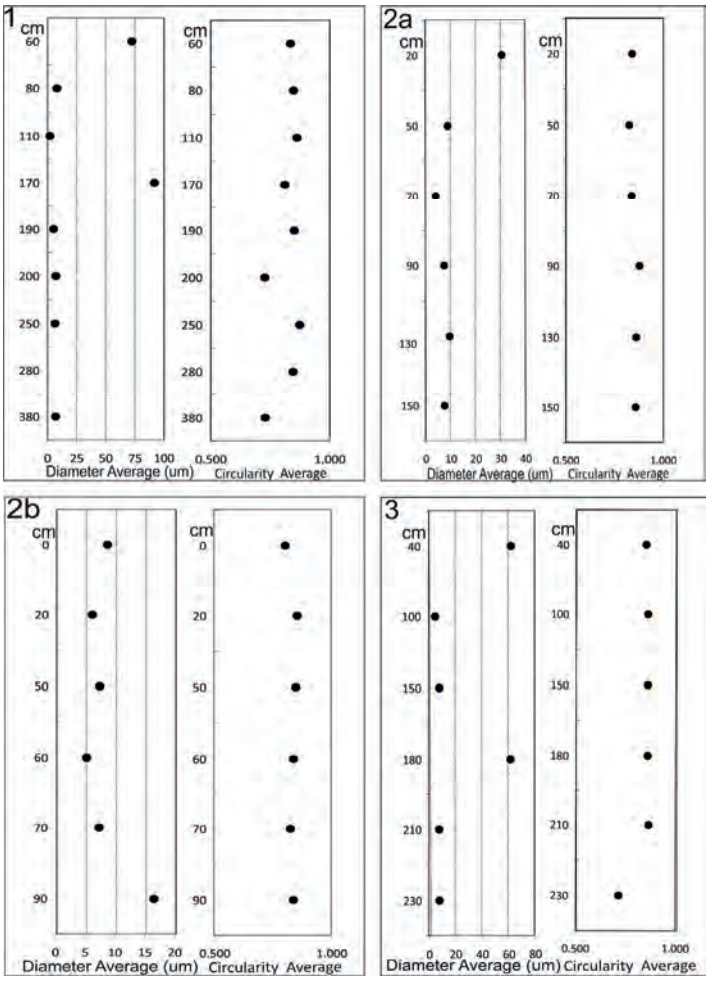

Figure 2: Diameter and average circularity of the analyzed samples Profile 1 (Pedras), Profile 2/a-b (Funil) and Profile 3 (Extrema)

4. Discussion

The studied sediments are originally fluvial deposits that transited through the underground karst system and deposited on nowadays abandoned dry valleys. The high sphericity of the grains may be related to the geomorphological context, since the paleo-rivers originate from the edge of Serra Geral, associated with the Urucuia Group and Chapadão Formation groups. The Urucuia Group, basically composed of sandstones, has three lithofacies that indicate sedimentation processes in a desert environment, dominated by eolian transport. This formation is basically composed of quartz grains, with fine to medium grain-sized particles and rounded grains. The Chapadão Formation outcrops significantly in the area and corresponds to lateritic dendritic and unconsolidated sands, which resulted from an intense erosive process (CAMPOS & DARDENNE, 1997; CRUZ, 2012b; BERBERT-BORN & TRINDADE, 2003; SIQUEIRA, 2017).

The grain size can be related to the transport distance from the source area. The more distal the source area, the higher the degree of reworking of the grains will be and consequently the smaller the grain-size will be at the time of deposition. The grain diameter can also vary depending on the flow energy, which in turn is linked to paleoclimatic variations. Wetter periods suppose priorly higher water availability and therefore higher transport capacity (HENRIQUES & VALADÃO, 2017; SUGUIO, 1973). Such variations are observed in Profile 3, which presents two phases of similar character with a considerable increase in grain size at a certain depth.

Furthermore, there are other factors that can influence the grain size, such as the original morphology of the minerals present in the lithology, their cleavage, *in situ* chemical processes, etc. (SUGUIO, 1973).

5. Conclusion

Morphoscopic analysis, involving diameter and circularity index, proved to be an interesting technique in the characterization of sedimentary deposits. From the data obtained, it was possible to identify sedimentary variations in the analyzed profiles that may be linked to source areas and/or climatic variations. The characteristics of the grains are in agreement with the literature for the indicated source area.

However, further analyses on other profiles are necessary to confirm these understandings. Such information, linked to other techniques, make it possible to define environmental conditions (for example anthropogenic, climatic and tectonic changes) and to propose models of landscape evolution.

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Record of the Pyrenean climate since the last Interglacial by two stalagmites from Moulis Cave (Ariège, S. France)

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Abstract

Two small stalagmites from the northern Pyrenean piedmont in SW France provide a discontinuous record of past climates between the last interglacial and the Holocene. Aims of the present work are twofold : 1. To evaluate the potential of the studied stalagmites as reliable paleoenvironmental / paleoclimatic archives; 2. To describe the various spelaean facies and their significance in terms of growth history and hydrological information about the infiltration conditions and drip-rate feeding the speleothems at time of their formation. For this purpose, we used a set of petrographical-geochemical techniques to characterize the successive growth units and internal architecture of stalagmites. Results show that stalagmite grew discontinuously from MIS 5 to 3.8 kyrs and presents several surfaces of growth interruption, some of which correspond to important hiatus evidenced by U-Th dating. Three active and relatively fast growth phases correspond to the MIS 5a-b , the Bølling-Allerød and Younger Dryas and to the Lower Holocene (11.6 to 6.2 kyrs). During the uppermost phase (between 6.2 and 3.8 kyrs), the stalagmite growth rate decreases drastically.

Résumé

Enregistrement du climat pyrénéen depuis le dernier interglaciaire par deux stalagmites de la Grotte de Moulis (Ariège, S. France). Deux petites stalagmites provenant d'une grotte du piémont nord pyrénéen dans le sud-ouest de la France ont fourni un enregistrement discontinu du paléoclimat entre le dernier interglaciaire et l'Holocène. Les objectifs de ce travail sont: 1) d'évaluer le potentiel des stalagmites étudiées en tant qu'archives paléoenvironnementales / paléoclimatiques; et 2) de décrire les différents faciès de ces spéléothèmes et leur signification en termes d'histoire de croissance et d'informations hydrologiques sur les conditions d'infiltration et les variations de débit d'alimentation des spéléothèmes au moment de leur formation. Pour cela, nous avons utilisé un ensemble de techniques analytiques pétrographiques et géochimiques pour caractériser les unités de croissance successives et l'architecture interne des stalagmites. Les résultats montrent que le spéléothème s'est développé de manière discontinue entre le MIS 5 et 3,8 ka et présente plusieurs surfaces d'arrêt de croissance, dont certaines correspondent à un hiatus important mis en évidence par les datations U-Th. Trois phases de croissance active et relativement rapide correspondent respectivement au MIS 5a-b, au Bølling-Allerød et au Dryas Récent, ainsi qu'à l'Holocène inférieur (11.6 - 6.2 ka). Au cours de la phase la plus récente (entre 6,2 et 3,8 ka), le taux de croissance de la stalagmite a diminué considérablement.

1. Introduction

This paper reports on two small stalagmites from the northern Pyrenean piedmont in SW France, which provide a discontinuous record of past climates between the last interglacial and the Holocene. The high potential of speleothems as reliable recorders of paleoclimate and environmental conditions is largely recognized and, for this purpose, there are a number of proxies which can be extracted from their petrography and geochemistry. The objectives of this work are twofold : 1. To evaluate the potential of the studied stalagmite as a reliable palaeoenvironmental / palaeoclimatic archive spanning various time-slices since the last interglacial. 2. To describe the various spelaean facies and their significance in terms of growth history and hydrological information about the infiltration conditions and drip-rate feeding the stalagmite at the time of its formation.

2. Setting, materials and methods

Moulis cave is located a few kilometers SW of the small city of Saint-Girons (Ariège), on the northern side of the Pyrenean range, and is developed in the Jurassic limestones and dolostones of the Arize massif sedimentary cover (Fig. 1). The two stalagmites presented here, MOU 4 and MOU 5 were found broken in a small gallery close to the entrance of the cave. The methodological approach used for the study of Moulis speleothem is basically the one described in PERRIN *et al.* (2019) for optimizing subsampling in speleothems, combined with more classical petrographical – geochemical analysis and also methods recently developed for understanding controls on the internal architecture of stalagmites (RAILSBACK 2013, PERRIN *et al.* 2014, MUÑOZ-GARCÍA *et al.* 2016, MARTÍN-CHIVELET *et al.* 2017). Large thin sections prepared continuously along the median growth axis of both stalagmites were observed with an optical petrography microscope and a fluorescence microscope. Raman microspectrometry was performed on thin sections to confirm and complete mineralogical identifications obtained from observations of thin sections with the petrographic microscope. SEM observations and EDS-microanalysis complete this dataset.

The stalagmite MOU 4 was sampled for U-Th dating. Ten subsamples were analyzed with a MC-ICP-MS at the Geotop (Montreal, Canada). Ages are reported in kyrs BP.

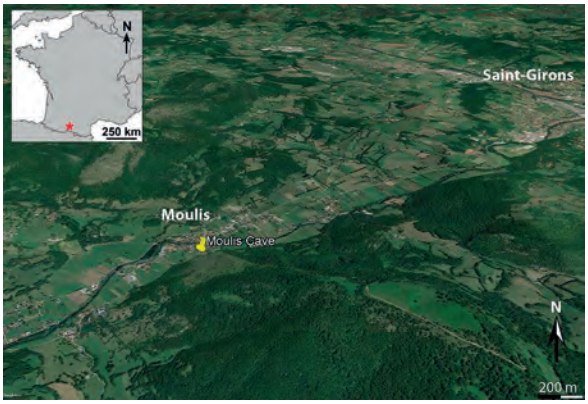

Figure 1: Location of Moulis Cave (aerial view Google Earth).

3. Results

Mineralogical species and potential diagenesis

The spelaean material consists of calcite, with no aragonite detected in the two stalagmites. Detrital material includes dolomite, quartz, iron oxides and hydroxides.

Neither detailed petrographical observations and SEM-EDS analyses, or Raman microspectrometry data have shown presence of aragonite or indication of recrystallization of aragonite into calcite. In both samples, calcite is therefore essentially primary. The two stalagmites are considered in a good state of preservation although partial dissolution processes have been evidenced at level of some discontinuities and at the base of MOU 5.

Facies and lamination

Several types of calcite are observed in both speleothems, the most common of which being the compact columnar calcite and the open columnar calcite. These form the major part of MOU 4 and upper part of MOU 5 and show a brown-green aspect in polished sections. Elongated columnar calcite is present at some levels and often bears some laminated layers of brown color in transmitted light and white-cream aspect in polished sections. These layers are rich in tiny elongated pores and organic components. The basal part of MOU 5 consists of coralloid knobs formed by radial-fibrous calcite (*sensu* KENDALL 1985).

Petrographical and luminescence microscopy, together with SEM imaging and EDS microanalysis, reveal the presence of different types of laminae (Fig. 2): visible laminae resulting from contrasting density of micropores (GENTY & QUINIF 1996), luminescent laminae and geochemical laminae expressed by slight differences in Mg-content.

Lamination occurs at different scales, the finest alternance of laminae (both visible and luminescent laminae) being annual.

Discontinuities

Three types of surfaces have been recognized in the two stalagmites. These are type E bounding surfaces associated with partial dissolution (RAILSBACK *et al.* 2013), growth interruption marked by a detrital clay deposit and discontinuities resulting from abrupt facies change (PERRIN *et al.* 2014, MARTÍN-CHIVELET *et al.* 2017).

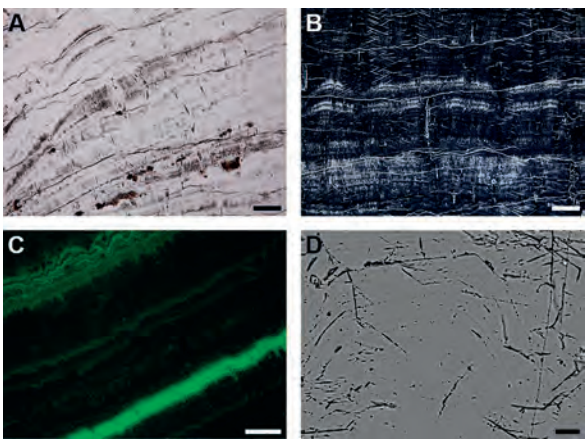

Figure 2: Lamination. A. Visible laminae, transmitted light, scale 500 µm. B. Visible laminae, dark field, scale 500 µm. C. Luminescent laminae, reflected light and GFP filter, scale 100 µm. D. Geochemical laminae, SEM BSE image, scale 10 µm.

Ten major surfaces have been identified in MOU 4 and five in MOU 5. These surfaces represent the boundaries of the major growth units. In both samples, additional minor surfaces occur (Fig. 3).

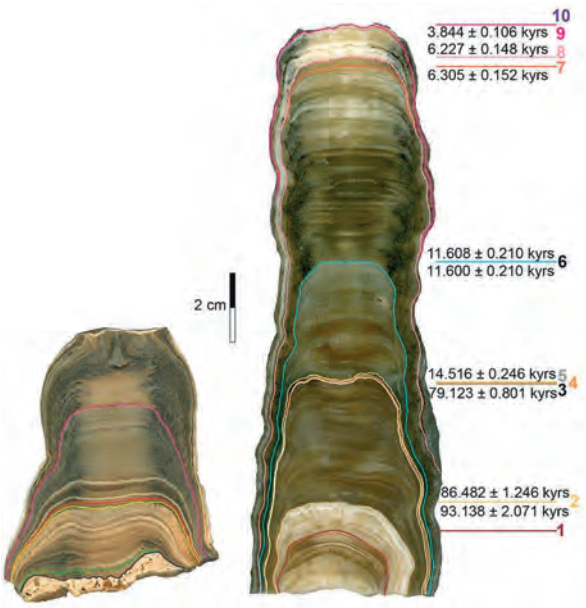

Figure 3: Median polished slabs of stalagmites MOU 4 (right) and MOU 5 (left) with major discontinuities (colored lines) and U-Th ages of MOU 4.

U-Th dating

Ten subsamples were selected in MOU 4 for U-Th dating. U-Th analyses provided ages ranging between 3.8 ± 0.1 kyrs and 93.1 ± 2.1 kyrs. These results show the occurrence of two major hiatus, both corresponding to major discontinuities during the development of MOU 4.

The second major surface corresponds to a growth interruption of about 6-7 kyrs while the group of discontinuities 3-5 represent a condensed level of about 6465 kyrs (Fig. 3).

Evolution of apex morphology and stacking pattern.

Both stalagmites nicely show that morphology of their apex and stacking pattern of growth layers have evolved through time. We have analyzed these variations in detail in order to get information about drip rate conditions during stalagmite growth.

After the first growth phase of coralloid knobs at the base, MOU 5 adopts a rimmed-shape apex morphology with a marked progradational stacking pattern. This gradually evolves into a flat-topped stalagmite with a retrograde geometry. Above the youngest major discontinuity, the apical morphology changes back to a rimmed shape during a mostly aggradational growth phase (Fig. 3).

MOU 4 consists of ten growth units bounded by major discontinuities. These units successively record changes from globular to irregular flat-topped, and rimmed apical shape before 79 kyrs. After the main condensed level and until the end of Pleistocene, apex morphology varies from rimmed to flat-topped and growth is characterized by largely dominated aggradational and retrograde trends. From the beginning of Holocene until 6.2 kyrs, the morphology of MOU 4 changes gradually from a rimmed to a flat top while the stalagmite widths vary from slightly progradational to aggradational with brief periods of retrograde stacking pattern.

4. Climate and hydrological record

The internal architecture, microstratigraphy and petrography of both samples express changes in the feeding patterns of both stalagmites in terms of drip rate variability, supersaturation state of feeding water relative to calcite, and infiltration events.

The lower half of MOU 5 records a higher drip rate variability relative to its upper part, periods of high infiltration associated with higher concentration in organic compounds. The upper part of MOU 5 is characterized by more homogeneous conditions with low and constant drip rate and low drip rate variability.

The basal unit of MOU 4 reflects changing conditions of drip rate variability and infiltration pattern and supersaturation state. During the interstadials 5b-5a of the last interglacial (86.5 – 79.1 kyrs), MOU 4 developed with a rather moderate growth rate and stable drip rate conditions. The full glacial period corresponds to a condensed level (79.1 to 14.5 kyrs) and three successive major growth interruptions in the stalagmite. MOU 4 resumed its growth at the beginning of the Bølling (14.5 kyrs) which was accompanied by a marked increase of warmth and moisture. The constant and moderate drip rate and low drip rate variability favored a relatively high growth rate for MOU 4. The Younger Dryas is recorded petrographically by a change from compact columnar calcite to open columnar calcite and an increase in drip rate variability. The lower Holocene until 6.2 kyrs corresponds to the period of highest growth rate for MOU 4. Hydrological conditions are rather stable and homogenous during the lower half of this unit and gradually become more variable toward the top. During the uppermost growth phase (between 6.2 and 3.8 kyrs), the growth rate of MOU 4 decreased drastically as a result of increasing frequency of high infiltration events and a decrease in supersaturation relative to calcite.

Acknowledgments

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Speleothems in iron ore caves in the Carajás National Forest, southeast Amazon

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Abstract

In the Carajás National Forest, about 1,500 caves in iron ore and canga deposits have been identified. The speleothems in these caves are all relatively small in size. Crusts and coralloids prevail, but draperies, small rimstone dams, irregular forms known as *pingentes* hanging from the ceilings, similar to stalactites, are also present. These speleothems are mainly formed of hematite, goethite and gibbsite, derived from the weathering of the cave bedrock. In caves with guano deposits, speleothems are larger and more abundant. Coralloids, crusts, stalactites, draperies, stalagmites and columns predominate, and are composed of phosphate, especially leucophosphite, phosphosiderite, strengite and spheniscidite. Sulphate crusts are present and consist of gypsum, aluminite and felsőbányaite. Phosphate and sulphate minerals are related to leaches resulted from the bacterial decomposition of guano, which react with rock or sediment to form speleothems. Using radiocarbon dating, guano trapped in a 17 cm long phosphate stalagmite was dated to 10.2 cal kyr BP (bottom) and 3.8 cal kyr BP (top), providing, to our knowledge, the first dates for phosphate speleothems in caves, and giving us a reference for the growth rate of these rare formations.

1. Introduction

The Carajás National Forest (CNF) covers an area of 411,949 ha and is located in the southeastern Brazilian Amazon, approximately 540 km south of Belém, the Pará State capital. Geologically, the Carajás Formation stands out, as a Neoarchean metavolcanosedimentary sequence within the Grão Pará Group. It is composed of banded iron formations (BIF) represented by jaspilites. The iron formation is covered by iron breccia generically known as canga, which act as caprock on plateau tops, regionally represented by the Carajás Ridge. The average temperature is 23°C and annual rainfall reaches 2,400 mm (PILÓ *et al*. 2015). Over 1,500 small caves have already been identified in the CNF some of which host more than 100,000 insectivorous bats (*Pteronotus gymnonotus* and *Pteronotus personatus*) and there are important guano deposits in them. In general, the caves are small, on average 30 m long. Dripping is significant inside the caves due to their proximity to the surface and porosity of the canga. Some caves function as springs. Temporary drainage channels can also occur. Speleothems of CNF caves have been reported by MAURITY & KOTSCHOUBEY (1995), PILÓ & AULER (2011), SCHERER *et al.* (2017), ALBUQUERQUE *et al.* (2018) and FIGUEIRA, *et al.* (2019). This work presents studies on speleothems from 36 caves in the region, totalling 91 samples of speleothems and 22 samples of guano for chemical, mineralogical and chronological analyses.

2. Materials and methods

To characterize the speleothems, the study selected 36 of the caves in the Carajás Ridge including 11 with large guano deposits (bat caves). Ninety-one samples of speleothems were collected for mineralogical and chemical analysis. The analyses were performed at the technological characterization laboratory of the Polytechnical School at the University of São Paulo – USP. The mineralogical analyses used the powder method and a Panalytical X-ray diffractometer (X'Pert model with an X'Celerator detector).
The chemical analyses (oxides) used an XRF spectrometer manufactured by Malvern Panalytical (Zetium model). Twenty-two guano samples were analysed at the Organic Correctives, Fertilizers and Residues Laboratory of the Luiz de Queiroz Higher School of Agriculture - ESALQ/USP. The determinations and methods used were: Phosphorus (P_2O_5) using a spectrophotometer and a vanadomolybdenic solution; Potassium (K_2O) and Sodium (Na) using flame photometry; Sulphur (S) using gravimetric technique with precipitation of Barium sulphate; Calcium (Ca), Magnesium (Mg), Copper (Cu), Manganese (Mn), Zinc (Zn), Iron (Fe) using extraction with HCl for atomic absorption photospectrometry. ^{14}C dating of eight guano samples and two stalagmite samples was carried out at the Beta Analytic Laboratory, Miami (USA), using Accelerator Mass Spectrometry (AMS) technique. In the stalagmite, the dated carbon originates from guano, deposited and intercalated with laminations of phosphate minerals (Figure 2).

3. Results

The main speleothems identified in the iron ore caves were coralloids, crusts, flowstones, *pingentes*, stalactites, stalagmites and columns (PILÓ & AULER, 2011, PILÓ *et al*. 2015). The coralloids are small, may be nodular, globular, botryoidal or coral-like in shape and situated mainly on walls, floors and boulders on the cave floor. Coralloids colours vary; they may be whitish, red, yellowish, dark brown or light grey. Coralloids can consist of iron oxide-hydroxide, especially hematite and goethite or of phosphates particularly strengite, $Fe^{3+}(PO_4)\cdot 2H_2O$), leucophosphite, $KFe^{3+}{}_2(PO_4)_2(OH)\cdot 2H_2O$, and phosphosiderite, $Fe^{3+}(PO_4)\cdot 2H_2O$ (usually associated) and less often, spheniscidite, $(NH_4)Fe^{3+}{}_2(PO_4)_2(OH)\cdot 2H_2O$, taranakite, $K_3Al_5(PO_3OH)_6(PO_4)_2\cdot 18H_2O$), rodolicoite, $Fe^{3+}(PO_4)$, and hureaulite - $Mn^{2+}{}_5(PO_3OH)_2(PO_4)_2\cdot 4H_2O$. Two sulphates were also detected among the coralloids, gypsum, $Ca(SO_4)\cdot 2H_2O$, and jarosite - $KFe^{3+}{}_3(SO_4)_2(OH)_6$.

Coralloids composed exclusively of iron phosphates usually present from 36% to 38% of P_2O_5 and 38% to 40% of Fe_2O_3. Phosphates associated with sulphates may contain up to 13.6% of SO_3. The crusts are relatively frequent in the caves and may cover small areas or in some cases, practically the entire cave. They are generated by seeping and flowing water. Crusts mainly cover the floors, but they can also cover walls, ceilings and boulders. They may be compact, laminated, banded or microbreccia and can be up to a few centimetres thick. Crusts can be red, yellow, white or dark grey. Crusts predominantly consist of hematite, Fe_2O_3, goethite, FeO(OH), and phosphates (strengite, phophosiderite, leucophosphite taranakite, hannayite, $(NH_4)_2Mg_3(PO_3OH)_4\cdot 8H_2O$, spheniscidite and variscite - $Al(PO_4)\cdot 2H_2O$. Crusts formed by bayerite, $Al(OH)_3$, were also documented. Crusts formed by sulphates alone (gypsum, aluminite, $Al_2(SO_4)(OH)_4\cdot 7H_2O$, and felsőbányaite, $Al_4(SO_4)(OH)_{10}\cdot 4H_2O$, were identified as well as others associated with phosphate (francoanellite - $K_3Al_5(PO_3OH)_6(PO_4)2\cdot 12H_2O$. Crusts formed exclusively by phosphates (newberyite, $Mg(PO_3OH)\cdot 3H_2O$, and monetite, $Ca(PO_3OH)$ consisted of 21.7% MgO, 40% P_2O_5 and 3.4% CaO. Other speleothems present in the caves are flowstones on the walls, originating from solutions seeping from fractures and small conduits known as canaliculi. The flowstones may form draperies and small rimstone dams on sloping walls, their colours being predominantly red, yellow and light brown.

The flowstones are mainly composed of Fe and Al oxyhydroxides (goethite, hematite, gibbsite, $Al(OH)_3$, lepidocrocite - $Fe^{3+}O(OH)$, and bayerite - Al(OH)3. Flowstones composed exclusively of phosphates (associations of phosphosiderite, spheniscidite and strengite), were less common. A sample of flowstone composed of iron and aluminium oxides and hydroxides consisted of 80.8% F_2O_3 and 2.9% Al_2O_3. The *pingentes* are downward projections from the ceiling or sloping walls consisting of ferruginous material similar to stalactites but with no central canal or concentric lamination. In general, they have many empty spaces inside them. They are either red or reddish brown and can be up to 30 cm long but just a few centimetres wide. Analysis of samples indicated a composition of oxides and hydroxides of iron (hematite, goethite and lepidocrocite) and aluminium (gibbsite). Stalactites and stalagmites are the most surprising forms in the iron ore caves (Fig. 1). The stalactites have a central canal, concentric growth layers and lengths of up to 1.5 metres. These rare speleothems are usually either dark brown, yellowish or reddish in colour.

Figure 1: Stalactites, stalagmites and columns of phosphatic minerals in cave S11B-0094. Photo: Ataliba Coelho.

The stalagmites have convex lamination and may take the shape of a cone or a candle. They are less frequent in occurrence than the stalactites and may reach a height of 50 cm. There are also some columns in the caves. The analysis of 18 samples of stalactites and stalagmites only identified phosphatic minerals paragenesis: spheniscidite-leucophosphite, strengite-phosfosiderite, leucophosphite-spheniscidite-phosphosiderite and leucophosphite-phosphosiderite-strengite-spheniscidite. In some of the samples, however, only a single phosphate was identified (leucophosphite or strengite). One iron phosphate stalactite registered 37.5% of P_2O_5 and 41.3% of Fe_2O_3.

Significant guano deposits were identified in the bat caves; they are rich in organic matter, high concentrations of C (40.1%), N (11.7%), P_20_5 (1.9 to 22.9%), Fe_2O_3 (1.2 to 22.3%) and minor but important content of K_2O (0.1 to 1.7%), CaO (0.03 to 4.8%) and SO_3 (0.1 to 6.4%). Guano pH ranged from 2.1 to 5.6. Phosphate minerals (spheniscidite, leucophosphite, hannayite, biphosphammite, $(NH_4)H_2(PO_4)$, and brushite, $Ca(PO_3OH)\cdot 2H_2O$, sulphates (gypsum, syngenite, $K_2Ca(SO_4)_2\cdot H_2O$, aphthitalite, $K_3Na(SO_4)_2$, and bassanite, $Ca(SO_4\cdot 0.5H_2O)$ and a nitrate gwihabaite, $(NH_4)(NO_3)$, have been identified in acid guano. ^{14}C dating of eight guano samples taken from the base of the deposits in six bat caves first identified two of them as dating from the end of the Pleistocene: 22,876 – 22,469 cal yr BP (Beta 544608) and 18,191 – 17,857 cal yr BP (Beta 521294). One sample corresponded to the upper Holocene 7,891 – 7,878 cal yr BP (Beta 521292). All the other sample datings were for the period of the last 4 thousand years 3,450 – 3,323 cal yr BP (Beta 544609), 2,464 – 2,305 cal yr BP (Beta 521293),

2,183 – 2,015 cal yr BP (Beta 521295), 2,018 – 1,890 cal yr BP (Beta 544607) and 1,882 – 1,728 cal yr BP (Beta 527797). Two ages were obtained from the guano that was intercalated with phosphate from a 17 cm long stalagmite (Figure 2). The base was dated as 10,296 - 10,187 cal yr BP (Beta 534951) and the top as 3,892 – 3,694 cal yr BP (Beta 534952).

4. Discussion

Speleothems in iron ore caves with no extensive guano deposits are of local occurrence and small, possibly due to the low dissolution of iron (III). In these caves there can be occurrences of coralloids, flowstones and crusts, mainly constituted of Fe and Fe/Al oxides and hydroxides, but there may be occurrences of phosphates associated to small, dispersed guano occurrences. The source of Fe and Al is undoubtedly the surrounding iron-bearing bedrock. The presence of Al is more marked in the canga (PILÓ & AULER, 2011). According to MAURITY & KOTSCHOUBEY (1995), the slow dissolution of oxides and hydroxides in the canga enables the mobilisation of Fe and Al in the form of colloids that flocculate after limited transport by the water flows, generating thin deposits of gels.

Figure 2. Sectioned phosphatic stalagmite showing the locations where samples were taken from for radiocarbon dating to obtain the ages.

The dehydration and crystallization of those amorphous products resulted in the generation of the speleothems in the Carajás caves. KAMP & CURI (2000) underscored that the main processes for the dissolution of iron are protonation, reduction by microorganisms and complexation by organic ligands. The soluble Fe (II) can circulate in the caves, oxidise and re-precipitate, generating secondary minerals. PARKER *et al.* (2013) demonstrated the action of reducing bacteria on Fe (III) in iron ore caves of Carajás. However, the greater diversity, abundance and size of speleothems is found in the bat caves. In those caves, which are larger than the regional average, it is possible to encounter stalactites, stalagmites, columns, coralloids and crusts sometimes almost entirely covering the floor, walls and ceilings. Phosphate speleothems predominate but sulphates also occur to a lesser extent. The phosphatic minerals in the bat caves are derived from guano, given that the banded iron formation of Carajás has very low P_2O_5 content (an average of 0.01%), according to MACAMBIRA & SCHRANK (2002). A variety of complex reactions takes place in the guano, especially bacterial decomposition, liberating nitric, phosphoric and sulphuric acids which react with rock or the sediments to form the secondary minerals (ONAC & FORTI, 2011; AUDRA *et al*. 2019). Inside the guano deposits the sulphuric acid reacts with the rock to form sulphates, notably gypsum, and the reaction with phosphoric acid produces phosphates (ONAC & VERES, 2003; HILL & FORTI, 1997). The guano deposits are acidic (pH 2.1 to 5.6) and samples from the base of the deposits are the most acidic, as already observed by WURSTER *et al.* (2015). In addition to expressive P_20_5 and Fe_2O_3 content the guano has K_2O, CaO, Na_2O, and SO_3 availability. Added to that, in the bat caves, are high humidity, high temperatures (>30°C in the inner zones) and the presence of ammonia originated from decomposition of bat urea. Those conditions have made the formation of a whole set of diversified phosphate and sulphate minerals possible, including rare ones like rodolicoite and hureaulite. Radiocarbon dating of guano samples indicates ages ranging from the end of the Pleistocene (22.0 cal kyr BP) testifying to the long duration of the presence of bat colonies in the caves. Another dating registered was for the beginning of the Holocene (8.0 cal kyr BP). Five ^{14}C in different bat caves placed the beginning of their guano deposits at times more recent than 3.5 cal kyr BP. None of the identified deposits were thicker than 1 m. Given the intense water activity (dripping and small flows) in most of the bat caves the guano deposits are being eroded and transported out of the caves. The identification of the most ancient deposits awaits a more ample prospection. Guano included in a well-laminated phosphatic stalagmite 17 cm long was dated, which gave an age for its base at 10.2 cal kyr BP and at the top 3.8 cal kyr BP. Not considering possible interruptions in the dripping of phosphate rich water and other variables such as climate, then the growth rate of that phosphatic stalagmite was 0.026 mm/year.

5. Conclusion

Most of the speleothems in the iron ore caves of the CNF are relatively small features mainly formed of hematite, goethite and gibbsite, derived from the weathering of the iron-bearing rock with a predominance of crusts and coralloids. In the active or inactive bat caves with deposits of guano, the speleothems are larger more abundant and more diversified. Coralloids, crusts, stalagmites and stalactites predominate, largely composed of phosphate, most notably, the minerals leucophosphite, phosphosiderite, strengite and spheniscidite. Sulphate crusts are also present consisting of gypsum, aluminite and felsőbányaite. The sulphate and phosphate minerals are related with the bacterial decomposition of guano which reacts with the rocks or sediments to form the speleothems. Radiocarbon dating in guano deposits indicate ages from around the end of the Pleistocene (22.0 cal kyr BP) to the Holocene (1.8 cal kyr BP), evidence of the long duration of bat colonies presence in the caves. One 17 cm-long phosphate stalagmite was dated thanks to the 14C dating of included guano layers, producing a first age information for phosphate speleothems in caves and a reference for the growth rate of these rare formations.

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Spéléothèmes des grottes *vs* spéléothèmes des systèmes anthropiques (carrières, souterrains …). Problèmes chronologiques et apport des éléments traces pour étudier et reconstruire les climats et/ou l'occupation ou l'utilisation des sols dans le passé.

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Résumé

Les spéléothèmes (de grottes ou de systèmes anthropiques comme les carrières ou les souterrains) sont utilisés depuis plus de 40 ans pour les reconstructions paléoclimatiques ou paléo-hydrologiques. Plus récemment, ils ont montré leur utilité pour retracer des changements dans l'occupation et l'utilisation des sols. Nous montrerons à travers plusieurs exemples, que si dans de nombreux cas des chronologies fiables peuvent être obtenues en utilisant les séries de l'uranium (U/Th), dans d'autres situations il est nécessaire de coupler des méthodes complémentaires (i.e. avec le ^{14}C ou le comptage des lamines par exemple). Une attention particulière sera portée sur l'utilisation des éléments traces et notamment les terres rares pour reconstruire les changements environnementaux ou climatiques passés. Nous comparerons en particulier leur étude dans un spéléothème de grotte (Sud de la France) et dans des spéléothèmes prélevés en milieu urbain (Paris), avec dans un cas la caractérisation du rôle et de la contribution des sols en fonction des changements du climat et dans l'autre celle de l'occupation du sol et son utilisation (activités anthropiques).

Abstract

Cave speleothems vs. speleothems in anthropogenic systems (quarries, underground ...). Chronological problems and the contribution of trace elements to the study and reconstruction of climates and/or land use in the past. Speleothems (from caves or from anthropogenic systems such as quarries or undergrounds) have been used for more than 40 years in paleoclimatic or paleo-hydrological reconstructions. Lately, they have shown their usefulness for the reconstruction of land use change. We will show through several examples, that if in many cases, reliable chronologies can be obtained by using uranium (U/Th) series, in others cases it is necessary to use several methods (i.e. cross analysis with ^{14}C or laminae counting for example). Particular attention will be given to the use of trace elements and especially rare earths elements for environmental reconstructions. Speleothem from a natural cave setting in southern France will be compared to speleothems-like deposit from urban areas (Paris), with in one case the reconstruction of soil activity according to climate variations and in the other that of land use (human activities).

1. Introduction

Les spéléothèmes sont de formidables archives climatiques. D'une part car ils peuvent, dans de nombreux cas être datés de manière absolue par la méthode uranium-thorium sur les derniers 600 000 ans (LI *et al*. 1989 ; HELLSTROM 2003) ou sur des périodes plus courtes par des méthodes relatives (PONS-BRANCHU *et al.,* 2014). D'autre part, l'analyse de traceurs géochimiques nous renseigne sur les conditions environnementales régnant au moment de leur dépôt. Les indicateurs environnementaux étudiés dans ces archives sont principalement les isotopes stables du carbone et de

l'oxygène (LABEYRIE *et al.,* 1967, FOHLMEISTER *et al*., 2020), mais aussi les teneurs ou rapports en éléments mineurs et traces (FAIRCHILD & TREBLE, 2009). Parmi ces éléments, les lanthanides, du nom du premier élément de cet ensemble (lanthane) auquel s'ajoutent l'Yttrium et le Scandium pour former le groupe des terres rares (rare earth elements-REE en anglais) sont encore très peu étudiées dans les spéléothèmes (BOURDIN *et al*., 2011). Les terres rares se caractérisent par des propriétés géochimiques relativement similaires. Elles sont par exemple toute trivalentes dans les conditions oxydo-réductrices de surface, à l'exception du Cérium (divalent ou trivalent), état spécifique de cet élément souvent à l'origine d'une anomalie négative ou positive dans un spectre de terres rares normalisées. Du fait de leurs rayons ioniques diminuants avec leur masse, les terres rares trivalents se distribuent et s'alignent sur un spectre normalisé, différemment selon leur comportement au cours des processus d'altération ou d'incorporation dans les minéraux. Les terres rares sont très utilisées dans les études de géochimie de surface, notamment pour l'étude des processus d'altération (CULLERS *et al*., 1987). Cependant, elles sont encore très peu étudiées dans les spéléothèmes.

Dans cet article, nous comparons l'utilisation des terres rares dans trois cas d'études différents, provenant de sites contrastés : un spéléothème de grotte naturelle (grotte de la Salamandre, Gard), un spéléothème de souterrain à Paris (aqueduc de Belleville) et un spéléothème souterrain d'une carrière au sud de Paris (Carrière de la Brasserie). Les deux premiers cas sont tirés de publications récentes (DRUGAT *et al.*, 2019 ; PONS-BRANCHU *et al.,* 2014) et le troisième est une étude inédite.

2. Matériel et méthodes

Les 3 sites de prélèvement, ont en commun d'être peu profonds. Les spéléothèmes ici étudiés se forment à partir d'infiltrations d'eau pluviales et sont tous laminés.

-**Salam 3** est une stalagmite de 50 cm de hauteur, prélevée dans l'Aven de la Salamandre (Gard), qui s'est développée pendant près de 2500 ans au cours de la transition entre la dernière période glaciaire et l'Holocène (DRUGAT *et al*., 2019). La chronologie a été déterminée par la méthode uranium thorium (U/Th), classiquement utilisée pour les spéléothèmes de plusieurs milliers d'années, avec correction de la fraction détritique par la méthode stratigraphique (ROY-BARMAN & PONS-BRANCHU 2016).

-**Bel 2** est une concrétion de 4 cm d'épaisseur prélevée dans l'aqueduc de Belleville (au nord de Paris) et dont la croissance couvre les derniers 300 ans (PONS-BRANCHU *et al.,* 2014). La chronologie a été déterminée par comptage des lamines et datations absolues (U/Th). Le croisement des 2 méthodes a permis de valider que la lamination des spéléothèmes de ce site en zone très urbaine est bi-annuelle comme dans les sites « naturels » des zones climatiques similaires.

-**Bras 1**, de 1 cm d'épaisseur seulement a été prélevé dans la carrière de la Brasserie à Paris (Figure 1) taillée dans les calcaires du Lutétien. Le concrétionnement était actif au moment du prélèvement (année 2012). Les lamines bien que présentes, sont peu marquées et leur comptage peu évident. Cet échantillon étant trop mince pour effectuer des prélèvements d'assez de matériel pour réaliser des datations U/Th, et son développement certainement très récent font que cet échantillon est un mauvais candidat pour utiliser cette méthode de datation.

10 mg de poudre ont été prélevés au sommet de la concrétion Bras 1 pour une analyse ^{14}C. L'objectif est ici d'évaluer la quantité de carbone mort pour tester la faisabilité de la datation ^{14}C dans ces concrétions. Les analyses ont été réalisées par l'équipe du Laboratoire de mesure du carbone 14 (LMC14) sur l'instrument national Artemis, suivant le protocole décrit dans DUMOULIN *et al*. (2017). Sur 3 niveaux, environ 3 mg ont été prélevés pour les analyses des éléments traces. Les échantillons ont été dissous dans l'acide nitrique (HNO_3 0.5N) afin d'obtenir des solutions à 100 ppm de calcium avant d'être analysés par ICP-QMS. Le protocole utilisé est celui décrit dans BOURDIN *et al.* (2011).

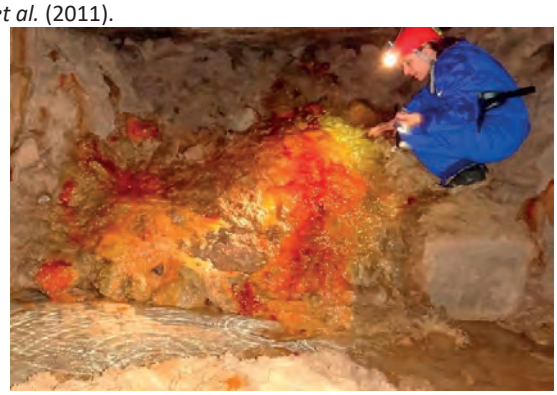

Figure 1 : Carrière de la Brasserie (Paris), site de prélèvement

3. Résultats et discussion

3.1. ^{14}C et discussion sur l'opportunité de datation sur les échantillons jeunes

Les données ^{14}C obtenues sur Bras 1 sont présentées dans le tableau (figure 2). L'échantillon analysé étant prélevé au sommet d'un spéléothème actif en 2012, le niveau d'une dizaine de mg couvre 5 à 6 lamines, soit environ 3 ans si les lamines sont bi-annuelles comme dans le cas des spéléothèmes de l'aqueduc du nord de Paris (PONS-BRANCHU *et al*., 2014).

N° SacA	Echantillon	pMC	Age ans BP
55096	Bras 1 - 15	61,69 ± 0,18	3880 ± 30

Figure 2 : résultat de l'analyse ^{14}C sur Bras 1. pMC ; pourcent de carbone moderne.

Sur la figure 3, le ^{14}C mesuré dans l'échantillon est comparé au ^{14}C atmosphérique de l'hémisphère nord (HUA *et al.* 2013). La différence entre les deux implique ici une quantité importante de carbone mort, de l'ordre de 40%. Cette proportion de carbone mort est ici particulièrement marquée. A titre de comparaison, elle varie entre 2.5 et 10% pour l'Aven de la Salamandre (GENTY *et al.*, 2001) et, en région parisienne (Paris-Versailles) dans un contexte urbanisé, celle-ci a été évaluée à deux fois moins (17-22%) pour des spéléothèmes de souterrains de Versailles et Paris (PONS-BRANCHU *et al.*, 2018). Dans ces derniers cas, une chronologie relative des spéléothèmes urbains a pu être établie en retraçant le signal ^{14}C du « pic des bombes » des années 1960s, avec un transfert rapide du carbone atmosphérique vers le sous-sol et l'influence probable d'une petite fraction de «*vieux carbone*» lié à l'utilisation de ressources fossiles (effet Suess). Dans le cas présenté ici (Bras 1), la proportion de carbone mort est beaucoup plus importante, et l'utilisation du « pic des bombes » pour établir la chronologie de cette concrétion dépendra fortement de l'importance de l'atténuation de ce pic et d'un possible temps de délai entre les variations atmosphériques et le transfert du carbone atmosphérique vers la concrétion. De nouvelles analyses sont nécessaires et pourront permettre de contraindre ces paramètres.

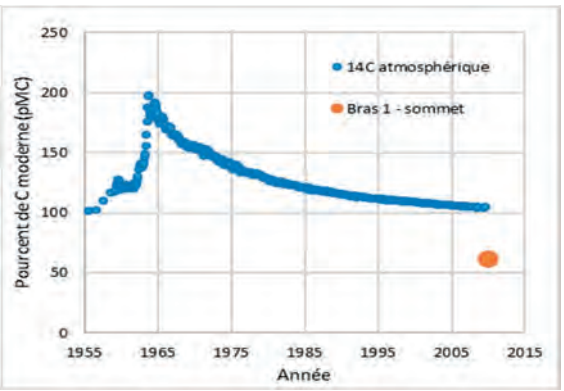

Figure 3 : comparaison entre le ^{14}C atmosphérique (HUA et al., 2013) et la mesure du ^{14}C au sommet de Bras 1.

3.2. Les terres rares

Seuls les lanthanides sont discutés ici. L'Europium (Eu) étant interféré par la présence de Baryum (interférences isobariques) lors de la mesure en spectrométrie de masse, cet élément n'est ici pas présenté.

Les concentrations mesurées dans Bras 1, varient de 1,7 à 27,8 ppb. Leurs teneurs ont été normalisées à celles d'une référence pour les roches sédimentaires (NASC, GROMET *et al.*, 1984) pour représenter en figure 4 le spectre en terres rares correspondant. Pour comparaison, les données normalisées au NASC des 2 autres échantillons (Bel 2 et Salam 3), ont également été ajoutées à cette Figure. Pour Bel 2, les données issues de 3 niveaux uniformément répartis suivant l'axe de croissance ont été reportés. Pour Salam 3, les moyennes correspondant aux 3 périodes climatiques enregistrées (Bølling–Allerød - réchauffement en fin de période glaciaire; Dryas récent - retour bref aux conditions glaciaires; Holocène - climat interglaciaire actuel) sont reportées.

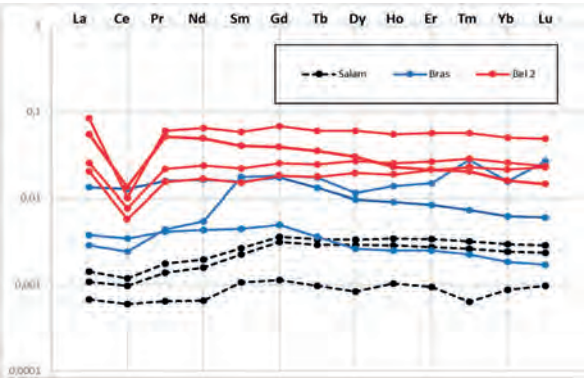

*Figure 4 : Spectres de terres rares normalisés (NASC) pour les échantillons de calcaire Bel 2 (*PONSBRANCHU *et al., 2004), Salam 3 (*DRUGAT *et al., 2019) et Bras 1 (ce travail).*

L'échantillon Salam 3 de l'aven de la Salamandre, présente les teneurs les plus faibles en terres rares, tandis que l'échantillon Bel 2, qui a incorporé pour les niveaux les plus jeunes des terres rares issues des activités anthropiques (PONS-BRANCHU *et al.,* 2014) présente les teneurs les plus élevées. L'échantillon Bras 1 de la carrière de la Brasserie présente des teneurs intermédiaires. Une anomalie négative marquée en Cérium est observée seulement pour Bel 2 (figure 4). Cette anomalie témoigne d'un effet de conditions oxydantes en amont de la percolation dans l'aqueduc. Cette anomalie n'est pas observée dans l'échantillon de la carrière de la brasserie comme dans celui du site naturel (aven de la Salamandre). La différence majeure entre l'échantillon de grotte naturelle et celui de la carrière sous le bois de Vincennes est « l'allure » générale du spectre des terres rares avec un enrichissement en terres rares lourdes et plus prononcé pour Salam 3 et à l'opposé un enrichissement en terres rares légères pour Bras 1 dans 2 échantillons sur les 3 analysés. Dans Salam 3, les différentes allures des spectres pour les 3 périodes s'expliquent par des proportions différentes de ces éléments traces en provenance du sol et/ou de la roche mère reflétant un lien direct avec les changements climatiques (DRUGAT *et al.*, 2019).

La différence entre les spectres de Salam 3 et Bras 1 peut s'expliquer par i) une origine des terres rares différente (roche mère et/ou sol) ; ii) un fractionnement différent du fait de processus géochimiques contrastés (modes et temps de dissolution de l'encaissant, précipitation primaire dans l'épikarst, vitesse de croissance des spéléothèmes) ; iii) un effet marqué du milieu urbain comme pour le site du Nord de Paris (Aqueduc de Belleville). La poursuite de l'étude devra inclure l'analyse de la roche mère de la carrière de la Brasserie ainsi que celle du sol sus-jacent. La fraction importante de carbone mort mise en évidence pour Bras 1 peut être un argument en faveur de processus géochimiques longs et complexes dans le sol et l'épikarst pour le site de la Brasserie.

5. Conclusion

Cette étude a permis de comparer trois spéléothèmes prélevés sur des sites très contrastés : un spéléothème d'une grotte du Sud de la France, un spéléothème d'aqueduc du Nord de Paris dans une zone urbanisée et un spéléothème d'une carrière parisienne, sous le bois de Vincennes. Les deux premiers échantillons avaient pu être datés par la méthode uranium/thorium malgré la présence de thorium détritique. Dans l'échantillon de la carrière parisienne, la méthode U/Th n'a pu être appliquée. La mesure du ^{14}C sur un dépôt actuel, montre une très forte proportion de carbone mort (~40 %) qui pourrait rendre difficile l'utilisation de cette méthode pour ce site, utilisée dans de nombreux cas pour les échantillons très récents (recherche du « pic des bombes » des années 1960s).

La comparaison des spectres des terres rares des 3 échantillons montre que i) l'échantillon de la carrière parisienne sous le bois de Vincennes présente des teneurs comprises entre les fortes concentrations de l'échantillon « urbain » et les faibles concentrations de l'échantillon de grotte naturelle ; ii) tout comme l'échantillon de grotte, l'échantillon de carrière ne présente pas d'anomalie en cérium contrairement à celui du site urbain ; iii) pour deux échantillons sur trois, la concrétion calcaire de la carrière de Vincennes présente un enrichissement en terres rares légères (par rapport aux lourdes) pouvant être comparé à ceux observés en zone urbanisée (Belleville)

Des études complémentaires en cours dans le cadre de l'ANR HUNIWERS permettront de comparer ces spectres aux sources de terres rares potentielles (sol, encaissant). Nous pourrons ainsi déterminer si cette formation peut être utilisée comme une archive environnementale à l'image des spéléothèmes étudiés précédemment.

Remerciements

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Le remplissage de l'aven du Devès de Reynaud (St-Remèze, Ardèche, S-E France) : rôle du karst dans la conservation des indicateurs sédimentologiques d'un enregistrement chronostratigraphique pléistocène

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Résumé

L'intérêt du remplissage de l'aven du Devès de Reynaud est reconnu depuis la fin du XIXème siècle. Ces dépôts ont été exploités, comme dans d'autres cavités de la région pour leur contenu en ossements (« la ruée vers les phosphates »). La stratigraphie actuellement accessible, outre son contenu paléontologique, montre 2 niveaux de retombées volcaniques. Ces téphras constituent 2 rares indicateurs exceptionnellement conservés par le karst, de l'activité de la province volcanique du Vivarais. Le montage du projet TéphrArd (2019) a rendu possible une mission destinée à relever cette séquence et à en effectuer le prélèvement pour établir son cadre chronostratigraphique : en précisant la nature et le contexte de mise en place des dépôts ; en contraignant chronologiquement la séquence, il existe plusieurs types de support de datation (os, dents, sédiments, spéléothèmes) ; en apportant de nouveaux éléments paléoenvironnementaux par l'étude des restes fauniques. Les dépôts caractérisent le fonctionnement d'un cours d'eau hypogé peu compétent, laissant peu de place à la dynamique gravitaire. Les téphras occupent une position secondaire. La chronologie couvre une période discontinue depuis les MIS 9/10 jusqu'à la fin du Pléistocène.

Abstract

The Devès de Reynaud infilling (St-Remèze, Ardèche, SE France): role of the karst in the conservation of the sedimentary indicators of a Pleistocene chronostratigraphical record. The interest of the Devès de Reynaud infilling is known since the end of the 19th century. The infilling has been exploited, like in other caves of this area for their bone richness ("phosphate rush"). The currently outcropping stratigraphic sections contain not only faunal remains but 2 volcanic ash falls too. These tephras are 2 scarce indicators of regional volcanic activity, exceptionally preserved by the karst. With the TephrArd's project (2019), it has been possible to organize a field mission into the Devès de Reynaud Cave. The aims were to study and sample sections to establish the infilling's chronostratigraphic frame by characterizing sediments and their depositional conditions; to constrain chronologically the sequence, using the different dating supports available (bones, teeth, sediment, speleothems); and to provide new paleoenvironmental elements through the study of faunal remains. Sediments result of underground stream dynamic with low competence. Sediments deposited by gravity are uncommon. Tephras are in secondary position. Chronology covers a discontinuous period from MIS 9/10 until the end of Pleistocene.

1. Introduction

L'aven du Devès de Reynaud est situé sur la commune de Saint-Remèze (1,5 km au SO de ce bourg) en Ardèche (Fig. 1). Il s'ouvre sur le plateau éponyme, dans les calcaires du Crétacé inférieur (Urgonien) à l'altitude de 385 m.

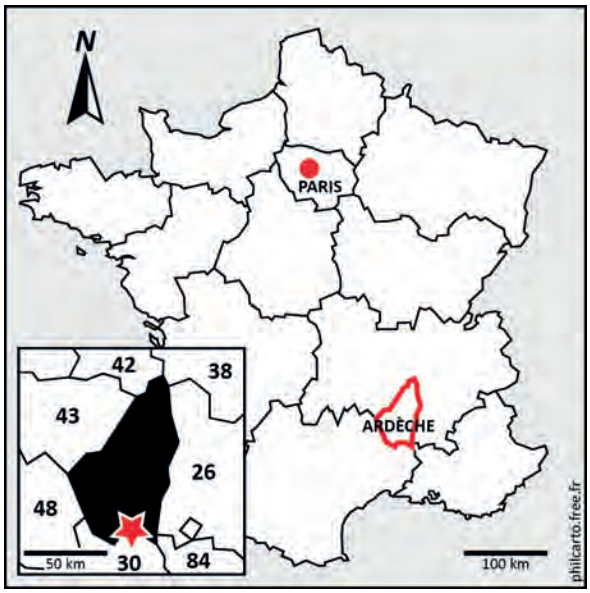

Figure 1 : Le département de l'Ardèche est situé au sud-est de la France. L'aven du Devès de Reynaud (étoile rouge) est localisé à l'extrême sud de ce département en rive gauche des gorges de l'Ardèche qui fait face à la rive gardoise.

Cette cavité est un puits, haut de 58 m recoupant un réseau horizontal à -36 m. À son extrémité sud, une salle contenait un important remplissage qui a livré au cours du dernier quart du XIXème siècle 1 tonne d'ossements de faune quaternaire et 2 retombées volcaniques (Fig.2). MARTEL (1894) relate la descente dans l'aven du préhistorien de Vallon-Pont-d'Arc, Ollier de Marichard. CHANTRE (1901) énumère les taxons fossiles qui ont pu être sauvés de l'aven. Les mineurs semblent avoir aménagé les parois du gouffre pour y installer des structures permettant d'y descendre aisément (BIGOT, 2015). L'épuisement du gisement fait oublier le gouffre. R. de Joly l'explore en 1937 (DE JOLY, 1937) sans retrouver de fossile malgré les fouilles entreprises (au mauvais endroit !). Le gouffre reste néanmoins bien connu des habitants puisqu'il « sert depuis un temps immémorial de dépotoir municipal ! [où] l'odeur est difficilement supportable et rend l'exploration très pénible. » (TRÉBUCHON, 1956). À la fin des années 1970, l'un de nous (YB) effectue la topographie de l'aven (BILLAUD, 1978). Il y retrouve de la faune et découvre les 2 niveaux de téphra. GUÉRIN (1980) l'attribue à la MNQ 26 (Pléistocène supérieur). L'analyse de la composition du téphra supérieur suggère à J.-F. Pastre que cette retombée provient de l'éruption phréatomagmatique d'un maar de la province vivaroise (DEBARD & PASTRE, 2008).

Figure 2 : Aven du Devès de Reynaud, salle des téphras. La coupe inférieure montre, dans sa partie inférieure l'impressionnante couche de sable noir interstratifiée dans les sédiments limoneux. Le géochronologue donne l'échelle. Cliché Projet TéphrArd 2019.

C'est dans le sillage de ces travaux préliminaires que le projet TéphrArd a été déposé en 2019, dans le cadre de l'AAP fédérateur du Département Homme & Environnement du Muséum national d'histoire naturelle. La finalité de cette étude est de contextualiser le remplissage conservé dans la salle d'où ont été extraits les ossements et dans laquelle on observe encore actuellement les 2 téphras : à partir de l'analyse sédimentologique des dépôts, essayer de comprendre leur mode de mise en place et de restituer un cadre chronologique grâce à la datation des différents supports de datation. L'apport des données obtenues à partir de l'étude des restes fauniques doit également contribuer à cette étude en apportant des éléments d'ordre paléoenvironnemental et (bio)-chronologique.
Le projet a pu financer une mission sur le terrain ainsi que plusieurs datations (^{14}C, U-Th, ESR sur dent).
Cette étude souligne le rôle considérable du karst dans la conservation des séquences sédimentaires.

2. Matériels et méthodes

Le projet TéphrArd s'appuie sur deux éléments essentiels : une mission de terrain qui a permis non seulement de fournir les matériaux destinés aux analyses mais également de permettre de faire le relevé des 2 coupes stratigraphiques de ce qui reste du remplissage sédimentaire ainsi que d'effectuer les observations associées. Le second élément du projet a consisté à l'analyse du matériel au laboratoire : analyses sédimentologiques, géochronologiques (datations) et paléontologiques. Les résultats tirés de ces dernières feront l'objet d'un article dans ces mêmes actes par l'une d'entre nous (M. Lepenant).

L'intégralité des échantillons a été prélevée lors de la mission réalisée sur le terrain en janvier 2019. Il s'agissait de sédiments, de spéléothèmes et de restes fauniques (os et dents). Les sédiments ont été préparés pour être analysés

par diffraction laser au granulomètre Malvern Mastersizer 2000. Les datations ont été réalisées sur 3 types de support : ossements par la méthode de ^{14}C, spéléothèmes par la méthode des séries de l'uranium (U-Th) et dents d'herbivores (ESR : résonnance électronique de Spin, traitement en cours).

Les analyses ont été réalisées dans les laboratoires de l'UMR 7194 HNHP (Musée de l'Homme et Institut de Paléontologie humaine) pour la sédimentologie, les séries de l'U, le dosage du collagène des os et les datations ESR. Les échantillons destinés aux datations ^{14}C ont été préparés à l'UMR 7209 et mesurés au LSCE (UMR 8212).

3. Résultats

La stratigraphie du remplissage (Fig. 3)

La salle où sont conservés les restes du remplissage a été vidée dans sa quasi-totalité par les ouvriers phosphatiers à la recherche d'ossements. Il subsiste néanmoins 2 témoins séparés par un hiatus de près de 5 m. Chacun d'eux contient une intercalation de sables noirs.

La coupe inférieure est constituée par un ensemble de matériaux fin à rares passées de granules calcaires. On observe une succession de niveaux argilo-limoneux finement lités dans lesquelles se trouve le téphra inférieur (TI). Il s'agit de sables noirs atteignant une épaisseur de 30 à 40 cm, de texture fine à moyenne très bien triés et finement lité. Sa teinte sombre trahit l'abondance du verre volcanique. La qualité du tri et les structures sédimentaires observées montrent qu'il s'agit de retombées volcaniques remobilisées dans le karst par la dynamique fluviatile comme le montre également les autres dépôts de cette séquence. Des arrêts de sédimentations sont marqués par la précipitation de deux planchers stalagmitiques. Les niveaux limono-argileux contiennent 2 zones où se concentrent les ossements.

La coupe supérieure présente une organisation comparable : succession argilo-limoneuse, passées sableuses, le téphra supérieur (TS), peu épais (5 cm) et 3 lits d'ossements. Un plancher stalagmitique clôt la séquence.

Les téphras

Ces 2 dépôts ont une granulométrie (sables bien triés) et une composition comparable (verre sombre et minéraux du socle : quartz, micas). Ces caractéristiques comme celle de la géochimie du verre (DEBARD & PASTRE, 2008) rapprocheraient ces retombées de l'activité phréatomagmatique de la province volcanique du Vivarais.

Les datations (Fig. 4)

La chronologie de la séquence établie à partir des datations actuellement disponibles (^{14}C et U-Th) s'étendrait au-delà des MIS 9/10 et jusqu'à la fin du Pléistocène.

D'après les chronologies établies pour le volcanisme vivarois (GUÉRIN & GILLOT, 2007 ; SASCO *et al.*, 2017) : TI se placerait dans la phase la plus ancienne (> 150 ka) et TS dans les phases les plus récentes (< à 45 ka).

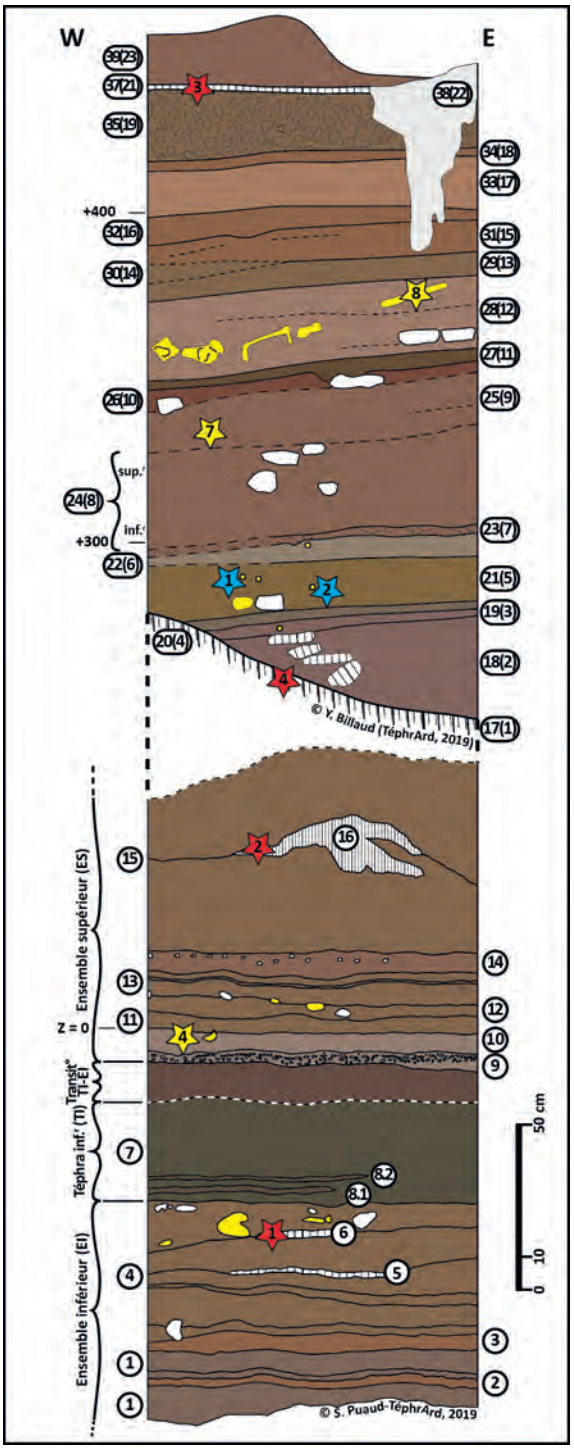

Figure 3 : Coupe stratigraphique synthétique du remplissage de la salle des téphras. Les 2 coupes présentent des faciès limono-argileux où la fraction grossière est rare et où 2 téphras sont interstratifiés (TI : 7 et TS : 27). La coupe supérieure repose sur une coulée stalagmitique. La coupe inférieure, topographiquement sous la coulée est stratigraphiquement au-dessus (pas d'inversion U-Th 1/4). Prélèvements géochronologiques (étoiles) : rouges (U-Th), jaunes (^{14}C), bleu (ESR).

	Codes			Âges		
	ECHoMICADAS	Muséum	Échantillon	yr BP	± 1σ	date calibrée (2σ)
^{14}C collagène (os)	2676.1.1	MUSE19105	PC14-4	> 45 000	-	-
	2677.1.1	MUSE19106	PC14-7	44 340	665	47 381-44262
	2678.1.1	MUSE19107	PC14-8	41 420	465	43 804-42 098

	Échantillon	Âge	+ Erreur	-	Âge corrigé	
U-Th spéléothème (calcite)	DdR2019-PUTh1	357 598	165 620	59 313	348 140	355 058
	DdR2019-PUTh2	70 926	2775	2669	59 820	67 402
	DdR2019-PUTh3	14 403	409	407	10 949	13 354
	DdR2019-PUTh4	> 479 923	-	-	-	-

Figure 4 : Résultat des datations effectuées à l'aven du Devès de Reynaud. Les datations ESR sur les tissus dentaires n'ont pas encore livré leur résultat. Tous ces résultats sont localisés sur la coupe stratigraphique de la figure 3.

4. Synthèse et conclusions

L'aven du Devès de Reynaud, situé sur la commune de Saint-Remèze en Ardèche méridionale, conserve dans une salle annexe à son puits d'entrée un remplissage sédimentaire conservant des témoins exceptionnels. Les restes fauniques qui ont rendu cet aven célèbre (voir la communication de M. Lepenant dans ces actes) ont donné notamment des restes de mammouth ou d'hyène. Outre ces témoins fossiles, les coupes encore présentes sur le site montrent 2 niveaux très nets de téphras. Ces retombées volcaniques constituent de très rares témoins des manifestations volcaniques de la province vivaroise. Quoique repris légèrement par la dynamique fluviatile, ces dépôts sont parfaitement caractérisables. Leurs caractéristiques géochimiques, minéralogiques et granulométriques permettent de les attribuer à la phase la plus ancienne et celle la plus récente de l'activité de cette province.

La mise en place de la séquence du Devès doit une part importante à l'activité du karst. Celle-ci se traduisant par l'accumulation des dépôts par le biais d'une rivière souterraine. L'étude des sédiments montre le peu de compétence du cours d'eau : le karst se comble de sédiments fins.

Une question majeure restée en suspens est celle du point d'entrée des ossements. S'agit-il d'un aven-piège ? La salle des téphras est à l'aplomb d'une cheminée actuellement obturée. Néanmoins aucun dépôt corrélatif ne se trouve associé à cette morphologie (cône d'éboulis). Il est également difficile d'invoquer uniquement la dynamique fluviatile afin d'expliquer une telle accumulation d'ossements à cet endroit. Cette question traduit la complexité du fonctionnement de cette cavité.

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Le remplissage de la grotte de Laang Spean (province de Battambang, Cambodge) : une archive sédimentaire témoin de l'activité du karst et un enregistrement de l'anthropisation en contexte tropical humide au cours du Pléistocène et de l'Holocène

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Résumé

La région de Battambang est avec celle de Kampot l'autre grand secteur karstique du Cambodge. Le démantèlement de l'épaisse formation carbonatée permienne des « calcaires ouraliens » n'a laissé aujourd'hui que des morphologies résiduelles : les phnoms. Situé à mi-chemin entre Battambang et la frontière thaïe, le phnom Teak Treng, est parcouru par 14 cavités. La plus vaste : Laang Spean (« la grotte des ponts ») est devenue un site préhistorique majeur de l'Asie du Sud-est continentale. La Mission Préhistorique Franco-Cambodgienne poursuit depuis 10 années les travaux initiés par les époux Mourer, à l'origine de la fouille du site dans les années 60. La salle centrale de cette immense caverne a livré un remplissage sédimentaire dépassant 10 mètres de puissance. Il constitue une archive sédimentaire qui a enregistré les modifications paléoenvironnementales et les conséquences d'événements géologiques régionaux depuis près de 400 ka. Outre cet enregistrement conservé par le karst, la stratigraphie livre, 4 niveaux d'occupation : les 2 niveaux les plus anciens (outils frustes sur calcaire et industrie sur silicifications) sont mal caractérisés, les niveaux hoabinhien (11-5 ka BP) et néolithique (~3 ka BP), sont abondants. Ils ont permis de définir une véritable aire d'habitat et un lieu d'inhumation.

Abstract

The Laang Spean Cave (Battambang Province, Cambodia): Pleistocene-Holocene karstic and anthropic records in a wet tropical context. Battambang and Kampot provinces are the main Cambodian karstic areas. The dismantling of the thick Permian carbonate formation of «Uralian limestones» has left some residual morphologies: the phnoms. Located halfway between Battambang and the Thai border, the phnom Teak Treng, is crossed by 14 cavities. The largest: Laang Spean («the cave of the bridges») has become a major prehistoric site of South-East Asia. Since 10 years, the Franco-Cambodian Prehistoric Mission has been continuing the work initiated by the Mourer spouses, who excavated the site in the 1960s. The central room of this immense cavern has a sedimentary filling exceeding 10 meters in thickness. It is a sedimentary archive that has recorded paleoenvironmental changes and the consequences of regional geological events since nearly 400 ka. Besides this sedimentary record controlled by karstic activity, there are 4 levels of occupation: the 2 oldest levels with chipped stone tools on limestone and local silicifications. These are poorly characterized. Hoabinhian levels (11-5 ka BP) and Neolithic (~3 ka BP) are abundant. They allowed us to define real habitat area and a place of burial.

1. Introduction : le site

Laang Spean (*grotte des ponts* en khmer) est située au Cambodge (Fig. 1A), au nord-ouest du royaume, dans la province de Battambang. Depuis cette ville, on suit la RN10 vers la Thaïlande jusqu'au village de Sdao. La grotte est à 5 km à l'ouest du village (Fig. 1B).

Cette cavité se développe à travers le phnom Teak Treang (Fig. 2). Le terme phnom désigne au Cambodge les reliefs (pas toujours karstiques) qui émergent de la plaine. L'exploration spéléologique de ce petit massif de calcaire attribué au Permien a montré l'existence d'un ensemble de 14 cavités (LAUMANNS, 2019). Très peu d'entre elles ont livré du matériel archéologique ; ces cavités ayant été fréquentées par les moines qui s'y installent en ermite ou bien par les villageois qui ont exploité et utilisé les remplissages sédimentaires comme fertilisants.

Celui du gisement de Laang Spean est resté vierge jusqu'à la reconnaissance de sa richesse archéologique par les époux Mourer en 1964. Fouillé lors de 3 campagnes il livrait alors les témoins inédits de l'activité des derniers chasseurs cueilleurs hoabinhiens et de leurs successeurs néolithiques (MOURER & MOURER, 1973 ; MOURER, 1994). La reprise du site, en 2009, par la Mission Préhistorique Franco-Cambodgienne (MPFC) (SOPHADY, 2014) a permis non seulement de mettre au jour des aires d'activité attribuées aux hoabinhiens (FORESTIER *et al.*, 2016), de riches sépultures néolithiques (ZEITOUN *et al.*, 2012 ; SOPHADY, 2016 ; SOPHADY *et al.*, 2016) mais également de découvrir des industries lithiques insoupçonnées obtenues à partir de matières 1ères locales (silicifications et calcaire). Outre ces découvertes, les dimensions imposantes de la cavité : il s'agit d'un couloir dépassant 60 m de long, 20 m de large où la voûte peut culminer à 30 m et la puissance de son remplissage, le substrat a été atteint 13,6 m sous la surface, classent désormais la grotte de Laang Spean parmi les grandes séquences du Pléistocène et de l'Holocène de l'Asie du Sud-Est continentale.

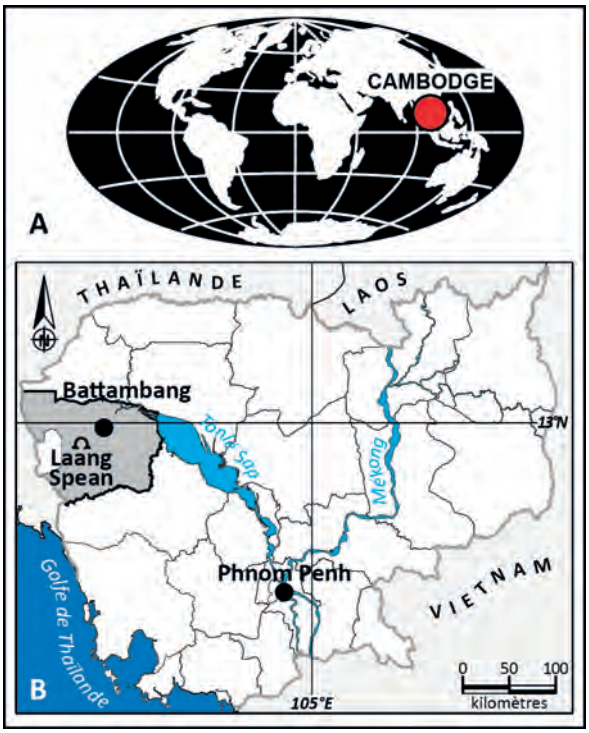

Figure 1 : Localisation du site préhistorique de Laang Spean. A) Le Royaume du Cambodge forme la partie ouest de l'extrémité de la péninsule indochinoise. B) La grotte est située à l'ouest du pays, près de la ville de Battambang entre le Grand Lac (Tonlé Sap) et la frontière thaïlandaise.

Figure 2 : Vue panoramique du Phnom Teak Treang. Cette morphologie karstique résiduelle abrite la grotte de Laang Spean dont l'entrée, dissimulée par la végétation, est approximativement située au niveau du cercle blanc. Ce relief abrite 13 autres cavités de moindre développement. Peu d'entre elles ont livré du matériel archéologique car les remplissages de ces cavités ont été très bouleversés (aménagement par les moines, vidange par les villageois). (Crédit photo S. Puaud / MPFC 2014)

2. Matériels et méthodes : la fouille

La fouille du site a été entreprise dans la partie centrale de la grotte (salle 2) à l'emplacement des premiers travaux. Son extension s'est effectuée selon un axe transversal (largeur de la salle). Un puits a été foncé en son centre afin de reconnaître l'intégralité de la séquence des dépôts. La stratigraphie a ainsi révélé une épaisseur atteignant 13,6 m. Le rôle du karst est à souligner car il est à l'origine du piégeage puis de la conservation des ensembles stratigraphiques. Son activité est également responsable d'une grande partie du dépôt du remplissage sédimentaire. On observe non seulement des spéléothèmes mais aussi des dépôts fluviatiles liés à l'activité d'un cours d'eau hypogé.

3. Résultats : la stratigraphie du remplissage sédimentaire

La stratigraphie du remplissage de Laang Spean comporte 30 unités (couches) qui se répartissent en 3 grands ensembles. Chacun de ces ensembles marque un changement dans les conditions de sédimentation.

L'assise sur laquelle repose la pile sédimentaire est constituée par le substratum calcaire. Ces carbonates marins sont attribués au Permien (FONTAINE, 2002). Ils sont recouverts en partie par un faciès carbonaté grisâtre pétris de perles de cavernes (couche 29) ou bien d'une épaisseur métrique de spéléothème (coulée stalagmitique, couche 28). Le spéléothème moule le substratum. Á sa surface, se développe un cortex d'altération noir d'une épaisseur de plusieurs millimètres. Il peut montrer une structure microlaminée où alternent des lits noir et blanc. L'altération affecte, par place, profondément le spéléothème puisque si l'on distingue encore les prismes de la calcite, ceux-ci sont devenus mats. Le faciès devient poreux et friable, il prend un aspect crayeux. Les sédiments de la couche 27 viennent recouvrir l'ensemble des faciès précédent. Il s'agit de sédiments très sombres, dépourvus de fragments grossiers, de structure sédimentaire et de texture sablo-limoneuse. Sa géométrie est complexe car ces dépôts s'observent de part et d'autre du spéléothème, l'intégrant à la faveur de cavités ou le recouvrant.

Le 1er ensemble s'observe entre 10 et 8 mètres de profondeur. Il s'agit d'un ensemble de sédiments sablo-limoneux pauvres en fraction grossière (calcaire, pulvérulent, portant un cortex noir) recouvre l'assise. Il s'y distingue 7 faciès superposés (couches 26 à 20), limités par des contacts érosifs. Outre le cortex noir de la fraction grossière, les transformations chimiques ont affecté le toit de la couche 26. La précipitation des oxy-hydroxydes de fer dans la porosité du faciès sableux est à l'origine des grès de la couche 25.

Le 2ème ensemble s'étend au-delà des couches 21/20, entre 8 et 5 mètres de profondeur. C'est un ensemble de sédiments aux faciès monotones de limons argileux. La base (couche 19) est plus argileuse, puis les sédiments deviennent plus limoneux (couche 18). Dans cet ensemble, les pierres ont perdu leur cortex noir d'altération.

Le 3ème ensemble se développe à partir de -5 m et jusqu'à la surface. La séquence stratigraphique est alors constituée par un ensemble de limons sableux carbonatés (25 % de $CaCO_3$). La fraction grossière devient de plus en plus abondante. Ces dépôts ont enregistré les modifications morphologiques de la grotte. Après un dernier témoin du fonctionnement karstique de la cavité, avec la précipitation du plancher stalagmitique 15/14, la présence de blocs, au-delà de la couche 14, témoigne de l'effondrement de la voûte de la cavité (Fig. 3).

Figure 3 : Vue de Laang Spean depuis l'entrée de la grotte. Le chantier est au 1er plan. Les parois, très dégradées, conservent néanmoins quelques coulées et draperies. Au second plan, l'effondrement du toit est à l'origine des fenêtres et du « pont ». (Crédit photo S. Puaud / MPFC 2015)

Ces changements majeurs ont modifié le mode de sédimentation et la nature du remplissage. C'est également dans cet ensemble que les témoins anthropiques deviennent abondants. Le remplissage est scellé par le dépôt d'écailles de calcaire résultant de la desquamation des parois de la cavité.

4. Synthèse et conclusion

Actuellement, une stratigraphie de 13,6 m a pu être reconnue dans la grotte de Laang Spean. Cette accumulation représente un fait exceptionnel qui rappelle et confirme le rôle prépondérant du karst dans la conservation des archives sédimentaires (MAIRE & POMEL, 1994), dont certaines, par leur rareté (téphras), pourraient s'avérer être des témoins uniques d'événements géologiques majeurs ayant un eu un impact global. La variabilité des faciès des dépôts observée à Laang Spean traduit la diversité des dynamiques sédimentaires responsables de la mise en place du remplissage. Ces dynamiques sont contraintes par les conditions environnementales qui se sont succédé dans la cavité et sa région depuis près de 400 000 ans. Cette date a été obtenue à partir de l'analyse isotopique (U-Th) de la calcite du spéléothème recouvrant le substratum calcaire formant l'assise des dépôts détritiques postérieurs.

Aujourd'hui, le phnom, ses cavités, Laang Spean et son remplissage en particulier sont complètement déconnectés de la plaine qu'ils surplombent de plusieurs 10^{aines} de mètres. L'isolement de ces 2 entités (phnom et plaine) est consécutif à l'abaissement drastique du niveau de base du réseau hydrographique. Ses fluctuations sont reliées à celles du niveau marin (eustatisme) qui ont pour origine la cyclicité

climatique glaciaire / interglaciaire (glacio-eustatisme). Dans le cas du contexte géologique régional de la péninsule indochinoise on ne peut négliger l'influence de la tectonique himalayenne et son rôle tectono-eustatique (DEMANGEOT & SCHNEIDER, 1971 ; CARBONNE, 1972 ; TAPPONNIER *et al.*, 1990 ; HUTCHISON, 2014). En effet, l'assise, le 1er et le 2ème ensemble sont le résultat de l'activité du karst. Ce fonctionnement implique que la plaine se situait au-dessus de son niveau actuel. La variation du niveau de base est à l'origine de l'arrêt progressif de l'alluvionnement karstique et de l'érosion de la plaine. L'effondrement du plafond de la cavité, qui a permis en outre de sceller le remplissage et de le préserver de l'érosion, peut également être consécutif à cette variation : le dégagement du phnom et son assèchement entraînent la détente de ses parois prédisposant ainsi la cavité à s'ébouler.

Ces premiers jalons sur l'interprétation de la séquence de Laang Spean réaffirment l'intérêt que peut susciter cette cavité. Si les témoins d'occupations préhistoriques confèrent au site une indéniable valeur patrimoniale, ses dépôts sédimentaires pourraient également devenir les marqueurs de grands événements géologiques d'ampleur régionale.

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The first cave occurrence of the mineral cattiite, $Mg_3(PO_4)_2 \cdot 22H_2O$

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Abstract

"Mravljetovo brezno v Gošarjevih rupah" is a maze-like cave in central Slovenia, almost entirely formed in the dedolomitized part of Middle Triassic dolostones. Fine-grained autochthonous and allochthonous clastic cave sediments are not abundant. Instead, the lower parts of the cave walls are often covered with thick (up to 1 cm) carbonate crusts (hydromagnesite, aragonite, dolomite, etc.) or, less often, with even thinner phosphate crusts. Rarely, gypsum crusts up to several cm^2 in size occur. On steep sections of the cave walls, an apparently dusty glittering coating appears in two places within the cave. Analysis of this material by XRD revealed peaks indicative of the presence of the mineral cattiite, along with other minerals (e.g. calcite, dolomite, hydromagnesite, etc.). To obtain further evidence, a SEM /EDS analysis was performed. It shows, among others, crystals with ribbed texture composed of oxygen, magnesium and phosphorus - the elemental composition corresponding to the mineral cattiite. In addition, the sample was subjected to FT-IR ATR analysis, which revealed a spectrum with the strongest peak characteristic of the mineral cattiite. Although cattiite, a hydrate magnesium phosphate, has been known as a synthetic phase since the 19th century, it was not described in nature until 2002 when documented in carbonatites from the Zhelezny mine (Kovdor Massif, Kola Peninsula, Russia). Here we describe for the first time the occurrence of the mineral cattiite in a cave environment. It could be the result of the interaction between the minerals of the host rock (i.e. dolomite) and the substrate on which the presence of rodent remains and activity was documented (possible source of phosphates). The specific microclimatic conditions measured over a one-year period in the cave could also play an important role in the formation of the cattiite.

1. Introduction

Caves are, thanks to their characteristic geological settings, relatively stable microclimatic conditions, i.e., humidity and temperature, and the presence of fluids with different chemistry, sites of secondary mineralization and deposition. A large number of different cave minerals crystallize in the form of individual mineral aggregates or speleothems (HILL & FORTI, 1997; ONAC & FORTI, 2011). Cave minerals and especially speleothems are mostly precipitated from saturated solutions (PALMER, 2007), although the formation of cave minerals may also be related to some biogenic factors such as the activity of microorganisms and the interaction of biogenic residues, the host rock and the cave environment (FORTI, 2001). The studied cave "Mravljetovo brezno v Gošarjevih rupah" (hereafter MBGR) in central Slovenia was formed in Triassic dolostone and has ramiform and maze-like pattern and numerous wall rock features such as ceiling cupolas, ceiling channels, dissolution pockets, chimneys, anastomoses and pendant residues. In addition, alteration of the dolomite host rock, i.e., calcitization or dedolomitization ("dedolomitization" refers to the partial or complete diagenetic transformation of dolomite to calcite), is present (OTONIČAR *et al*., 2016). The calcite resulting from the alteration of the dolostone, i.e., dedolomitization, covers most of the cave walls, while the cave ceilings are almost entirely composed of dolostone host-rock due to the subsequent condensation corrosion which caused calcite cover to fall off. In addition, remains of rodents and their activity in the form of bones, feces, and bite marks were observed on the cave walls. Mineral samples were also collected during the geological and geomorphological mapping of the MBGR. Various minerals occurring in different forms and in different locations in the cave were analyzed. However, the main objective of the article is to present the first cave find of cattiite, $Mg_3(PO_4)_2 \cdot 22H_2O$, a hydrated magnesium phosphate.

2. Materials and methods

Powdery mineral aggregates, consisting of the mineral cattiite among other minerals, occur as dusty glittering coatings over steep sections of dolomite and dedolomitized cave walls in two large patches (up to 1 m^2). Three bulk samples were analyzed by X-ray diffraction (XRD) at the Karst Research Institute ZRC SAZU, Slovenia, using a Bruker D2 PHASER diffractometer with CuKα anode, 30 kV, current 10 mA and equipped with a Lynxeye_XT in Cu_HighResolution mode. The samples were scanned in the range of 3-70° 2θ with a scanning speed of 0.02° 2θ/0.2 s. Data acquisition and processing were performed using Bruker's EVA 5.1 software. All three selected samples were observed under an Olympus SZ61 stereomicroscope equipped with an Olympus SC50 digital camera, and the

different types of crystals and grains were separated and mounted on special holders using carbon tape. Three fresh, uncoated samples were examined using a JEOL JSM -IT100 Scanning electron microscope (SEM) equipped with an Energy Dispersive X-ray Spectroscopy (EDS) detector. Observations were carried out in backscattered electron mode under low vacuum (40 Pa) at an accelerating voltage of 15 kV and a working distance of 10 mm. The third method used to analyze the polymineral samples was FT-IR spectroscopy. It was performed on a Bruker LUMOS II microscope with the Attenuated Total Reflectance (ATR) method using a germanium prism, which allows direct measurement of the samples without any preparation. The positioning speed settings were set to medium, medium pressure of the germanium prism, the aperture opening 50 µm and 512 scans in total, background settings were set automatic and scanning of background was performed before scanning the sample.

3. Results

Hydromagnesite, aragonite, and dolomite occur in 1 cm-thick crusts, phosphates in thin mm-thick crusts, while gypsum rarely occurs in crusts covering surfaces up to several cm^2 in size. Samples of the dusty, glittery coating were collected during two surveys in the cave. The XRD pattern of the coating (Fig. 1) shows, in addition to the common minerals associated with the cave sediments and bedrock (i.e. calcite, dolomite, quartz, hydromagnesite, and a small amount of clay minerals), peaks that fit well with the intensities and d-spacing values (Å) of natural and synthetic cattiite reported in the literature (see BRITVIN *et al.,* 2002): 7.99, 5.33, 4.46, 3.19, 2.84, 2.72, 2.66 Å. Some other peaks of relatively high intensity are hidden in peaks of other minerals, e.g. dolomite, quartz and calcite.

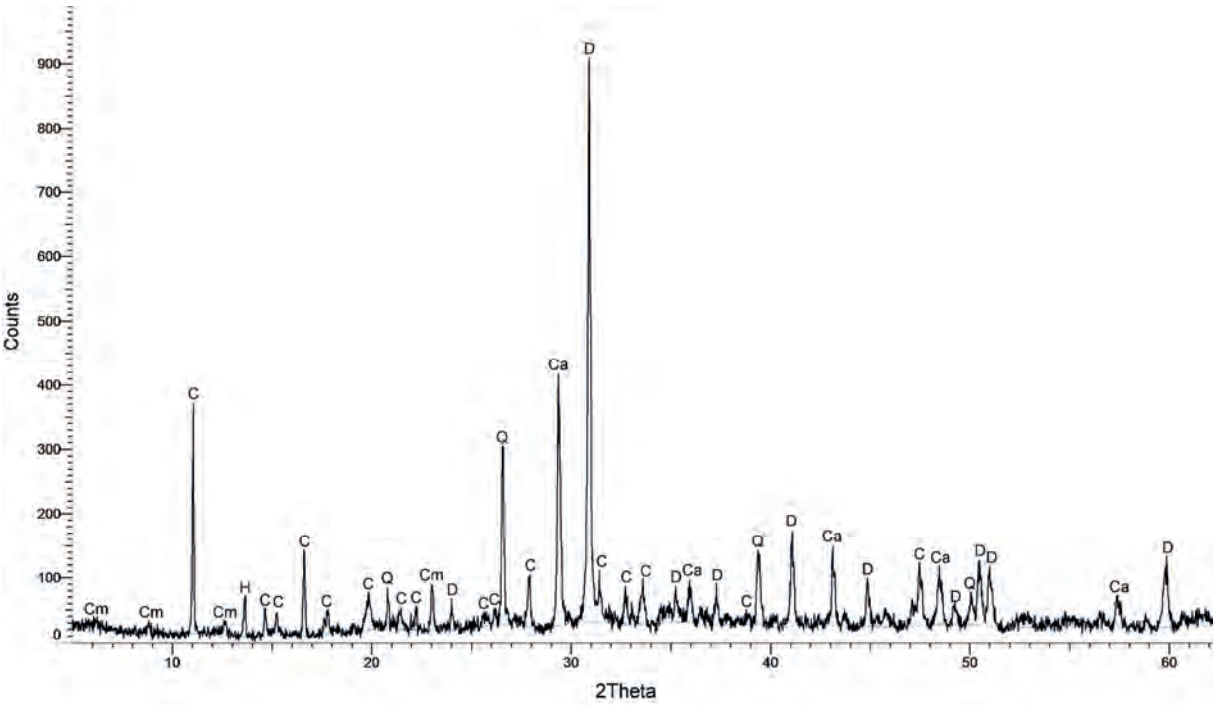

Figure 1: XRD spectrum of the bulk dusty glittering coating containing cattiite (C), calcite (Ca), dolomite (D), quartz (Q), hydromagnesite (H), and a small amount of clay minerals (Cm).

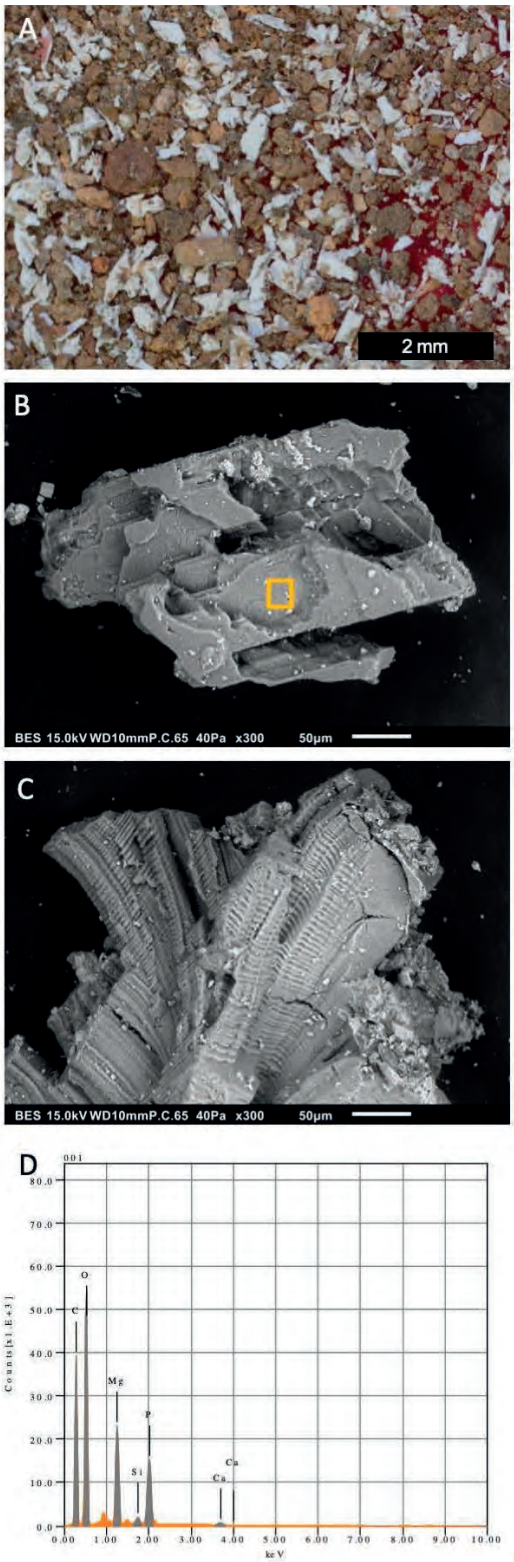

Figure 2: A) Sample containing cattiite observed under a stereomicroscope. Brown and orange grains are weathered fragments of host rock and white, matte crystals are interpreted as cattiite. B) Corroded tabular cattiite crystal. The orange square is the point where EDS analysis was made (D). C) Irregular crystal of cattiite with ribbed texture. D) Semi-quantitative chemical analysis of crystal section shown in B.

Additional SEM /EDS analyses were performed on the samples to confirm the presence of cattiite. Samples containing cattiite consist of a mixture of weathered fragments of host rock and various types of crystals (Figure 2A). Most common are white and matte crystals up to 1 mm in length, interpreted as cattiite based on their observation under SEM reported below. The crystals have a tabular or irregular habit (Figure 2B) and many exhibit a very peculiar ribbed texture representing growth patterns (Figure 2C). EDS analysis shows mostly P and Mg and small amounts of Al, Si, and Ca, probably derived from nearby small crystals of clays or carbonates (Figure 2D). The peak of carbon is mostly due to the carbon tape used to bond the samples. This composition is compatible with cattiite, although it could also correspond to dehydration products such as bobierrite.

On the IR spectrum, peaks of three major minerals previously detected by XRD were shown, including cattiite. The strongest peak of cattiite is shown at a wavelength of 1006 cm^{-1} and represents the asymmetrical stretching vibrations of $(PO_4)^{3-}$ (Figure 3; see BRITVIN *et al.,* 2002). The peak at a wavelength of 1663 cm^{-1} represents vibrations of water molecules in the cattiite structure (Figure 3; see Britvin et al., 2002), however it could also be a signal of hydromagnesite, a mineral present in the sample. In addition, hydromagnesite peaks are detected at wavelengths 1484 cm^{-1} and 1426 cm^{-1} (Figure 3), which overlap with the main calcite peak at 1425 cm^{-1}. The calcite peaks are shown at wavelengths 872 cm^{-1} and 714 cm^{-1} (Figure 3). To obtain a better IR spectrum for cattiite, it is necessary to isolate cattiite crystals from the mineral mixture and perform additional FT-IR analyses.

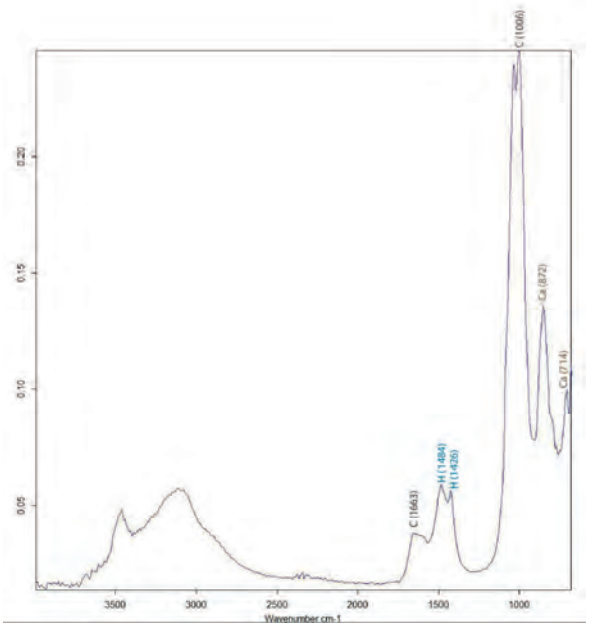

Figure 3: FT-IR spectrum of the polymineral sample shows main peaks of three minerals present in sample, i.e. cattiite (C), hydromagnesite (H) and calcite (Ca). Cattiite peaks are present at wavelengths of 1663 cm^{-1} and 1006 cm^{-1}.

4. Discussion and conclusion

During geological and geomorphological mapping of MBGR cave in central Slovenia, glittery coating representing a polymineral aggregate was sampled on rock ledges and steep cave walls. The samples were subjected to XRD analysis, which showed spectral overlapping with cattiite, among other minerals. Small crystals with ribbed texture (growth patterns) were observed in SEM/EDS analysis of the same samples. Elemental analysis of these crystals showed them to be composed of oxygen, magnesium, and phosphorus, and as such consistent with the composition of cattiite. The third method used to analyze the samples was FT-IR ATR, which showed a spectrum containing the main peak of cattiite, representing the asymmetrical stretching vibrations of $(PO_4)^{3-}$ in the crystal structure. Cattiite is a high-hydrate magnesium orthophosphate, and although it has been known as a synthetic phase since the 19th century, it was first described in nature only in 2002 at the Zhelezny mine (Kovdor Massif, Kola Peninsula, Russia; BRITVIN *et al.* 2002). There, cattiite occurs as a secondary mineral crystallizing in centimeter-sized cavities in veins formed in carbonatite rocks. On this occasion, in MBGR, the mineral cattiite was described for the first time in a karst cave. Possible factors that led to the crystallization of cattiite in this unexpected location were the interaction between dolomite, derived from weathering of the host rock, and phosphates, derived from rodent remains.

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Secondary cave minerals and sedimentary deposits in orthoquartzite and metaquartzite caves of South America: a review on their genesis and significance

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Abstract

Several caves in orthoquartzite or metaquartzite lithologies have been explored in South America in recent years. Even if the host rock is usually over 90% quartz, with very few other mineral components, surprisingly, these caves host remarkable and diverse secondary mineral deposits. Their presence poses a range of questions regarding minerogenesis and the relationships between these minerals, the weathering processes affecting the quartzite host rock, and microbial activity. This review aims to discuss the different mineral groups detected in quartzite caves, their paragenesis and potential significance. Opal at different degrees of amorphisation is often associated with stromatolithic structures suggesting that microbial communities play a role in its deposition. In addition, amorphous silica is often found in association with sulphates. Moreover, phosphates-sulphates and phosphates are in some cases surprisingly abundant. Iron and manganese oxides and hydroxide deposits have also been widely documented in the form of flowstones, stalagmites, stalactites and even rimstone dams. Nitrates, carbonates and several types of clay minerals have also been documented from quartzite caves. Specific microbial groups have been identified within various geochemical and mineralogical niches. Lastly, mineral deposits of considerable thickness may offer proxies for past environments and climates or could be associated with palaeontological remains.

1. Introduction

The exploration and study of quartzite and quartz-sandstone caves have increased significantly in the last twenty years, with several new caves – some of them reaching kilometres of development – explored mainly in ancient cratons of South America (AULER & SAURO, 2019). While these discoveries have strongly raised the attention on the topic of solutional weathering processes in quartz-rich lithologies (WRAY & SAURO, 2017), up to now only few studies have been performed on the significance of secondary mineral deposits found in these peculiar cavities. Forty years ago, URBANI (1980) has highlighted the wide variety of secondary minerals that can be found in quartzite caves and discussed the interesting minerogenesis of these special geochemical environments. Since then, several minerals, including new mineral species, have been found, ranging from sulphates, phosphates, iron and manganese hydroxides, nitrates, phyllosilicates and different varieties of amorphous silica. These discoveries have opened new and challenging fields of research, ranging from studies on mineralogical and geochemical processes, to investigations on the microbial

Figure 1: Silica speleothems growing on quartzite boulders in Imawarì Yeuta, Auyan Tepui, Venezuela (photo A. Romeo/La Venta)

mediation of silica precipitation. This also opened the possibility to use silica speleothems as palaeoclimate proxies (LUNDBERG *et al.,* 2010 and 2018). In this short review we underline the potential of mineralogical studies in caves carved in quartz-rich lithologies, a field of research very young compared to similar work in epigenic and hypogenic carbonate terrains.

2. Silica deposits

Silica speleothems have been found in a number of silicate rock cave systems around the world and represent the most tangible evidence of solution and redeposition of detrital and authigenic silica from within quartz sandstones and quartzites. These secondary deposits are usually composed of amorphous silica like opal-A or cryptocrystalline forms like chalcedony and exhibit a wide variety of shapes, forms and internal structures. Silica speleothems are usually of limited dimensions compared to their calcium carbonate relatives, but recent discoveries within the giant cave systems of the Venezuelan Tepuis and in Chapada Diamantina in Brazil, have shown siliceous formations of up to several metres in size, with much larger and more abundant range of types than previously thought (AUBRECHT *et al.,* 2008; SAURO *et al.*, 2013).

Silica speleothems usually differ in morphology from the well-known calcium carbonate ones. Classical stalactites and stalagmites of silica made by direct inorganic precipitation from seeping waters are less frequent than in carbonates, due to the extremely rare conditions that are needed to allow aqueous silica solutions to reach supersaturation. When this does happen, it is usually through evaporative processes on cave roofs, forming stalactites of limited dimensions lacking an inner feeding tube. Thus, silica soda-straw and translucent opaloid stalactites have only been rarely documented (URBANI, 1996). Instead, they often present irregular coralline or popcorn forms with greyish or brownish colours. Wind-guided forms are common, because evaporation is controlled mainly by the peculiar cave microclimate and thus precipitation happens only where the micro-environmental conditions are favourable (CARREÑO & URBANI, 2004; SAURO *et al.,* 2013). The biggest opal-A stalactites that have been documented are in the Sarisariñama *Tepui* and in the Imawarì Yeuta Cave in Auyan *Tepui* in Venezuela, but significant flowstones and stalagmites have been reported also from Gruta do Lapão and Gruta do Atoleiros in Chapada Diamantina in Brazil.

One of the most challenging research concerns is the absolute dating of silica speleothems in order to provide a minimum age for the speleogenesis of the caves or to generate the necessary chronology for potential palaeoclimate and palaeo-environmental reconstructions. Carbonate speleothems have been used extensively for these purposes. Silica speleothems being usually very small in size and convoluted in form, it is difficult to extract any useful information from them and they have only rarely been dated. However, as abiotic or biogenic silica deposition is undoubtedly controlled by environmental factors, a potential record of climate variations over thousands or even millions of years should exist. In addition, most of the quartz sandstone caves are situated in areas where detrital or metamorphic rocks are dominant, and thus records from classical carbonate speleothems are lacking. The first successful attempt of dating an opal stalactite was in 2001 from E.R. Lawrence (GONZÁLEZ and GÓMEZ 2001). Afterwards, LUNDBERG *et al.* (2010) successfully used the U-Th system through Thermal Ionisation Mass Spectrometry (TIMS) analysis to date different layers of an opal-A biospeleothem from the Chimantá *Tepui*. This preliminary analysis represents one of the first Quaternary palaeoclimate records documented in the Guyana Shield of South America. This research field remains open (LUNDBERG et al., 2018) and future attempts with advanced technology like Sensitive High-Resolution Ion Micro Probe (SHRIMP) could provide additional results, extending the dating applicability also to the U/Pb system. Once the analytical methods are better defined, it is clear that silica speleothems will represent exceptional palaeoclimate proxies, potentially extending into the Early Pleistocene or even to the Pliocene.

3. Other secondary minerals

Speleothems in orthoquartzite and metaquartzite caves are not only composed of pure silica but also of a wide range of other secondary minerals. Whilst secondary minerals in classical limestone caves are well studied, there is still a lot of research potential in quartzite environments.

URBANI (1976, 1980) carried out the first studies on secondary minerals in quartz sandstone karst environments. He reported several secondary minerals from Venezuelan caves, including carbonates, nitrates, oxides/hydroxides, phosphates, and sulphates. Early in the 70s, a new mineral was found in the Autana Cave, a potassium aluminium nitrate called sveite (SVE deriving from the Sociedad Venezolana de Espeleologia) (MARTINI & URBANI, 1984), confirming the high potential of discovering unknown mineral species and new minerogenetic mechanisms in these environments.

Secondary minerals pose a range of questions on the relationships between minerogenesis and quartzite bedrock weathering. Sulphates are in some cases surprisingly abundant. Gypsum has been documented in Venezuela in the caves and big shafts of the Sarisariñama
and Roraima *tepuis* and, in the Muchimuk cave system in Chimantá *Tepui* and in impressive amounts in the Imawarì Yeuta cave system in the Auyan *Tepui*. Also, caves in the Chapada Diamantina (Brazil) host frequent deposits of acicular or massive gypsum. In general, gypsum occurs as acicular crystals, flower-like morphologies, and crusts, sometimes covering hundreds of square metres of cave surfaces. Alunite, aluminite, and jarosite are other common sulphate minerals found in quartz-sandstone caves despite these environments have never been considered a favourable for the deposition of sulphates due to the very

low sulphur content (in the form of sulphate or sulphide) of the bedrock, which is usually entirely composed of quartz with minor clay minerals. Therefore the source of these sulphates is still a matter of debate. Isotopic studies have provided interesting clues on the potential provenance of these minerals from atmospheric sulphates in the Amazon region. However, in some cases their origin could be related to microbial processes interacting with iron oxide layers in the host rock.

SAURO *et al.* (2014) reported an association of sulphates and phosphates (sanjuanite and rossiantonite) collected in a branch of the Akopan-Dal Cin cave system, in the Chimantá massif. Sanjuanite was previously described from only two other places in the world (Argentina and Yakutia) but never from caves, whereas rossiantonite represents a newly described mineral (GALLI *et al.,* 2012).
In addition, in caves from the Chapada Diamantina associations of sulphates (gypsum, barite), carbonates (aragonite), phosphates (newberyite) and amorphous silica are currently under study by some of the authors.
Iron and manganese oxides and hydroxide deposits have also been widely documented in quartz sandstone caves, in the form of flowstones, stalagmites, stalactites, crusts and even rimstone dams. The most common minerals are goethite and hematite. Imawarì Yeuta Cave in Venezuela hosts the world's biggest iron hydroxide stalagmites, with deposits in the order of tens of cubic metres and up to ten metres high. The genesis of these deposits is still debated, possibly a product of laterisation of strata of clays and feldspars, or related to weathering of Banded Iron Formations within the quartz sandstone.

In general, several unanswered questions remain in this complex mineralogical field, and future studies will require a wide use of isotopic, microprobe and SEM investigations.

Figure 2: Chandeliers of opal, barite and aragonite in Gruta do Atoleiros, Chapada Diamantina, Brazil (photo A. Romeo)

4. Microbial role on minerogenesis in quartz-rich cave environments

Microbes appear to have a limited role in the formation of calcium carbonate speleothems compared to abiotic chemical processes like degassing and evaporation. On the contrary, several authors have suggested that the influence of microbes seems to play a predominant role for silica precipitation, even if the biogeochemical mobilisation mechanisms are unknown (WRAY & SAURO, 2017, and references therein). This is clearly demonstrated by the fact that SEM examination of the surface and interiors of most silica speleothems has frequently shown features that could be biological filaments, extracellular polymeric substances (EPS) and different kinds of biofilms. These silica deposits show a variety of morphologies (mushroom-, egg-, coral-and stromatolite-like forms), most of them characterised by layers constituted of amorphous silica (amorphous gels and Opal-A) encrusting biological components (cells, filaments, EPS, etc.). Because of this, AUBRECHT *et al.* (2008) proposed to consider these speleothems as subsurface silica stromatolites. Recent studies on the microbiology of quartzite caves have shown that silica-dominated sites are unique niches where peculiar microorganisms thrive in oligotrophic environments *(*KUNICKA-GOLDFINGER, 1982; BARTON *et al.,* 2014; SAURO *et al.*, 2018).

A recent paper from SAURO *et al.* (2018) shows – through Illumina-based sequencing technologies - the involvement of chemoautotrophic bacteria in silica speleothem growth, with the absence of photosynthetic organisms which are commonly found in surface silica sinters and carbonate stromatolites. Silica deposits from cave floors and walls demonstrate abundance in chemoautotrophic microbial communities possibly involved in silica mobilisation for nutrients scavenging from quartzite-bedrock minor elements (i.e., barium, iron, aluminium, etc.). However, 16S rRNA gene-based analysis only describes the composition of microbial communities that might be involved in silica mobilisation, without providing indications on specific microbial functions. Metabolic pathways involved in biomediated silica mobilisation are under study by some of the authors of this contribution and could be crucial to understand the functional role of microorganisms in mobilising silica, providing important information for the comprehension of the silica cycle on our planet (GHEZZI *et al.*, 2021). Similarly, other secondary minerals in orthoquartzite and metaquartzite caves could be related to microbial activity. This is the case for thick sulphate deposits not related to the bedrock, or very rare phosphate-sulphates that show the potential presence of filaments and EPS that could be related to specific microbial metabolisms at SEM. Preliminary studies on Imawarì Yeuta Cave (Venezuela), show that each geochemical niche is associated with specific minerals and particularly with similar microbial communities, fostering the idea that chemoautotrophic processes could be often at the base of minerogenesis.

This topic shows still a huge potential for further studies, including the role of iron-oxidising bacteria in the formation of iron hydroxides and associated mobilisation of silica, as observed in several Brazilian iron caves (PARKER *et al.*, 2018).

5. Conclusion

The study of silica deposits and other secondary minerals found in orthoquartzite and metaquartzite caves shows a great potential for better understanding the minerogenetic processes in these peculiar geochemical environments.
In addition, the interaction between microbial communities and various chemical elements could provide unexpected discoveries, with implications on the understanding of silica and sulphur cycles on Earth. The use of silica speleothems, or other mineral deposits, for radiometric dating and palaeoclimate studies is still at the beginning but show promising preliminary results.

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New Powerful paleoclimatic Cycles Recorded in Speleothems

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Abstract

Studies of Quaternary climate change are particularly important for determining the extent and scale of the contribution of natural and anthropogenic processes in global warming. For their research we applied measurements of paleoluminescent records, stable isotope records and absolute dating of cave flowstones from the Duhlata cave, Bosnek, Bulgaria.
Using periodogram analysis of the measured records, we established the existence of new cycles of Quaternary climate change with durations of 15 100, 10 800, 9 400, 8 400, 6 900, 5 500, 5 000, 4 700, 3 600, 3 100, 3 000 and 2 800 years. Their intensity is comparable to that of the Milankovitch cycles, which cause glaciations.
In a $\delta^{13}C$ Speleothem Record from Duhlata cave, Bulgaria, we found a positive value of $\delta^{13}C$. It is rather unusual and the only way to explain it, is that all carbon in the speleothem was supplied from the bedrock above the cave during the formation of the corresponding layer in the speleothem. Such a situation can happen only during total covering of the ground above the cave by ice during glaciations. Only in such cases can neither organic nor air carbon dioxide reach the cave.

1. Introduction

Carbon has two stable isotopes, ^{12}C and ^{13}C, and one radioactive isotope, ^{14}C. The stable carbon isotope ratio, $\delta^{13}C$, is measured against Vienna Pee Dee Belemnite (VPDB). The stable carbon isotopes are fractionated primarily by photosynthesis. The $^{13}C/^{12}C$ ratio is also an indicator of paleoclimate: a change in the ratio in the remains of plants indicates a change in the amount of photosynthetic activity, and thus in how favourable the environment was for plant growth (FAURE, 1987). During photosynthesis, organisms using the C3 pathway show different enrichments compared to those using the C4 pathway, allowing scientists not only to distinguish organic matter from abiotic carbon, but also what type of photosynthetic pathway the organic matter was using.
C3 plants constitute about 90% of all plants today and include algae and autotrophic bacteria and comprise the majority of cultivated plants, including wheat, rice, and nuts. C4 plants are adapted to hot, dry environments, and include the important human food crops of maize, millet, sorghum, and sugar cane, as well as tropical savanna grasses and sedges. There is a kinetic fractionation associated with carboxylation of ribulose bisphosphate that has been determined by several methods to be –29.4‰ in higher terrestrial plants. Bacterial carboxylation has different reaction mechanisms and a smaller fractionation of about -20‰. Thus for terrestrial plants a fractionation of about –34‰ is expected from the sum of the individual fractionations. The actual observed total fractionation is in the range of –20 to –30‰ (FAURE, 1987). The disparity between the observed total fractionation and that expected from the sum of the steps presented something of a conundrum. This solution appears to be a model that assumes the amount of carbon isotope fractionation expressed in the tissues of plants depends on the ratio of the concentration of CO_2 inside plants to that in the external environment: the more photosynthesis depletes the CO_2 in the plant interior, the lesser the fractionation that occurs (FAURE, 1987). Some paleoenvironmental information can be obtained only by comparison of different proxies in the same sample. For example the comparison of ^{TM13}C and luminescent records can potentially help determine the temperature dependence of ^{TM13}C variations and the main source of CO_2 in the speleothem. Traditional explanation of ^{TM13}C variations in a speleothem by variations of the ratio between C3/C4 type plants growing over the cave cannot explain observed temperature dependence of ^{TM13}C records (SHOPOV *et al.,* 1994, SHOPOV, 2006) in some speleothems. The amplitude of the observed ^{TM13}C variations is bigger than that, which can be produced by C3/C4 type plant variations. So it is more likely to be produced by variations of the major sources of carbon in speleothems, such as the bedrock carbon fraction and soil carbon in many cases (SHOPOV, 2006).

2. Materials and methods

$\delta^{13}C$ and $\delta^{18}O$ records (Fig.1a) were measured in McMaster University Stable isotope lab. on a gas mass spectrometer, from CO_2 extracted from the relevant layer in the calcite speleothem along the same traverse in the same sample as the luminescent record (Fig. 1b).

A luminescent record (Fig. 1b) was obtained by microphotometry of a photometric quality photographic image of phosphorescence of a double side polished cross section of the sample along its growth axis, which was scanned on a high-resolution scanning microdensitometer Joyce Loebl with 10 microns step and 20 x 200 microns window, allowing optical smoothing of the scan. Phosphorescence of the speleothem calcite was excited by an impulse Xe-lamp. Such excitation produces luminescence of fulvic and humic acids incorporated in the relevant layers of calcite speleothems during their growth (SHOPOV *et al.,* 1994, SHOPOV, 2006). Their concentration in each layer is a proxy of soil temperature during its formation, which is determined by solar insolation of the surface in the case of grass cover over the cave like the one over Duhlata cave.
This sample was dated with 7 TIMS U/Th dates in 2 independent labs (Fig. 2).

3. Results

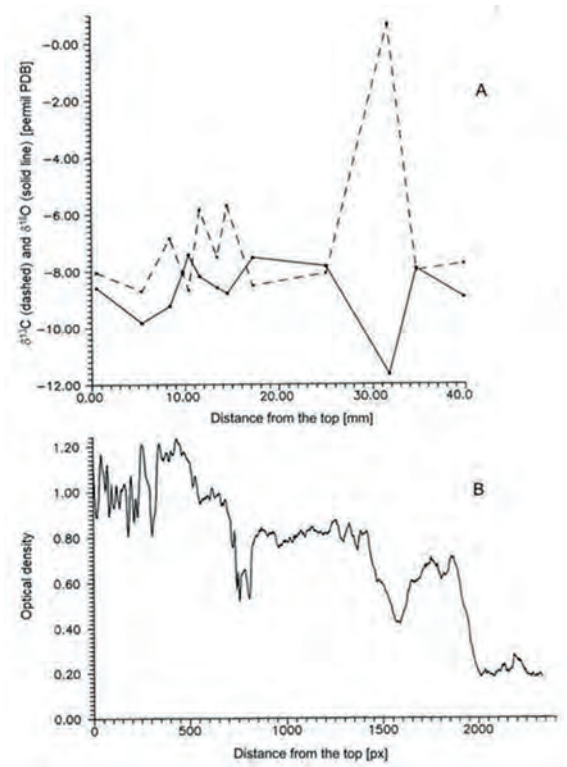

Figure1: Speleothem paleoclimatic records from Duhlata cave near Bosnek, Bulgaria. a. (up) TM13C (dashed) and TM18O (solid line) records [in permil PDB] from a flowstone from Duhlata cave near Bosnek, Bulgaria..b. (down) paleoluminescence proxy record, with time step from 251 to 445 years/px (depending on the growth rate of the speleothem) along the same path in the same sample as the record on FIG.1.a. Linear step of this record is 48 px/mm (0,0208 mm/px)

The aim of this work is to study the possibility to use $\delta^{13}C$ speleothem records for determination of total freezing of the ground during glaciations. We studied the region near Bosnek on the south slope of Vitosha Mts., Bulgaria. Careful study of this flowstone from Duhlata cave shows that it grew continuously during the last 250,000 years (STOYKOVA *et al.*, 2003). This is rather unusual for speleothems, because during full glaciations usually there is no water supply for speleothem growth or cave waters are not saturated with calcium carbonate and start to dissolve speleothems. Either way this leads to the development of hiatuses in speleothems.

Sample	Distance from the top [mm]	$^{230}Th/^{234}U$ [10^3 years]	2σ error [10^3 years]
I 9	*12-13*	*89*	*+/- 4*
Bu1	13-15	93	+/- 1
N 14	*19-20.5*	*243*	*+24* *- 19*
Bu2	18.5-22	258	+ 44 - 30
O15	*20.5-22.5*	*314*	*+32* *- 25*
Bu3	25-28	323	+ 60 - 39
S19	*25.5-26.5*	*382*	*+58* *- 36*
U21	*27-28.5*	*Infinite*	*N/A*
Bu4	31-36	Infinite	N/A

Figure 2: TIMS U/Th dates of the studied speleothem. Dates Bu1-Bu4 are measured by Derek Ford in McMaster University, while this in italic- by Joyce Lundberg, Carleton University, Canada.

We studied a calcite flowstone growing over the floor of Urinarnika hall of Duhlata cave near Bosnek, Bulgaria. The sample is located approximately 50 m below the surface and 500 m away from the cave entrance. We measured a paleoluminescence record from this speleothem, with a time step of 251 to 445 years (Fig.1.b) as established by

STOYKOVA *et al.* (2003), who determined precisely the variations of the growth rate of this speleothem. This record has a constant linear step of 0,0208 mm/px, but variable growth rate measured in mm/yr, which yieds variable time step of the record. We measured $\delta^{13}C$ and $\delta^{18}O$ records along the same path in each sample (Fig.1.a). $\delta^{18}O$ record correlates with the paleoluminescence record, suggesting a positive correlation with the paleotemperature. It has deep minima during the studied glaciation producing positive value of $\delta^{13}C$ (Fig.1.a).

4. Discussion

In this $\delta^{13}C$ record of a calcite flowstone from the Duhlata cave, Sofia region, we found a positive value of $\delta^{13}C$. This is a very unusual value of $\delta^{13}C$ in cave calcite. In fact, there are no other such cases known in the specialised literature. The only way to explain this is that all the carbon in the runoff comes from the limestone bedrock above the cave during the formation of the corresponding layer in the calcite flowstone, because only the carbonate rocks have a positive value of $\delta^{13}C$ (FAURE, 1987). Such a situation can occur only during total covering of the ground above the cave by ice during a glaciation. In this case, the organogenic and airborne carbon dioxide cannot reach the cave and do not participate in the deposition of calcite. Consequently, all CO_2 in the speleothem comes from the bedrock (which has positive $\delta^{13}C$ values, like the one observed in the studied speleothem (FIG. 1.a)). Due to extremely low thermal conductivity of the ice even when the surface *is* totally covered by ice, the glacier melts in the bottom at the contact with the bedrock, producing running water, which denudes carbonate rocks and may deposit speleothems.

Cycle	Error	Intensity (%)
15100	+/- 605	99.8
10800	+/- 308	100
9400	+/- 236	53.1
8400	+/- 186	49.1
6900	+/- 125	70.5
5800	+/- 89	16.4
5500	+/- 80	23.4
5000	+/- 67	34.5
4700	+/- 57	24.1
4000	+ /- 42	18.8
3600	+ /- 33	8.7
3300	+/- 29	11.3
3100	+/- 26	8.3
3000	+/- 25	6.2

Figure 4: paleoclimate cycles from the Duhlata cave (in years), error of determination the duration of the cycle (in years) and intensity of the cycles (in % of the most intense cycle).

We tried to date the corresponding calcite layer with the generally accepted method for absolute dating of such samples: U/Th dating (Fig. 2), but it turned out that the age of the layer in the sample, which was deposited during total freezing of the ground during glaciation is greater than the maximum dating limit with this method (600,000 years). Thus far it is impossible to determine the precise age of this most interesting event.

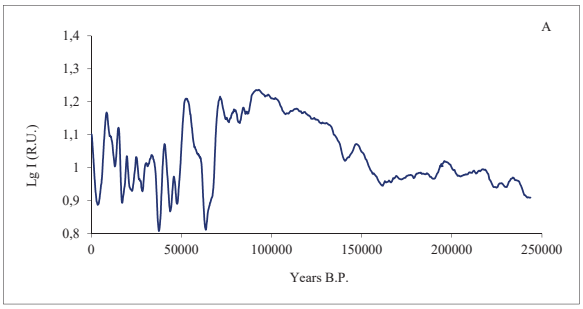

Figure 3: paleoluminescence record from Duhlata Cave, Bulgaria, dated by Evolutive Spectral Analysis (STOYKOVA et al., 2003, STOYKOVA et al., 2008)

To compare the intensities of all cycles, present in a time series (SHOPOV *et al*., 2004) designed a special algorithm and computer code- Real Space periodogram analysis that plots the periodogram in the coordinates -Cycle Intensity/Period. We used it to calculate intensities of the cycles presented in the paleoluminescent record on FIG.2. It demonstrated the existence of new very powerful paleoclimatic cycles of 10800, 15100, 6900, 9400 and 8400 years. Their intensity is comparable to that of the Milankovitch cycles, which cause glaciations. Orbital variations of insolation (Milankovitch curves) are theoretically calculated with 5 approximations (arbitrary presumptions), as a result of which they describe only about 50% of the variations in the instrumental paleoclimatic records and have shifts of the timing of their maxima and minima with several to ten thousand years. The established cycles can explain the observed differences between the theoretical curves and the instrumental records.

We also found several less intensive new cycles with duration of 5500, 5000, 4700, 3600, 3100, 3000 and 2800 years (Fig. 4). They produced prominent millennial variations in the record on Fig.3. Accordingly, STOYKOVA *et al*. (2008) paleoclimatic cycles with duration between 16000 and 11 years are of solar origin, so these cycles probably are due to solar variations.

paleoluminescence record on Fig. 3 covers the last 250,000 years, during which this speleothem grew continuously. Several hiatuses of unknown duration are identified in the older section of the speleothem. They might be due to periods of severe glaciations or droughts following the studied period with positive value of speleothem $\delta^{13}C$.

5. Conclusion

We demonstrated the possibility to use $\delta^{13}C$ speleothem records for determination of total covering of the ground by ice during glaciations. This way we found the existence of a total glaciation in the region around Sofia, Bulgaria, occurring before 600ka, the limit of the U-Th dating that was applied.
We established the existence of very powerful cycles of Quaternary climate change with duration of 10800, 15100, 6900, 9400, 8400 as expressed in the luminescence record. Their intensity is comparable to that of the Milankovitch cycles, which cause glaciations.
The established cycles can explain the observed differences between the theoretical curves and the instrumental records.
We also found several less intensive cycles with duration of 5500, 5000, 4700, 3600, 3100, 3000 and 2800 years.
These cycles are probably due to solar variations producing prolonged climatic cycles.

Acknowledgments

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Ice-free alpine caves during Pleistocene glaciations

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Abstract

Caves located above the timberline are characterised by low temperatures and the local presence of perennial ice accumulations. It is thus not surprising that early analyses of such high-elevation caves suggested that speleothem growth occurred primarily during climate periods at least as warm as the present interglacial. More recent studies confirm preferential formation of stalagmites and flowstones during comparably warm and humid climate epochs allowing vegetation and soil formation at these altitudes. Some caves, however, provide compelling evidence that speleothems also formed during much colder and less humid times of the Pleistocene, conditions which would lead to freezing conditions in the karst. This enigma of caves warm enough to allow the presence of liquid water and the growth of speleothems during glacial times can be resolved invoking the superposition of the caves by temperate glaciers.

This contribution provides a concise overview of how a glacier above a cave can lead to non-freezing conditions in the cave, how glacial-age speleothems can be identified, and what they tell us about the highly dynamic history of the long ice ages in the Alps.

Résumé

Grottes des Alpes non englacées durant les glaciations pléistocènes. Les grottes situées au-dessus de la limite de la forêt se caractérisent par de basses températures et par la présence locales d'accumulations pérennes de glace. Aussi n'est-il pas surprenant que les premières analyses de ces cavités d'altitude aient suggéré que la croissance des spéléothèmes avaient commencé lors de périodes au moins aussi chaudes que l'interglaciaire actuel. Des études plus récentes ont confirmé la formation des stalagmites et des planchers durant des époques au climat suffisamment chaud et humide pour permettre le développement de sols et de végétation à ces altitudes. Toutefois, certaines grottes recèlent des preuves convaincantes que des spéléothèmes se sont aussi formées durant des périodes plus froides et moins humides du Pléistocène, conditions favorables à la présence de gel dans les grottes. Cette énigme des grottes suffisamment chaudes pour que l'eau liquide y circule et pour que les spéléothèmes se forment pendant les périodes glaciaires peut être résolue si l'on pense que les massifs pouvaient être occupés par des glaciers tempérés.

Cette communication fait le point sur la façon dont un glacier surmontant une grotte peut créer les conditions de circulation d'eau, sur l'identification de spéléothèmes contemporains de périodes glaciaires et sur ce que ces spéléothèmes nous apprennent sur les dynamiques sur le long terme de l'englacement dans les Alpes.

1. Introduction

Alpine caves, i.e. caves located above the timberline, are commonly close to the 0°C isotherm. Climate cooling will therefore profoundly affect their microclimate and their hydrology. Severe climate deterioration will lead to three possible scenarios, mainly controlled by the regional hydroclimate and the local topography: (a) permafrost will develop in the catchment above the cave, (b) a temperate glacier will form on the karst terrain, or (c) a small ice cap frozen to the ground will develop on top of the karst. The first and third case may lead to perennial ice formation inside the karst.

Speleothems provide a direct record of drip water availability and hence ice-free conditions in the subsurface. An increasing number of studies utilising stalagmites and flowstones dated by U-series techniques reveals an unexpected pattern: speleothems in alpine caves are not restricted to interglacials of similar or greater warmth as the Holocene; they also formed during colder climate periods including stadials. In some caves such cold-climate speleothems appear in fact to be more abundant than warm-climate ones, although this may be due to the fact that glacial periods comprised some 85% of the time of the last half million years while interglacials were underrepresented.

Paradoxically, non-freezing and hence ice-free caves during glacial periods can be explained by burial underneath glacier

ice. And if the host rock of the cave contains finely disseminated pyrite, common in dark grey limestones and marls, these times in the Pleistocene may be precisely registered by speleothems.

2. Concept

In order to prevent an alpine cave from freezing during a cold climate, a temperate glacier has to be present on top of the cave. The base of such a glacier is at the melting point and meltwater available during the ablation season will find its way into the karstic subsurface. Warm-based glaciers dominate the alpine cryosphere today. They were also abundant during glacials and sculptured the mountains by carving U-shaped valleys and cirques, leaving behind smoothed and striated rock surfaces. The karst beneath such a glacier is prevented from freezing because of two processes, insulation from the winter chill by the snow, firn and ice blanket, and meltwater transferring latent heat during the summer into the karstic rock underneath the glacier. This meltwater can also entrain clastic sediment and may even result in paragenetic cave enlargement.
Speleothems are the best recorders of such periods of ice-free conditions in a karst system, provided that the galleries are not filled by sediment and/or seasonally flooded. Growth of speleothems at temperatures barely above the freezing point in a subglacial setting requires special conditions because of the absence of soil-derived carbon dioxide as the starting point for karstification. These conditions are met in rocks that contain finely disseminated pyrite. These microscopic sulphide crystals form early diagenetically in sediment that contains dispersed organic matter. This is commonly the case in grey limestones and dolomites and in particular in dark grey marls. In light grey carbonate rocks, however, pyrite is usually absent. Upon contact with water containing dissolved oxygen, pyrite weathers and gives rise to sulphuric acid which dissolves the carbonate rock. These redox reactions also take place when the catchment of the cave is unglaciated and covered by vegetation. During the warm climate regime, however, karst dissolution by pedogenic carbon dioxide overwhelms pyrite oxidation because of the abundance of soil carbon dioxide compared to the generally small amount of pyrite present in the host rock and its slow reaction kinetics.
To summarise this concept, alpine caves can stay above 0 °C and speleothem growth does not need to stop at the onset of climate cooling if a warm-based glacier covers the cave and pyrite is present in the host rock.
Unfortunately, modern subglacial caves are very rare in the Alps and we are unaware of monitoring data of such a system. The proof-of-concept, however, was provided already some four decades ago by a pioneering study of Castleguard Cave, a large cave that extends underneath the Columbia Icefield of the Canadian Rocky Mountains and features both active drip sites and speleothems (ATKINSON et al., 1983).

3. How to recognise « glacial » speleothems in alpine caves

There is currently no field-deployable instrument that allows determination of the age of a speleothem nor the climate conditions under which it formed back many thousands of years in the past. The answers to both questions can only be found via sophisticated laboratory analyses. There is, however, one field observation that provides a first hint on whether glacial-age speleothems can in principle be expected in a given cave, i.e. the presence of secondary gypsum. This evaporite mineral indicates the presence of sulphides in the host rock which give rise to dissolved sulphate in the seepage water upon oxidation. Gypsum precipitation requires evaporative concentration of these solutions, typically enhanced by the cave wind.
Five main lines of evidence exist to identify speleothems that formed in subglacial settings, i.e. without soil, during glacial climates. They are ideally applied in combination and these criteria cannot be transferred to other climate regions without significant adjustments.

Chronology
Speleothems can be accurately dated by U-series techniques. Although precision worsens with age and becomes poor beyond about half a million years, younger speleothems can be dated with very small uncertainty. This is further improved by obtaining multiple ages, documenting the growth history of individual speleothems in detail. Comparing a speleothem or a growth period therein with well-established climate records provides an important first step to assess the climate of a given time interval registered by a speleothem. The most widely used reference for the Quaternary period (and beyond) are the Marine Isotope Stages (MIS), which are based on deep-sea sediments and are of global significance. Even-numbered stages designate glacials and if a stalagmite from an alpine cave formed e.g. during MIS 6, the penultimate glacial, then chances are high that this growth would not have been possible without a glacier covering the catchment.

Oxygen isotopes
A second line of evidence utilises the stable isotopic composition of oxygen of the speleothem calcite. This parameter is a function of the cave air temperature and the oxygen isotopic composition of the drip water. The main control in alpine caves is the latter which reflects the water that enters the karst and which itself carries climate information. Studying speleothems of different age and climate from a cave system allows the identification of the oxygen isotopic composition of warm-climate speleothems, e.g. those of Holocene age. Pleistocene speleothems with significantly lower oxygen isotope values from the same or neighbouring caves are thus a strong indication that they formed during a considerably colder climate. If a cave today is already close to 0°C then it is difficult to explain

speleothem growth during a colder climate without invoking superposition by a warm-based glacier.

Carbon isotopes
Probably the strongest argument in favour of speleothem deposition in a subglacial setting are stable carbon isotope values close to or even exceeding the values of the host carbonate rocks (which in the Alps are exclusively of marine origin and thus show characteristic carbon isotope values). The carbon isotope composition of speleothems is sensitive to the influx of carbon from the soil giving rise to negative values. Care must be taken if the rock overburden is very thick and/or the mean travel time of the drip water is long. Both factors buffer the carbon isotope signature of the drip water towards the higher host rock values and may disguise a soil provenance.

Petrography
Speleothems formed without a soil cover commonly, but not exclusively, are composed of dense crystalline and often semi-transparent calcite showing a very low abundance of impurities. This may seem counterintuitive considering the model of subglacial meltwater entering the karst. What this may indicate, however, is that subglacial speleothems are fed by seepage water using very slow flow routes, where the water is in contact with finely disseminated pyrite. In contrast, glacier meltwaters preferentially use fractures and larger karst conduits.

Growth rate
The model of very slow seepage as opposed to fracture flow feeding subglacial stalagmites is consistent with the observation that these speleothems may show extremely slow growth rates, down to about 1 micron per year (e.g., WENDT et al., 2020). In contrast, warm-climate stalagmites in alpine caves show rates of a few tens of microns up to about a tenth of a millimeter per year. Importantly, and in contrast to warm-climate speleothems, subglacial stalagmites do not exhibit systematic changes in growth rate across even large and abrupt climate transitions. This underscores the decoupling of calcite precipitation dynamics from surface conditions as long as liquid water is present in the subglacial karst system.

4. Case studies

Results from five caves in the Eastern and Western Alps are briefly summarised below. These caves developed in host rocks (limestone, marble) containing sulphides and detailed studies of speleothems have shown that the temperature in these caves remained above the freezing point even during some glacial periods.

Kleegruben Cave
The first duplicated record of stalagmites that very likely formed during times of glacier ice coverage emerged from Kleegruben Cave, Zillertal Alps, which opens at 2165 m. Today, the cave interior air temperature is 2.4°C. The stalagmites grew across stadial-interstadial climate shifts of MIS 3, including Heinrich 5, a major cold event in the North Atlantic realm (SPÖTL et al., 2006). There is no change in growth rate between interstadials and stadials but the oxygen isotope composition of the stalagmites registers these climate swings at high resolution.

Spannagel Cave
Located about 1 km south of Kleegruben Cave with the main entrance at 2524 m, this 12 km-long system yielded several stalagmites and flowstones that record growth at times when the nearby glacier was sliding over this cave. As recent as 1850 AD about two thirds of the cave was underneath the glacier tongue. Today's temperature in this cave is 1.8-2.2°C. Times when Spannagel Cave was covered by temperate glacier ice include MIS 3, 7, 8, 9 and 10 (SPÖTL & MANGINI, 2007). Interestingly, there are no records of glacial maxima (i.e. MIS 2 or 6). This might suggest that during these extreme periods the glacier above this high-alpine cave becomes partly cold-based.

Sieben Hengste cave system
This extensive system north of Lake Thun yielded a replicated set of stalagmites that grew continuously across MIS 2, broadly equivalent to the Last Glacial Maximum (LUETSCHER et al., 2015). Today's cave temperature at the sampling point is 4.2°C and its elevation is 1540 m (surface at 1755 m), i.e. about 1 km lower than at Spannagel Cave. The Sieben Hengste stalagmites record millennial-scale climate swings by their oxygen isotopic composition, while the carbon isotope values lack a soil signal. No change in growth rate occurred during millennial- to centennial-scale climate shifts. Speleothem deposition, however, ended abruptly at 14,700 years ago, precisely at the time of major northern hemispheric warming. This event most likely records the melting of the ice cover and the lack of soil on this barren land to promote karstification and warm-climate speleothem growth.
More recent work has shown evidence of a persistent talik, at least affecting some parts of this cave, during MIS 6, the penultimate glacial (HONIAT et al., 2018), as well as during parts of MIS 10 and 12 (M. LUETSCHER, unpublished data).

Klaus Cramer Cave
Located at 1964 m in the Allgäu Alps of Austria close to the border to Germany, today's air temperature in this cave is 1-2°C. A small stalagmite yielded a 17,400 year-long record covering the transition from the prominent Greenland Interstadial 19 to the long stadial equivalent to MIS 4. This is a time when the alpine glaciers advanced significantly, possibly even into their foreland. Deposition of this stalagmite continued uninterruptedly across this large climate shift and shows no change in growth rate either (BOCH et al., 2011).

Ongoing research on other stalagmites yielded evidence of ice-free conditions in this cave also during earlier glacials, including MIS 10 and 12 (C. SPÖTL & G. MOSELEY, unpublished data).

Melchsee-Frutt cave system

A series of large caves is located between about 1300 and 2450 m in the Melchsee-Frutt region of central Switzerland (mean cave air temperature 2.9°C). Drill cores as well as fully recovered stalagmites from three of these caves (Schratten cave, Betten cave, Neotektonik cave) yielded evidence of speleothem growth during interglacials including the Holocene but more abundantly during glacial periods: MIS 2, 3, 4, 5, 6, 8 and 10 (FOHLMEISTER et al., 2019, and unpublished data). The oxygen isotope records of these stalagmites register fine-scale climate swings and the carbon isotope signature attests a soil-free catchment, likely overlain by a temperate glacier during cold periods.

5. Conclusions

Speleothems from cold high-elevation caves are sensitive paleoenvironmental archives because they form close to the freezing point of water, and alpine soils - the source of carbon dioxide for karstification - are thin and vulnerable. Climate cooling is therefore widely considered to result in speleothem growth stops. This widely, however, ignores the fact that climate cooling will lead to a lowering of the equilibrium line altitude and the expansion of glaciers. A temperate glacier overflowing a karst system can prevent the latter from freezing. Although glacials were generally less humid than interglacials, alpine caves had a much higher chance of being glacier-covered during the ice ages (and hence being kept “warm”) than caves at lower elevation elsewhere which were often in the permafrost zone. Times of non-freezing conditions in caves overlain by temperate glaciers cannot be recorded by speleothems unless the host rock contains disseminated pyrite. It is therefore not surprising that alpine caves carved in rather pure limestone (e.g. Wetterstein and Dachstein Formations in the Eastern Alps) lack glacial-age speleothems. In contrast, speleothem growth in limestones interlayered with marls e.g. of Cretaceous age, wide-spread in the Western Alps, recorded ice-free conditions in the karst during times of superposition by glaciers.

Subglacial speleothems provide unique and precise windows into how alpine caves behaved during the long glacial periods. Combining them with the study of warm-climate speleothems controlled by soil dynamics (e.g., MOSELEY et al., 2020; WILCOX et al., 2020) as well as cryogenic cave carbonates (as robust indicators for the presence of cave ice accumulations), allows for the interpretation of alpine caves on glacial-interglacial time scales in addition to the production of extremely valuable information about climate and landscape evolution precisely registered by well-protected speleothems in the subsurface.

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On a new occurrence of rapidcreekite from NW Romania

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Abstract

Rapidcreekite, $Ca_2(CO_3)(SO_4)\bullet 4H_2O$ has only been reported from a handful of locations around the world. The mineral was discovered in 1983 on an affluent of Rapid Creek (Yukon, NW Canada) and since then in a few locations with different lithological settings, but usually associated with gypsum and another carbonate. Its first cave occurrence was reported in 2009 from Diana Cave, SW Romania. Here we present data on a new occurrence of rapidcreekite in a cave in NW Romania, where the mineral is associated with gypsum and calcite, as well as detrital quartz and muscovite. The cave filling consists of forest soil accumulated from the surface. Rapidcreekite occurs as tiny white crusts and nodules in cracks in the soil fill, or covering seeds, insects or older crusts consisting of calcite and gypsum, down to depths of 15-20 cm in the sediment (but never on the surface), more frequently in areas corresponding to drips from the ceiling. The rapidcreekite crystals form groups of 1-2 µm rhombic bipyramids and may also replace gypsum. The source of sulfur necessary for the formation of gypsum and rapidcreekite is most likely pyrite disseminated in the limestone.

Résumé

Sur une nouvelle occurrence de rapidcreekite du nord-ouest de la Roumanie. Rapidcreekite, $Ca_2(CO_3)(SO_4)\bullet 4H_2O$, n'a été signalée que dans une peu d'endroits dans le monde. Le minéral a été découvert en 1983 sur un affluent de Rapid Creek (Yukon, NW Canada) et depuis lors dans quelques endroits avec des paramètres lithologiques différents, mais généralement associé au gypse et à un autre carbonate. Sa première occurrence dans une grotte a été signalée en 2009 dans la grotte de Diana, dans le sud-ouest de la Roumanie. Nous présentons ici des données sur une nouvelle occurrence de rapidcreekite dans une grotte du nord-ouest de la Roumanie, où le minéral est associé au gypse et à la calcite, ainsi qu'au quartz et muscovite détritiques. Le remplissage de la grotte est constitué de sol forestier accumulé de la surface. Rapidcreekite se présente sous forme de minuscules croûtes blanches et de nodules dans les fissures du sol, ou recouvrant des graines, des insectes ou des croûtes plus anciennes constituées de calcite et de gypse, jusqu'à des profondeurs de 15 à 20 cm dans les sédiments (mais jamais en surface), plus fréquemment dans les zones correspondant aux gouttes du plafond. Les cristaux de rapidcreekite forment des groupes de bipyramides rhombiques de 1 à 2 µm et peuvent également remplacer le gypse. La source de soufre nécessaire à la formation de gypse et de rapidcreekite est très probablement la pyrite disséminée dans le calcaire.

1. Introduction

Rapidcreekite, $Ca_2(CO_3)(SO_4)\bullet 4H_2O$ was first described by ROBERTS et al. (1986), in the Rapid Creek area (Dawson mining district, Yukon, NW Canada), otherwise known for its diversity of phosphate occurrences (ROBERTSON 1982; ROBINSON et al. 1992; GUNTER 2020). In its type locality, rapidcreekite is a secondary mineral, associated with gypsum, aragonite and kulanite, another uncommon phosphate. Since its discovery, a few other natural occurrences of rapidcreekite have been reported from Czechia (cave occurrence - ŽAK et al 2010), Germany, Greece, Norway (in mines), Poland (mine and slag dump), and Romania (cave occurrence - ONAC et al. 2009, 2013). Its structure was refined in 1996 by COOPER & HAWTHORNE and in 2013 by ONAC et al. A new occurrence of rapidcreekite was discovered in the Plopiş Mountains on the Ponor karst plateau, situated at the limit of three counties from the NW part of Romania: Sălaj, Cluj and Bihor (Fig. 1). The karst plateau is formed on Triassic (Anisian) limestones and dolomites (GABRIAN et. al 2010). In May 2018, during a student field trip, a 1.3 m long “den” was discovered at 699 m a.s.l. on the southern side of the plateau and a short exploratory dig opened a relict phreatic passage, 0.8 m high and 0.6 m large, which is blocked by sediments after 10 m. The thickness of the sediments in the passage cannot be determined yet, however two short cores, covering the first 50 cm, were sampled. The cave filling consists of forest soil accumulated from the surface, with variable amounts of organic material (leaf fragments, seeds, charcoal, insect elitrae), bones, lithoclasts (limestone, dolomite, quartzites), and broken speleothems.

2. Materials and methods

The cores sampled from the sediment at the bottom of the passage were described in the laboratory and sub-sampled for charcoal, pollen, and clay mineral analysis. Several coatings and powdery deposits (tiny white crusts and

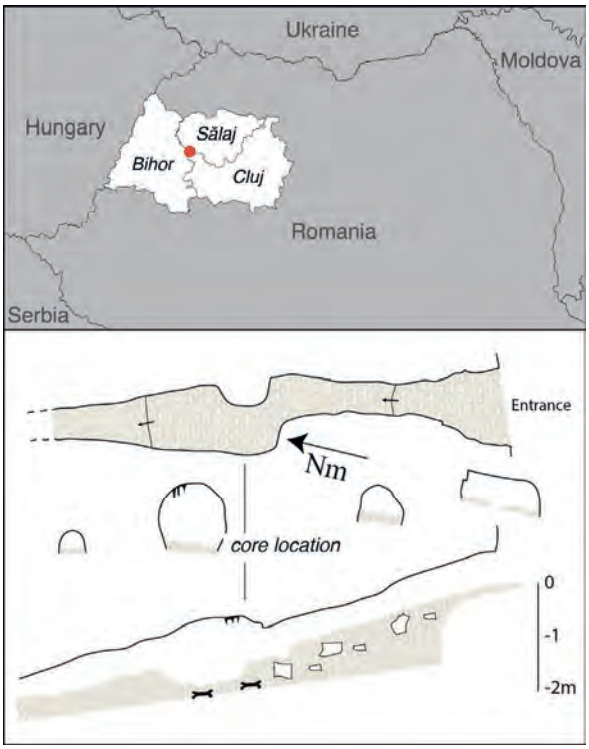

Figure 1: top: Location of the Ponor plateau in NW Romania; bottom: Passage map with the location of the core and samples described in the text.

nodules), as well as fragments of host rock, speleothems (stalactites and centimetric crusts), and bones were found when dividing the subsamples. They were selected primarily for X-ray powder diffraction (XRPD), scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) analyses. XRPD analyses were done with a Bruker D8 Advance diffractometer, using Cu and Co tubes and a linear LynxEye detector. Selected powders from the samples were analyzed generally between 3.8 - 64˚ 2Θ. Pattern calculations were performed with the Mercury software using the *.cif* files available online. For clay minerals, XRPD analyses on the oriented mounts were achieved after air-drying, ethylene-glycol solvation for 24 h and thermal treatment at 400°C and 550°C for 1 h. The Bruker DiffracEVA 2.1 software with the PDF2 database from ICDD were used to identify the mineral composition. The clay minerals were identified in accordance with MOORE & REYNOLDS (1997). For SEM observations the samples were mounted on double-sided adhesive carbon tabs on aluminum holders and covered with a 10 nm gold layer, then observed with a Hitachi SU8230 electron microscope equipped with an Oxford Instruments elemental analysis system. Additional EDS analyses were done on uncovered samples using a specially designed sample holder with lateral clamps, to avoid bias from the adhesive carbon tabs.

3. Results and discussion

1. ***Rocks and clay minerals***. XRPD analyses of the rock fragments recovered from the sediment revealed the presence of both limestone and dolomite in the lithoclasts. The clay mineral analysis has shown a fairly uniform composition of the sediment samples taken from 5 different levels, with vermiculite, muscovite and kaolinite the minerals identified, similar to the soil samples collected from the plateau surface.

2. ***Speleothems.*** Considering the limited extent of the cavity and the type of samples retrieved from the sediments, the mineralogical composition of the samples was surprisingly diverse: aside from the clay minerals, *carbonates* (calcite, Mg-calcite), *phosphates* and *sulfates* were identified in various samples. As expected, centimetric stratified crusts and short stalactites buried in the sediment consisted primarily of calcite. Little calcite crusts were also found at or near the sediment surface. At several levels in the sediment we found phosphate crusts (separately hydroxylapatite and brushite) on bones and on broken calcite speleothems, indicating that a small source exists for phosphoric acid in the sediments. As brushite and gypsum are isostructural, the occurrence of one or the other was determined through SEM - EDS, the presence of P or S indicating the mineral present.

3. ***Sulfates***. The two sulfates identified were gypsum and rapidcreekite, in two different types of samples: a. *Gypsum and calcite centimetric crusts* (Fig. 2), containing white calcite on the outside part and translucent gypsum in a central millimetric band, separated by a thin layer of manganese oxides of bacterial origin (probably ranciéite). Rapidcreekite was first identified on the edges of this particular gypsum layer.

b. While separating subsamples for clay mineral analysis, we noticed *millimetric nodules and powdery deposits* on desiccation cracks, insect elitrae and small limestone fragments occurring at various depths in the sediment cores (more frequently between 10 cm and 20 cm, less frequent below 30 cm and never near the surface). 25 X-ray powder diffraction on 13 such deposits have shown they consist invariably of gypsum and rapidcreekite, with detrital quartz and muscovite. Rapidcreekite, identified from the reflections in the diffraction pattern at d-spacings 7.78 (100), 4.31, 3.88, 3.24, 3.10, 2.92 and 2,79, very close to

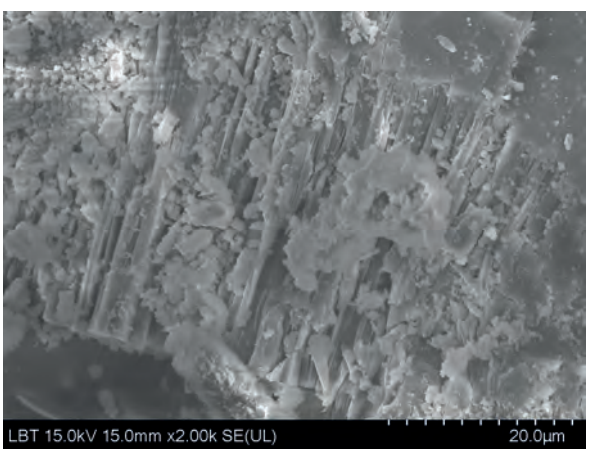

Figure 2: Fibrous gypsum in a calcite and gypsum crust

the pattern determined by ROBERTS et al. (1986), is however never occurring as the main mineral, some of the lines being partially masked by gypsum and quartz which have higher crystallinity (Fig. 3). As only 7 reflections in the diffraction patterns could be correlated to rapidcreekite with certainty, and due to its occurrence only in mixtures, calculating the crystal structure was not possible. Nevertheless, comparing the XRPD pattern with the structures available, we imply that the new phase is consistent with rapidcreekite. At SEM, rapidcreekite crystals form groups of 1-2 µm elongated rhombic bipyramids with perfect cleavage (Fig. 4). EDS analyses invariably show Ca, S, C and O as main constituents, with various elements also occurring in minor amounts, most likely from detrital contribution (Si, Fe, K and Al) and with variable amounts of P. In most instances gypsum may be identified by its larger (5 – 30 µm), typically monoclinic-prismatic crystals and by the lack of carbon in its composition.

An EDS spectrum similar to the rapidcreekite crystals is shown by slightly larger (up to 5 µm), monoclinic crystals, which may represent pseudomorphs after gypsum (Fig. 4). As we found both brushite and gypsum in different samples, we also verified if ardealite, with the chemical formula $Ca_2(SO_4)(HPO_4)\bullet 4(H_2O)$ and a somewhat similar diffraction pattern (first reflection at d=7.74 Å (100)), was not present. In 6 measurements done on the subsample taken from 9 cm in the core, the P content determined through EDS was 6.7 – 8% with C <2%, pointing to a likely presence of ardealite (which has ~9% P). However, all the other subsamples (i.e. from cm 10, 12, 14 etc) had a phosphorus content between 0.1 and 1.6% (with a mean of 0.5% for the crystals in Fig. 3), indicating the absence of ardealite.

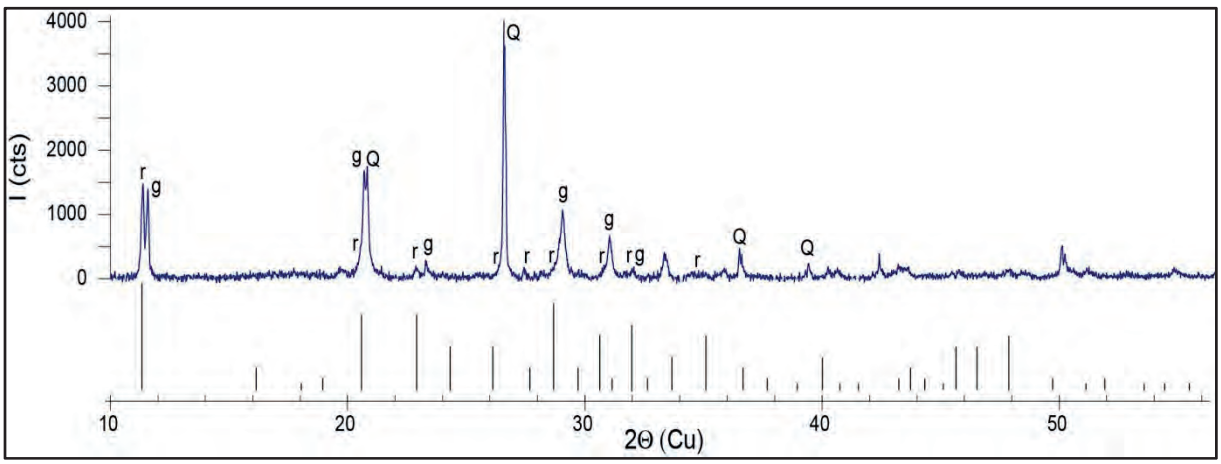

Figure 3: X-ray powder diffraction pattern for a sample containing rapidcreekite (r), gypsum (g), and quartz (Q) with the lines from the pattern of ROBERTS et al. (1986) for comparison.

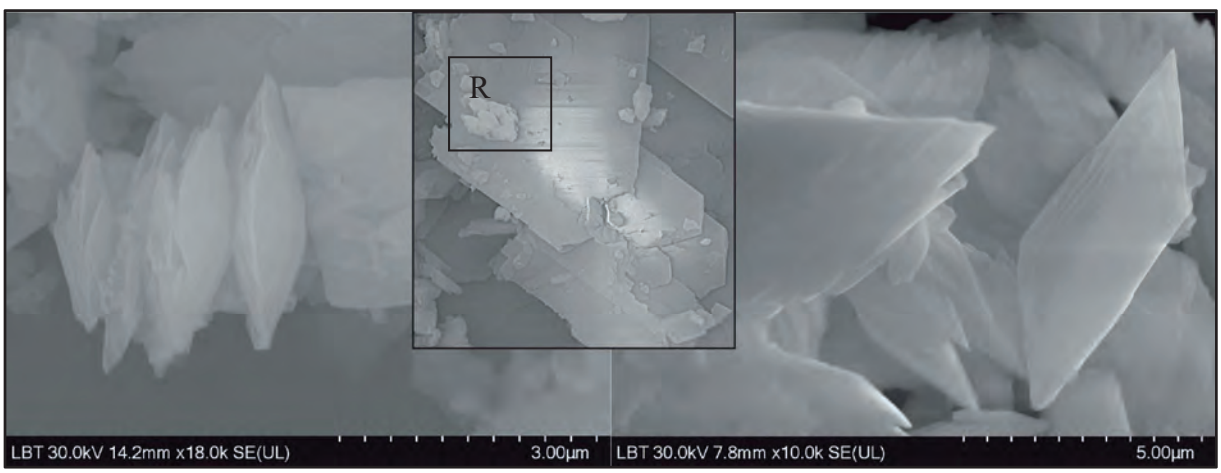

Figure 4: SEM images of rapidcreekite crystals (left) and monoclinic prisms originally of gypsum (right) with similar chemical (EDS) composition. Inset: gypsum crystals (ca. 10 µm long) with rapidcreekite crystals (R, 1µm).

5. Concluding remarks

The study of soil-like sediments from a short cave passage located in the Ponor karst plateau, NW Romania has uncovered a mineral association consisting of carbonates (calcite, Mg-calcite), calcium sulfates (gypsum, rapidcreekite), and phosphates (hydroxylapatite, brushite, and ardealite). The main focus of this study was the third occurrence of rapidcreekite in a karstic environment. Although not present as the main mineral in any of the samples analyzed, and with crystals very rarely over 2 µm in size - and as such posing various analytic inconveniences - its reflections present are consistent with the pattern obtained by ROBERTS et al. (1986) on crystals from the type locality. EDS analyses sustain our inference, the low phosphorus contents differentiating the crystals from ardealite, which has a somewhat similar diffraction pattern. The depositional environment is different from the two cave occurrences already published (ONAC et al. 2009, 2013 and ŽAK et al 2010), rapidcreekite forming in a passage filling in which it is directly associated only with calcite and gypsum, the carbonate being provided by the few drip points existent in the ceiling of the passage. Up to this point, the SEM and EDS data seem to suggest that rapidcreekite crystals are formed on the surface of existing gypsum aggregates as a secondary phase, and also probably replacing gypsum. Another peculiarity of the occurrence is the fact that in close vicinity (1 cm away), crusts and nodules very similar in appearance consist of calcium phosphates (brushite and minor ardealite), pointing to the presence of very localized sources of phosphorus and sulfur inside the passage sediments. The initial source of sulfur for the gypsum speleothem formation is most likely pyrite disseminated in the limestone host rocks.

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What's going on in (published) cave science?

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Abstract

In the frame of session 03 – Cave deposits - of the International Congress of Speleology (ICS) it is not easy to achieve a complete 'state of the art' for the ongoing ***cave deposits*** research. Recent occurrence and evolution of some topics studied in cave sciences are analysed with the Scopus analytic tool, an easy-to-use tool accessible via universities, to have a first-order overview of 'what's going on in (published) cave science'.

Résumé

Que se passe-t-il dans la science des grottes (publiée) ? Dans le cadre de la session 03 – dépôts des grottes - du Congrès international de spéléologie (ICS), un "état des lieux", de la recherche actuelle concernant cette thématique, reste difficile. Les thématiques récentes et l'évolution des sujets de recherche concernant les sédiments des grottes sont analysés à l'aide de l'outil analytique Scopus accessible via les universités. Cet outil relativement facile à utiliser permet d'avoir un aperçu rapide de ce qui se passe (est publié) en « science des cavités naturelles ».

1. Cave science analysis

In the frame of session 03 – Cave deposits – of the International Congress of Speleology (ICS), it may be a nice but difficult task to achieve a complete 'state of the art' for the ongoing research in cave deposits. In times where the search term ***cave*** yields some 2 million entries in Google Scholar, a detailed study would need many years of reading unless some machine-learning techniques pop-up for such tasks in the near future.

With the development of the scientific knowledge in cave sciences, several research themes are now more specialised in peculiar topics, within each of the scientific communities forming the general community in cave science research field: bacteria and fauna, the palaeoclimate-based research in speleothems, geohazards, planetary speleology, etc. Even though the cave environment is a geographically defined place, the extension of such a research environment into the karst geosystem drives many other interdisciplinary studies and is not only limited to the aforementioned examples.
Therefore, keeping this interdisciplinary dimension in cave sciences is an asset and congresses such as the ICS are important activities for keeping this interdisciplinarity alive.
Scopus, web-of-science or Google Scholar, often-used commercial or open abstract and citation databases, offer a convenient tool to visualise publication tendencies and evaluate the relative importance of topics. Scopus shows that a huge number of papers (~40,000) have been published in cave sciences since 1960. However, these results should be considered very carefully and taken only as roughly informative, since these 40,000 publication-like documents include other topics than the types of cave research investigated here. It probably includes a number of documents on stomachal cavities, biological research and a minor part deal with engineering, spatial or military research. Looking for more (adequate) specific terms leads to a number of publications in the several hundreds referenced in Scopus.

It is important to note that Scopus takes into account only peer-reviewed referenced papers, while a probably higher amount of works is published in other types of papers (e.g. conference proceedings, oral communications, grey literature) as is suggested by the ~80,000 results delivered on the Google search engine for "**cave deposit**". However, this inquiry gives a broad picture of the ongoing research on cave sciences and helps evaluate in a first order the origin and relative importance given to the topic in 'cave sciences' publications throughout the last 70 years (1950-2020).

2. Evolution of publications concerning speleothem and cave sediments

A first search on the terms ***speleothem(s)*** and ***cave sediment(s)*** in Scopus yields a total number of publications of ~2,500 and 500 respectively. The extension of the term ***cave sediment*** to ***cave sediment or cave deposit or karst sediment or karst deposit*** increases the number of publications to ~1,500 (over the entire period 1950-2020).
When the inquiry on Scopus is restricted to a specific topic in cave sciences, such as ***speleothem(s)*** and ***cave sediment(s)*** etc., it appears that more work is generally published on chemical cave deposits than on detrital cave deposits. This is also reflected in our session 03 where 75% of the deposited abstracts concern chemical cave deposits, i.e. 'classical' speleothem and other mineralisation studies, while probably a part of the sedimentary work done in caves is presented in session 8 - archaeology and palaeontology in caves.

A view of the publications since 1960 (Fig. 1) reveals an increase in publications for all the topics, especially since the beginning of the 2000's.

While the number of cave-related papers in general still increases steeply, the increase in the number of speleothem-related papers displays some deceleration since ~2013. Regarding papers publishing ***cave sediment***-related topics, there seems to be a deceleration followed by a continuous decrease since 2011.

It is rather surprising that for a topic such as ***caves and bacteria***, the increase in the number of publications started simultaneously as for publications in other topics, but at a slower pace. Nonetheless, it is clear that today the number of annual publications for the topic of ***caves and bacteria*** is close to the number of publications for ***cave sediments***.
We would probably expect a continuous increase in publications on this promising topic in the future.

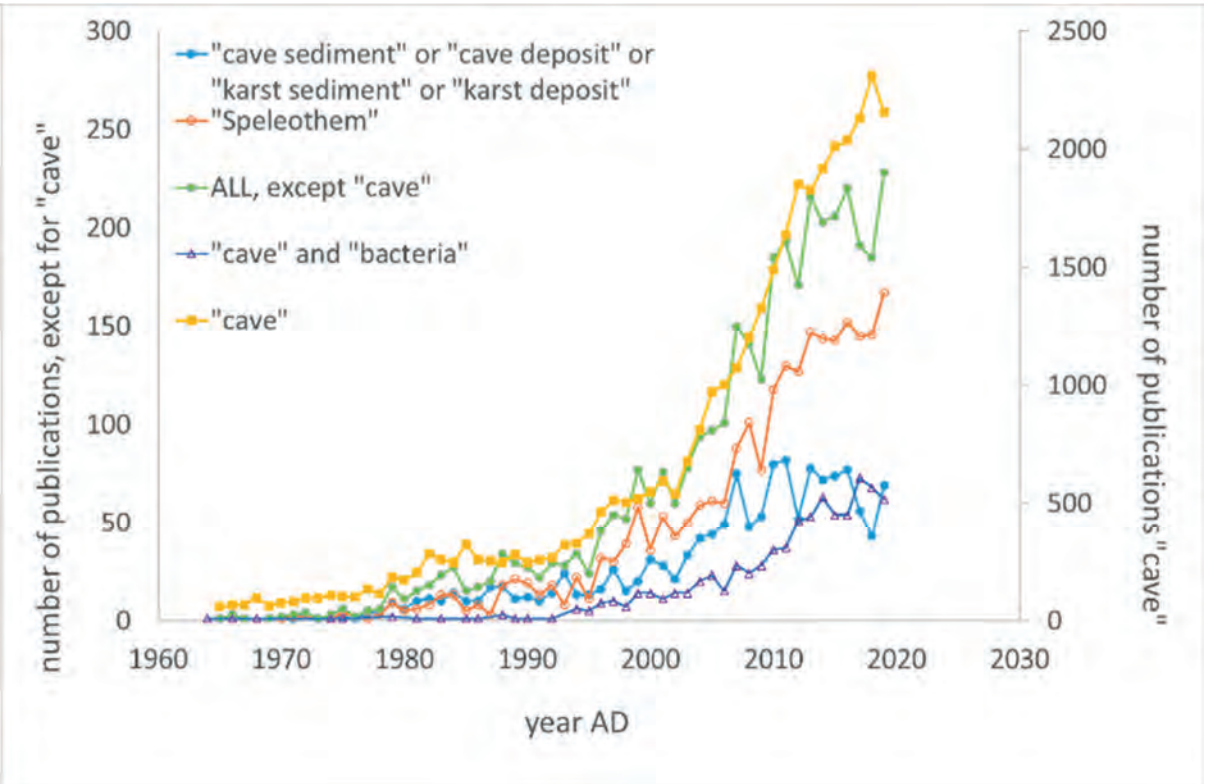

Figure 1: Evolution of the number of publications concerning selected topics. Secondary y-axis refers to the graph of the term "cave" only; *Source: Scopus accessed between 19 July and 6 December 2020*

3. Interdisciplinarity in cave science

Another inquiry on Scopus focusing on the disciplines (e.g. earth-science, environment/agriculture, arts and humanities, social, etc.) defined in scientific journals where the topics ***cave sediment(s)*** and ***speleothem(s)*** are published, show a relatively high degree of interdisciplinarity (Fig. 2).

Earth and planetary science represents the largest discipline where both topics are published (between 40 to 50% of the publications related to both topics), followed by the art and humanity, environmental, agriculture and social disciplines, representing each around 10% of the publication in both topics. Finally, disciplines like Biochemistry, engineering, Immunology/microbiology represent in total less than 10% of the publications in both topics.

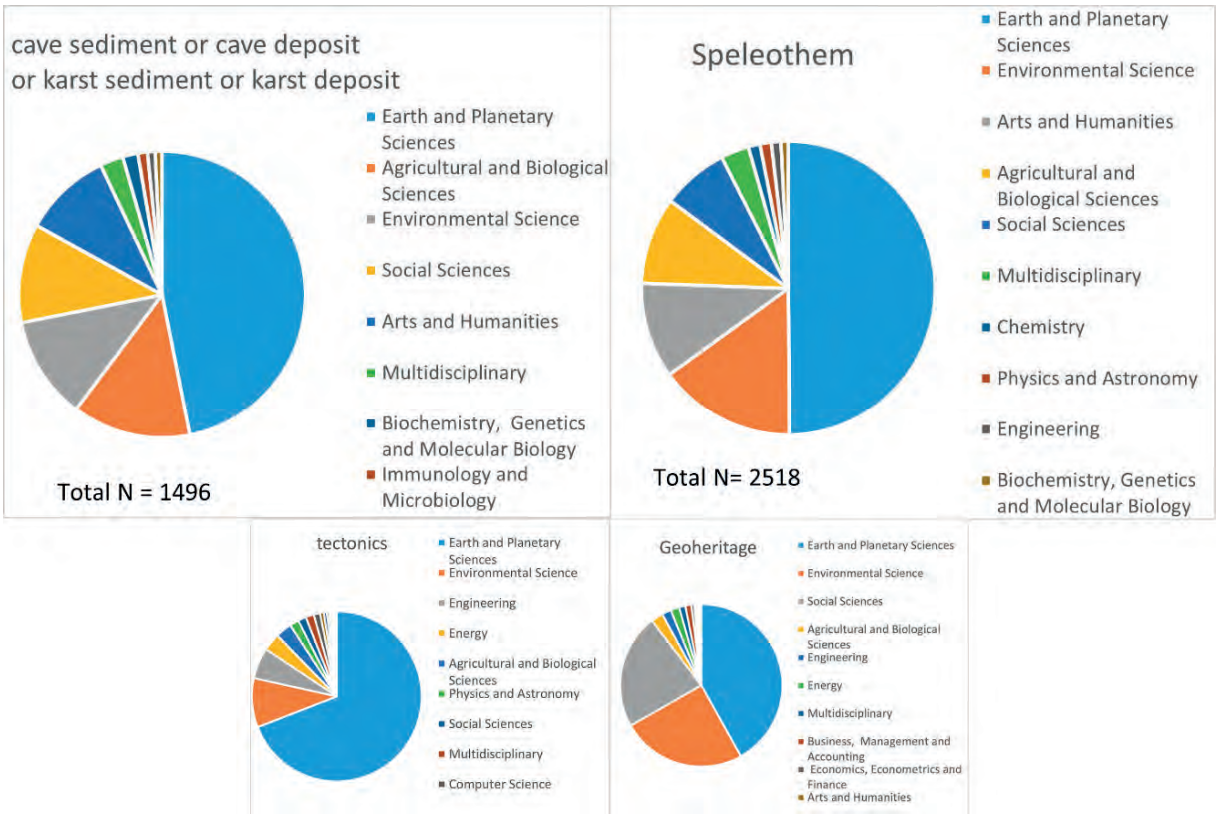

Figure 2: View of the diversity of disciplines in which scientific papers on 'cave sediments' and 'speleothem' are published. For comparison, the same inquiry was completed for the scientific topics 'tectonics' and 'geoheritage'.

Recent initiatives in the 'speleothem community' were to produce a worldwide database for publications in speleothem and cave sediment science. Therefore, the Speleothem Isotope Synthesis and AnaLysis (SISAL) group was created in 2017 under the patronage of PAGES (http://pastglobalchanges.org/science/wg/sisal/intro). This group of volunteering researchers (post-doc, PhD student, Lecturer, senior researcher) delivered a huge work to collect speleothem and cave monitoring data in a single database (ATSAWAWARANUNT *et al.,* 2018). First comparative papers came out recently for each continent.

Other speleothem-related topics concern the continuous efforts in the speleothem-based research field: palaeoclimate reconstructions in Asia (e.g. monsoon cycles and their influence), the chemistry components of speleothems (e.g. calcite-aragonite, calcite formation in ice-caves), new proxies (e.g. clumped-paleothermometer, biomarkers) increased number of analyses with new techniques (e.g. micro X-ray fluorescence spectrometry; Laser-induced Break-down spectroscopy). A still unanswered question in speleothem-based research fields concerns the consequences of diagenesis and chemical changes on the U/Th content and thus on the obtained ages in speleothems. Presentations on rare cave minerals given in session 03 are noteworthy, showing the growing interest in such topic (*cf.* CLEARY *et al.*; LO CONTE *et al.*;TĂMAŞ and others, 2021- this volume) even though it represents a small part of the cave science in general.

For publications related to cave sediments, several recent papers deal with the dating of cave sediments and especially the use of cosmonuclides. The potential of cosmogenic $^{10}Be/^{36}Cl$ for dating of guano deposits for instance is presented by MCFARLANE & LUNDBERG (2021, this volume).
Finally, geochemical, spectroscopic or radar techniques seem to be regularly used in recent studies to investigate or map cave sediments, in line with the continuous development of instrumentation and analytical techniques applied on cave deposits.

4. Epilogue and conclusion

The short bibliographical analysis presented here concerns essentially professional scientific publications and unfortunately does not take into account other types of publications in the so-called *grey* literature. Such publications, not referenced in scientific databases (e.g. local/regional or national caving journals, journals in other languages than English) could represent a considerable amount of information, closer to the several tens of

thousands results given by Google. This literature, eschewing the official peer-reviewed process may also include innovative subjects and views.

Overall, publications on ***cave sediment(s)***, ***speleothem(s)*** and ***caves and bacteria*** are following the general increase in publications, but with a deceleration to decreasing trend for the number of publications on ***cave sediment(s)*** in the last years. There is, however, a remaining potential for an increase in the number of publications on ***caves and bacteria***.

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Sedimentary evolution of the Bruniquel Cave, France

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Abstract

The Bruniquel Cave along the Aveyron River in southern France, is known to be a remarkable archaeological site with its Neanderthal structures of broken stalagmites dated at 176.5 ± 2.1 ka and revising our knowledge of Neanderthal behaviour. Besides the archaeological finds, the cave also contains important natural detrital deposits of several meters thick and several generations of speleothems. The study and dating of the deposits indicate a long sedimentary history of at least 400 ka as indicated by the oldest ages obtained from a remobilised stalagmite lying on the present-day cave floor. At least three detrital infill and speleothem deposition cycles are observed. Flowstone U-Th dating suggests that the cave displays its current environment since 130 ka (MIS 5), while the good preservation of the anthropogenic Bruniquel structures suggests that no important sedimentary changes occurred in the cave since ~ 176 ka (MIS 6).

Résumé

Evolution sédimentaire de la grotte de Bruniquel, France. La grotte de Bruniquel, située le long de l'Aveyron dans le sud de la France, est connue pour être une "grotte archéologique" intéressante. Elle contient des structures de stalagmites brisées datées de 176,5 ± 2,1 ka et attribuées à l'Homme de Néandertal, ce qui contribue à réviser nos connaissances sur le comportement de Néandertal. Outre les découvertes archéologiques, la grotte contient d'importants dépôts détritiques naturels de plusieurs mètres de haut et plusieurs générations de spéléothèmes. L'étude et la datation des dépôts indiquent une longue histoire sédimentaire d'au moins 400 000 ans, comme l'indiquent les âges les plus anciens obtenus à partir d'une stalagmite remobilisée reposant sur le sol actuel de la grotte. Plusieurs, et au moins trois, cycles de "dépôts de sédiments détritiques et de spéléothèmes" sont observés. La datation U-Th de la calcite suggère que la grotte n'a pas beaucoup changée depuis 130 000 ans (SIM 5), tandis que la bonne préservation des structures anthropogènes de Bruniquel suggère qu'aucun changement sédimentaire important n'a eu lieu dans la grotte depuis ~ 176 ka (SIM 6).

1. The Bruniquel Cave, anthropogenic structures and animal traces.

The Bruniquel Cave is situated in front of the medieval Bruniquel village, nearby the 'confluence of the Vère river with the Aveyron River. The cave (Fig 1) develops in Bajocian limestone at approximately 50 meters above the Aveyron River. The cave was discovered in the early nineties by the Société Spéléo-Archéologique de Caussade, a local caving club. At 300 meters from the entrance, several strange, roughly circular structures of broken stalagmites were discovered. The cave is structured as a single, rather straight gallery, in general 15 meters large and 2 to 5 meters high. The gallery is, rich of warmly coloured speleothems and several large rimstone basins. Several bear hollows are observed along the cave. A first archaeological study, led by F. Rouzaud and M. Soulier (ROUZAUD et al., 1997), including a ^{14}C dating of a burnt bone fragment, indicated an age of at least 47 000 years (ROUZAUD et al., 1995). In 2016, uranium-thorium dating of the stalagmites inside the largest structure during a second archaeological study led by JAUBERT, VERHEYDEN and GENTY et al. (2016), indicated an age of 176 500 years with an uncertainty of ±2 100 years. The age came as a surprise and changed our perception of Neanderthals as the first cavers, mastering perfectly well their underground environment. Besides, the discovery indicates that these humans perfectly mastered fire and had already strong social bands, regarding the complexity of the constructions.

The structures, although well preserved, seem to have undergone some damage, likely due to gravity, flooding or the presence of bears. To better understand the history of these structures, as well as of the entire cave, the study of the cave and its deposits is one aspect of the general study of the site. The gallery formed through the limestone hill surrounded by the river and suggests two possible entrances. Indeed, the current entrance was opened by digging in the sediments and the limestone. The cave is rich in speleothems and several phases of speleothem deposition are clearly observed. Complex sedimentary profiles and a wide range of speleothem ages suggest a rich cave history prior to the construction of the structures. First observations and mapping of the cave deposits, combined with U-Th dating of speleothems, give some first insights in the successive infilling phases in the cave. A preliminary simplified model of the general sedimentary dynamics and resulting endokarstic landscapes is proposed.

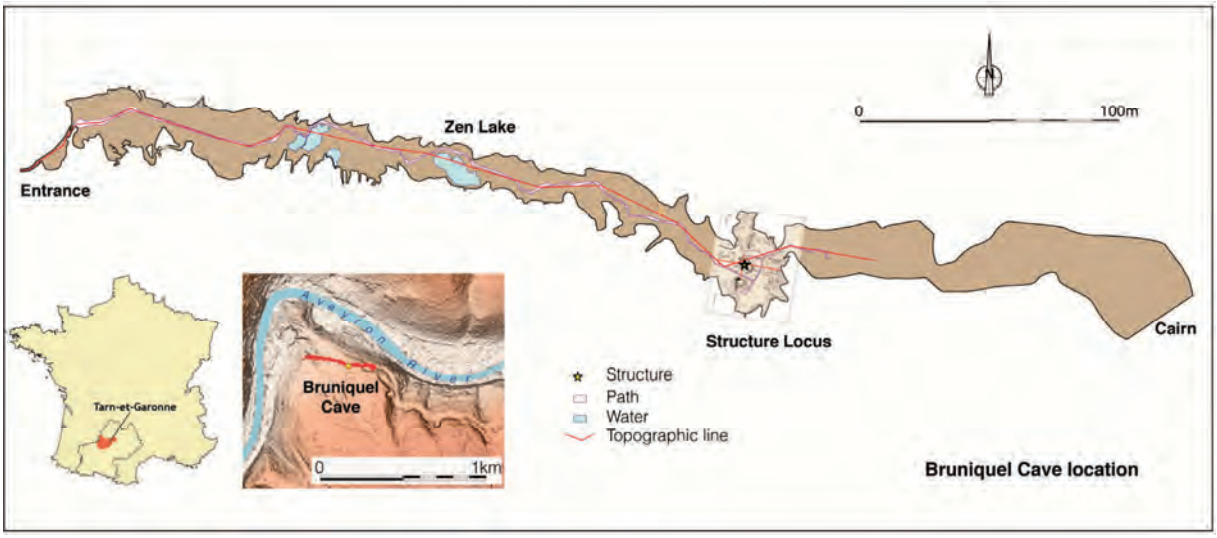

Figure 1: Location and map of the Bruniquel Cave.

2. Speleothem growth over five Glacial-Interglacial cycles

The BR-stm-8 stalagmite (Fig. 2) was found, completely embedded in clay, lying on the pathway just before the massive fallen limestone rock called the 'Chaos' area. This area is situated at ~100 m from the entrance. The stalagmite has two distinct basal 'crowns' suggesting a partial sedimentary burial and restart of speleothem growth on this new ~10 cm detrital layer. The internal sedimentary structure of the stalagmite confirms a significant cave infilling at ~347.9 (± 8.0) ka as demonstrated by the remaining detrital layer between two calcite layers and the more recent speleothem on top of it (Fig. 2, circle). Several other 'detrital episodes' are detected in the stalagmite during the final phase of the Interglacial ~MIS 11 and the Glacial, ~MIS 10 periods (Fig. 3). A final, more stable and rapid, calcite growth occurred from 335.1 ± 3.1 ka up to the top of the stalagmite at 330.4 ± 4.0 ka, in agreement with ~MIS 9 interglacial conditions.

In total, already ~100 speleothem ages were obtained from speleothems in the Bruniquel cave since the start of this study in 2014. The ages indicate speleothem growth over 5 Glacial-Interglacial cycles (Fig. 3). This is in agreement with in-cave observations of several speleothem phases alternating with or embedded in detrital infills, identified during mapping of the cave, demonstrating a multiphase sedimentation history.

Figure 2: Bruniquel Cave – Internal section of the BR-stm-8 stalagmite (middle) found ex-situ (left) in vicinity of the 'Chaos'. Right: MC-ICP-MS U-Th dating results (Hai Cheng, Xi'an Jiaotong University). The circle indicates incorporated detrital sediments with new stalagmite growth on top of it.

3. Relation with regional climate

The alternating detrital and speleothem deposition in temperate regions is known to be closely linked to climate, more specifically to alternating warm and cold periods (QUINIF et al., 2006). Figure 3 shows the U/Th ages obtained from speleothems in the cave against Northern Hemisphere climate reference curves. Results reveal speleothem deposition during Glacial and Interglacial periods with, however, limited speleothem deposition during the coldest glacial episodes and with several detrital infill episodes during declining interglacial and glacial periods as suggested by BR-stm-8. Further work will focus on the relation between warm phases (Interstadials) of glacial periods and speleothem deposition.

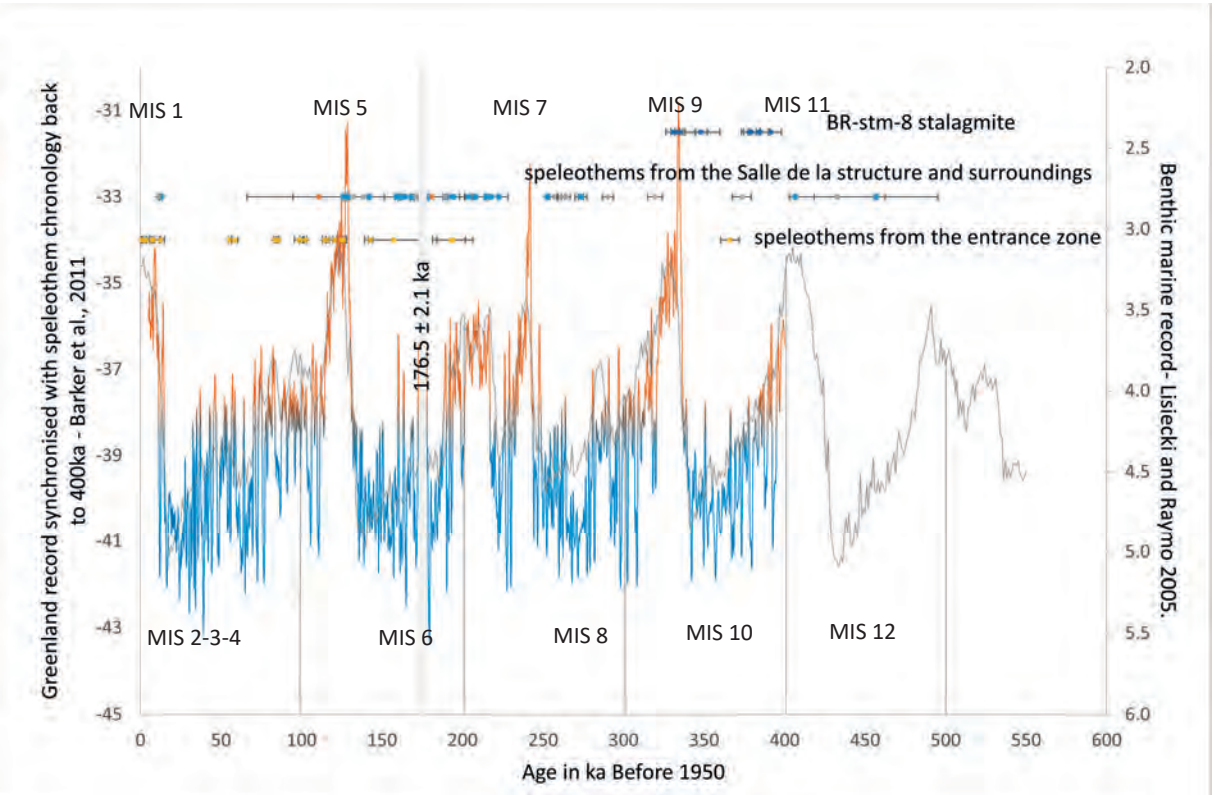

Figure 3: Bruniquel Cave – Speleothem ages reported on the northern hemisphere climatic curve. The succession of Interglacial (IG)(MIS 1, 5, 7,..) and Glacial (G) (MIS 2-3-4, 6, 8, 10) periods are highlighted by the red and blue colours respectively. The age of the Neanderthal structure (176.5 ka) including its uncertainty (±2.1 ka) is indicated by the grey vertical bar. The ages of other dated speleothems in the cave are indicated as dots above the climatic curve and their uncertainties are shown as horizontal lines at each side of the dot. The BR-stm-8 stalagmite for example, was deposited during the IG-G-IG periods ~MIS 11-*10-9.*

4. Multiphase sedimentary dynamics in the Bruniquel Cave – a first model

Besides the indications for past regular flooding of the cave in the BR-stm-8 stalagmite, other observations on the sedimentary dynamics can be made. No cobbles or gravel are found in the cave, with exception of those found in the entrance collapse. Fine grained deposits are found on horizontal limestone ledges, even several meters high. Moreover, at several places in the cave and especially more than 300 meters from the current entrance, indications occur for suffosion, i.e. where loose material is drained by percolation water and disappears in underlying voids. Remnants of clay deposits, slumping of the clay, destabilized stalagmites, and swallow holes are strong indications for the existence of an active drainage underneath the main gallery of the Bruniquel Cave.

Since no indications are found up to now for a main high-energetic river flowing through the gallery, we hypothesis detrital deposition by low energy floods, during higher basal levels (*cf.* QUINIF, 1989). The suffosion holes in the gallery may therefore have functioned as 'sources' for upcoming water and the main gallery may have played the role of an overflow gallery resulting in the multiphase sedimentation (Fig. 4).

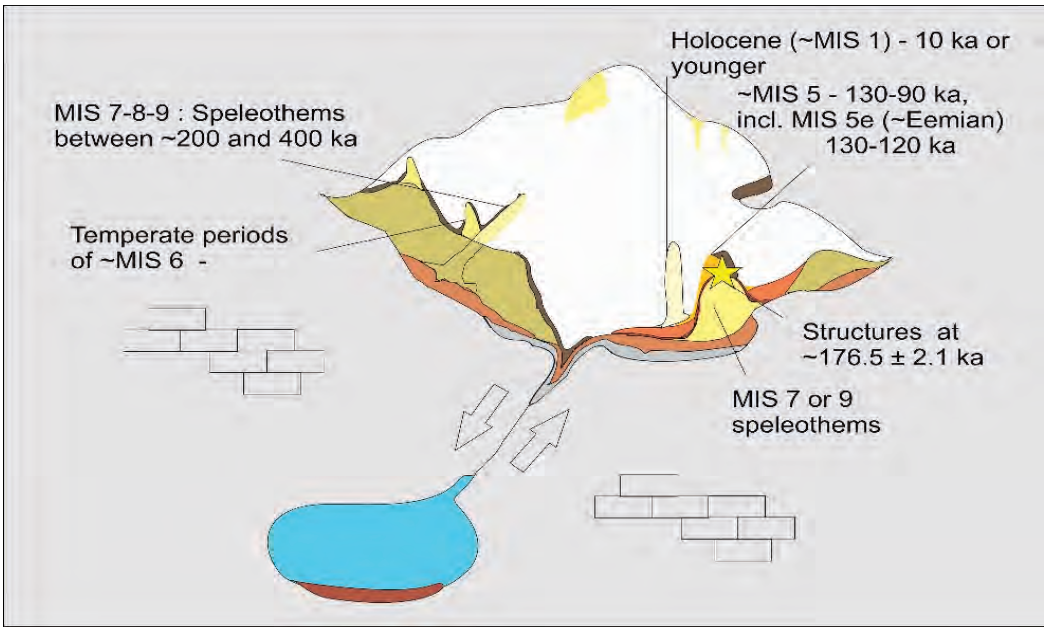

Figure 4: Bruniquel Cave –Simplified model of sedimentary dynamics in the cave leading to the current endokarstic landscape.

5. General conclusions and perspectives.

A first assessment of the sedimentary deposits in the Bruniquel cave leads to a preliminary model for the sedimentary dynamics in the cave. The generally fine-grained deposits observed up to now in the cave and the absence of clear high energetic river morphologies suggest a multiphase sedimentation due to successive flooding related to changes of water base levels, eventually climate driven. An active karstic system underlying the main gallery seems responsible for suffosion phenomena and could have played a role in successive flooding of the main gallery, which could have functioned as an overflow of the karstic system. Within this cave evolution, the 'anthropogenic' period is strictly constrained between 174 ka and 179 ka. Further studies will look for the underlying active system, continue mapping and dating of sediments and explore in detail the relation with climate. The dating of speleothems together with detailed morpho-stratigraphic observation is crucial in the elaboration of an environmental evolution model of the cave and its surroundings.

Acknowledgments

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The barite conundrum: active growth of non-hydrothermal $BaSO_4$ speleothems in Lechuguilla Cave (New Mexico, USA)

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Abstract

Barite ($BaSO_4$) speleothems have been reported from caves around the globe and interpreted to have chiefly formed in phreatic, hypogene, hydrothermal settings. Here, we report two contrasting types of barite speleothems – bluish tabular pool crystals and actively dripping greenish stalactites – which today form at lower temperatures in the non-hydrothermal environment of Lechuguilla Cave, New Mexico, USA.

SEM analysis, together with energy- and wavelength-dispersive X-ray spectroscopy (EDS, WDS) as well as X-ray diffraction (XRD), characterize the habit and chemical composition as barite. In both elements, fractionation of the minor element calcium is related to growth along different crystal faces whereas variations in strontium are mirrored in blue color zoning of the pool crystals.

Two possible modes of non-hydrothermal barite precipitation are discussed: (1) intense evaporation driven by thermal atmospheric convection cells, or (2) mixing of barium-rich, sulfate-poor water with water rich in sulfate. Both processes, in isolation or in combination, lead to supersaturation and could explain formation of the investigated barite speleothems. Observations of three types of microbes on the pool barite crystals showing evidence of incrustation raises the question whether (3) there is a potential involvement of microbial activity in the temperate barite precipitation in Lechuguilla Cave.

1. Introduction

The formation of barite ($BaSO_4$) in continental settings is usually associated with hydrothermal activity supporting the formation of massive barite as a component of ore deposits (HANOR 2000). Remobilization and phreatic reprecipitation of barite in a hypogene hydrothermal karst environment is believed to be responsible for the majority of the known occurrences of barite as a cave mineral (HILL & FORTI 1997). For at least some of those occurrences, a hydrothermal origin has been demonstrated by analysis of fluid inclusions and/or sulfur stable isotope analyses (for review, see DUBLYANSKY 1997).

Barite speleothems that formed in the vadose zone under subaerial conditions in caves are rare (e.g. MALTSEV & MALISHEVSKY 1990, HILL & FORTI 1997, ONAC *et al.* 2014) and active formation has not been demonstrated for any of these occurrences. The fact that barite can form in non-hydrothermal settings in the ocean (GRIFFITH & PAYTAN 2012), such as cold vent sites (GREINERT *et al.* 2002, STEVENS *et al.* 2015), has raised the question whether barite could also form in caves under non-hydrothermal conditions. In a recent paper (WISSHAK *et al.* 2020) we have characterized two such types of actively growing barite speleothems in a temperate environment (normal-temperature cave setting = 5-25°C sensu DUBLYANSKY 1997), both discovered in Lechuguilla Cave, New Mexico, USA. Lechuguilla Cave is among the world's largest cave systems and has recently surpassed 150 miles (~240 km) of survey (WISSHAK 2020). The cave formed in the carbonate rocks of the Permian Capitan Reef Complex in the Guadalupe Mountain uplift through hypogene sulfuric acid speleogenesis (HILL 2000). Substantial deposits of gypsum were left behind as a byproduct and their secondary dissolution and reprecipitation led to the formation of a wide variety of speleothems (e.g. DAVIS 2000, POLYAK & PROVENCIO 2001). Lechuguilla Cave contains many rare cave minerals, many of which are directly or indirectly related to sulfuric acid speleogenesis (DUCHENE 1997, DAVIS 2000, POLYAK & PROVENCIO 2001). This inventory includes greenish barite stalactites that drip water, first identified in an area called 'Frostworks', and bluish barite crystals forming at the bottom of a calcite-lined pool in an area called 'Blanca Navidad'. Our detailed analysis of samples taken from these two sites has employed a combination of crystallographic investigation, micro-structure analysis, and elemental mapping (WISSHAK *et al.* 2020). Based on the results and circumstantial evidence from the geological and speleological setting we have discussed potential modes of these types of non-phreatic and non-hydrothermal barite precipitation.

In this proceedings paper, we briefly summarize our findings and provide an outlook on our anticipated future research on these and related unusual speleothems.

2. Materials and methods

A database of all suspected and confirmed occurrences of barite and celestine in Lechuguilla Cave was compiled from expedition reports and the mineral inventory database maintained by the Carlsbad Cavern National Park.
Two samples were taken from barite speleothems, one piece of a broken stalactite from 'Frostworks' and one subaqueous crystal from a pool in 'Blanca Navidad'.
Samples were air-dried, photographed, and subsamples were prepared for scanning electron microscopy (SEM) undertaken with a Tescan VEGA3 xmu at 20 keV.
Samples were ground to powder for X-ray diffraction (XRD) analysis on a Philips PW1729 X-ray generator with a 2200 Watt 60 keV Cu X-ray source. Analyses were run at 40 keV and 30 mA in a 2 Theta range from 15 to 60°.

High-resolution elemental mapping of resin-embedded and polished samples with wavelength dispersive X-ray spectroscopy (WDS) was carried out on a JEOL Superprobe JXA-8200 electron microprobe. Elemental maps were produced on a 5 to 10 µm grid with a 10 µm probe diameter at 100 ms dwell time, 15 keV acceleration voltage and a beam current of 100 nA. Detailed maps were acquired on a 1 µm grid at the margin of the crystals, with a 1 µm probe diameter at 100 ms dwell time, 15 keV acceleration voltage and a beam current of 100 nA. Quantitative transects were logged in 5 to 10 µm spacing across overview maps, and 1 µm spacing across detail maps, applying 5 or 1 µm probe diameters, respectively, at 15 keV acceleration voltage, 50 nA beam current.

3. Results

Numerous greenish to greenish-bluish stalactites were found within a perimeter of about 500 m in the western branch of the cave. They are up to 20 cm in length, have moist surfaces, actively drip water, in some cases form greenish splash points below (Fig. 1A-B). Our sample is composed of an aggregate showing parallel crystallites resulting from parting, tabular to the pinacoid base c {001} in the orthorhombic system. The outer surface of the stalactite primarily shows faces of the prism m {210} and pinacoid a {100} (see Fig. 2 for a diagram of the crystallographic properties). Several hundred bluish tabular crystals, up to 2 cm in size, were found growing in a shallow pool, lined with calcite spar, in the 'Blanca Navidad' area (Fig. 1C), situated also in the western branch of the cave. Our sample is a nearly idiomorphic platy crystal, tabular to the pinacoid base c {001} in the orthorhombic system, and lateral faces are formed by the prism m {210}. Along the latter, the crystal shows a blue color zonation.
Mineral identification of both samples via XRD analysis in the 15° to 60° (2θ) range matches the peak signature of barite. No other mineral was detected in the samples.
High-resolution element mapping via WDS shows a homogeneous distribution of the major elements Ba, S, and O, in a stoichiometric relationship corresponding to that of barium sulfate ($BaSO_4$). This applies also to the outer margin of the crystal, which was mapped and profiled with 1 µm resolution, thereby excluding the presence of a detectable layer of witherite ($BaCO_3$). Calcium (Ca) and strontium (Sr) were the only detected trace elements; other elements that can substitute for Ba in barite (Ca, K, Ra, Pb, and more rarely Fe, Cu, Zn, Ag, Ni, Hg, V; HANOR 2000, GRIFFITH & PAYTAN 2012), were not detected. Concentrations of Ca and Sr vary with growth along the prism m {210} faces, reaching concentrations of up to 4,820 ppm and 26,200 ppm, respectively, in the case of the pool crystals. Calcium concentrations are higher in parts that grew along the pinacoid face c {001}, whereas Sr was found relatively depleted in these zones, thus showing an inverse pattern. The respective Sr/Ca ratios cluster accordingly. Concentrations of Sr mirror the blue color zoning in the pool crystals in that the outermost (youngest) zone shows the highest Sr concentrations and most intense coloration.

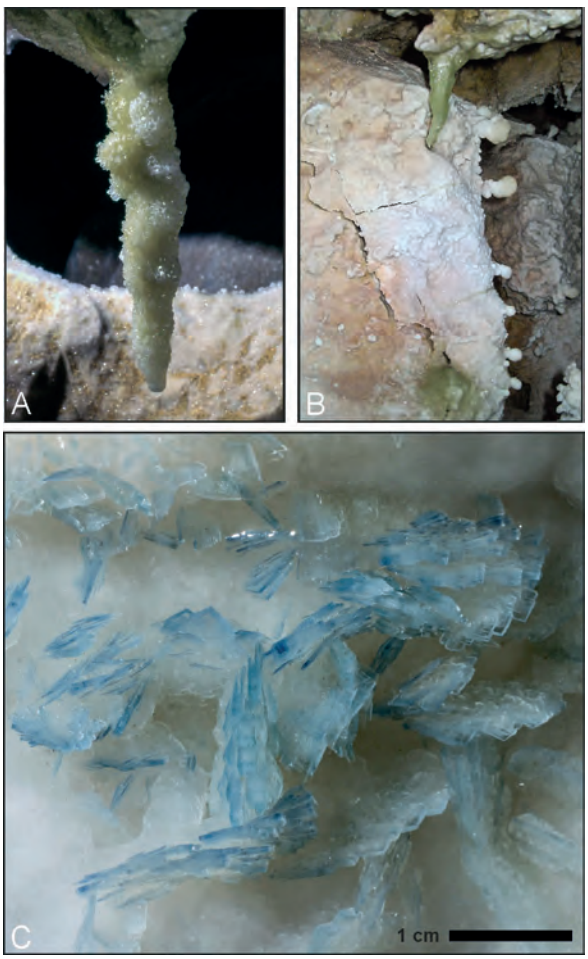

Figure 1: One of several greenish barite stalactites in the Frostworks area (A), another one with a greenish splash point below (B), and subaqueous barite crystals with blue color zoning in a shallow pool in Blanca Navidad (C).

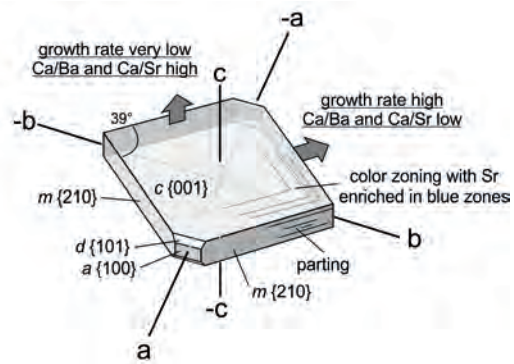

Figure 2: Mineralogical properties of the sampled barite speleothems: The crystallographic axes and principal faces are shown for an idiomorphic tabular crystal prismatic to the pinacoid base c {001}. Parting occurs parallel to c {001} and color zoning (pool crystals only) parallel to the prism faces m {210}. High growth rates along m {210} and a {100} show low Ca concentrations, whereas slow growth along m {210} leads to relatively high Ca concentrations.

Three types of microbial morphology were identified on, and partly embedded within the sampled barite pool crystal: Type 1 microbes form filaments 0.3-0.4 µm in diameter and were found collapsed on the surface with associated coccoidal cells or spores. Some filaments enter or exit deep trenches or angular holes formed by crystal overgrowth.
Type 2 microbes are only evident where the barite has grown around the original organic filaments, leaving incrustations that mimic their structure. These incrustations suggest unbranched filaments, 0.2-0.4 µm in diameter, meandering on the surface of the crystal and originating from a circular central area. Individual furrows or the entire structure are partially overgrown by younger barite crystallites, along with barite precipitating between filaments to form micro-terraces.
Evidence of Type 3 microbes are rod-shaped incrustation structures, three to five microns in length and about one micron in diameter, observed in broken sections of the crystal.

4. Discussion

The classical interpretation of barite speleothems as a result of phreatic hydrothermal activity can be excluded for both the barite stalactites and the barite pool crystals that are likely still forming today in the vadose and temperate environment of Lechuguilla Cave (see our discussion in WISSHAK *et al.* 2020). For tackling this conundrum, we discuss three possible underlying processes of non-hydrothermal barite precipitation that might be active, in isolation or in combination, in Lechuguilla Cave: 1) evaporation, 2) mixing of water rich in barium with water rich in sulfate, and 3) microbial activity:

1) Evaporation model: Significant evaporation can lead to supersaturation with respect to barite, leading to precipitation until saturation is reached. Prominent thermal atmospheric Rayleigh-Benard convection cells in Lechuguilla Cave have long been identified as drivers for condensation and evaporation, controlling the formation of corrosion residues / ferromanganese deposits and leading to directional growth of speleothems, respectively (e.g. QUEEN 1994). In 'Frostworks', corrosion residues at the ceiling and aragonite frostwork on calcite popcorn at the bottom, together with the observation of significant airflow in the area, suggest that condensation and evaporation take place. Evaporation is also conceivable for the barite pool in 'Blanca Navidad', where recharge and discharge of water is via discrete seepage from flowstone only, complemented by occasional drips from overlying stalactites, so that the retention time in the pool is considerable. This part of 'Blanca Navidad' is rich in aragonite frostwork and other speleothems that are indicative of surface diffusion and evaporation. The observed Sr concentrations and color zoning might provide circumstantial evidence for episodes of increased evaporation and a temporarily closed system, as Ba is removed preferentially over Sr from aqueous solutions (HANOR 2000).

However, considering the poor solubility of barite in water (2.2 mg/l at 18°C; SEIDELL 1940), this scenario requires immense amounts of water to evaporate to form barite speleothems the size of the documented stalactites.

2) Mixing model: An alternative model is mixing of waters from two different sources, one rich in Ba^{2+} and devoid of SO_4^{2-}, the other rich in SO_4^{2-}. Mixing of such waters would result in supersaturation with respect to barite and instant precipitation until saturation is reached (HANOR 2000, GRIFFITH & PAYTAN 2012). In Lechuguilla Cave, this scenario is conceivable where condensation water meets percolating meteoric water, or at mixing points of meteoric waters with different pathways. An obvious source of sulfate is contact with the abundant secondary gypsum deposits, whereas barium ions might derive from the host rock, corrosion residues, ore deposits, or other sources to be identified.

3) Microbe model: The discovery of microbes associated with the barite pool crystals (we cannot exclude their presence in the case of the stalactites) raises the question whether there could be microbial involvement in the precipitation of these barite speleothems, or whether the documented association is coincidence. There is a growing body of evidence that microbial activity is an integral component of barite formation, particularly in the marine realm (STEVENS *et al.* 2015 and references therein), but also in terrestrial settings (SENKO *et al.* 2004). For instance, some bacteria mediate barite precipitation by means of sulfur/sulfide-oxidation. In the latter context, the recent discovery of massive gypsum and a substantial deposit of elemental sulfur only few meters above the barite speleothems in 'Barite Boulevard' is a puzzling finding that may hold a key for the understanding of the barite precipitation below in terms of microbial sulfur-oxidizing activity.

5. Outlook

In a future project, we plan to study the closely related sulfate mineral celestine ($SrSO_4$). Barite and celestine form a solid solution series (see HANOR 2000 for a review) and both occur and form speleothems in Lechuguilla Cave. This provides a unique opportunity to study the two minerals in concert.

Plans are being made for two research expeditions that revisit most of the confirmed or suspected occurrences of barite and celestine in the cave. Detailed documentation of the minerals in situ together with targeted sampling will allow a mineralogical and geochemical 'fingerprinting' (stable isotope signatures and trace element concentrations) and, as far as technically possible, age determinations of these occurrences. Water samples, together with evaporation experiments and autonomous data loggers, will provide the essential environmental data and information on the water chemistry for assessing the contribution of three potential modes of mineralogenesis in the cave, and for evaluating the value of barite and celestine speleothems as a geochemical archive for environmental change.

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Updates on Račiška pečina sedimentary sequence studies (SW Slovenia)

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Abstract

The Račiška pečina cave sediment sequence represents Late Pliocene up to Holocene chronostratigraphy and climate records. It is one of the best-preserved cave records of paleoenvironmental changes for the last 3.4 Ma. The investigated sedimentary sequence was mainly characterized by the deposition of layers of huge speleothem domes with long hiatuses which started to grow when the cave was detached from its hydrological function. Occasional deposition of speleothem layers was interrupted by the sedimentation of clay to silt material originating from the surface above the cave. In these clastic sediments, a Pleistocene fauna was present, in which specimens of subterranean gastropods *Zospeum* sp. were also found. A detailed chronology of the Račiška pečina section based on magnetostratigraphy and isotopic-oxygen stratigraphy was prepared and correlated with paleontological, U-series, and radiocarbon results. The section contains important and representative Pleistocene fauna, the Pliocene/Pleistocene transition and Matuyama/Brunhes boundary, and information on climate changes. The research of the section has shown that speleothem domes contain a lot of different data that cannot be collected in a single borehole or stalagmite.

1. Introduction

1.1. Research aim and cave settings

Here we present an overview of geochronological and environmental studies of the sedimentary sequence from Račiška pečina relict cave situated in the SW part of Slovenia (Fig. 1). The section covers the period from 3.4 Ma to the present with the characteristics of sedimentation in changing cave environment with long-lasting depositional hiatuses (ZUPAN HAJNA *et al.*, 2021). Regarding the characteristics of karst areas where landscapes are exposed to chemical denudation, cave sediments from different environments and hydrological zones are often the only sediments representing the terrestrial phase of landscape evolution (ZUPAN HAJNA *et al.*, 2010, 2020).

The cave Račiška pečina (Reg. No. 935; 45°30´12,10˝N; 14°09´00,83˝E; 609 m a.s.l.; Fig. 1) is situated in the south-eastern part of the Matarsko podolje, which geographically belongs to the NW edge of the Dinaric karst. The Matarsko podolje is a 20 km long and 2–5 km wide flat valley-like karst surface between mountain Slavnik and the Brkini hills (ZUPAN HAJNA *et al.*, 2008). The cross-sections of the surface indicate south-westwards inclination of the bottom, dissected by several dolines (MIHEVC, 2007). The longitudinal section shows that the surface gently rises from about 490 m a.s.l. at Kozina village (in the north-west) to 650 m a.s.l. on the south-eastern end. The Brkini hills are composed of Eocene flysch rocks (marls, quartz sandstone, and conglomerates) dissected by the fluvial relief. Contact karst with 17 sinking allogenic streams from the Brkini hills characterizes the podolje margin along with their contact with the Cretaceous and Paleocene limestones. More than a hundred vadose caves are known in the karst plain. The allogenic discharge into the karst is responsible for the creation of several large blind valleys and large caves filled with allogenic sediments (MIHEVC, 2007).

Streams sink at 480 to 510 m a.s.l.; some can be followed in the accessible caves down to their terminal sumps at 370 to 430 m a.s.l. The deepest cave is 150 m in-depth, and the longest is more than 6 km. A great oscillation of karst groundwater was observed. Water tracing showed that the sinking streams flow to three groups of springs: (1) submarine springs along the coast in the Kvarner Bay on the south, (2) springs in Istria on the south-west, and (3) the Rižana springs at 70 m a.s.l. on the west (KRIVIC *et al.*, 1987).

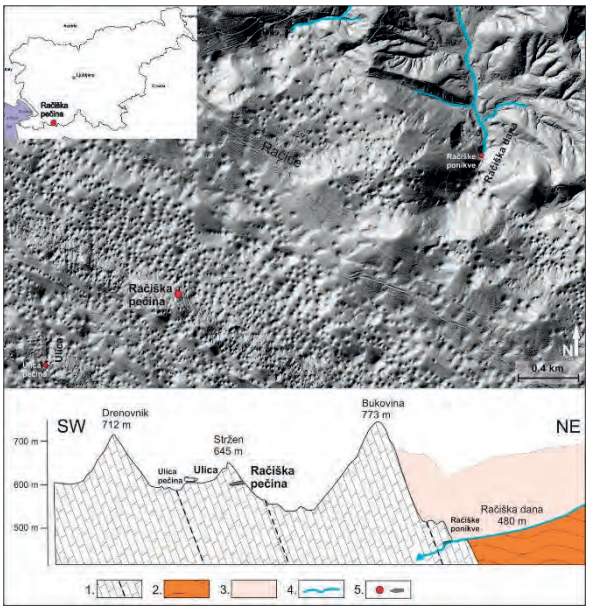

Figure 1: Location of the cave Račiška pečina in SW Slovenia, and on DEM of the contact karst area (RS Lidar data, Geodetski oddelek ARSO) with schematic cross-section. Legend: 1– carbonates (limestones and dolomites from the Early Cretaceous to the Paleocene and Eocene) dissected by faults, 2– Eocene flysch rocks, 3– schematic outline of the relief from the time when Račiška pečina was an active water passage with a supposed sinking stream, 4– sinking streams in blind valleys, 5– cave entrances and caves.

The cave was formed in the Lower Cretaceous thick-bedded limestones and dolomite with limestone breccias and dolomitized limestones. Strata dip generally towards the north-east at an angle of 30° (ŠIKIČ *et al.*, 1972). The area is part of the Komen Thrust Sheet with NW-SE Dinaric and Transverse-Dinaric faulting, common for the structural unit of External Dinarides (PLACER, 2008).

1.2. Relict cave Račiška pečina and its studied section

The cave consists of about 340 m long simple horizontal N–S-directed passage, which is a relic of an old cave system partially opened to the surface by denudation processes. The passage is mostly over 10 m wide and 5–10 m high. The entrance is open to the north/northeast, and on the south side, the passage ends with the breakdown material. The passage is mostly filled with allogenic sediments, massive flowstones, and stalagmites.

In the first half of the 20th century, the cave was used as a military arsenal. For this purpose, the cave floor was leveled and some large trenches were made in old massive speleothem domes. Skeletal remains (teeth, bones) and footprints were found on the cave floor, and scratch marks of the extinct *Ursus spelaeus* sp. were found on the cave walls and speleothems (MIHEVC, 2003). Before the military use of the cave, biologists visited the cave and found cave beetles (VERHOEFF, 1933). Even though the cave was redone and used as a military object for decades, it is still quite rich in subterranean fauna (*e.g.* POLAK *et al.*, 2012). Remains of Neolithic pottery were found at the cave entrance (JAMNIK, 2001), while Paleolithic pottery and tools were found in the cave (SKORUPAN, 2003). Our studied sediment section with a long-lasting record of deposition (HORÁČEK *et al.*, 2007; ZUPAN HAJNA *et al.*, 2008, 2010, 2020; PRUNER *et al.* 2010) is located about 200 m from the cave entrance. The studied section (Fig. 2) is about 13 m long and 3 m high filling the mouth of a narrow side passage. It is composed of flowstone layers intercalated by clays in some places.

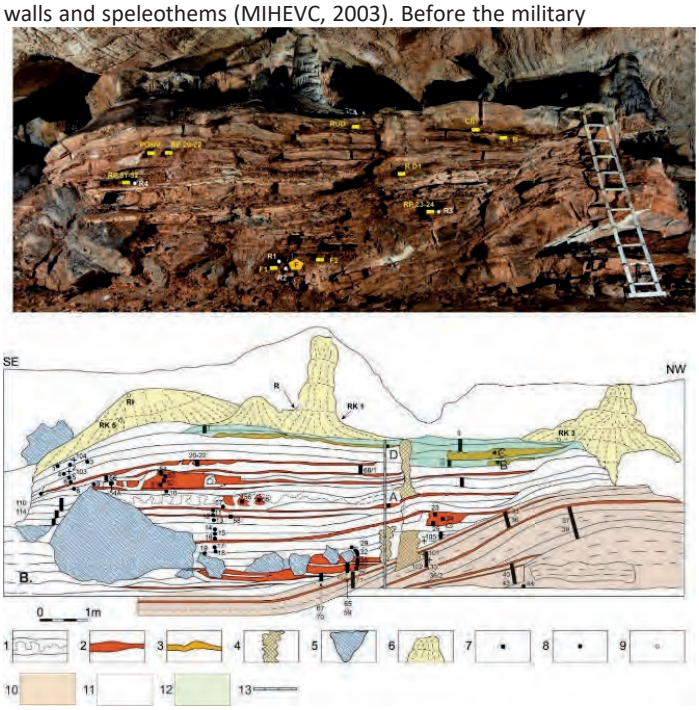

Figure 2: The studied sedimentary section Račiška pečina with the positions and numbers of fauna and paleomagnetic samples. Legend: 1 – rimstone pools, 2 – red clay layers, 3 – yellow clay layers, 4 – stalagmites, 5 – breakdown blocks of limestone, 6 – youngest speleothems, 7 – slices of speleothem layers for paleomagnetic analyses, 8 – cubes, 9 – positions of cores (RK), 10 – lower segment, 11 – middle segment, 12 – upper segment, 13 – schematic position of stable isotopes samples.

2. Materials and methods

The studied section (Fig. 2) is about 13 m long and 3 m high filling the opening of a narrow side passage. It is composed of flowstone layers intercalated by clays in places. The composite sampled thickness was 6.34 m. The section was cut out in speleothem sometime after 1933 by soldiers. The section is vertically composed of three principal segments (Fig. 2). The lower part in the NW side of the section is composed of brown to reddish-brown massive but porous speleothems, with some interbeds of red clays, two angular unconformities, and the remains of broken stalagmites (brown in Fig. 2). The middle part of the section (white in Fig. 2) consists of sub-horizontal laminated, mostly porous flowstones intercalated by calcite rimstones and thick layers of red clay with rare fauna remains (F in Fig. 2), very poorly preserved, fragile, and composed primarily of small fragments of tooth enamel (HORÁČEK *et al.*, 2007). The top part of the section (light green in Fig. 2) is composed of massive, mostly laminated speleothems with two lens-like interbeds of yellow grey clayey sediments with Ursus spelaeus bone fragments. Some of the upper flowstone layers contain black laminae enriched in organic carbon, which can be attributed to repeating human settlements in the cave (ZUPAN HAJNA *et al.*, 2008).

In fifteen years of research of this section, we have used a multi-proxy approach: paleomagnetism and magnetostratigraphy, mineralogy, geochemistry, sedimentology, petrology, stable isotopes, paleontology, and dating. The main focus of our work was on the paleomagnetic research of the sediments, while numerical dating methods were used to improve the correlation of the obtained paleomagnetic results with GPTS (CANDE & KENT 1995; GRANDSTEIN *et al.*, 2012; COHEN & GIBBARD, 2019), and paleontological finds further contributed to the chronological classification of the sediments.

3. Results and discussion

The magnetostratigraphic profile was correlated with the GPTS and calibrated by paleontological data (HORÁČEK *et al.*, 2007). The lower part, according to fauna determined in the middle part above, was dated from ~3.4 Ma at the bottom up to 2.58 Ma at its top. In the middle part, the boundary of N- and R-polarized magnetozone within the basal layer with fauna (F) can be identified with the bottom of C2n Olduvai subchron (1.95 Ma). The sequence represents the whole Olduvai subchron and terminates at 1.77 Ma. The upper part of the section starts shortly below Brunhes/Matuyama boundary (in R-polarized magnetozone) and terminates above charcoal lamina dated by 14C dating to ~3 ka.

All thicker clay layers of the section were examined for faunal remains. Already published results (HORÁČEK *et al.*, 2007) helped to correlate the magnetostratigraphic profile with GPTS (CANDE & KENT, 1995; GRADSTEIN *et al.*, 2012) and to interpret the cave environment (MOLDOVAN *et al.*, 2011). New material was sampled in 2019, the bones of large mammals have been collected in clays (sample C and B in Fig. 2). It is possible to summarize that the available morphological evidence supports the assignment of studied specimens to large cave bears (*Ursus* ex gr. *spelaeus*) and, on the other hand, the present material does not bear any characters which would be diagnostic for brown bears. This determination is supported also by the finding circumstances (ZUPAN HAJNA *et al.*, 2021). All small mammal items obtained from the upper part of the section seem to belong to *Clethrionomys glareolus* or a form closely related to that extant species dated to Late Early Pleistocene (Q2) to Recent. The fragment from F2 can be tentatively attributed to the genus *Pliomys*, in which major radiation appeared during the earliest Pleistocene (MN17–Q1). Gastropods, their fragments, and imprints were found in 3 samples of red silty clays correlating with paleomagnetic samples (Fig. 3): PONV, RP 51–52, and F2. Their determination and comparison were not possible in such a short time, but regarding their form, we suspect that they belong to genus *Zospeum* sp. which represents subterranean gastropods living in caves, mostly of Dinaric karst, where some species are endemics (BOLE, 1974). The authors believe that these are the first fossil subterranean snails founds (Fig. 3).

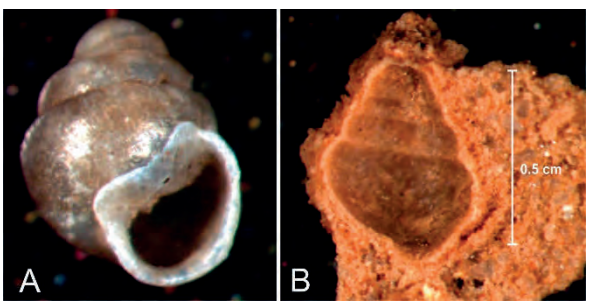

Figure 3: Specimen of Zospeum sp. (A) from sample RP 51–52, and an imprint of the Zospeum sp. from the sample F2.

Three dark layers (soot) between flowstone layers were radiocarbon dated ~11 ka, ~9 ka, and ~3 ka (ZUPAN HAJNA *et al.*, 2021). A detailed chronology of the Račiška pečina section based on magnetostratigraphy and isotopic oxygen stratigraphy was created and correlated with paleontological, U-series, and radiocarbon results. The climatic changes during the growth of the section were at about 2.6–2.5 Ma ago mostly controlled by global Atlantic Ocean factors, while about 0.78 Ma ago by regional Mediterranean Sea factors (ZUPAN HAJNA *et al.*, 2021).

4. Conclusion

The studied Račiška pečina sediment sequence was mostly characterized by the deposition of speleothem layers with long hiatuses after the cave was detached from its hydrological function. Occasional deposition of speleothem layers was interrupted by sedimentation of clay to silt size material originated from the surface above the cave. In those clastic sediments, rare fauna was present in which we also found specimens of subterranean gastropod *Zospeum* sp. The Račiška pečina section is a really important source of climate information for the last 3 Ma including the Pliocene/Quaternary and Matuyama/Brunhes transitions.

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New data on selected minerals from Monte Guisi Cave, Sardinia

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Abstract

The southwestern part of Sardinia (Iglesiente) has been Italy's most important Pb-Zn ±Ag ore region and remains a world renown location for its rich mineral association described from mining galleries and numerous caves discovered during exploitation activities. Hosted in calcite skarns heavily mineralized by Pb-Zn (±Ba) Mississippi Valley Type deposits, Monte Guisi Cave contains a fascinating mineralogy; this report presents an updated overview of 17 cave minerals assigned to five chemical groups (sulfides, oxides/hydroxides, carbonates, sulfates, and silicates). The majority of the secondary minerals represent oxidation and/or hydrolysis products of various Pb-, Zn-, and Cu-bearing sulfides and are rather common in ore-related caves (e.g., cerussite, malachite, azurite, brochantite). However, the occurrence of dundasite, a hydrous carbonate of lead and aluminum first described as cave mineral from Monte Guisi, is intriguing due to the presence of Al, whose source remains unknown. The rich Cu-bearing secondary mineral assemblage could hold the key for understanding the genesis of plancheite, a hydrated copper silicate, first reported as cave mineral from this location. We show that the conditions leading to Cu carbonates precipitation are different from those for Cu silicates, thus implying two different paragenetic associations.

Symposium 08

Archaeology and Palaeontology in caves

Special session

Paleospeleology

Philippe GALANT (chief) (FR)

Karst Paleoecology

Nicolas LATEUR (chief) (FR)

Natural Traps

Evelyne CRÉGUT-BONNOURE (chief) (FR)

Archeology and Paleontology in caves

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English

Archeology and paleontology in karst environments is a subject as vast and complex as the underground networks themselves. Throughout the Quaternary, fauna and Man have frequented the same environments. While these communities, both human and animal, have always been able to adapt and occupy extremely diverse ecosystems and environments, they have also frequented very particular environments such as caves and karstic networks.

Because of their configuration and their (at least partial) 'isolation' from external phenomena, such as meteorological variations, these underground environments are particularly conducive to the preservation of traces and remains resulting from incursions, sometimes ancient, into these environments by human groups or by various animal guilds.

Archaeological and palaeontological research in the karst environment benefits from a long history, but also from new technical or technological advances, and from an ever-increasing amount of knowledge enabling us to describe the methods of occupation and frequentation of the deep environment. We should briefly mention the case of animal visits, as attested by palaeontological remains (bones, bioglyphs), which are generally associated with specific occupations (carnivore dens, wintering or hibernation sites) or simple, episodic and occasional passages. Even more recurrently, we should mention the trap caves, which are quite specific contexts resulting both from the ethology of the species that roam karstic landscapes and from natural phenomena that cause bone accumulations during major colluvium formations.
The underground world has also been frequented by humans. The use of the underground environment by successive human communities since prehistoric times and throughout the historical periods is a well-established fact. They correspond to numerous uses, which, depending on the period, take on cultural or even cultic, social or economic uses. The initial exploration that will lead to the knowledge and therefore the choice of the site according to the needs is an essential prerequisite to an effective use. In fact, a simple curiosity visit is an aspect that should not be neglected. These often tenuous signs of exploration, of a paleo-speleology, must attract our full attention, as well as the more obvious traces of frequentation such as representations of cave art.

It is obviously only much later, in a very contemporary time frame, through exploration, research and study activities, that speleologists reveal the sometimes spectacular remains of these occupations. Although the underground environment may appear to many as a hostile environment, for some it rhymes with research and discovery. This quest for knowledge, this incessant curiosity, even crosses borders and international communities of researchers and cavers join this adventure in the deep.

This is what symposium 8 is all about, trying to represent this diversity of disciplines, chronologies and geographical areas, all of which contribute to the same goal, understanding a little better who we are.

Français

L'archéologie et la paléontologie en milieu karstique, un sujet aussi vaste et complexe que les réseaux souterrains eux-mêmes. Tout au long du Quaternaire, faunes et hommes ont parcouru les mêmes environnements. Si ces communautés, humaines et animales, ont, de tout temps, su s'adapter et occuper des écosystèmes et environnements extrêmement diversifiés, elles ont de fait également fréquenté des environnements très particuliers tels que les grottes et les réseaux karstiques.

Ces milieux souterrains, de par leur configuration et leur « isolement » (au moins partiel) des phénomènes extérieurs, tel que les variations météorologiques, sont particulièrement propices à la préservation des traces et vestiges résultant des incursions, parfois anciennes, dans ces environnements par des groupes humains ou par différentes guildes animales.

Les recherches archéologiques et paléontologiques en milieu karstique jouissent d'un historique ancien, mais aussi de nouvelles avancées techniques ou technologiques, et de connaissances toujours plus nombreuses nous permettant de dépeindre les modalités d'occupation et de fréquentation du milieu profond. Mentionnons brièvement le cas des fréquentations animales, tels qu'en attestent les vestiges paléontologiques (ossements, bioglyphes), qui sont généralement associées à des occupations spécifiques (tanières de carnivores, lieux d'hivernation ou d'hibernation) ou à de simples passages, épisodiques et ponctuels. De façon plus récurrente encore, évoquons les avens pièges, des contextes tout à fait spécifiques conséquence à la fois de l'éthologie des espèces qui fréquentent les paysages karstiques et résultant de phénomènes naturels qui sont à l'origine d'accumulations osseuses lors d'importantes formations de colluvionnements.

Le monde souterrain a également été fréquenté par les hommes. Ces fréquentations du milieu souterrain par des communautés humaines qui se sont succédé depuis la Préhistoire et tout au long des périodes historiques constituent un fait bien établi. Elles correspondent à de nombreuses utilisations qui, selon les époques, revêtent des usages culturels voire cultuels, sociaux ou économiques. L'exploration première qui amènera la connaissance et donc le choix du site en fonction des besoins est un préalable indispensable à une utilisation effective. De fait, la visite de simple curiosité constitue un aspect à ne pas négliger. Ces indices d'explorations, d'une paléospéléologie, souvent ténus, doivent attirer toute notre attention ; tout autant que des traces de fréquentations plus évidentes telles que les représentations d'art pariétal.

Ce n'est évidemment que bien plus tard, dans une temporalité alors tout à fait contemporaine, dans leurs activités d'explorations, de recherches et d'études, que les spéléologues révèlent les vestiges, parfois spectaculaires, de ces occupations. Si le milieu souterrain peut paraître à beaucoup comme un milieu hostile, il rime pour certains avec recherches et découvertes. Cette quête pour la connaissance, cette curiosité incessante, dépasse même les frontières et ce sont des communautés de chercheurs et de spéléologues internationaux qui rejoignent cette aventure des profondeurs.

C'est bien ici tout l'enjeu d'un tel symposium, tenter de représenter cette diversité des disciplines, des chronologies, des aires géographiques, tout cela concourant à la même chose, comprendre un peu mieux encore qui nous sommes.

Fouilles paléontologiques dans la grotte Tempiette (Entremont-le-Vieux, Savoie, France) : Un aven-piège à bouquetin et chamois. Photo : Christophe Griggo.

Paleontological excavations in the Tempiette cave (Entremont-le-Vieux, Savoie, France): An ibex and chamois trap. Photo: Christophe Griggo.

Absolute Temporality of Cave Pictographic Rock Art in Puerto Rico

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Abstract

In the Caribbean, the islands of Puerto Rico have the highest density of rock art. Rupestrian art is one of the most popular cultural contributions of our indigenous societies to the modern society being conspicuously used in advertising agencies, tourism, handcrafts and sports. Even though rock art is of such salience, the absolute chronology of more than 500 settings of these cultural manifestations is currently unknown. In this study, our goals for the rupestrian art in PR are to provide an absolute chronology, improve the chronology of archeological sites, create a sequential timeline of these manifestations, establish the temporality of the newly discovered pyrographs, and update the National Register of Historic Sites. We dated 30 pigment samples from 6 caves using accepted archeological techniques of radiocarbon dating from the Center for Applied Isotope (Georgia, USA). Based on our results, the rupestrian art sequence consisted in geometrical patterns (730 – 390 BC), a hiatus (cal. AD 100 – 600), anthropomorphic (cal. AD 660 – 1400), zoomorphic (cal. AD 1200 – 1500) and post-colonial (1500 – present) stages. Dated rupestrian art and evaluation of the sites provide clear chronological trends for the indigenous history of Puerto Rico.

Résumé

Datations absolues de l'art rupestre dans les grottes de Porto-Rico. Dans les Caraïbes, les îles de Porto Rico ont la plus forte densité d'art rupestre. L'art rupestre est l'une des manifestations culturelles les plus populaires de nos sociétés indigènes pour la société moderne et est même utilisé dans les agences de publicité, le tourisme, l'artisanat et les sports. Même si la valeur de cet art rupestre est reconnue, la chronologie absolue de plus de 500 décors de ces manifestations culturelles n'est pas connue. Dans cette étude, nos objectifs pour l'art rupestre à Porto Rico sont de fournir une chronologie absolue, d'améliorer la chronologie des sites archéologiques, de créer une chronologie séquentielle de ces manifestations, d'établir la temporalité des pyrographes nouvellement découverts et de mettre à jour le Registre national des sites historiques. Nous avons daté 30 échantillons de pigments de 6 grottes en utilisant des techniques archéologiques acceptées de radiocarbone du Center for Applied Isotope (Géorgie, USA). Sur la base de nos résultats, la séquence d'art rupestre consistait en des motifs géométriques (730 - 390), un hiatus (100 - 600), antropomorphe (660 - 1400), zoomorphe (1200 - 1500) et postcolonial (1500 - présent) étapes. L'art rupestre daté et l'évaluation des sites peuvent aider à imaginer le cadre indigène de Porto Rico sur 3000 ans et l'utilisation de dates en céramique peut être étendue à 5000 ans.

1. Introduction

Rupestrian rock art is located all around the Puerto Rico archipelago and its one of the most popular aspects of our ingenious societies. Modern Puerto Ricans use rupestrian art for local products, tattoos, advertising and company's logos and many more. Puerto Rico has the highest density of rupestrian rock art of the Caribbean but the absolute chronology of the more than 500 rock art contexts are not well known [DUBELAAR et *al*. (1999) and ROE (2009)].

Presently, many studies have been carried out to understand the chronology of various manifestations of rupestrian rock art of Puerto Rico using different typological methods aiming at categorizing their iconographic diversity and establishing their relative temporality. These methods include stylistic, seriation and cross-media isomorphism, among others, which have been used to establish the relative chrono-cultural context of the different images identified on the island [DUBELAAR (1999), RIVERA-MELENDEZ (1996) and ROE (1993 and 2005)]. To refine the temporal resolution of rock art on the island, its antiquity has been approximated indirectly on the basis of its spatial proximity to absolutely dated archaeological contexts [ROE (1993), OLIVER *et al.* (1999), OLIVER (2001)]. Establishing guidelines for direct dating of rock art is first step in order to refine the absolute chronology of this type of manifestations in Puerto Rico.

This study measured the dating (absolute temporality) of 29 samples of black pigments derived from pictographs of various caves on the main island of Puerto Rico. The main objectives are : *i)* provide an absolute chronological basis for the island pictographic rock art, *ii)* redefine the chronology of various archeological sites with murals in caves on the island, *iii)* sequence changes in the iconographic manifestations of rock art in Puerto Rico, iv) establish the temporality of the pyroglyphs (a newly identified type of rock art), *v)* update the information of rock art present in the sites considered or nominated for the National Register of Historic Places in Puerto Rico.

2. Methods

To create absolute chronological guidelines to temporarily contextualize the rock art of the island, 30 black pictographs of various chronological and cultural contexts from caves in the north, center and south of Puerto Rico were dated. Figure 1 shows the locations of the 6 caves sampled: a) Cueva Matos, b) Cueva Ventana Intermedia, c) Cueva Soto, d) Cueva del Abono, e) Cueva Gemelos and f) Cueva Lucero. This is the first study on the island that has contemplated using a deep chronology perspective to create an absolute temporality frame based on the diversity of rock manifestations in Puerto Rico and the Caribbean.

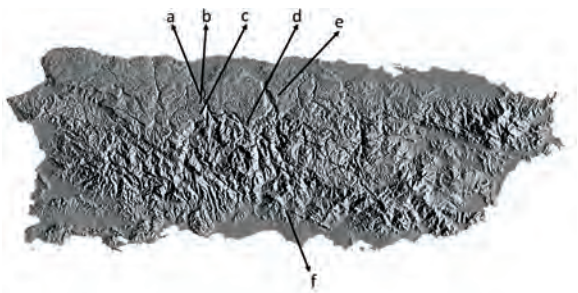

Figure 1: Location of the cave sites on the island of Puerto Rico: a) Cueva Matos, b) Cueva Ventana Intermedia, c) Cueva Soto, d) Cueva Abono, e) Cueva Gemelos and f) Cueva Lucero.

To obtain the pigment samples of the pictographs to be dated, the protocols established by ROWE (2005) were followed, as they have also been successfully applied in Isla de Mona by SAMSON *et al.* (2017). In order to minimize the amount of material to be extracted from each image and to protect the morphological integrity of the pictograph, only pigment samples of approximately 1 to 2 mg of circumscribed spaces that did not erase any specific element of the image or alter its general configuration were collected. Each pictograph was photographed before and after removal of the sample to accurately locate the impacted area, as well as its original and remnant morphology. To validate the dating method samples of two superimposed pictographs were obtained in Cueva Ventana Intermedia, which yielded dates in accordance with the observed picto-stratigraphic sequence. The material was removed with sterile metal dental equipment and was then placed in sealed glass containers for eventual processing. Samples then were processed by Dr. Alex Cherkynski at the Center for Applied Isotope Studies at the University of Georgia, who has a long history of research on the use of particle accelerator mass spectrometry (AMS) for micro-samples in archaeological studies. The dates were calibrated using corrections provided by the CALIB 7.07 program in which INTCAL13 is included for terrestrial date. GUTIERREZ-CALVACHE and ARRAZCAET-DELGADO (2006) explained that the AMS technique is considered the most important and efficient method for dating organic pigments in rock art at present.

Figure 2: Superimposed pictographs in Cueva Ventana Intermedia used to validate temporal measurements.

The caves from which the samples were collected were mapped using Light Detection And Ranging (LiDAR). These cave maps can be used to locate the rock art panels and other features of these negative physiographic spaces and can also be employed in future studies for conservation purposes. The Geoslam ZEB1 (3-D Laser Mapping) handheld mobile LiDAR was used to obtain the measurements. It is a mobile laser scanning system that uses relative measurements of the environment through which the system's infrared light travels. The system obtains the data and map the area in about the same time it takes to walk. The data acquisition speed is 43,200 pts/s with a range of 30m. The field of view is 270° by 100° and its source is a 905 nm laser diode. During data processing the system estimates the vectorial position using simultaneous localization and mapping. The result of the data collection are millions of data points that create a point cloud. Then, MeshLab software (www.meshlab.com) was used to create the cave.

3. Results

For this study, most of the rock art contexts were associated with the pre-colonial period of Puerto Rico, although some examples of graphic records associated with early and contemporary colonial period were also noted. Figure 3 shows examples of rock art sampled and Figure 4 shows the radiometric results for the samples collected on this study. A black pigment was collected for each of the 29 dated samples as it is shown in Figure 3 (circles). Based on archeological evidence found on the sites or nearby, RODRIGUEZ-RAMOS (2014), placed Cueva Ventana Intermedia, Cueva Matos, Cueva Gemelos and Cueva Abono in the *Discovery and Humanization of Puerto Rico* period (4000 – 500 BC) and Cueva Lucero associated with Taino occupations, which fall in the *Political and Regulation Nucleation* period (1000 – 1500 AC). ROUSE (1993) identified this period as Archaic Age and Ceramic Age respectively. At this moment, no artifacts have been found in Cueva Soto which makes the direct dating of its rock art a fundamental element to establish its temporality.

A diverse suite of rock art was found during this study as it is shown in Figure 3 and mentioned in Figure 4. The rock art types were abstract, anthropomorphic, zoomorphic and others that included geometrical shapes and modern graphical images.

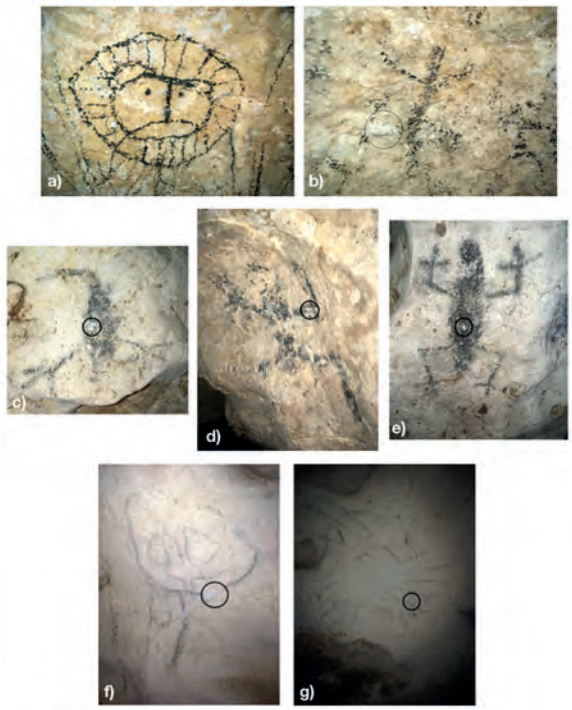

Figure 3: Examples of the cave rock art used in this study: Cueva Ventana Intermedia, a) "Lion" and b) zoomorphic, Cueva Matos zoomorphic (c, d, e) and Cueva Gemelos, f) anthropomorphic and g) sun. The circles correspond to the sampled collected for radiometric dating.

Additionally, cave maps for the six study sites were obtained with LiDAR. The maps can be used as a research and/or conservation tool to protect caves that have rupestrian rock art and can be affected by tourism companies and non-regulated visitors. Figure 5 shows Cueva Lucero cartography created with a total of 24 million data points (point cloud) and MeshLab, which represents the geometrical properties of the cave.

Cave	Samples	Date Range (cal. AD)	Type
Cueva Abono	4	1480 - 1670	anthropomorphic & abstract
Cueva Gemelos	2	690 - 1630	anthropomorphic, zoomorphic & others
Cueva Lucero	9	1220 - Modern	anthropomorphic, zoomorphic & others
Cueva Matos	4	1280 - 1670	zoomorphic & abstract
Cueva Soto	3	910 - 1450	pyrographs
Cueva Ventanta Intermedia	7	730 BC - 1650	anthropomorphic & zoomorphic

Figure 4: Summary of radiometric results for direct dating of the collected samples and the type of rock art.

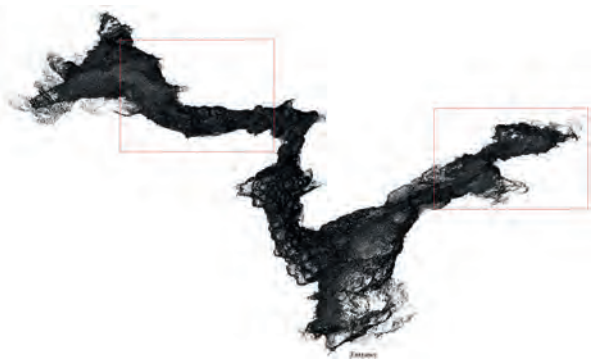

Figure 5: Example of a cave (Cueva Lucero, 50 m by 90 m area) map generated with LiDAR. The red squares are the region or rock art in this cave. Generated with MeshLab.

4. Discussions

Cueva Ventana Intermedia (Arecibo, PR) is known as well as Cueva León and is one of four caves in the Cueva Ventana Cave System. This cave contains an impressive pictographic panel in the eastern wall. The panel contains abstract, zoomorphic and anthropomorphic images. A reticulate pictograph produced a date from 730 to 390 cal. BC and indicates a pre-Arawak presence in the cave and coincides with archeological artefacts found in other nearby caves. In Figure 2 a group of superimposed images are shown. The underlying image depicts what has traditionally been identified as a Taino sun image, dated between cal. AD 900 to 1630. The famous Lion image (Figure 3a) is the center of the panel and dates back to cal. AD 1500 – 1650, thus falling in the early colonial period. Further analysis of the representation of this image is needed. Indeed, similar representations have been interpreted as solar designs from pre-Columbian period in the Caribbean. Cueva Matos (Arecibo, PR) has 28 documented pictographs in the southeast wall and multiple petroglyphs on cave speleothems. The dates obtained extended from late pre-colonial to early colonial period. Most of the images were zoomorphic in shape. For this cave, the oldest pictographs measured were an ornitomorphic image (Figure 2c) dated between cal. AD 1280 – 1400 and two zoomorphic images representing lizards and iguanas (Figure 3 d, e) dated to cal. AD 1300 – 1420 and cal. AD 1430 – 1630, respectively. Cueva Abono (Utuado, PR) also known as Cueva Mujeres was a cave used for guano extraction which impacted the archeological images and artifacts. A zoomorphic image was dated to cal. AD 1480 – 1650 while an abstract image (combination of parallel lines connected with a perpendicular one) dated to cal. AD 1510 – 1670. These images seem to indicate their production during the early colonial period, while the archaeological evidence of the cave accords with the earliest period of occupation of the island, *circa* 3000 BC. Cueva Gemelos (Morovis, PR) samples consisted of anthropomorphic and solar images (Figure 3 f, g). The date for the anthropomorphic pictograph was the oldest for this cave, going back to cal. AD 690 – 880, thus being situated in the *Social and Cultural Diversification* period as suggested by RODRIGUEZ-RAMOS (2014). The solar image dates to cal. AD 1040 – 1260 and is therefore later than the similar image previously noted in Cueva Ventana Intermedia. Cueva Soto (Arecibo, PR) has its unique rock art. In this cave can be found a panel on the cave roof with pyroglyphs, which are images made with the soot

derived from torches. The observed pyroglyphs contain representations that include simple and bearded faces (cal. AD 1410 – 1450), abstract images and as well a *Capá eye* (cal. AD 910 – 1030). In the southern wall of the cave, multiple images were documented, depicting what appears to be a form of ancient writing, a ship, and zoomorphic images that need further analysis. Cueva Lucero (Juana Díaz, PR) contains a wide variety of indigenous images as well as 19th century representations of churches and other elements of the time as well as a modern graffiti (Figure 5). Two zoomorphic images (a turtle and a bird) from the cave's right (northern) red square in Figure 5 were dated to cal. AD 1270 – 1390 and cal. AD 1640 – 1800 respectively. All the other images were located the cave's left (southern) red square region. In this wall, we measured a zoomorphic image dated to cal. AD 1220 – 1300, a decorated *Atabeyra de Caguana* dated cal. AD 1280 – 1420, a round geometrical image dated to cal. AD 1440-1630, a sand clock image dated to cal. AD 1450 – 1630, a zigzag geometrical image dated to cal. AD 1480 – 1560, an image with African traits dated to 1390 - 1500 cal. BC. This cave is unique in the island as it presents an entire spectrum of dates and types of rock art.

5. Conclusion

The main objective for this study was to determine the absolute temporality of cave pictographic rock art in Puerto Rico, with 29 samples collected in six caves. Our results can be used as starting point for future studies due to the limited samples and quantity of caves that were studied. The abstract pictographic elements found correspond to the *Discovery and Humanization of Puerto Rico* period. After this period, the use of caves for manifestations increased an anthropomorphic image then appear at AD 700, after a hiatus in cave use that had started in 100 BC. The presence of bearded faces and solar images increased after 1000 AD. (period of *Political and Regulation*).

The available chronological data also underscore the difficulty the unilineal evolution schemes of the rock art of Puerto Rico. The diversity of rock art showcases the plural social and cultural landscape that existed in the island over time, even after the European intrusion.

Acknowledgments

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Exploitation des ours au Paléolithique : les sites avec des restes d'ours isolés et portant des traces de boucherie

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Résumé

Ces dernières années ont vu se multiplier les découvertes, dans des grottes ou des sites de plein air paléolithiques, d'ossements d'ours portant des traces d'exploitation. Dans certains de ces gisements, les restes d'ours sont peu nombreux, isolés au milieu d'autres restes fauniques et ils montrent un fort pourcentage de traces de boucherie. Ils attestent souvent d'une exploitation et d'un transport des peaux, durant lequel certains ossements des pattes sont restés attachés aux peaux. Dans l'état actuel des découvertes, le taxon représenté dans ces sites est l'ours brun (*Ursus arctos)*.

Abstract

Bear exploitation in Paleolithic time: sites with few bear remains and high ration of cutmarks. Among paleolithic sites yielding evidence of bear exploitation, some present only few bear remains but a high ratio of bear bones with cutmarks. They often attest of hide procurement and hides were probably transported with feet bones still attached. At the current state of research, in these sites, the bear is *Ursus arctos*.

Introduction

Après une période de grand scepticisme vis-à-vis de cette idée, le fait que des ours aient pu être exploités au Paléolithique a fait son chemin et les découvertes de sites qui en contiennent les preuves se multiplient. Il devient même possible de distinguer des types de gisements avec des caractéristiques différentes, en fonction des activités d'exploitation qui y ont été menées (ARMAND, 2018). Parmi eux, les sites dans lesquels, au sein d'assemblages fauniques riches et variés, les restes d'ours sont rares, mais où une majorité d'entre eux portent des traces de boucherie, ont attiré notre attention et nous livrons ici des éléments de réflexion les concernant.

Méthodologie

Les données à partir desquelles nous avons travaillé sont bibliographiques, excepté pour les sites de Font-de-Gaume (Dordogne), Castanet (Dordogne) et Vidon (Gironde), pour lesquels nous avons participé à l'étude. Nous avons recherché dans la littérature, les mentions de traces de boucherie, et plus particulièrement de stries de découpe, sur des restes d'ours. Les taxons sont ceux mentionnés dans les publications.

Plusieurs variétés de sites avec un degré d'implication de l'homme qui varie.

Les découvertes d'ossements d'ours des cavernes se font surtout dans des grottes qui ont servi de lieux d'hibernation et où les ours sont morts de façon naturelle.

Certaines tanières, plus rares, ont abrité des ours bruns (*Ursus arctos)*.

Dans ce type de gisement, on trouve parfois quelques ossements portant des stries de découpe d'origine anthropique et qui permettent de suspecter un charognage très occasionnel. Parmi ces sites, on peut citer le gisement moustérien du Régourdou (Dordogne) dans lequel les restes d'ours brun montrent un très faible pourcentage de stries de 0,05 % (CAVANHIE 2010), les niveaux moustériens de Divje Babe en Slovénie (TURK & KAVUR 1997) où sur les ossements d'ours des cavernes (*Ursus spelaeus)*, on compte 0,004 % de stries de découpe et le site aurignacien d'Hohlenstein Stadel (Allemagne) où cette fois, encore pour l'ours des cavernes, KITAGAWA *et al.* (2012) mentionnent 0,05 % de marques de boucherie.

Mais dans certaines tanières, les pourcentages de stries de découpe peuvent être plus élevés, l'exploitation touche plus d'individus, démontrant une stratégie de charognage plus poussée ou parfois même des activités de chasse (rarement démontrée).

Le niveau châtelperronien de la grotte de Font-de-Gaume (Dordogne) s'inscrit dans cette catégorie. On y observe 13 %

de stries sur les ossements d'ours des cavernes. Les courbes de mortalité montrent une majorité de jeunes individus et, pour les adultes, ce sont surtout des femelles qui sont présentes. Ces arguments plaident plutôt en faveur de l'utilisation de la grotte comme tanière pour hiverner (ARMAND *et al*. 2003). Sur ces lieux de mort naturelle, il est difficile de trancher en faveur de la chasse ou du charognage, mais, même s'il s'agit de charognage, il était organisé et récurrent parce que plusieurs ours ont été exploités.

Dans le niveau gravettien de la grotte d'Hohle Fels (Allemagne), 6 % des ossements d'ours des cavernes présentent des stries de découpe (KITAGAWA *et al*. 2012) et une vertèbre porte un fragment de pointe en silex (MÜNZEL & CONARD 2004). Mais, comme le soulignent KITAGAWA *et al* (2012) : "This specimen alone cannot speak to the degree in which cave bears were exploited systematically".
Pour d'autres sites, les auteurs qui ont mené les études archéozoologiques ont évoqué la chasse, parce que les ours étaient représentés en quantité importante, qu'ils semblaient avoir subi le même traitement que les Ongulés présents dans les mêmes niveaux et que les courbes de mortalité, ainsi que la saisonnalité, n'étaient pas celles d'un site de mort naturelle. Ce sont plutôt des sites de plein air.

Dans le gisement de Biache-Saint-Vaast (Pas-de-Calais), dans des niveaux moustériens, les ours bruns et les ours de Deninger (*Ursus deningeri)* sont en majorité des adultes et AUGUSTE (1995) décrit des stries de découpe quasiment sur toutes les portions du squelette.
À Taubach (Allemagne), ce sont des ours bruns, en majorité des adultes, qui ont été les proies des néandertaliens. Le pourcentage de stries sur les ossements est élevé (26 %), mais il doit être envisagé avec précaution, car lors de la collecte des vestiges, ancienne, une sélection aurait été faite (BRATLUND 1999).

Enfin, il existe des sites dans lesquels le mode d'acquisition des ours est difficile à interpréter. Au sein des assemblages fauniques, les restes d'ours sont peu nombreux et ils ne se trouvent ni sur un lieu de mort naturelle, ni sur un lieu de chasse ou de traitement des carcasses, mais ils présentent un pourcentage élevé de stries de découpe.
C'est à ce dernier type de site que nous avons décidé de nous intéresser pour ce travail. Nous les passerons en revue en détaillant leurs caractéristiques pour essayer de comprendre à quoi ils correspondent.

Les sites avec peu de restes d'ours et avec des traces d'exploitation

En l'état actuel des découvertes et des données bibliographiques que nous avons pu trouver, les gisements qui ont livré quelques restes d'ours, avec une forte proportion de traces anthropiques, sont au nombre de huit, pour dix niveaux (les sites de Crvean Stijena et Hohle Fels comptant chacun deux niveaux différents).

Le site moustérien de Sant'Agostino, en Italie, a été étudié par STINER (1994). Trois restes d'ours bruns ont été découverts dans le niveau S1 et ils représentent 0,5 % du nombre de restes. Une de ces pièces, une première phalange, porte des stries de découpe, ce qui a permis à l'auteur de conclure à une exploitation de la peau.
Dans le site de Crvean Stijena au Montenegro, des niveaux moustérien et uluzzien ont livré des restes d'ours avec des marques de boucherie. Ces éléments n'ont pas été déterminés d'un point de vue spécifique. Dans les deux cas, il s'agit de métapodes, qui sont par ailleurs les seuls restes d'ours déterminés dans leurs niveaux respectifs. Pour le Moustérien, il s'agit d'un fragment distal de métapode non déterminé et pour l'Uluzzien, d'un métacarpien 5. Là aussi, la peau semble être le produit recherché (MORIN & SOULIER 2017).

Dans l'Aurignacien (fouilles Peyrony) de l'abri Castanet (Dordogne), sur les quatre restes d'ours brun, un fragment de canine, une deuxième molaire supérieure, et deux premières phalanges, représentant 0,8 % des restes fauniques identifiés, une des deux phalanges porte des stries (Fig. 1). Une exploitation de la peau a été envisagée (ARMAND 2006). D'autre part, la molaire est percée, mais il s'agit d'un autre registre d'exploitation que nous laisserons de côté ici.

Figure 1 : phalange 1 d'ours brun avec stries, abri Castanet. Photo P. Jugie, MNP, les Eyzies-de-Tayac.

Plus haut, nous avons déjà parlé du niveau gravettien d'Hohle Fels, mais c'était à propos de l'exploitation de l'ours des cavernes or, dans ce même niveau, trois restes d'ours brun sur cinq portent des traces de boucherie et, dans le niveau aurignacien, un reste sur trois (KITAGAWA *et al.* 2012). L'étude ne précise pas de quels ossements il s'agit, ni à quoi correspondent les stries de découpe.
À Polesini (Italie), dans les niveaux épigravettiens, trois restes d'ours bruns sont présents parmi plus de 40 000 restes. Un fémur porte des stries, qui semblent liées à une action de désarticulation (STINER 1994).
Dans le Magdalénien de l'abri Vidon (Gironde), avec deux vestiges, l'ours brun représente 0,4 % des restes. Un fragment d'ulna porte des marques attestant d'activités de désarticulation et de décarnisation (CAMPMAS *et al*. 2011).
À l'abri Mège (Dordogne), deux premières phalanges d'ours ont été découvertes dans un niveau magdalénien. D'après CAPITAN *et al* (1906) : « Plus massives que chez l'*Ursus arctos*, elles appartiennent probablement à un *Ursus spelaeus* de taille moyenne ou petite… Les phalanges d'ours portent des traces d'incisions au silex : étaient-elles des

amulettes ?? ». L'attribution à l'ours des cavernes nous parait douteuse, parce que la présence de ce taxon au Magdalénien n'a jamais été signalée. D'autre part, Jean-Baptiste MALLYE (communication personnelle) nous a indiqué qu'il s'agissait de stries de découpe, ce qui remet en question l'utilisation en tant qu'amulette et semble plutôt démontrer une utilisation de la peau.

Lors d'une révision des vestiges fauniques du Morin (Gironde), MALLYE *et al*. (2018) ont décompté cinq restes d'ours brun dans l'ensemble A et un reste dans l'ensemble B et ils soulignent que « à l'exception de la belette et de l'hermine, toutes les espèces présentées ici portent des traces témoignant de leur exploitation par l'homme », mais ne détaillent pas l'implantation et le nombre de ces marques.

Eléments de réflexion

Site	Culture	Taxon	NR ours	NR ours avec traces de découpe	NRDt	Produits utilisés
Crvean Stijena	Moustérien	*Ursus sp.*	1	1	242	Peau
Sant'Agostino niveau S1	Moustérien	*Ursus arctos*	3	1	857	Peau
Crvean Stijena	Uluzzien	*Ursus sp.*	1	1	288	Peau
Castanet	Aurignacien	*Ursus arctos*	4	2	466	Peau
Hohle Fels	Aurignacien	*Ursus arctos*	3	1	1562	?
Hohle Fels	Gravettien	*Ursus arctos*	5	3	2194	?
Polesini niveau 5	Epigravettien	*Ursus arctos*	2	1	7095	Désarticulation
Vidon	Magdalénien	*Ursus arctos*	2	1	476	Désarticulation, viande
Abri Mège	Magdalénien	*Ursus spelaeus ?*	2	2	?	Peau
Le Morin	Magdalénien, Azilien	*Ursus arctos*	6	?	4925	?

Figure 2 : Sites avec peu de restes d'ours et fort pourcentage de traces de découpe (NR = nombre de restes, NRDt : nombre de restes déterminés taxonomiquement).

Dans l'état actuel des découvertes, les sites avec peu de restes d'ours, mais où une majorité d'entre eux porte des stries de découpe, concernent l'Homme de Néandertal et l'Homme moderne. Le plus ancien de ces sites, Crvean Stijena a un âge estimé entre 52 200 à 78 300 ans (MORIN & SOULIER 2017) et les plus récents sont magdaléniens (Fig. 2). Quand le taxon a été déterminé au niveau spécifique, il s'agit toujours d'ours brun, excepté à l'abri Mège où une attribution à l'ours des cavernes (CAPITAN *et al*. 1906) nous parait toutefois discutable.

L'exploitation est souvent orientée vers la recherche des peaux. Les phalanges et les métapodes qui portent des stries sont sans doute restés attachés aux peaux, quand elles ont circulé. Ce transport de peau vers des lieux qui ne sont pas ceux où a eu lieu l'exploitation des animaux ne permet pas de savoir quel a été le mode d'acquisition, mais ROMANDINI & NANNINI (2012) ont avancé que la chasse était sans doute nécessaire pour obtenir des peaux en bon état. D'autre part, la chasse à l'ours brun est bien avérée dans des sites comme Biache-Saint-Vaast (AUGUSTE 1995) et Taubach (BRATLUND 1999).

L'absence de sites montrant un transport de peau d'ours des cavernes hors de leur contexte d'exploitation devra être confirmée. Mais, à ce stade, elle nous conduit à nous poser des questions. Il ne s'agit pas d'une non-exploitation de l'ours des cavernes qui, au contraire, est le taxon sur lequel on observe le plus d'activités de boucherie, les peaux étant les produits les plus recherchés (ARMAND 2018). Il s'agit peut-être d'un problème de contexte, l'importation de peau étant impossible à détecter dans des gisements où les ours des cavernes ont été exploités assez intensément. Elle pourrait ne pas être décelable non plus, dans les tanières où les ours ont hiberné et où ils ont été faiblement exploités, les métapodes et les phalanges portant des traces de découpe pouvant être aussi bien le résultat d'une exploitation sur place que d'une importation de peau.
Mais quoiqu'il en soit, en l'état actuel des découvertes, il n'existe pas de site avec seulement quelques restes d'ours des cavernes et un taux de stries élevé. On pourrait pourtant imaginer le transport d'une peau d'ours des cavernes vers un site d'habitat, depuis l'endroit où ont eu lieu la chasse et les activités de boucherie.

Si, dans l'avenir, il est bien confirmé que ce type de site n'existe pas pour l'ours des cavernes, il faudra alors se poser des questions sur l'origine de cette différence entre l'ours des cavernes et l'ours brun. S'agirait-il de variations dans les modes d'acquisition de ces deux taxons ? En lien avec des différences écologiques ou éthologiques entre les deux espèces ? Ou bien de différences dans la façon d'utiliser les produits issus du corps de ces animaux ?

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Identification par SIG des karsts du Mozambique et d'Afrique australe

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Résumé

Le Grand Rift Est Africain et l'Afrique du Sud, sont les rares régions ayant révélé des fossiles d'homininés anciens vieux de plusieurs millions d'années. Les découvertes, dans le « Berceau de l'Humanité (UNESCO) », sont faites à l'intérieur de cavités protégées de l'érosion. Lors de la mission Human Origins In Mozambic & Malawi –HOMME- de 2019 (FOURVEL et *al.*, 2021, ce volume) la découverte de faunes anciennes dans les grottes du Mozambique révèle que ce territoire, à mi-chemin entre les deux grandes régions fossilifères africaines, présente un grand potentiel archéo-paléontologique. Dans ce but, un doctorat a débuté en mars 2019. Il est financé par la bourse *80Prime* de la *Mission pour les Initiatives Transverses et Interdisciplinaires* (MITI) du CNRS. Le but est de réaliser un diagnostic karstologique du Mozambique, à partir des cavités bien connues de l'Afrique du Sud (BRUXELLES, 2019), pour découvrir des grottes à prospecter lors de nos prochaines missions. Cet article présente le travail cartographique préliminaire effectué, préalable aux missions de terrain, afin de guider les prospections.

Abstract

Mozambique and Southern Africa karsts identification by SIG. The Great East African Rift and South Africa are the rare areas in which hominin fossils several million years old have been found. The finds, in the "Cradle of Humanity (UNESCO)", are made inside cavities protected from erosion. The old fauna discovered in Mozambican caves during the 2019 mission of the Human Origins in Mozambic & Malawi (HOMME) project (FOURVEL, 2021, this volume) indicates that this territory; located between these two great african fossiliferous regions, could contain an archaeo-paleontological potential. To this end, doctoral research, started in March 2019, is funded by the *80Prime* grant of the "*Mission pour les initiatives transversales et interdisciplinaires*" of the CNRS. The aim is to carry out a karstological survey in Mozambique to identify caves to be explored during future fieldwork sessions. In this article, we present a preliminary cartographic work, conducted prior to the fieldwork, dedicated to the preparation of survey maps.

1. Introduction

Au Mozambique, trois principaux massifs carbonatés renferment plus de 80 grottes (LAUMANNS, 1998). La mission HOMME de 2019 a permis de visiter 33 de ces cavités (Fig.1). Sur la base de cette reconnaissance, l'objectif est maintenant de définir les nouveaux secteurs de prospection des missions futures. Pour cela, une base de données cartographique est réalisée dans un système d'information géographique (SIG), qui synthétise l'ensemble des données de terrains existants : cartographiques et bibliographiques. L'exploitation du SIG permet l'élaboration de minutes de terrain des massifs à prospecter. Ce sont des fonds de cartes, adaptées à nos études morphokarstiques, qui permettent de faire de la prospection archéo-paléontologiques.

2. Méthodologie de la base de données cartographiques sous SIG

En premier lieu, un SIG a été créé à partir des données de prospections des missions précédentes au Mozambique (missions HOMME de 2018 et de 2019) ; en Namibie (missions Human Origins in Namibia HON de 2015, 2016, 2017 et 2018) et en Afrique du Sud. Puis, ont été ajoutés des inventaires de cavités (LAUMANNS, 1998 ; MERCATER et *al*. 2013 ; PICKFORD 1990, 2013 et 2019 ; grottocenter.org).
Le SIG a été complété par les relevés altimétriques japonais, notamment celles disponibles gratuitement depuis d'avril 2020 : AW3D30. Ces datas brutes permettent de produire des modèles numériques de terrain (MNT), à la résolution de 30 mètres (1 arc second). À partir du MNT on calcule des modèles ombrés, des cartes de pentes, des cartes hypsométriques permettant de faire une analyse géomorphologique de chaque massif karstique. Les cartes géologiques des pays concernés, sont ensuite intégrées dans le SIG et sont listées dans le tableau 1. Ces formations géologiques ont nécessité une harmonisation numérique (vectorisation des rasters par exemple) et stratigraphique (en éliminant les frontières nationales notamment). Après avoir compilé les données existantes, sont rajoutées les nouvelles datas, c'est-à-dire les analyses morphokarstiques (cartographie des dépressions fermées, des dolines et des paléo-vallées, report en surface des réseaux karstiques, analyse des paléosurfaces, etc.), dans le but d'identifier les futures cibles de prospection.

Country	RasterVector	Name	Link	Authors	Scale	Year
South Africa	V	rsa_1m_shape_layer_font_tar	http://www.geoscience.org.za/images/Maps/DataFile/rsa_1m_shape_layer_font_tar.zip	Counsil of Geoscience	1M	2019
	V	CGS_RSA1M Geological polygon	http://geoscience.org.za/cgs/	Counsil of Geoscience,De Beer	1M	2019
	R	Geological map of the Republic of South Africa and the Kingdoms of Lesotho and Swaziland				
	R	Composite map : Geological map of the republic of South Africa and the kingdoms of Lesotho and Swaziland		Counsil of Geoscience : C. Frick & N. Keyser	1M	1997
	R	Chronostratigraphic map of the republic of south africa and the kingdoms of Lesotho and Swaziland		Counsil of Geoscience	2M	2008
	R	Simplified geological map of the republic of south africa and the kingdoms of Lesotho and Swaziland		Counsil of Geoscience, Johnson & Wolmarans	2M	2008
	R	Gautenf ond North West Dolomite Units		Water Geosciences Consulting, Holland	1,5M	2009
	R/V	2626 - 2628 - 2528 - 2526 250,000 Geological Series		Department of mineral and energy affairs, Director General L.Alberts, D. Sc., F. Inst. P., F.S.A.I.M.M; Geological survey, Chief Director P.J.Smit, P.D	250k	1986
	R	2527DA DB DC DD 500,000 Series		Departement of mines Van Mynwese	500k	
Mozambic	V	Mozambique1M_Lithology_v1.MAP	https://www.orrbodies.com/resource/geology-mozambique-1987/	Instituto Nacional de Geologia, BRGM Patrice Pinna, Pascal Marteau; JF Becq-Giraudon	1M	1987
	R	Carta Geological		Counsil of Geoscience		2008
	R		https://www.yumpu.com/en/document/read/5167791/gtk-consortium-geological-surveys-in-mozambique-arkistogsffi	GTK Consortium		
	R	GTK_MZ_1832_1833,1834,1835,1932_1933,1934,1935, 2032_2033,2034_2035		GTK – ITC – GONDWANA – SGU – GEUS, Direcçao nacional de geologia,M.I. Lehtonen, H. Mäkitie, T.Manninen, B.Gustafsson, T.Eerola, T.Koistine e C.Åkerman	250k	2006
Malawi	V		http://www.masdap.mw/	Department of Surveys		
	R	Geology map of Malawi	https://nla.gov.au/nla.obj-2053903552/view	Bloomfield, Mason, Habgood	1M	1966
Botswana	V	Atlas of Namibia Project Directorate of Environmental Affairs	http://geoscienceportal.geosoft.com/Botswana/api/Extraction/Download?folder=3b2e3d05-7f3c-4d78-983a-f0eb001e7e29&file=geol-botswana.zip	Ministry of Environment and Tourism		2002
Namibia	V	SIG_Namibie (Geology, hydrogeology etc)		?	?	2015
	R	Atlas of Namibia Project	http://www.uni-koeln.de/sfb389/e/e1/download/atlas_namibia/e1_download_physical_geography_e.htm	SF B 389 ACACIA	7,5M	2003
Madagascar	V	Simplified Geology of Madagscar	https://databasin.org/maps/	Conseration Biology Institute (Besairie,1964)	1M	2010

Tableau 1 : Sources bibliographiques et caractéristiques des cartes géologiques compilées en janvier 2021.

3. Synthèse cartographique des massifs karstiques en Afrique australe

Le SIG permet de réaliser des cartes synthétiques, dont un exemple est donné en figure 2 : la carte des massifs carbonatés (en rouge) et des grottes connus (en noir) de l'Afrique australe. Pour réaliser cette carte, nous avons, tout d'abord, cartographié les dolomies néoarchéennes (-2,6 Ga) de Chuniespoort (Malmani supergroup). Elles affleurent notamment dans le « Cradle of humankind ». L'extension de ces dolomies a été suivie de part et d'autre de cette région fossilifères, notamment vers le Gauteng et le plateau de Ghaap. De l'autre côté du désert du Kalahari, en Namibie, ce sont les formations carbonatées d'Otavi (Damara supergroup) d'âge néoprotérozoïque (1 Ga à 500 Ma), qui ont été cartographiées. Ce sont les reliefs karstiques du Kaokoveld, d'Otavi et des Aha Hills. Au Mozambique, trois principaux massifs karstiques carbonatés sont présents (Fig. 3). Les analyses, reportées dans le tableau 2, ont permis de caractériser les karsts de Buzi (Fig.4), de Cheringoma et de Buchane, situés dans les formations carbonatées d'âge tertiaire (66 à 40 Ma). Au nord du Mozambique et au Malawi, de nombreux petits affleurements de marbres, d'âge précambrien (4,560 Ga), ont été aussi cartographiés (CUMBE, 2017). Ils pourraient faire l'objet de visites de prospection. Les formations carbonatées de Madagascar ont aussi été représentées, notamment les karsts de Tsingy.

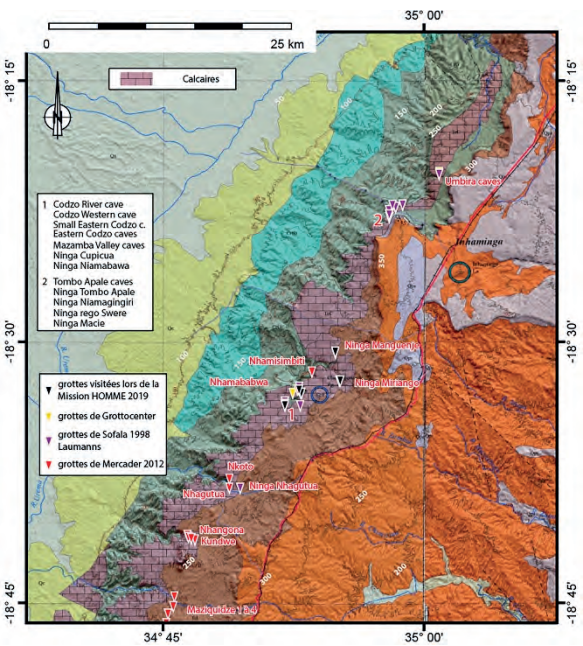

Figure 1 : Localisation des cavités visitées en 2019 (en noir) et contexte géologique régional du Massif de Cheringoma.

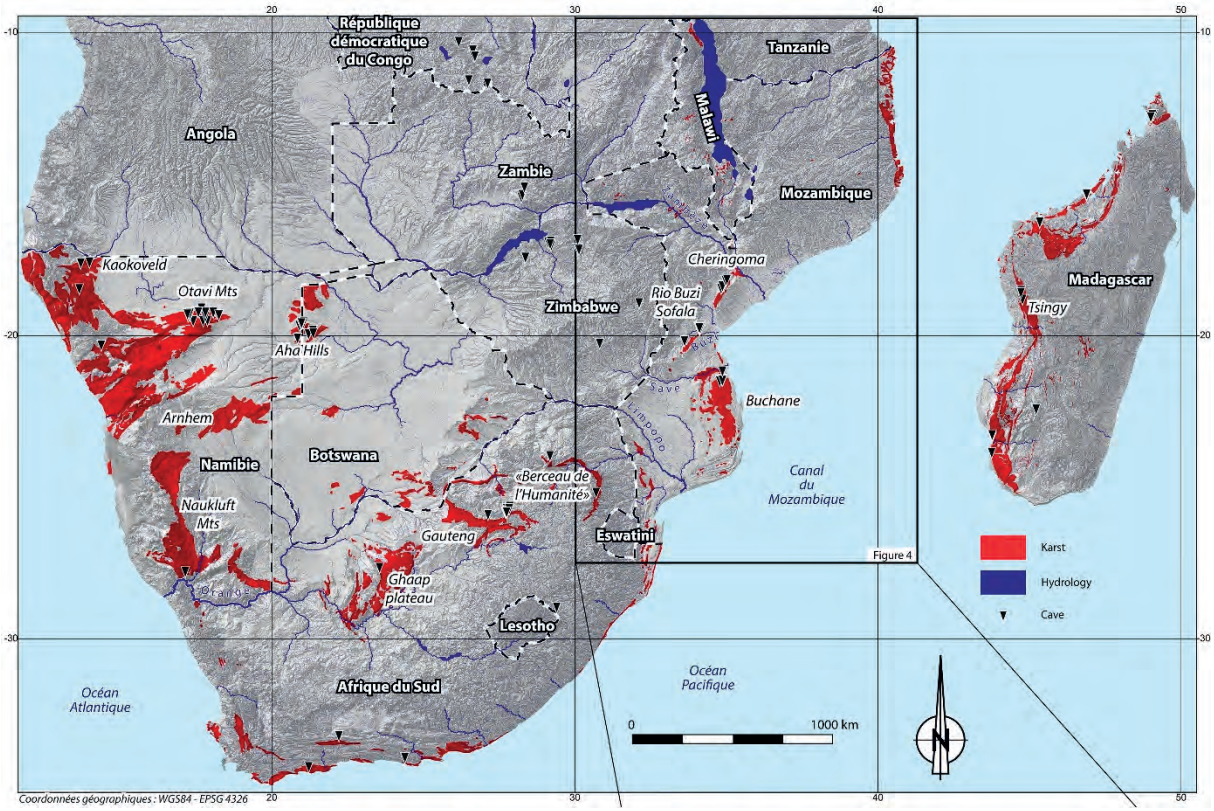

Figure 2 : Carte synthétique des massifs karstiques et des cavités de l'Afrique australe (état d'avancement de janvier 2021).

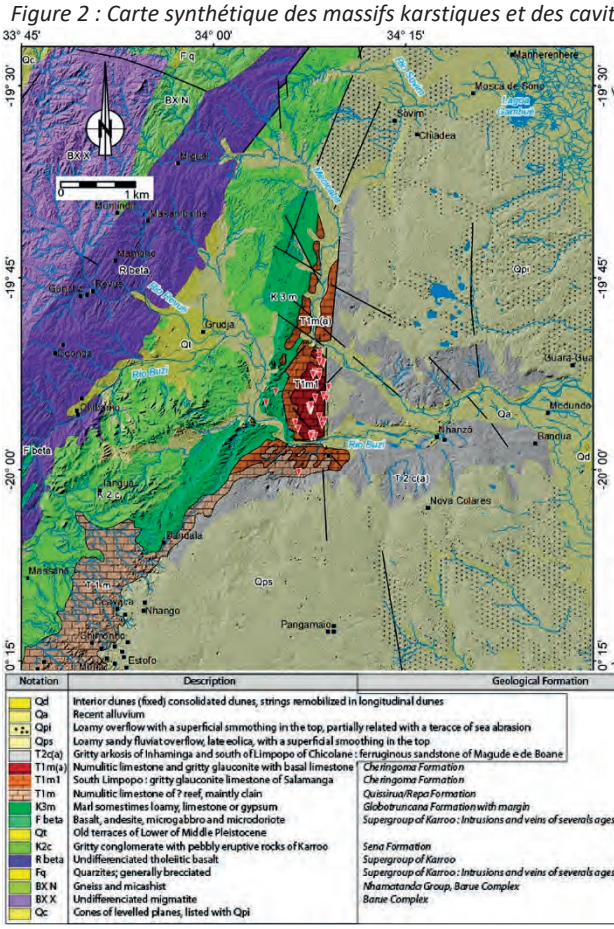

Figure 4 : Contexte géologique de Buzi

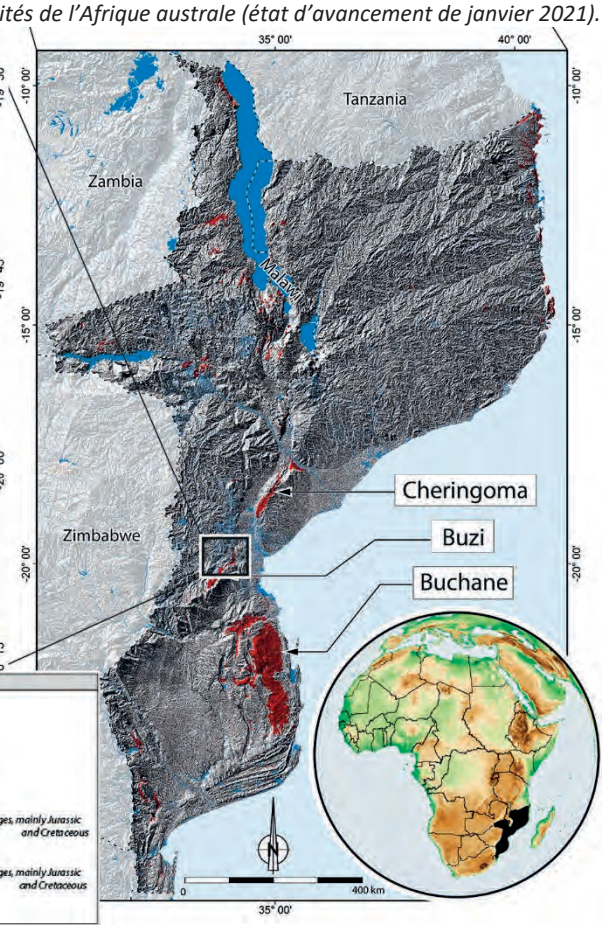

Figure 3 : Karsts (en rouge) du Mozambique et du Malawi.

Karstic massif	Geologic Formation	Age	Name	Lithologic description	Thickness	Area (km2)	Caves	Caves names
CHERINGOMA	Quissirua/Repa	Cenozoic (Eocene)	T1m	Numulitic limestone or ? reef, mainly clay	30 m - 1400 m	311	2	Ninga Manguenje, Western Codzo Cave
	Sancul / Cogune	Cenozoic	T2m	Fossileferous reef limestone, sandy at the base	?	633	8	Ninga Miriango, Eastern Codzo, Smalller Eastern Codzo, Ninga Niamabawa, Ninga Cupicua, Mazamba Valley, Codzo River
BUCHANE	Jofane / Morrumbene	Cenozoic	T2m(a)	Reef limestone or sandy limestone	11 to 50 m	12689	11	Magochene, Embondeiro, Cagi(Caverna X), Inhaluele, de Cobra, Caverna VIII, Caverne VI/Via/II
BUZI	Quissirua/Repa	Cenozoic (Eocene)	T1m	Numulitic limestone or ? reef, mainly clay	30 m	566	2	Nyaboa caves, Boca complex
	Cheringoma	Cenozoic	T1m(a)	Numulitic limestone and glauconic sandstone with limestone at base	200 m	39	21	Dimba, Mutanda Francisco, Xonondo, Kunangua, Muchakaima, Chipayike, Goonde
	Cheringoma	Cenozoic	T1m1			99	8	Pwanda, Maconjo, Chipayike, Gruta Maruluwire

Tableau 2 : Caractéristiques géologiques des trois principaux massifs karstiques du Mozambique.

4. Cartographie haute-résolution des karsts du Mozambique et du Malawi

Le potentiel karstique des régions de Cheringoma, Buzi et Buchane est connu depuis les prospections spéléologiques de Laumanns en 1998, 1999 et 2015. La cartographie haute résolution du plateau calcaire de Cheringoma (Fig. 1), qui s'étend sur plus de 50 km et à l'altitude constante de 250 m, montre qu'il est incisé par des canyons qui ont recoupé de nombreuses cavités. Une prospection systématique le long de ces canyons pourrait permettre de découvrir de nouvelles cavités, notamment au nord. Au sud de la rivière Buzy, les calcaires de la formation Quissirua / Repa, représentés par des caissons sur la figure 4, affleurent vers le sud sur plus de 500 km^2. Ils devront être prospectés car ils sous-tendent un plateau assez élevé et karstifié.

La cartographie d'autres formations carbonatées, non encore reconnues, du Mozambique et du Malawi, offre un potentiel non-négligeable de découvertes. Ces karsts seront explorés lors des deux prochaines missions vers le nord du pays et au Malawi. Le travail de terrain et l'acquisition de nouvelles données permettra d'affiner le modèle karstique au retour de mission et permettra d'améliorer la compréhension que nous avons de ces karsts.

5. Perspectives et suite de la thèse

La cartographie sera étendue à l'ensemble de l'Afrique durant la thèse. Concernant le Mozambique, l'analyse des karsts sera couplée à celles des données géologiques de sismique-réflexion, réalisée au fond du canal du Mozambique pour la recherche pétrolière et qui permet d'avoir la géométrie des dépôts sédimentaires au droit des deltas du Zambèze et du Savé. D'après ces études, ces fleuves ont commencé leurs travails d'érosion dès le Crétacé. Ces corrélations permettront, peut-être, de dater le creusement des karsts eux-mêmes. En effet, il est important de préciser non seulement leurs âges mais aussi, celui de leurs démantèlements qui a permis le piégeage des fossiles d'homininés anciens.

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An early Middle-Age dark layer in Bosnian stalagmites: possible link to an historical event?

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Abstract

In four stalagmites sampled in Mračna Pećina Cave (Bosnia and Herzegovina) in 2014 for palaeoclimate research, a dark layer was observed. According to U-Th dating, its deposition occurred at circa 1.19 ka (circa 750 A.D.). Its sharp boundaries, fluorescence properties, excess in carbon determined by SEM EDS analyses, and its age, suggest an origin related to torch/candle soot, leading to the hypothesis of intense cave frequentation during a short time window. Human bones found in a nearby cave, and coated by a dark deposit resulting from combustion, were dated to about 1.18 ka BP. This raises questions about a potential historic correlation between the two discoveries. Indeed, this was a period of unrest in the Balkan region: it was marked by migration of people from NE Europe during a cool climate anomaly, which may have led people to use caves as temporary shelters. The coincidence of these two ages points to speleothems as potentially useful recorders for historical/archaeological disciplines, as they can preserve/ historical information that can be precisely constrained in time.

1. Introduction

Stalagmites are considered among the best continental archives for providing precise and continuous datasets on past climate and environmental fluctuations. Their strong potential in such studies resides in their growth processes. Far from the surface, they grow slowly over long periods of time, protected inside caves from strong erosional and weathering processes. During stalagmite formation, precipitating calcite incorporates information from both surface and cave environments. Here we present a tentative interpretation of a dark layer found close to the top of four Holocene stalagmites sampled in Mračna Pećina Cave (Bosnia and Herzegovina). Its origin is thought to be related to human activities inside the cave, thus highlighting the potential of stalagmites as archives of historical and archaeological information.

2. Material and Methods

Four stalagmites (BS8, BS9, BS14 and BS15) were sampled in 2014 in Mračna Pećina Cave, located about 40 km NE from Sarajevo (Bosnia and Herzegovina). This cave was discovered in the XX century and is now accessible through an artificial entrance and concrete stairs which were built between the First and the Second World Wars for tourist visits (DANEŠ, 1921). The natural entrance is now partially occluded by a rockfall. Preliminary sample preparation (cutting along the growth axis and surface polishing) revealed the presence of a sharp dark layer close to the top of each stalagmite (Fig. 1). In the wider context of palaeoclimate research at the site, the stalagmites were dated to constrain their growth history.

To identify the age of the dark layer, powder samples of 50 to 70 mg of calcite were collected above and below the layer in each stalagmite using a CNC drilling machine (MicroProto systems MicroMill 2000). Ages were determined using U-Th disequilibrium dating according to the methods described in HELLSTROM (2003) and modified in DRYSDALE *et al*. (2012). The isotopic ratios were analysed with a Nu Instruments Plasma multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) housed in the School of Earth Sciences at the University of Melbourne (Australia). Raw ages were corrected according to the stratigraphic approach described in HELLSTROM (2006). The concentration of trace

elements incorporated into the calcite crystal lattice has been analysed continuously along the growth axis of stalagmite BS15 only, allowing to test if there is a significant change in trace element concentrations through the dark layer. This analysis was performed in the Isotope Geochemistry laboratory of the School of Earth Sciences at the University of Melbourne using a HelEx laser ablation system coupled to an Agilent 7700x quadrupole ICP-MS instrument, as described in WOODHEAD *et al*. (2007) and DRYSDALE *et al*. (2012). Thin sections of all stalagmites were prepared and observed with an optical microscope. Thin sections of stalagmites BS14 and BS15, which best displayed the dark layer, were observed with an Olympus BX51P polarizing microscope. Fluorescence was observed using a 50-watt tungsten light source, filtered by two filter cubes enabling the observation of UV radiation (laboratory B. Bagolini, University of Trento, Italy). The BS15 thin section including the dark layer was also analysed using micro-Raman technology with a Horiba Jobin Yvon J64000 coupled with a reflected light microscope at the Pôle Optique et Microscopies, Institute Néel-Département PLUM of the University of Grenoble-Alpes (France) using a laser pulse intensity of 0.5 mW and a microscope magnification of 50x. At the Université Savoie Mont Blanc (EDYTEM laboratory, France), two powder samples including the black layer from BS14 and BS15 stalagmites were analysed using FTIR vibrational spectroscopy. Finally, scanning Electron Microscope (SEM) analyses were performed using a Stereoscan 440 at the Université Savoie Mont Blanc on powder samples collected from the dark layer in BS14 and BS15 stalagmites and directly on the polished surface of the BS15 sample.

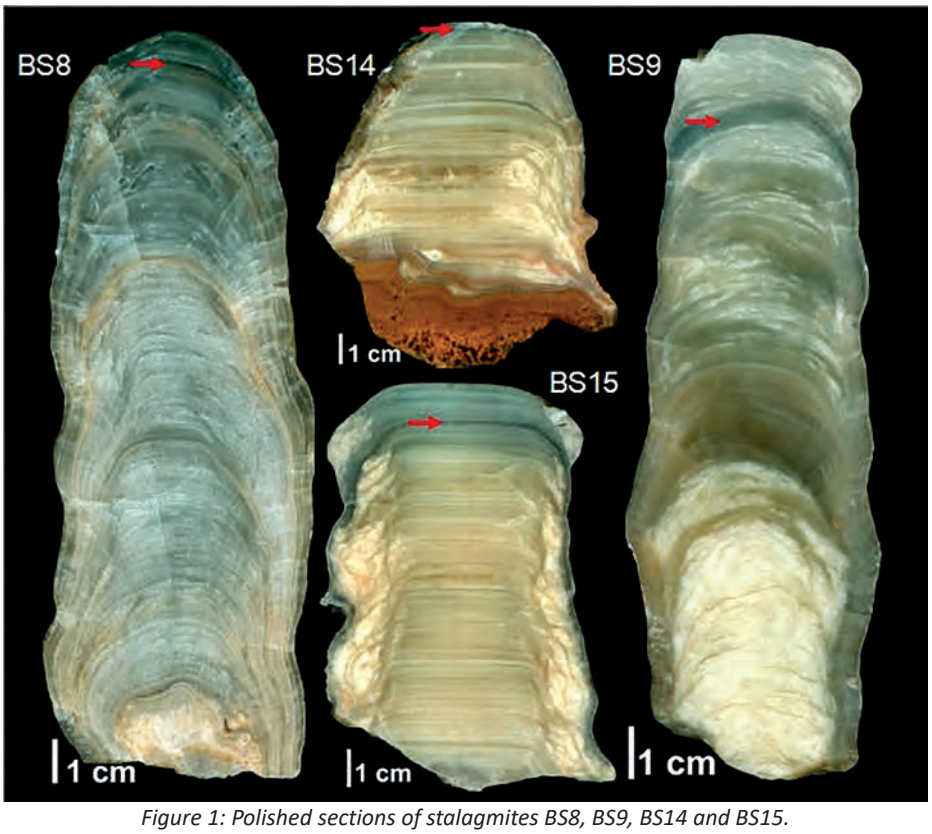

Figure 1: Polished sections of stalagmites BS8, BS9, BS14 and BS15.
Red arrows indicate the position of the dark layer in each stalagmite.

3. Results and discussion

Dark coatings on cave walls and speleothems are often related to manganese and iron oxides. Indeed, Mn-Fe rich bedrock may provide iron and manganese ions which can be released into water under anoxic conditions. An example is provided in GÁZQUEZ *et al.* (2011) for El Soplao Cave (Spain): cave gallery flooding created the anoxic conditions necessary for manganese and iron to be mobilised and dissolved into water. These metals deposited on cave surfaces and their subsequent oxidation under epiphreatic conditions, possibly mediated by microbial activity, caused the formation of black crusts (GÁZQUEZ *et al.*, 2011; NORTHUP *et al.*, 2003). However, there is no evidence of phreatic conditions in Mračna Pećina cave. Furthermore, laser-ablation trace element analyses on stalagmite BS15 do not show the presence of significant Mn or Fe concentrations in the dark layer, thus excluding the possibilities of Mn-Fe in black-layer formation. Besides trace element analyses, both FTIR and micro-Raman analyses failed to identify the origin of this layer, returning results indicating calcium carbonate only, possibly because of the strong prevalence of the calcite signal (FTIR analyses) as the dark material is included into the compact calcite crystals. However, the observation under the fluorescence optical microscope showed the presence of fluorescent material forming the black layer, suggesting an organic origin (Fig. 2).

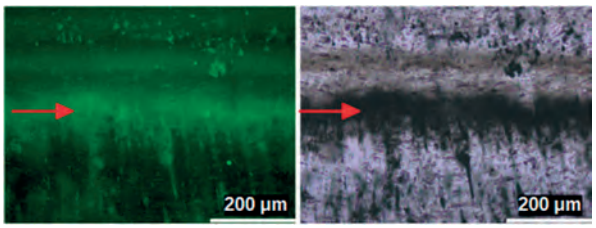

Figure 2: Microphotographs of the black layer in the BS14 stalagmite (red arrow). Left: luminescence emitted under UV lamp excitation Right: plain light.

SEM observations on coarse powder drilled from the black layer support this hypothesis, allowing the identification of an excess of carbon atoms concentrated in the thin black coating of calcite crystals (Fig. 3).

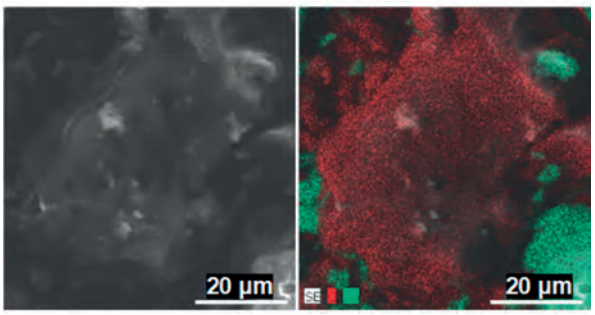

Figure 3: SEM image of coarse calcite powder sampled in the black layer. Left: secondary detector picture. Right: chemical mapping of Ca (green) and C (red) concentration.

Considering these results, the C excess detected in correspondence to the dark layer, which appeared to be fluorescent, might be related to the combustion of organic material leading to the formation of fluorescent carbon nanoparticles coating the stalagmite surfaces, as observed by LIU *et al*. (2007) for soot produced by candles.

Today, the cave walls and speleothems in the area close to the main entrance of Mračna Pećina Cave preserve a pervasive dark coating, which is believed to be related to intense cave frequentation using torches during the early XX century, when the cave became accessible to tourists. Thus, a similar context may have caused the deposition of the detected soot laminae. U-Th dating returned low U concentrations and low $^{230}Th/^{232}Th$ ratios, resulting in large age uncertainties, especially in BS14 samples. Although BS14 dating was imprecise, the stalagmite was included in this study because it was useful for the investigating of the origin of the dark layer. According to the age-depth models of stalagmites BS15 and BS9, which were the most precise, the dark layer deposited at 1.19 ± 0.13 ka (error-weighted mean of the age-model ages of the dark layers from the two stalagmites). Unfortunately, it is not possible to precisely replicate this result in stalagmites BS8 and BS14 due to the large age uncertainties and the presence of several hiatuses which cannot be resolved by the age-depth models. However, considering the U-Th results for samples taken above and below the dark layer in each stalagmite, it is reasonable to infer the layer to be coeval in all four stalagmites, since it falls within the age uncertainties (Fig. 4).

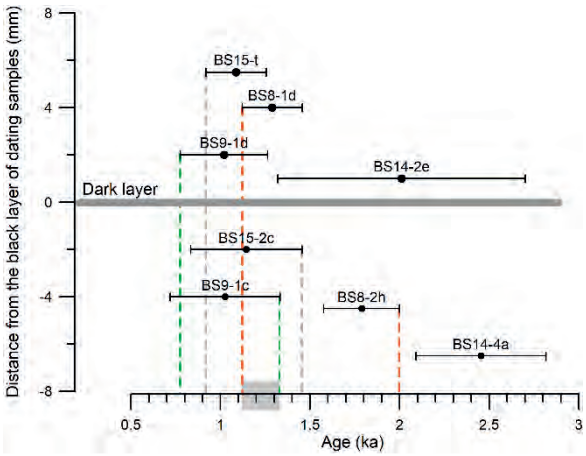

Figure 4: U-Th results (ages: black dots; age incertitude: black horizontal bars) for stalagmites BS8, BS9, BS14, and BS15 of samples below and above the black layer. Results are represented as a function of their distance from the black layer in each stalagmite: positive y-values represent samples above the black layer; negative y-values correspond to results below the black layer. Vertical dotted lines (green for BS9, grey for BS15 and orange for BS8) indicate the projection on the x-axis of the lower and upper limit of the age intervals inside which the black layer was deposited. The grey box on the x-axis indicates the likely age range inside which the dark layer was deposited. BS14 dating, characterised by large age uncertainty, was not considered reliable in determining the age of the dark layer.

Interestingly, in a cave located in the same region (Golubovici Cave, Gosina plateau, Bosnia and Herzegovina), explored by the Novara caving group between 2003 and 2007 (CELLA & TORRE, 2005; CELLA *et al.*, 2011), human bones covered by a dark coating were found. No human skull was found in this cave and the motivation and timing of their removal is unknown. A local legend tells of a group of people being asphyxiated by smoke inside this cave during historical times, however, observations carried out by a collaborator of the Institute of Anthropology of the University of Turin suggested the exposition of those bones to high temperatures (500-700°C) (CELLA *et al.*, 2011). Radiocarbon dating on the bones gave an age of ~1180 ± 80 cal. yr BP, which appears to be synchronous with the deposition of the soot layer on Mračna Pećina Cave speleothems (CELLA *et al.*, 2011; Cella, personal communication). According to CELLA *et al.* (2011), J. Daneš, who was commissioned in 1917 by the Austro-Hungarian army to examine some Bosnian caves, provided a first description of Gobulovici cave as a religious site; he mentioned the presence of several darkened human skeletons and evidence of excavations. The lack of archaeological records in Bosnia dating back to this period prevents the association of these findings to any specific historical event. However, the period was characterised by a combination of harsh winters and a tumultuous sociopolitical situation, resulting from the massive migration of populations from North-Eastern Europe to the Balkans. There were tensions between the Byzantines, the Bulgarians and other Slavic tribes (e.g., FINE, 1991; HINES *et al.*, 1999) and periodic outbreaks of the bubonic plague caused massive deaths in the whole Byzantine Empire and

in Europe between the VI and VIII centuries, starting with the Justinian's Flea (541-542 AD; ROSEN, 2007). In this context, it is plausible to advance the hypothesis that Golubovici cave was used for inhumation at the same time as Mračna Pećina cave served as a temporary shelter to local people, at difficult times. The dating of the dark layer in both caves suggests a short time window, centered on 1.19 ± 0.13 ka BP, which coincides with a period of degraded climate and societal turmoil. Besides, no evidence of prolonged frequentation over long period of times (i.e., archaeological findings, graves, artificial modification of cave morphologies) has been found so far in Mračna Pećina cave, but frequent visits involving the use of torches could have been sufficient to deposit the observed soot layer.

4. Conclusion

A dark coating of stalagmite surfaces during their growth has been observed in four stalagmites from Mračna Pećina Cave. U-Th dating suggests its deposition occurred at 1.19 ± 0.13 ka. Several analyses were performed to identify its composition. Trace element, micro-Raman and FTIR results did not provide any useful information about the nature of the dark lamina. The detection of fluorescent material, together with the identification of carbon atoms concentrated on the coated crystal surfaces, suggest it is composed of organic-rich soot. It could be related to the use of candles/torches, thus indicating intense cave frequentation during a relatively short time window. The comparison with burnt human remains in a nearby cave, of approximately the same age, raises questions about an historical link between the two findings. Our results highlight that speleothems have the potential to preserve markers of human history or activities, thereby providing a way of dating them.

Acknowledgments

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Archéologie en contexte karstique subaquatique : une nouvelle approche des dépôts anthropiques et naturels à la résurgence de la Lesse aux grottes de Han (Province de Namur, Belgique)

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Résumé

Les grottes de Han sont une référence dans le domaine de la karstologie mais aussi dans celui de l'archéologie subaquatique. À partir des premières découvertes en 1959 dans le lit de la Lesse souterraine, des milliers d'artefacts datés du Néolithique aux périodes modernes ont été recueillis. Sous la direction de M. Jasinski, les opérations subaquatiques ont principalement concerné de 1963 à 1978, le *Tournant du jour* situé à 70 m en amont du porche de la résurgence, puis sous ce dernier, dans le *Trou de Han*, de 1978 à 1983. Ce dernier secteur fait depuis 2012 l'objet d'un nouveau programme par le Centre de Recherches Archéologiques Fluviales (CRAF) afin d'obtenir des éléments de compréhension de l'évolution du cours de la Lesse et de ses abords. Ouverte de la rive gauche au centre de la rivière, la zone fouillée a permis de lever une coupe de près de 4 m de hauteur, atteignant à la base des niveaux néolithiques. Bien que marquée par quelques lacunes, cette séquence vient documenter l'évolution d'un milieu particulier, tant aquatique que souterrain.

Abstract

Archaeology in an underwater karst context: a new approach to anthropic and natural deposits at the Lesse resurgence in the Han caves (Province of Namur, Belgium). The caves of Han-sur-Lesse are a reference point for both karstology and underwater archaeology. From the first discoveries in 1959 in the riverbed of the underground Lesse, thousands of artifacts from the Neolithic to the modern period have been collected. Under the direction of M. Jasinski, the underwater operations mainly concerned, from 1963 to 1978, the *Tournant du jour* located 70 m from the resurgence, then under the porch, in the *Trou de Han*, from 1978 to 1983. Since 2012, this sector is the focus of a new program by the "Centre de Recherches Archéologiques Fluviales" (CRAF) to obtain elements of understanding of the evolution of the river Lesse and its surroundings. Opened up from the left riverside to the centre of the river, the excavated area made it possible to record a section almost 4 m high, reaching the Neolithic levels at the base. Although marked by a few gaps, this sequence documents the evolution of a particular environment, both aquatic and underground.

1. Introduction : un site emblématique

Le domaine des grottes de Han-sur-Lesse (Province de Namur, Belgique), exploité depuis 1856, est l'une des attractions touristiques les plus emblématiques du sud de la Belgique. Il s'agit de l'une des rares grottes en Europe à être traversée par une rivière : la Lesse. Celle-ci disparaît dans le gouffre de Belvaux et réapparait quelques centaines de mètres avant sa résurgence au *Trou de Han* après avoir traversé l'ensemble du massif de Boine au sein d'un réseau souterrain complexe. L'intérêt archéologique des grottes a été mis en évidence pour la première fois en 1902 dans le cadre des fouilles de la Galerie des Grandes Fontaines (De PIERPONT 1904). Suite à la découverte en 1959 des premiers vestiges dans la rivière, des fouilles subaquatiques débutent en 1963 sous l'impulsion de M. Jasinski. Elles révèlent l'importance du site avec la mise au jour de milliers d'artefacts appartenant principalement au Néolithique, à l'âge du Bronze Final et au second âge du Fer (JASINSKI 1965). Les méthodes et techniques alors mises en œuvre ont permis d'enregistrer la répartition planimétrique de ces objets. Mais leurs assemblages apparaissant hétérogènes sur le plan chronologique, les études typologiques ont pris le pas sur l'examen des contextes de découverte (voir en particulier les travaux de E. Warmenbol).

La nature et la qualité des objets amenaient toutefois à mettre l'accent sur la fonction cultuelle des lieux (DELAERE et WARMENBOL 2019 ; JASINSKI et WARMENBOL 2017).
Lors de la reprise des fouilles en 2012, la partie profonde du lit de la rivière a été délaissée afin de s'intéresser pour la première fois au talus immergé de la rive gauche de la Lesse. Son intérêt tenait à la présence de nombreux blocs rocheux, dont certains de plusieurs mètres cubes, qui, en constituant un obstacle pour nos prédécesseurs, avaient permis de préserver des niveaux archéologiques. Une fouille stratigraphique présentait l'opportunité de caractériser les périodes de fréquentation de la cavité, tant sur le plan typochronologique qu'en termes d'évolutions du paysage tant d'origine anthropique (aménagements de berge…) que naturelle (effondrements isolés ou liés à des phases sismiques). En revanche, ces blocs posaient des contraintes techniques pour le déroulement de la fouille.

2. Nouvelle approche, nouvelles méthodes

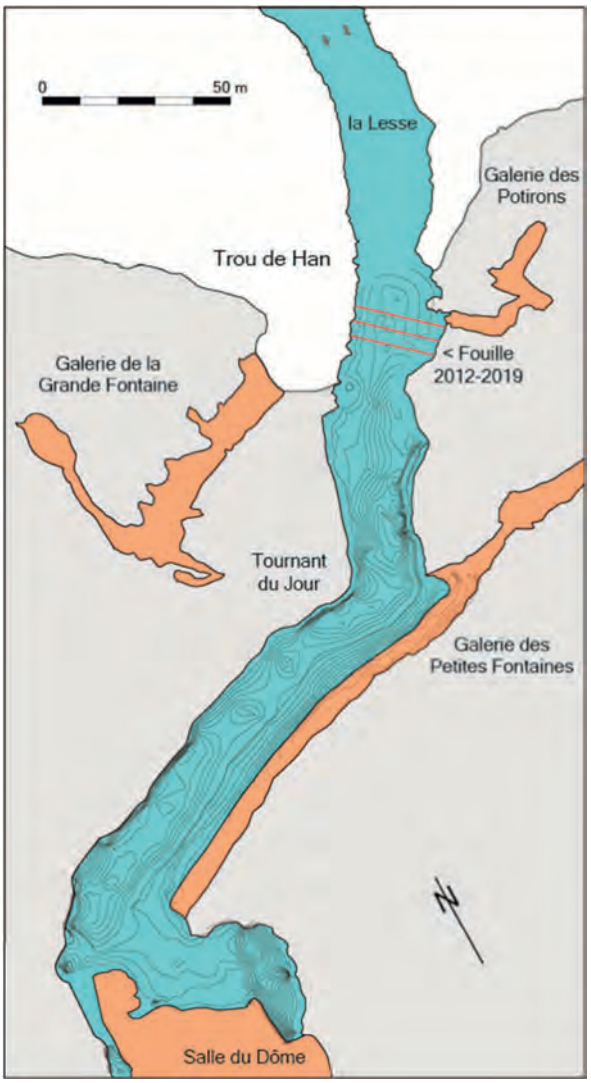

Figure 1 : La résurgence de la Lesse, de la salle du Dôme au Trou de Han (d'après M. Georges et B. Huyghe 1998).

De 2012 à 2014, une première tranchée (T1) de 4 m de large a été implantée en travers de la rivière (Fig. 1). La fouille a été entreprise entre le lit de la rivière et la rive gauche à proximité d'un secteur fouillé de 1978-1983. À l'issue des trois premières années de fouilles (2012-2014), excepté quelques fragments de céramiques protohistoriques découverts au fond de la tranchée, nous avons constaté que la majorité du dépotoir identifié était postérieure au 14e siècle.

La zone devenant trop exiguë pour poursuivre la fouille en sécurité et sans provoquer l'effondrement des coupes, une nouvelle tranchée de 4 m de large (T2) a ensuite été implantée en 2015, directement en amont de la première tranchée. À la fin de la saison 2016, la jonction entre les deux tranchées a été réalisée après la fouille de la berme témoin (DELAERE et ANSIEAU 2019).

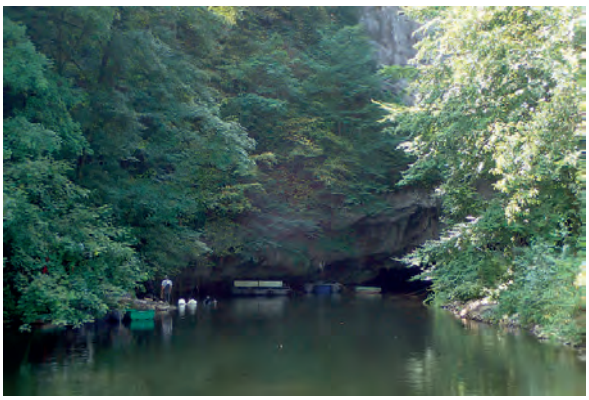

Figure 2 : La fouille au Trou de Han (cliché YB).

Avec les mêmes préoccupations, une nouvelle zone a été ouverte de 2015 à 2018, sur 4 m de large à la jonction entre T1 et T2 pour accéder aux couches profondes. Cela a permis d'atteindre et de documenter pour la première fois en stratigraphie des niveaux protohistoriques. Les vestiges découverts apportent un éclairage nouveau sur ceux issus des fouilles anciennes du *Tournant du jour* (1963-1978) et celles du *Trou de Han* (1978-1983).
La synthèse des observations dans les différentes tranchées permet pour la première fois d'obtenir une séquence stratigraphique des dépôts de la Lesse, couvrant un temps long, de la Protohistoire à la période actuelle (fig. 3).
Si les gros blocs issus d'effondrement du plafond ont permis la préservation des niveaux sous-jacents, ils ont rapidement constitué un risque pour la poursuite de la fouille. En conséquence, depuis 2019 une partie de l'équipe s'emploie à les perforer, éclater et extraire morceau après morceau, en particulier le plus important (dit "pierre n°1" ou "linteau"). Les niveaux sous-jacents ainsi dégagés étant exposés à l'érosion, la fouille a été ciblée sur 9 m² en face et sous le "linteau". Descendue sur 1,1 m sous la base du linteau dans des niveaux sableux et plus ou moins organiques (Fig. 4), elle a ensuite été poursuivie sur une surface restreinte entre de gros blocs (DELAERE et ANSIEAU 2021).

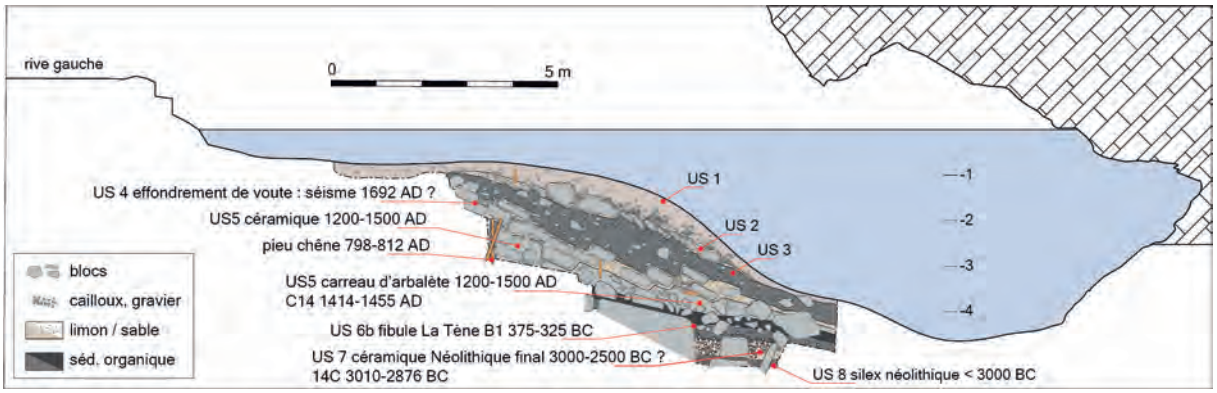

Figure 3 : Coupe transversale du lit de la rivière et aspect général de la séquence sédimentaire (synthèse CD).

3. Des archives sédimentaires préservées

À l'aplomb du front de taille dégagé dans le "linteau", une coupe de 160 cm de hauteur a pu être réalisée, montrant les potentialités du site en termes d'enregistrement sédimentaire. Trois points sont à noter : au sommet, deux nouvelles unités sédimentaires, 4b-i et 4b-ii ; dans la partie médiane, la présence d'un pieu ; à la base, des niveaux protohistoriques (Fig. 4).

US 4b-i : ensemble composite de niveaux peu épais, sable plus ou moins argileux de couleur gris-brun, sable grossier et petits galets (ø 5-7 cm). Léger pendage vers l'amont.

US 4b-ii : très nombreux cailloux et galets dans une matrice de sable. Épaisseur augmentant de 12 à 20 cm vers l'aval. Le niveau vient en recouvrement d'un grand bloc de 70 cm de longueur et de 20 cm d'épaisseur. La poursuite du niveau vers l'aval, au-delà de ce grand bloc, est probable mais reste à confirmer. À la base, le sommet érodé d'un pieu en bois apparait. De section circulaire, son diamètre est de 9 cm.

Cette unité et la précédente viennent s'intercaler dans la séquence reconnue plus près de la rive.

US 5a : niveau de couleur gris sombre constitué de cailloux et de petits blocs calcaires de 10 à 20 cm, dans une matrice indurée de sable et de débris végétaux abondants. Épaisseur de 20 et 30 cm. Traversé par le pieu, lequel présente une inclinaison vers l'amont.

US 5b : au-dessous d'un niveau de sable grossier épais de 5 cm, niveau de sable argileux sombre avec des blocs calcaires hétérométrique, avec des dimensions de 10 à 60 cm. Les débris végétaux sont absents. La base est marquée par la présence de nombreux gravillons et l'apparition du sommet de très gros blocs. Également traversée par le pieu dont la pointe vient buter et se déformer sur un petit bloc. La longueur totale du pieu est de 80 cm.

US 6a : sédiment sablo-limoneux de couleur noir, très organique avec de nombreux débris végétaux. Présence de quelques galets. Dans la partie inférieure, concentration importante de charbons de bois.

US 6b : sédiment sablo-limoneux sombre de couleur cendrée entre de grands blocs. Un fragment de tesson protohistorique a été prélevé *in situ* dans ce niveau.

Signalons également la présence d'une racine d'un arbuste qui pourrait indiquer la présence d'un ancien paléosol à proximité, observation également constatée dans le secteur de fouilles 2018 (mais dans l'US 7). L'US 6b a été datée entre 850 et 50 BC.

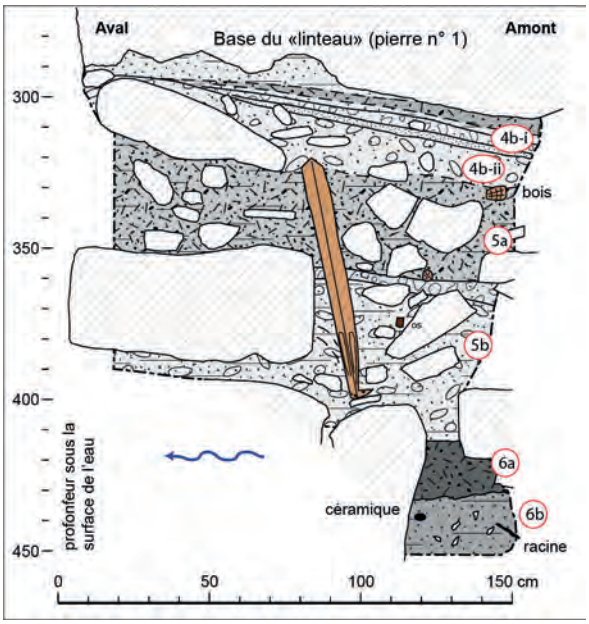

Figure 4 : Coupe stratigraphique à l'aplomb du Linteau

Au total, 2 547 artefacts et écofacts ont été enregistrés, avec 163 fragments de céramique (6,40 %), 998 fragments et concrétions métalliques, principalement du fer (39,18 %), 200 fragments de verre (7,85 %), incluant des verres anciens de teinte orangée, 25 éléments lithiques (0,98 %), 4 fragments de « cuir » (0,16 %) dont une semelle ancienne qui se distingue de celles découvertes dans les niveaux des 17-18e siècles, 205 fragments organiques (8,05 %, majoritairement d'origine naturelle), 883 éléments de faune (34,67 %) et 69 éléments divers (2,71 %), principalement du matériel moderne et intrusif mis au jour durant le nettoyage des sédiments de crues hivernales avant les opérations de fouilles.

4. Quel apport ?

Le "linteau" correspond à une portion de banc calcaire détachée de la voute surplombant la rivière. Il repose dans un niveau ayant livré de la céramique du 16e siècle. La présence dans ce même niveau de nombreux autres blocs dont plusieurs également de grande taille permet d'envisager un écroulement en masse dont le déclenchement pourrait être dû à un événement sismique similaire à celui de 1692 rapporté par la littérature (ALEXANDRE et *al*. 2012).

Le matériel céramique recueilli au-dessous de la base du linteau peut être rapporté à l'époque médiévale par l'étude typologique préliminaire. Les vestiges mérovingiens et carolingiens viennent documenter la culture matérielle de périodes qui étaient encore peu représentées sur le site.

Les études sont en cours mais quelques précisions chronologiques peuvent être apportées sur la séquence sédimentaire.

Dans la partie inférieure de l'unité 4b-ii une balle en plomb de mousquet ou d'arquebuse a été découverte *in situ*. Ce type de balle apparaissant au 14e siècle, il donne une date *post quem* (ou date plancher) pour l'US 4b-ii. La date la plus récente est antérieure au 16e siècle indiqué par le niveau du "linteau".

Étant en chêne, le pieu présent dans la coupe a pu faire l'objet d'une analyse dendrochronologique. La séquence mesurée comporte 62 cernes. Comme il s'agit d'un échantillon isolé, sa datation est plus délicate à assurer. Trois dates sont envisageables, en 824, 1421 et 1820 ap. J.C. (communication de Michel Timperman, 2020). Celle de 1820 ne peut être retenue, le pieu étant scellé par le "linteau", lui-même associé à du mobilier du 16e siècle. La date de 1421 est envisageable mais implique que le pieu a été totalement érodé avant le dépôt de l'US 5a, ce qui, compte tenu du calage chronologique ne laisse qu'un laps de temps court. De plus, ce qui n'apparaît pas sur la coupe, c'est que le pieu passe entre des gros blocs, ce qui était difficile à réaliser "à l'aveugle" depuis le sommet de l'US 5a. Ce qui n'était pas le cas depuis le sommet de l'US 5b. La date de 824 apparaît donc comme la plus probable. Cette hypothèse est confortée par la découverte en 2016, à quelques mètres de distance, d'un autre pieu en chêne pour lequel une date en 812 ap. J.C. a été proposée.

5. Conclusion

Les nouvelles campagnes de fouille dans le cours de la Lesse, menées maintenant depuis près de 10 ans avec une approche stratigraphique, ont permis de documenter pour la première fois la séquence des dépôts, du Néolithique à l'époque actuelle. Des éléments d'interprétation sont apportés sur les transformations naturelles et anthropiques de la grotte de Han.

Récemment, après l'enlèvement partiel d'un très gros bloc effondré de la voûte, un sondage a mis en évidence des niveaux préservés, absents des autres secteurs d'intervention. Les données chronologiques obtenues (étude du mobilier archéologique, datation objective) couvrent la période du 9e au 15e siècle de notre ère. Elles réduisent de moitié une période qui était jusqu'alors considérée comme de faible activité dans la cavité. Ces résultats montrent, si besoin était, les potentialités d'un milieu particulier, généralement délaissé car considéré comme perturbé et érodé par la dynamique fluviale.

Remerciements

Nous remercions la direction et le personnel du Domaine des Grottes de Han, Brigitte Malou, administratrice déléguée de la Société des Grottes ; Michel Timperman, conservateur des collections archéologiques ; Marc Lissoir et ses collaborateurs ; l'Agence Wallonne du Patrimoine, Christian Frébutte, archéologue; Eugène Warmenbol, professeur à l'ULB, Yves Quinif (UMons), ainsi que l'équipe du CRAF, archéologues, plongeurs, conservateurs et techniciens.

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Apports de l'approche intégrée dans l'étude des fréquentations, aménagements et usages passés. Application à Cloggs cave (État de Victoria- Australie)

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Résumé

L'étude de Cloggs cave (Australie) bien que connue de longue date pour ses vestiges paléontologiques (mégafaune) et archéologiques, a été reprise en 2019 compte tenu de la stratigraphie très complexe des dépôts contenant ces témoins. Les nouvelles recherches remettent à plat les connaissances acquises notamment l'association supposée de la mégafaune pléistocène (42000 ans) et des fréquentations humaines du site. Cet article présente quelques-uns des résultats acquis croisant les données archéologiques, géomorphologiques, environnementales et les datations obtenues par AMS, ^{14}C, OSL, et U/TH. L'approche intégrée dans l'étude de Cloggs cave a permis de distinguer différentes périodes de fréquentations humaines de la grotte à partir de 23 530 cal BP, de préciser l'accès à la cavité par les *Old people*, et de mettre en évidence différents aménagements et usages de la grotte par les communautés passées. Entre 2000 et 1600 cal BP, la cavité a été aménagée, régulièrement fréquentée et l'objet d'exploitation de la calcite et de prélèvements à des fins de consommation de papillons de nuit Bogong qui estivaient dans la grotte.

Abstract

Implications of an integrated approach in the analysis of past human occupations, arrangements and uses of Cloggs cave (Australia). The study of Cloggs cave, although known for a long time for its palaeontological (megafauna) and archaeological remains, was resumed in 2019 due to the very complex stratigraphy of the deposits containing these witnesses. The new research revisits the knowledge acquired, in particular the supposed association of the Pleistocene megafauna (42,000 years old) and the human occupation of the site. This article presents some of the results obtained by cross-referencing archaeological, geomorphological and environmental data with AMS, 14C, OSL and U/TH dating. The approach integrated in the Cloggs cave study has made it possible to distinguish different periods of human use of the cave from 23,530 cal BP onwards, to specify access to the cave by Old people, and to highlight different developments and uses of the cave by past communities. Between 2000 and 1600 cal BP, the cave was developed, regularly visited and the object of calcite exploitation and the taking of food from Bogong moths which summered in the cave.

1. Introduction

Cloggs Cave (État de Victoria-Australie) est connue dans la littérature archéologique depuis les travaux de J. Flood qui proposait une survie tardive de la mégafaune (22,900 ± 2000 ans) (Flood 1980) et une coexistence de près de 25 000 ans avec les premières communautés humaines arrivées sur le continent australien. Les causes de l'extinction de la mégafaune ont donné lieu à de nombreux débats dans lesquels le site de *Cloggs cave* apparaît comme un cas de plus en plus isolé. C'est dans ce contexte que l'étude de *Cloggs cave* a été reprise en 2019 à la demande de la *Gunaikurnai Land and Waters Aboriginal Corporation*, représentant les propriétaires traditionnels aborigènes. Les nouveaux travaux ont mobilisé les données géomorphologiques, archéologiques (David et *al*., 2020 ; Delannoy et *al*., 2020 et 2021), un important cortège de datations (AMS ^{14}C, OSL et U/Th - David et *al*., 2021) et des analyses fines des vestiges archéologiques (Stephenson et *al*., 2020). Les données acquises ont été intégrées dans une même et seule chaîne de raisonnement afin de préciser les conditions d'accès à la grotte, de définir les périodes de

fréquentation par les *Old People* ainsi que les différents usages passés. Dans cet article, après une brève description de la cavité, sont essentiellement abordés les aménagements et les usages de la grotte par les communautés passées.

2. Description de *Cloggs Cave*

La grotte s'ouvre à 72 m d'altitude en rive droite de la *Buchan River* entre la localité de Buchan (État de Victoria-Australie) et sa confluence avec la *Snowy river*. Elle surplombe de quelques dizaines de mètres le talweg de la vallée marquée par une succession de méandres encaissés dans les bas plateaux calcaires (200 m d'altitude). Son porche d'entrée et l'escarpement calcaire au-dessus d'un ancien méandre constituent des éléments marquants du relief (Fig.1).

Figure 1 : Porche d'entrée de Cloggs Cave dans l'escarpement calcaire recoupé par un ancien méandre de la Buchan River (Cliché J.J. Delannoy).

Le porche d'entrée (8 m) se réduit fortement pour se raccorder à un conduit de dimension métrique (entrée actuelle) qu'ont emprunté les *Old People* dès leurs premières incursions dans la grotte (20 500-23 000 ans ; David et *al*., 2020). Dès le franchissement de l'entrée, la galerie s'élargit et descend vers la *Main Chamber*)(Fig.2). C'est dans cette salle que J. Flood (1980) a réalisé une profonde excavation archéologique (2m de profondeur qui a été rafraîchie et réétudiée récemment (David et *al*., 2020a). Une fracture de direction NW-SE guide le développement de la galerie principale ; de part et d'autre de la *Main Chamber*, elle se subdivise en deux entités : l'*Upper et Lower Gallery*. Vers le NNW, la *Lower Gallery* bute sur une fissure impénétrable. Vers le SE, la géométrie de l'*Upper Gallery* retient l'attention par la forte pente du talus en direction de *l'Upper Chamber* et sa nature limono-argileuse qui contraste avec la morphologie de la galerie (paroi et plafond d'effondrement). L'*Upper Chamber*, en contrehaut de *l'Upper Gallery,* se caractérise par la sub-horizontalité de son sol. On retrouve ici aussi l'absence de blocs alors que la géométrie de la salle résulte indéniablement de processus gravitaires. Une petite alcôve prolonge vers le NW la petite salle d'*Upper Chamber* ; en cul de sac, basse de plafond et légèrement excentrée, cette alcôve est relativement préservée du cheminement. Elle se caractérise par rapport au reste de la cavité par un abondant concrétionnement où on relève différentes générations stalagmitiques. Au sud-ouest de la *Upper Chamber*, un bas passage accède à l'*Upper Passage*, étroite galerie qui bute rapidement sur un conduit impénétrable. De cette rapide description, il ressort que Cloggs cave est une petite grotte pénétrant très peu dans le massif. Néanmoins, les études archéologiques et paléontologiques en font une cavité de référence des Alpes australiennes pour sa mégafaune et ses vestiges. L'analyse archéo-géomorphologique permet de faire ressortir d'autres valeurs notamment les différents usages et transformations de la grotte au cours de ses fréquentations (Delannoy et *al*., 2020).

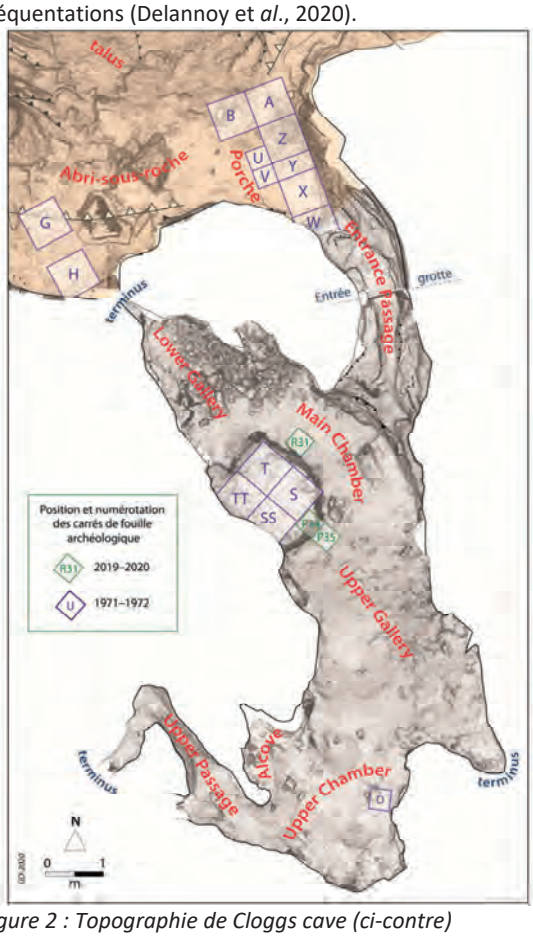

Figure 2 : Topographie de Cloggs cave (ci-contre)

3. Approche intégrée et analyse archéo-géomorphologique

L'étude croisée des données archéologiques et géomorphologiques ont permis (i) de dissocier les phases d'occupation de la grotte par la mégafaune (52 000 ans) et les *Old people* (à partir de 20 000 ans) (Delannoy et *al*., 2020), et (ii) mettre en évidence différentes activités anthropiques. Seul le second volet est ici développé. Il est organisé autour de trois usages : les aménagements de la cavité, les activités d'extraction et de broyage de la calcite et un exemple singulier d'usages traditionnels des grottes par les *Old People*.

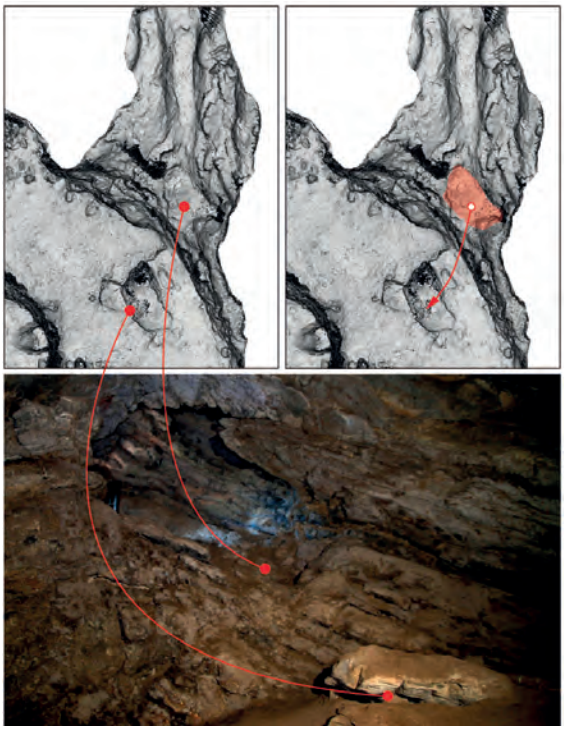

Figure 3 : Blocs déplacés sur le sol en contrebas du ressaut d'accès à la grotte pour faciliter la descente. (J.J. Delannoy)

Figure 4 : Pierre redressée rappelant une silhouette d'oiseau (cliché B. David)

Le relevé géomorphologique à haute résolution spatiale couplée avec les données archéologiques et les résultats des datations a permis de relever trois aménagements de nature très différente. Le premier est lié à l'aménagement de la descente vers la *Main Chamber*. En contrebas du ressaut, deux blocs sont posés sur le talus limono-argileux : ces blocs proviennent du boyau d'entrée où ils ont été délogés, puis déplacés au bas du ressaut afin d'en faciliter la descente. Cet aménagement de la descente est en lien avec les fréquentations de la grotte entre 2400 et 1600 Cal BP si on se réfère aux datations des niveaux archéologiques sur lesquels reposent ces blocs (David et *al*. 2020 ; Delannoy et *al*., 2020) (Fig.3).

Dans ces mêmes horizons, une roche a été retrouvée dont la forme rappelle la silhouette d'un oiseau. Elle a été redressée et maintenue verticalement à l'aide de petites cales rocheuses (David et *al*., 2020) (Fig. 4). La datation des niveaux archéologiques sur lesquels repose la « roche-oiseau » indique qu'elle a été érigée vers 2000 cal BP. Des cendres se sont par la suite accumulées autour ; elles proviennent de différents foyers à proximité de la structure ; leurs datations permettent de rapporter que la « roche-oiseau » était un élément central au sol de la *Main Chamber* et ce pendant au moins 439 ans. L'étude archéologique indique que les foyers se sont succédé durant 18 à 22 générations soulignant ainsi que la grotte a été un espace très fréquenté par les communautés passées.

Un autre secteur aménagé a été mis en évidence : il s'agit de *l'Upper Chamber* et de l'alcôve qui la prolonge (Fig. 5). Au fond de celle-ci, huit blocs sont disposés en un cercle et calés à l'aide de petits éléments rocheux.

Ne provenant pas du plafond concrétionné, l'origine de ces blocs a été recherchée dans la cavité. Au regard de leur taille et de leur épaisseur, ils proviennent d'un petit cône de blocs écroulés sur le remplissage argilo-limoneux de l'*Upper Chamber*, juste en face de l'alcôve. On relève de plus l'absence de quelques blocs sur ce cône au regard des strates effondrées d'un petit surplomb. Compte tenu de ce déplacement intentionnel, les blocs posés à plat au sol entre ces deux espaces constituent des éléments en cours de cheminement (Fig. 5). Au côté de ce cercle de pierre, le sol est recouvert d'une poudre blanchâtre composée de débris calcitiques. L'analyse de ces débris permet d'écarter l'hypothèse d'un encroûtement calcitique qui aurait été involontairement écrasé par le passage de visiteurs. La facture des débris permet de les associer à des stalactites et fistuleuses concassées et broyées en une poudre plus ou moins grossière. Trois arguments appuient cette seconde hypothèse : (i) le bri quasi systématique des stalactites présentes dans cet espace et de ses proches abords ; (ii) l'absence de stalactites cassées au sol et (iii) la présence de meules retrouvées dans les niveaux datés entre 2 100 et 1 600 cal BP et contenant dans les anfractuosités de la poudre de calcite broyée. Ils sont témoins d'actions volontaires de prélèvement et de préparation de calcite par les communautés humaines ayant fréquenté la grotte. Les datations U/Th réalisées sur les stalactites cassées et les repousses ultérieures indiquent que les plus anciens bris volontaires de concrétion remontent à 23 000 ans ; cette action de prélèvement et d'usage de la calcite à des fins médicinales selon les traditions aborigènes s'est poursuivre longtemps si on se réfère aux niveaux archéologiques de la meule contenant de la calcite. Ces niveaux datés de 2 100 à 1 600 cal BP sont contemporains de la structure « roche-oiseau ».

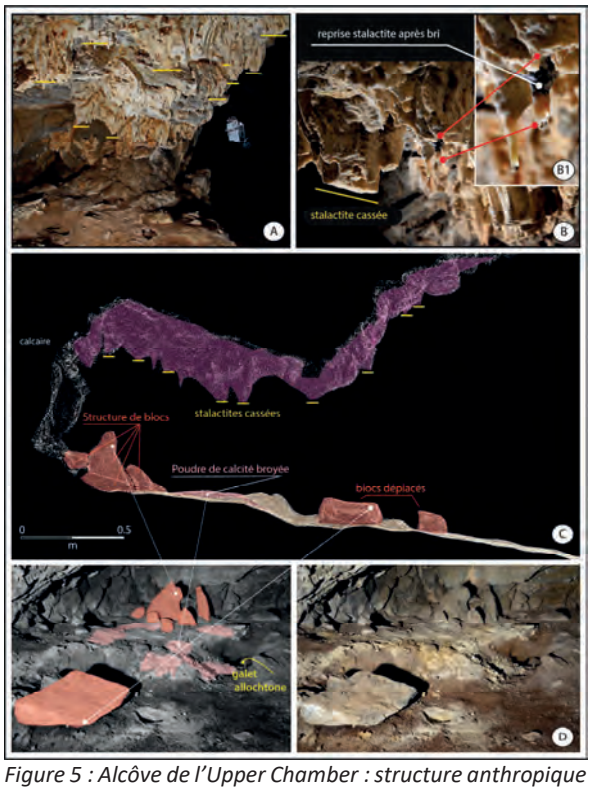

Figure 5 : Alcôve de l'Upper Chamber : structure anthropique et témoins de prélèvements de calcite (J.J. Delannoy)

L'analyse fine des résidus contenus dans les micro-anfractuosités de plusieurs autres meules présentes dans les niveaux archéologiques souligne un autre usage singulier de la cavité par les *Old people* : celle du prélèvement dans la grotte de papillons de nuit en vue d'être consommés (Stephenson et *al*., 2020). L'étude des résidus permet ici de préciser leur préparation : le détachement des ailes et des pattes du reste du corps était facilité par la chauffe de la pierre avant d'être broyés (Fig. 6). Les papillons ainsi broyés étaient associés à des préparations compte tenu de leur très grande teneur en protéines.

Les fragments retrouvés sur les meules de Cloggs cave permettent d'identifier l'espèce prélevée et consommée : les mites Bogong (*Agrotis infusa*). Cette identification fait le lien avec des récits des colons européens qui relataient que, dans les années 1820, les Aborigènes du sud-est de l'Australie récoltaient des papillons de nuit Bogong lors de leurs migrations estivales vers les hautes montagnes. Chaque printemps (septembre), ces papillons descendent vers le sud sur plus de 1000 km. Voyageant de nuit, leur déplacement dure plusieurs jours, voire semaines. Arrivés dans les Alpes australiennes, ils estivent (fin septembre à mars) par centaines de milliers dans les grottes. Si cette pratique était connue dans les périodes historiques, on ne les connaissait pas pour les temps plus anciens, ici entre 1600 et 2000 ans.

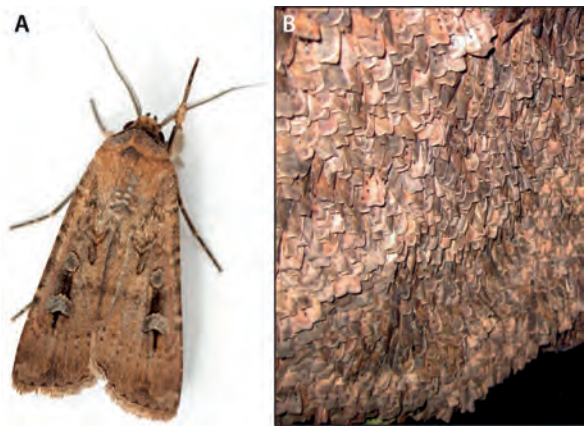

Figure 6 : (A) Mites Bogong (Agrotis infusa)(Cliché A. Narendra). (B) Paroi de grotte couverte de papillons de nuit (cliché E. Warrant).

4. Conclusions

L'étude intégrée de Cloggs cave a été initiée dès les nouvelles recherches entreprises début 2019. Son objectif était de croiser les données issues des différents champs de recherche impliqués afin de répondre aux problématiques d'accès, de fréquentation et d'usages de la grotte par les communautés passées. Cet article présente quelques-uns des résultats acquis autour d'une période comprise entre 2000 et 1600 cal BP durant laquelle la grotte a été aménagée, exploitée pour ses concrétions et visitée saisonnièrement pour prélever et préparer les papillons de nuits Bogong en tant que ressource alimentaire traditionnelle des *Old people.*

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CISAP : Une équipe de l'INRAP spécialisée dans les interventions au sein des structures profondes

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Résumé

L'activité de fouille archéologique amène fréquemment les archéologues à la découverte de structures profondes complexes telles que des puits, des souterrains, des aqueducs voire des mines ou des avens lors de leurs opérations. Ces structures particulières sont généralement difficiles d'accès et présentent un certain nombre de risques qu'il convient de prendre en compte avant d'en réaliser l'étude. L'INRAP (Institut National de Recherches Archéologiques Préventives) a fait le choix, en 2016, de se doter d'une cellule spécialisée dans l'intervention sur ces vestiges singuliers (CISAP). Cette communication a pour objectif de présenter le protocole mis en œuvre pour fouiller ces cavités, qu'elles soient verticales ou horizontales. Elle insistera sur les aspects techniques spécifiques à la sécurisation de la fouille en profondeur, en prenant en compte des risques particuliers liés au travail en hauteur et en espace confiné.

Abstract

CISAP: An INRAP team specialized in interventions on deep structures. Archaeological excavations frequently lead archaeologists to the discovery of complex deep structures such as wells, undergrounds, aqueducts or even mines or sinkholes during field research. These particular remains are generally difficult to access and expose a number of risks that archaeologists must deal with to carry out the study. The INRAP (French National Institute for Preventive Archaeological Research) made the choice, in 2016, to set up a specialized unit in intervention on these unique remains (Cisap). This communication aims to present the protocol implemented to excavate these cavities, whether vertical or horizontal. It will insist on the specific technical aspects of securing deep excavation, taking into account the particular risks associated with working at height and in confined spaces.

1. Introduction

La fouille de structures archéologiques profondes, telles que les puits, les souterrains, les aqueducs, les mines ou encore les cavités naturelles est une opération délicate qui s'inscrit dans un cadre plus large : l'étude d'un site archéologique. Ces structures renferment fréquemment des éléments permettant une meilleure compréhension de l'occupation humaine du site étudié (mobiliers non préservés en surface, éléments organiques propices à une restitution paléo-environnementale…), motivant ainsi la mise en œuvre de moyens pour en faire l'acquisition.

Toutefois, en préalable à la mise en place et à réalisation de la fouille, un certain nombre d'éléments doivent être pris en compte : géologie du terrain d'intervention, accessibilité de la structure, positionnement au sein d'un ensemble de vestiges, déroulement du reste de l'opération sur le chantier.

À ces premiers éléments s'ajoute la considération des risques intrinsèques à la fouille de structures profondes : travail en espace confiné, évacuation des déblais, gestion de l'arrivée d'eau et pompage, *etc*. Ces risques doivent être identifiés en amont et pris en compte pour réaliser la fouille manuelle et exhaustive dans les règles de l'art et le respect de la règlementation en vigueur.

La plateforme utilisée par l'équipe CISAP (Cellule d'intervention sur les structures archéologiques profondes) permet la prise en compte de l'ensemble de ces risques et contraintes, et répond aux dispositions légales en vigueur.

2. La plateforme CISAP – Principes généraux

Depuis 2016, l'INRAP a fait le choix de poursuivre l'activité initiée par Jean-Marc Féménias de l'association ArchéoPuits en faisant l'acquisition d'une plateforme dédiée à la fouille des structures profondes.

Celle-ci consiste en un assemblage de tubes d'échafaudages de 3 m de côté liés entre eux par des colliers de serrage octogonaux, assurant la cohérence de l'ensemble. Ce montage est modulable en fonction de la configuration du terrain et/ou de la structure à fouiller. Une trémie de 1 m de

côté, permettant l'accès entre la surface et la structure, est encadrée par un bâti de treuil destiné à recevoir tous les équipements réglementaires nécessaires à la fouille et supportant une charge de 400 Kg (Fig.1) :

- Treuil électrique sur potence rotative pour la montée et la descente du personnel, ainsi que la sortie des déblais
- Boîtier électrique étanche pour l'alimentation du treuil et la mise en route des différents équipements (ventilation, éclairage, pompage, *etc.*)
- Treuil manuel de secours
- Antichute obligatoire pour les phases de travail en suspension et lors de toute montée / descente du personnel.
- Ligne de vie du fouilleur évoluant en fond de fouille.

Pour compléter ces dispositifs, une ventilation est fixée sous le plancher de la plateforme afin de garantir un apport d'air sain en continu pendant la fouille.

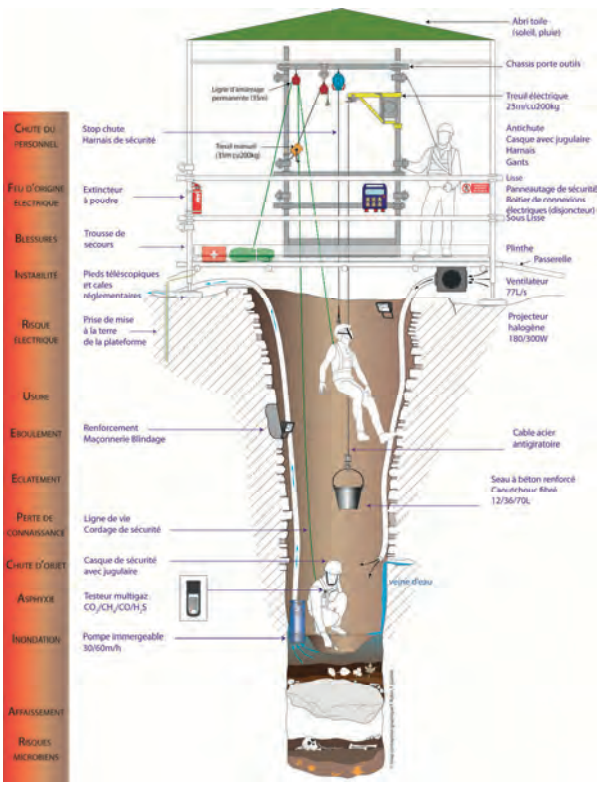

Figure 1 : schéma type d'intervention et de prévention des risques.

L'ensemble de l'installation répond aux procédures réglementaires spécifiques en vigueur. Cette configuration rend par ailleurs possible le travail par un binôme d'agents spécifiquement formés à son utilisation et à l'intervention sur ce genre de structures.

Une fois ces équipements mis en place, et avant toute intervention dans le conduit, une phase de vérification quotidienne du matériel est réalisée. Elle s'accompagne d'un contrôle des EPI (casques et harnais) et d'un test de qualité d'air dans la structure à l'aide d'un détecteur multi-gaz. En effet, les conduits tels que les puits peuvent piéger des gaz dangereux avec plusieurs risques reconnus comme l'intoxication, l'explosion ou l'asphyxie. La réalité du risque nécessite l'équipement permanent du fouilleur d'un détecteur multi-gaz lors du travail dans la structure.
Ces vérifications et mises en place quotidiennes sont consignées dans une fiche spécifique, le « permis de pénétrer ». Ce document, élaboré par l'équipe elle-même, s'inspire de son homologue des égoutiers. Il est signé pour accord par les intervenants avant chaque reprise du travail.

À l'issue de ces indispensables préalables, la phase de fouille peut débuter. Le travail s'organise autour de postes tournants : un treuilliste en surface assure la remontée des seaux et veille à la sécurité du fouilleur en contrôlant à la fois les circonstances de sa progression mais également l'environnement en surface (proximité de personnes, d'engins, météo).

Le fouilleur est exposé à un certain nombre de contraintes potentielles (Fig. 2) :

- Sécurisation de l'excavation en cours et en fin de fouille : contrôle des parois
- Exiguïté : manque de recul, impossibilité de faire des coupes
- Visibilité réduite : problème de caractérisation des couleurs, nuances
- Progression difficile selon la nature des comblements : accumulation de blocs, tassement des argiles, instabilité des sables…
- Arrivée d'eau : complication de la lecture des sédiments, difficulté de prises de vue
- Rapidité d'exécution et continuité : risque accru de déstabilisation du cuvelage une fois vidé

Les déblais évacués sont traités en surface par d'autres archéologues pour récupérer les artéfacts présents dans les sédiments, les matériaux humides faisant l'objet d'un traitement spécifique par tamisage sous l'eau. Un certain nombre de prélèvements paléo-environnementaux (carpologie, palynologie, entomologie, *etc.*) sont par ailleurs directement réalisés par le fouilleur.

Une fois l'excavation vidée de ses comblements, une campagne de clichés généraux et de détails est réalisée visant à documenter le plus précisément possible la structure : nature de la roche, traces de tailles, aménagements dans les parois, morphologie du creusement, arrivée(s) d'eau. L'enregistrement est complété par un relevé manuel du profil et parfois photogrammétrique. L'ensemble de ces travaux est réalisé en suspension ; leur durée nécessite parfois le recours à une sellette afin de répondre au risque du syndrome du harnais.

Le démontage de la plateforme marque la fin de l'intervention. La présence de la cavité nécessite des mesures de sécurité spécifiques, soit par l'obturation de la tête du conduit à l'aide de madriers, soit en conservant le harnachement et les dispositifs antichute.
La désobstruction d'une cavité, quelle qu'elle soit, crée un danger nouveau qu'il est nécessaire de prendre en considération. Des mesures préventives sont proposées et mises en œuvre par l'opérateur de la fouille commanditaire en fonction de la nature et des contraintes du projet d'aménagement : remblaiement intégral ou plus rarement obturation sécurisée en vue d'une remise en fonction de l'ouvrage profond.

Enfin, en mesure de sécurité, la spécificité de ce type d'intervention ajoutée à une forte mobilité géographique ont conduit à réfléchir à la problématique des secours. Un document spécifique est envoyé au centre de secours le plus proche avec les informations nécessaires et une visite sur site est proposée.

Figure 2 : fouille des niveaux humides d'un puits (© P. Georges, Inrap).

3. Acquis et retours d'expérience

Depuis le démarrage de son activité, l'équipe de la CISAP a réalisé près de cinquante interventions sur le territoire national.
La multiplicité des contextes géographiques et géologiques a également permis d'identifier les contraintes spécifiques à chaque milieu et d'anticiper les mesures techniques à mettre en œuvre. Ces paramètres, qui existaient lors de la réalisation de l'ouvrage, trouvent des réponses dans les méthodes de fonçage et de cuvelage adoptées à l'époque.
La quasi-totalité des interventions porte sur des ouvrages dédiés à l'approvisionnement en eau. L'essentiel concerne des puits, les rares exceptions portant sur des regards d'aqueducs, des bassins et une galerie.
Les profondeurs atteintes sont clairement déterminées par le mode de captation de la ressource et sa localisation dans le sous-sol. Si les moyennes sont comprises entre 5 et 12 m, certains exemplaires sont moins profonds, d'autres dépassent les 20 m. Ce paramètre implique le recours à des équipements de fouille et de sécurité adaptés.

L'aménagement des parois n'est pas systématique et dépend de la nature des matériaux encaissant. En surface, les chemisages en pierres sèches côtoient les maçonneries au mortier. Parfois des cuvelages en matériaux périssables sont préservés. Ces derniers se retrouvent en profondeur sous la forme de boisages assemblés à mi-bois destinés à soutenir les élévations (ou construction ?).

Figure 3 : vue depuis la surface d'un puits antique intégralement fouillé selon la méthode utilisée par l'équipe de la CISAP (© J. Dolbois, Inrap)

La désobstruction des conduits, modifiant l'équilibre des forces au sein de l'ouvrage, nécessite une veille constante de la stabilité des parois et l'évaluation du risque. Sa prise en compte peut se traduire par des procédures de renforcement des parois sous la forme de boisages ou reprises de maçonnerie (Fig.4).

Figure 4 : exemple de mise en œuvre de boisage en contexte instable pour garantir la sécurité des parois lors de la fouille (© N. Gryspeirt, Inrap)

4. Conclusion

L'INRAP s'est dotée en 2016 d'une cellule spécialisée dans la fouille des structures profondes. Depuis sa création, l'équipe de la CISAP a réalisé une cinquantaine d'interventions sur l'ensemble du territoire national ; elles concernent en immense majorité des structures verticales, et plus rarement ayant un développement horizontal. L'augmentation du nombre d'opérations témoigne de l'apport scientifique réel à la compréhension des sites archéologiques et leur environnement.

La sécurisation des protocoles d'intervention et la montée en compétences des agents de la CISAP entraîne des sollicitations sur de nouveaux contextes à explorer nécessitant l'acquisition de nouvelles pratiques.

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The HOMME project – *Human Origins in Mozambique and Malawi Environments*: looking for our origin in the Mozambican karst

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Abstract

Mozambique is a crucial area for unravelling our evolutionary history, during the early phases of the Quaternary. Indeed, located at the southern end of the Great Rift between Southern and Eastern Africa, this area plays a key-role in our understanding of the paleobiogeography of fauna documented in the fossil record of East and South Africa. The Human Origins in Mozambique and Malawi Environments – HOMME – project aims to identify evidence of early hominins in this area, which is under-studied as compared to eastern and southern African regions, as well as to characterize the paleoenvironmental contexts in which the genus *Homo* emerged. This paper presents the results obtained during our first field season. We explored various karstic cavities located along the Buzi river and the Cheringoma Plateau (west and north off Beira). Our explorations reveal the potential of the Mozambican karst systems for providing new Plio-Pleistocene paleontological evidence. In particular, we report various endokarstic deposits containing paleontological remains. These promising findings reveal the richness of this area and the fundamental role of the karst in trapping and preserving fossils. Accordingly, this project will certainly fill in a number of gaps in the paleobiogeography and paleobiology of early hominins.

Résumé

Le projet HOMME - Human Origins in Mozambique and Malawi Environments : à la recherche de notre origine dans le karst mozambicain. Enclavé entre l'Afrique australe et l'Afrique de l'Est, le Mozambique est un secteur essentiel à la compréhension de notre histoire évolutive et ce en particulier pour les phases anciennes du Quaternaire, entre 2,6 et 2 Ma. Le Mozambique, par sa situation géographique comprenant la partie terminale du Grand Rift, apparaît comme la clef des problématiques paléobiogéographiques entre les deux grandes aires est- et sud-africaines. Le projet HOMME – Human Origins in Mozambic and Malawi Environments – vise à identifier, dans ce secteur encore trop peu étudié, les traces du passage des Homininés anciens (Australopithécinés et premiers *Homo*) ou, tout du moins, à caractériser les paléoenvironements au sein desquels ils ont pu évoluer. Nous présentons ici les premiers résultats de nos premières campagnes de terrain. L'exploration de plusieurs cavités karstiques, à l'ouest (secteur de la Buzi River) et au nord (secteur de Cheringoma Plateau) de la ville de Beira, nous a permis de reconnaître l'importance et les potentialités archéo-paléontologiques des réseaux karstiques mozambicains. Des reliques de brèches endokarstiques riches en matériel paléontologique (dont porc-épic, hyène, phacochère) ont d'ailleurs été identifiées. À l'issu de cette campagne, le matériel osseux et la présence de brèches fossilifères laissent entrevoir la richesse du secteur qui nous permettra, à terme, de combler nombre de lacunes concernant la paléobiogéographie des Homininés anciens.

1. Introduction

For decades, the Great East African Rift has been considered the cradle of humankind. Indeed, it has delivered numerous fossils and stone tools of ancient hominins, covering the emergence of *Homo* genus, in addition to the oldest *Australopithecus*. Equally important is another area located in South Africa, that can also claim to be a cradle of humankind. Here, over the last 80 years, a large number of fossils of *Australopithecus*, *Paranthropus* and *Homo* and stone tool artefacts have been found in palaeokarsts, 50 km Northwest of Johannesburg. However, complications with dating the fossils and artifacts have led most to believe the South African cradle fossils are significantly younger than those in East Africa, limiting the awareness of the potential antiquity of this area's fossils.

Very recently, the dating of the almost complete *Australopithecus,* nicknamed 'Little Foot', produced an age of 3.67 Ma. This date, supported by other stratigraphic and faunal evidence, demonstrated that South Africa has a

hominin fossil record almost as old as East Africa, placing it in an ideal time period to yield the earliest evidence of the evolution of the genus *Homo*. If we consider that in both cases, the hominin fossils and artifacts are preserved in geological traps (i.e., the rift valley and the caves), what about the rest of Africa? Shouldn't we consider the whole of Africa as a potential cradle of humankind, with fossils preserved in natural sediment traps all over the continent?

On this idea, an interdisciplinary team built the Human Origins in Mozambique and Malawi Environments project to search for fossil sites in the karsts that surround the southern end of the Great East African Rift. This geomorphologically promising region provides an opportunity to link the Great East African rift sites of East Africa and the karst sites of South Africa.

2. Materials et methods

During the survey mission of the HOMME project in 2019, we explored several karstic cavities distributed on two distinct areas, around the Buzi River on the one hand and on the Cheringoma Plateau on the other. Our vision of the archeo-fauna has been built around two complementary aspects. First it was necessary to recognize the elements of breccia that were preserved and containing bone material. A first *in situ* examination has allowed a preliminary identification. Then, whenever possible, the reworked paleontological material (the material naturally extracted from the eroded breccia) has been analyzed more in details (osteology, morphometry) in order to define the taxonomic attribution of these specimens.
The different paleontological series presented here come from two distinct cavities (fig.1): Dimba 2, along the Buzi River, and Ninga Miriango in the Cheringoma Plateau area. These two sites yielded samples from ancient phases of the Quaternary. We hereby present the preliminary results of our paleontological approach regarding the different areas visited and the knowledge brought to the Plio-Quaternary Mozambican's context on one side and more generally in the frame of the relations between these two eastern and southern African wide areas.

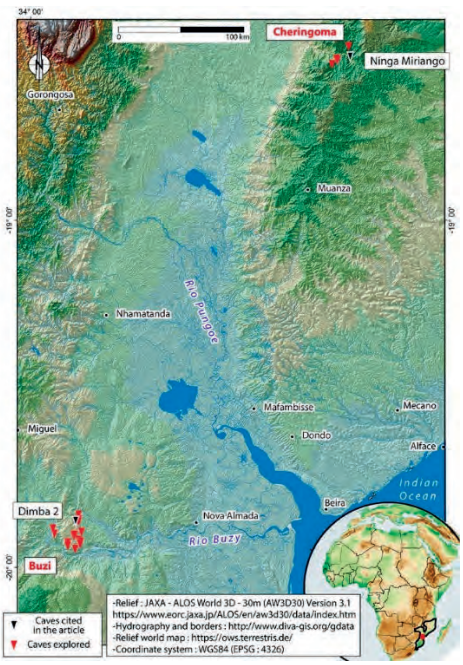

Figure 1: Location of the explored cave sites.

3. Résultats

3.1. Dimba 2 (Buzi river area)

Dimba 2 cavity is located near the city of Estaquinha in the Sofala Province, along the Buzi River (100 kilometers west of Beira). During the survey, material was found in two areas: the South Junction and the Aval Diverticulum.
Within the Aval Diverticulum, we saw and collected a lot of odontoskeletal material. These remains, spread on the surface (and not encased in a hardened breccia matrix) seem to represent two different events. Part of the fauna seems quite recent and could result from the current activities of the local fauna. The other part grabbed our attention. The specimens exhibit a patina that appears to be ancient, with some degree of fossilization and smooth bone surfaces indicating that they have been transported by flowing water. Among these apparently "ancient" elements, we found warthog teeth (n=8), a baboon tooth and a hyena mandible (cf. *Crocuta*; fig.2).
The South Junction is also interesting. The remains of the South Junction are still in a primary position in a breccia matrix. At least three taxonomic groups can be recognized: porcupines, suidae and equidae.

Figure 2: Hyena mandible from Dimba 2. Photo. A. Beaudet.

A fragment of mandible shows the typical morphological traits of a large-sized rodent attesting of the presence of a porcupine. Unfortunately, since the specimen was not extracted from the breccia, it is not possible to establish a more precise diagnosis. We thus attribute it to the Hystricidae, likely to the genus *Hystrix*.
A mandible fragment bearing a molar (m3?) attests to the presence of a suid. The specimen was not extracted during our survey. The tooth that is visible exhibits a high degree of

hypsodonty, excluding an attribution to *Potamochoerus*. Such degree of hypsodonty is typical of the *Metridiochoerus-Phacochoerus* lineage. In absence of more morphological data, this specimen can be attributed to either *Metridiochoerus* or *Phacochoerus.*
Finally, a maxillary molar and a fragment of premolar/molar still encased in the breccia indicate the presence of an equid (the family of horses, zebras, donkeys). At the moment, it is not possible to establish if the specimens belong to a single individual or more. It could be attributed to a large equid (genus *Equus*/*Eurygnathohippus*).

3.2. Ninga Miriango (Cheringoma plateau)

Ninga Miriango is a long cave (about 600 m long; see LAUMANNS 1998), located near Codzo. Survey in this cave was limited by the presence of large bat colonies of several thousands of individuals. Our observations were mostly limited to the entrance, representing a survey area of 40-50 m. The preliminary observations are indicative of the paleontological potential. It was possible to detect some breccias. Some of the breccia holding fossil material is attached to the walls of the cavity (at a height of 1.60-1.80 m from the ground). Together with the fossils contained in the hard breccia, there are also some large charcoal fragments (of cm size). The main question regards the contemporaneity of these charcoals with the fossils since the deposits are scattered, as well as with a second deposit found close (at around 5 m from the wall breccia) which deposit represents a remaining mount of sediment accumulation, hardened and containing large pieces of rock. The exposed paleontological material is scarce but brings useful information to reconstruct the sedimentary history and the chronology of the deposits.
It is noteworthy that, together with a vertebra of a large bovid, a well-preserved sub-complete suid mandible has been found and is compatible with an attribution to the warthog *Phacochoerus* or to the ancestral form *Metridiochoerus* (fig.3). The specimen is broken in four parts. The symphysis (anterior area of the mandible where the incisors and canines are inserted) is partially preserved. The mandibular bodies, right and left, still bear second and third molars. The first molars are lost post-mortem, the socket of the right one being filled by sediment. The occlusal surfaces of the preserved molars show advanced wear; the cusps are heavily worn, showing large enamel islands, in particular on the third molars. The overall morphology and the dental formula (0p / 3m) are typical of warthogs (and of all the calde relatives). A more detailed morphometric analysis should be undertaken to clarify the taxonomic attribution of this specimen. In the meantime, we attribute it to the *Metridiochoerus-Phacochoerus* lineage.

Figure 3: Suid mandibule (Metridiochoerus/Phacochoerus) from Ninga Miriango. Photo. A. Beaudet.

4. Bio-chronological implications

The paleontological remains that were discovered during the 2019 expedition are promising for the future. Establishing a chronological frame was one of the aims and the taxonomic identification of the uncovered fossil remains opens toward several hypotheses.
Regarding the suids, the oldest fossils attributed to *Phacochoerus* come from the Shungura Formation Mb. C in Ethiopia, toward 2.8-2.5 Ma (SOURON 2012). The recent species *Ph. africanus* is quite frequent in the South African Late Pleistocene sediments (AVERY 2019). It is noteworthy that the presence of *Ph. antiquus* was reported in the Early Pleistocene site of Gladysvale, as well as at Sterkfontein and Swartkrans (review in AVERY 2019). *Ph. antiquus* appears to represent an intermediate morph between the ancestral species *M. modestus* (found between 2.2 and 0.7 Ma) and the modern taxa of *Phacochoerus* (SOURON 2012). Concerning material from Dimba 2, it seems very similar to *Phacochoerus*, but a detailed analysis will be needed to exclude the hypothesis that it could belong to the older genus *Metridiochoerus,* known to have existed between the Pliocene and the Pleistocene. While there is a clear phyletic relationship between *Metridiochoerus* and *Phacochoerus*, the evolutionary history of the two genera remains to be elucidated further (SOURON 2012). *M. modestus* is one of the most recent species of *Metridiochoerus* and is recorded in all the African continent between 2.2 and 0.7 Ma, thus limiting its biochronological value. Conversely, earlier forms of *Metridiochoerus* enable establishing the *terminus ante quem* of a fossil assemblage. It is the case of *M. andrewsi* that is found in Malawi (Chiwondo Beds) and South Africa (Makapansgat), disappearing just after 2 Ma, succeeded by other species (TURNER & ANTÓN 2004; BISHOP 2010).
The discovery of porcupine remains in the breccia at the South Junction from Dimba 2 is of interest. The oldest occurrence of *Hystrix* in southern Africa dates to the Pliocene of Langebaanweg (HENDEY, 1984) and Makapansgat (DE GRAAFF 1960). Even if the phylogeny of porcupines remains a matter of contention, the South African Pliocene species *H. makapanensis* (= syn. *H. major*) precede the Early Pleistocene taxon *H. africaeaustralis*. It is noteworthy that the large-sized porcupine *Xenohystrix crassidens* is recorded in the Pliocene sediments of Makapansgat, likely related to the lineage of the crested porcupine *H. cristata*, currently absent from southern

African environments (GREENWOOD 1955). Porcupines are major accumulators of bones in caves and are known for their ossiphageous behavior in both extant and fossil taxa (BRAIN 1981). In fact, porcupines collect bones in the environment or from assemblages accumulated by carnivores (e.g., hyena) and bring them in caves, creating accumulations of odontoskeletal remains. Studying such accumulations made by porcupines allows reconstructing paleoenvironments in details.

For the equids, the identification of species is critical, especially when searching for ancient paleontological assemblages, about the Neogene-Quaternary boundary. There is a consensus regarding the first occurrence of *Equus* (from the Equinini tribe, representing real horse) in Africa around 2 Ma. *E. capensis*, a large-sized horse, seems to appear in South Africa only after this date and persists until the end of the Pleistocene. Before 2 Ma, only members of the Hipparionini tribe (archaic horses) are recognized in southern Africa. Two species of *Eurygnathohippus* are identified in South Africa: *Eu. hooijeri* from the Pliocene of Langebaanweg (BERNOR & KAISER 2006) and *Eu. cornelianus*, that appears around the Neogene-Quaternary boundary and persists until the Middle Pleistocene, about 500 ka (BERNOR *et al*. 2010). The detailed study of the tooth from Dimba 2 should be done in order to characterize the taxonomic affinity.

5. Conclusions and perspectives

Paleontological potential of the karstic cavities of the Buzi River and Cheringoma Plateau has been confirmed by the 2019 expedition. Dimba 2 shows the high potential for fossil discoveries. While it accumulates the remains of at least three taxa (from the South Junction breccia) on a limited exposed surface, the identification of these taxa can bring relevant information regarding the chronology of the sedimentary filling:

i) for the suid, the identification at the genus level.

ii) from a taphonomic point of view, the role of porcupines in the accumulation should be elucidated; the phyletic relationship between *H. makapanensis* and *H. africaeaustralis* should be questioned.

iii) the equids represent the third element whose study could help understanding the chronological frame.

It is the association of the three identified taxa that will enable assessing the age of the Dimba 2 assemblage to the Neogene-Quaternary boundary. In parallel, the specimens from Ninga Miriango confirm the high potential for the recovery of ancient fauna from Mozambique. These expeditions of the HOMME project open toward promising prospects setting the bases for solid research and revealed promising perspectives, either for fieldwork or for the analysis of new fossil specimens.

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Grotte preistoriche e catasto in Campania: analisi preliminare per la classificazione tipologica delle cavità

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Riassunto

La Campania è una regione del Sud Italia che presenta molte cavità naturali in cui si registra un'evidenza archeologica databile al periodo preistorico. Lo studio di questi contesti non può prescindere dalla collaborazione tra le discipline dell'archeologia e della speleologia. Il presente contributo, infatti, si inserisce in uno studio più ampio, oggetto di una tesi di dottorato in corso, il cui obiettivo è indagare per la prima volta la relazione esitente tra le grotte e il paesaggio antico. Il problema affrontato in questa sede è il tentativo di normalizzazione dei termini e delle nozioni relative alle cavità sia in ambito speleologico che archeologico. In quest'ultimo campo, questo aspetto è utile alla definizione e alla comprensione delle forme di occupazione in grotta. Lo studio è stato condotto su un campione di cavità sinora note del comprensorio salernitano, ubicate sui Monti Alburni, Monti Picentini, Monte Cervati e Basso Cilento. Sono stati presi in considerazione i fattori morfometrici delle cavità (apertura, altezza, profondità) ed è stato evidenziato il rapporto tra questi e lo spazio interessato direttamente dalla frequentazione antropica. Sono illustrati i risultati preliminari del metodo che ha permesso di eleborare una prima classificazione delle cavità differenziate in riparo, caverna e grotta.

Abstract

Prehistoric caves and cadastre in Campania: preliminary analysis for the typological classification of cavities. Campania is a region in southern Italy with many natural cavities in which there is archaeological evidence dating to prehistoric times. The study of these contexts cannot ignore the collaboration between the disciplines of archaeology and speleology. This paper is a part of a topic of PhD thesis, which aims to investigate for the first time the relationship between caves and the ancient landscape. In this paper I explore the possibilty to normalise terms and notions related to caves in both speleological and archaeological contexts. In this field, this aspect is useful to definite and understand the forms of antropic occupation in the caves. The study focuses on a sample of known cavities in the Salerno area, located on the Alburni, Cervati and Basso Cilento mountains. The morphometric factors of the cavities (opening, height, depth) were considered and the relationship between these factors and the antropic settlement. I will illustrate the preliminary results of this method: a classification of the cavities divided into shelter, cavern and cave.

1. Introduzione

La Campania è tra le regioni italiane con il maggior numero di grotte. Si contano 1090 cavità terrestri, 159 marine e 58 subacquee (Dati Catasto Grotte Campania). Il Catasto regionale, nato in seno al Gruppo speleologico Club alpino italiano, sezione di Napoli, è gestito dal 1998 dalla Federazione speleologica campana (RUSSO *et al* 2005). Molte di queste grotte presentano un interesse archeologico dalla preistoria all'età medievale. In questa sede saranno esaminati i siti caratterizzati da una frequentazione di età preistorica e protostorica. Il rapporto tra speleologia e archeologia, due discipline diverse ma profondamente complementari per lo studio di contesti archeologici in grotta, non ha sempre raggiunto risultati felici, incidendo spesso sulla bontà delle indagini archeologiche. Se è vero che molti siti sono stati scoperti grazie alla ricerca speleologica, è anche vero che spesso il mancato coinvolgimento tempestivo di archeologi ha comportato l'irrimediabile perdita e lettura del deposito. È, dunque, auspicabile, una linea di ricerca che si avvalga delle competenze di entrambe le discipline, a vantaggio della conoscenza del territorio (VENTURINO GAMBARI 2011). Il problema affrontato in questa sede e che costituisce anche una delle criticità è il tentativo di normalizzazione terminologica e classificazione delle nozioni, in relazione alla morfologia delle cavità (grotta, caverna, riparo), un aspetto importante in campo archeologico per la definizione e la natura delle forme di occupazione antropica in grotta.

2. Materiali e Metodi

Lo studio ha preso in esame un campione di 39 grotte con evidenza archeologica, ubicate sul Massiccio degli Alburni (14), Basso Cilento (20), Monte Cervati (5) e Monti Picentini (1). In questa zona, a causa della sua natura geologica, si rileva il 90% dei siti in grotta sinora identificati (Fig. 1). Sono state considerate le cavità in cui si registra una frequentazione estesa dal Paleolitico Medio (200.000 BP) fino all'età del Ferro (950 a.c.). Si è proceduto in primo luogo, all'individuazione dei contesti ascrivibili agli orizzonti cronologici in esame, in base all'incrocio dei dati disponibili in letteratura e in alcuni casi all'esame congiunto del materiale archeologico. Si è così ottenuta una scheda che contempla la descrizione del deposito archeologico oltre ai dati di natura geologica disponibili nel catasto grotte.

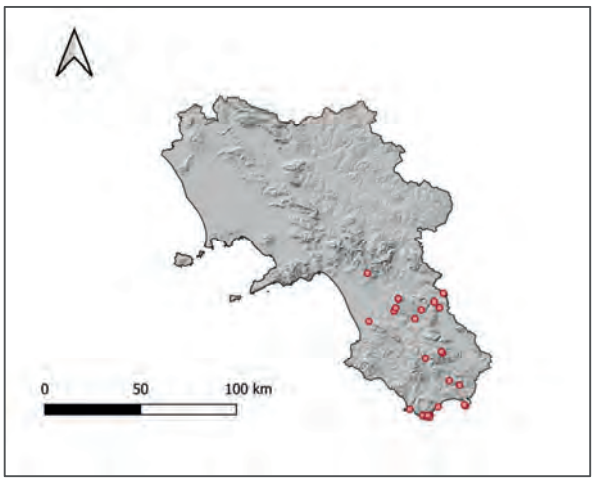

Figura 1: Distribuzione areale delle cavità con evidenza archeologica preistorica e protostorica

In secondo luogo, è stata effettuata l'analisi dei dati morfometrici delle grotte: andamento, natura, quota, sviluppo planimetrico, profondità. Nella scheda catastale esistente, il parametro morfometrico dell'andamento si distingue in tre categorie: orizzontale, sub-orizzontale e verticale.

Per quanto riguarda il campione qui analizzato, si osservano i seguenti dati nelle rispettive aree carsiche. Per l'area del Massiccio degli Alburni risultano 7 cavità ad andamento orizzontale e 7 con andamento sub-orizzontale. Sul Monte Cervati, 2 risultano con andamento orizzontale e 3 sub-orizzontale, sui Picentini 1 sub-orizzontale. Nell'area del Basso Cilento, 10 sono le cavità con andamento orizzontale e 9 sub-orizzontali. Rispetto alla natura di queste cavità, quelle ad andamento orizzontale risultano tutte terrestri tranne in due casi, si tratta di due cavità marine nell'area del Basso Cilento. Per quelle ad andamento sub-orizzontale si registra una sola cavità marina nella stessa area. Per quanto riguarda le quote, queste sono espresse in valori assoluti sul livello del mare attuale. Sul totale delle grotte che si aprono sulle tre aree, la quota massima registrata è sul monte Cervati a 1151 m s.l.m, il valore minimo è invece attestato nella zona del Basso Cilento, dove si contano 11 cavità con valori di quota compresi tra 0 > 6 m. sl.m. (Dati Catasto Grotte Campania).

Per quanto attiene lo sviluppo planimetrico, questo parametro è espresso in metri e ne riporta l'intera estensione nota. Sono stati poi esaminati 22 rilievi delle cavità del campione. (Dati Catasto Grotte Campania). Nell'esame dei rilievi è stato preso in considerazione il dato morfometrico totale, questo è stato confrontato con la parte recante effettive tracce di occupazione antropica desunta dai dati bibliografici e di archivio. La tipologia è stata condotta, elaborando uno schema del rapporto tra sviluppo totale e parte direttamente antropizzata.

Per la distinzione delle tre categorie del riparo, della caverna e della grotta sono stati considerati tre parametri: la larghezza e l'altezza dell'apertura ricavata dai rilievi, la profondità e la porzione occupata dello sviluppo planimetrico totale).

Si è tentato di definire le tre categorie analizzando il rapporto tra le tre dimensioni. Se una delle dimensioni o entrambe (larghezza o altezza dell'apertura) risultano prevalenti, la cavità è definita come riparo; se il rapporto tra le due dimensioni è vicino a 1, sarà definita come caverna; la grotta, è invece, definita tale se la dimensione prevalente è la profondità.

3. Risultati

Dall'incrocio dei dati archeologici è stato possibile aggiungere al catasto speleologico una cavità non risultante per le aree prese in esame (Grotta del Pino, Sassano). L'applicazione del metodo empirico, basato sul rapporto delle tre dimensioni ha permesso di individuare sul campione di 22 cavità: 5 ripari, 9 caverne e 8 grotte. (Fig. 2). Per la categoria del riparo il rapporto tra la larghezza dell'apertura e l'latezza comprende i seguenti valori: $1.5 \leq x \leq 3.3$; la categoria della caverna ricade in questo intervallo: $1 \leq x \leq 1.6$; e la grotta comprende valori compresi tra $0.3 \leq x \leq 2$ (Fig. 3). Si è tentato un primo approccio di definizione puntuale per le tre categorie: occorre precisare che molte cavità conservano nel toponimo l'appellativo di «grotta» talvolta risalente al momento della scoperta. In rari casi, laddove è evidente una chiara evidenza geologica descritta come «scavernamento» la cavità ha assunto la connotazione di riparo come nel caso del Riparo del Poggio a Marina di Camerota. Come si evince dalle sequenze disponibili per Castelcivita (GAMBASSINI, 1997) e Riparo del Poggio (AA.VV. 1996), queste risultano frequentate dal Paleolitico Medio (ca 200.000-150.000) al Paleolitico Superiore (ca 40.000). Frequentazioni più tarde sono attestate a Riparo dello Zachito, con fasi dell'età del Bronzo Medio, fasi 2-3 (1400-1300 a.c.) e probabilmente un orizzonte più tardo ascrivibile all'età del Ferro (D'AGOSTINO, 1981). Va inoltre fatta un'ulteriore precisazione valida anche per le caverne. Come già esplicitato, è stata presa in considerazione la parte effettivamente interessata da attività antropica. Dunque, per cavità come le Grotte di Castelcivita che presentano uno sviluppo planimetrico di 5 km e che risultano essere la cavità

più lunga in tutta la Campania, la frequentazione è attestata nella parte iniziale, la cosidetta «antegrotta» (in questo caso, inoltre, bisogna tener conto dei lavori di sbancamento dovuti all'installazione dell'impianto turistico tra gli anni '20 e '30 del secolo scorso, lavori che hanno indubbiamente alterato lo stato originario dei luoghi). Un altro caso esemplificativo è quello di Grotta Pertosa (LAROCCA 2017), che reca uno sviluppo planimetrico di 3 km ma l'area occupata risulta essere la sala di ingresso lunga ca 100 metri. Le caverne individuate risulterebbero frequentate nel Paleolitico Superiore fino al Neolitico come la Grotta della Serratura, Marina di Camerota (MARTINI, 1993). Un'importante sequenza stratigrafica che copre un range cronologico dal Paleolitico medio all'Età del Rame è attestata nella grotta della Cala nello stesso comune (MARTINI *et al.* 2018). Nella zona più interna della Campania, i dati finora noti, circa la frequentazione delle caverne sono più abbondanti a partire dal Neolitico e poi nell'età del rame (Grotta dell'Ausino a Castelcivita (PICIOCCHI, 1972), e il riparo di San Michele a Sant'Angelo a Fasanella (AURINO 2013). Una più incisiva frequentazione si registra per l'età del Bronzo Medio nella Grotta del Tavaniello e San Michele a Olevano sul Tusciano (PICIOCCHI, 1973). La Grotta di Pertosa ha restituito esigue tracce di una frequentazione databile al Neolitico finale, evidenzierebbe, invece, una documentazione archeologica più abbondante per il periodo dal Bronzo Medio 2 all'età del Ferro (FUSCONE 2015, LAROCCA 2017). Tra le cavità classificabili come «grotte», sia scrive quella di Polla, che ha restituito un cospicuo deposito databile dal Neolitico (D'AGOSTINO, 1981) all'età del Bronzo. (DI LORENZO *et al.* 2017*).*

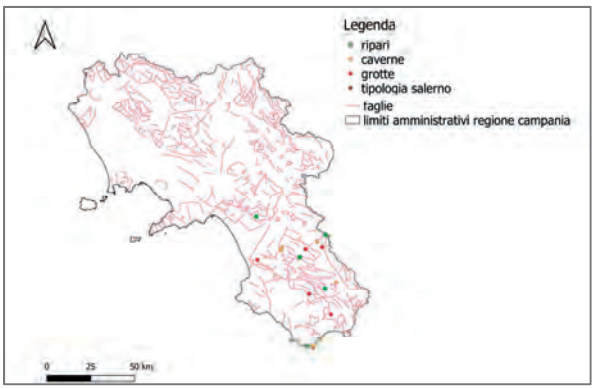

Figura 2: Tipologia delle cavità distribuite nelle tre aree carische.

4. Discussione

La disamina presentata lascia alcuni problemi aperti. Si precisa che il lavoro è ancora in corso e questo costituisce un primo tentativo di analisi in base ai dati disponibili e finora reperiti. Inoltre, si ricorda che il catasto aderisce alle linee guida definite dalla Società Speleologica Italiana nel 1993. In base a questi standard e criteri una cavità è registrata a catasto se presenta uno sviluppo planimetrico di almeno 5 metri. Inoltre, il rapporto tra lo sviluppo spaziale e le dimensioni dell'ingresso deve essere maggiore di 1. Secondo questo criterio una cavità profonda 20 m e con ingresso ampio 20 m non viene accatastata. Questo criterio viene eccepito nel caso in cui una cavità presenti un interesse storico, archeologico e scientifico. (RUSSO *et al.* 2005). Tuttavia, queste caratteristiche non sono spesso di immediata lettura e quindi facilmente individuabili, soprattuto se si considera il fatto che non tutti gli speleologi possiedono competenze archeologiche così come non tutti gli archeologi possiedono competenze e attitudini alla esplorazione delle grotte. La proposta di classificazione qui esposta, per tentare di normalizzare la terminologia, è utile ai fini della definizione delle funzioni attribuite alle cavità in chiave diacronica. Si ribadisce che lo studio è in corso anche per definire tali relazioni. Inoltre, c'è da considerare, nei fattori di criticità, il fatto che il lemma «riparo» rispetto a quelli di caverna e grotta sembrerebbe già possedere intrinsecamente una pregnanza semantica riferibile a una funzione, appunto di riparo, con un'allusione all'uso "domestico" dello spazio formatosi geologicamente.
Un ulteriore fattore di criticità nella definizione delle classi è anche rappresentato dall'illuminazione delle superfici esposte e se questo possa essere considerato un criterio aggiuntivo nella definizione delle classi. Nella fattispecie dei ripari la superficie esposta è quasi totalmente illuminata dalla luce esterna, nelle caverne l'illuminazione è parziale, assente nelle grotte.

id	sito	area	sv.pl.	prof	largh.	h	sp. occ.	crono	sp/h	tipo
1	grotta di castelcivita	alb	5400	-33	15.0	15.0	12	PM-PS	1.6	cav
2	grotta san giovanni a piro	bc	85	4	20.0	13.0	41	PM	1.5	cav
3	grotta degli iscolelli	bc	93	-50	27.5	20.0	20	PI	1.3	cav
4	grotta dell'ausino	alb	362	20	8.0	5.0	12	N, E, BM, BF	1.2	cav
5	grotta della cala	bc	41	0	21.0	18.0	41	PM, PS,M,N , E	1.2	cav
6	grotta di pertosa	alb	3300	46	24.0	24.0	100	N, BM, BT,PF	1.0	cav
7	grotta del pino	cer	20	-5	10.0	10.0	20	E, BA,BM	1.0	cav
8	grotta degli infreschi	bc	86	0	4.5	4.0	26	PM	1.1	cav
9	grotta di fra' liberto	alb	13	9	9.0	9.0	9	N	1.0	cav
10	grotta di polla	alb	1010	-88	12.0	6.0	110	N, E, BM	2.0	gr
11	grotta della serratura	bc	77	3	12.0	15.0	77	PS,M, N	0.8	gr
12	grotta di fraulusi	cer	83	30	10.0	12.5	83	BM	0.8	gr
13	grotta III del tavaniello	bc	9	0	1.3	2.0	9	BM	0.7	gr
14	grotta della madonna del granato	cer	12	1	1.0	1.5	2	BM, BT, PF	0.5	gr
15	grotta del noglio	bc	76	0	7.5	12.0	50	PS, BM	0.6	gr
16	grotta dei cocci del pittari	bc	130	14	0.9	1.0	35	BM	0.3	gr
17	grotta della faccia di bronzo	alb	26	11	1.0	4.2	4	BM	0.3	gr
18	grotta del poggio	bc	11	0	5.0	1.5	5	PI,PM,PS, E, BM	3.3	rip
19	grotta nardantuono	pic	130	22	28.0	10.0	65	E, BM	2.8	rip
20	grotta a sud dei vallicelli	cer	74	-5	12.5	5.0	6	PM-BM	2.5	rip
21	grotta della zachito	alb	7	0	25.5	12.2	10	BM, PF	2.0	rip
22	grotta di san michele a fasanella	alb	100	0	22.0	14.4	7	E,BM	1.5	rip

Figura 3: abbr. aree carsiche (alb =alburni, bc=basso cilento, pic=picentini, cer=cervat). S. pl. =sviluppon planimetrico espresos in mt; prof.= profondità; largh. = larghezza apertura; h= altezza apertura; sp. Occ. = spazio occupato da evidenza antropica espresso in mt risppoetto allo sv. pl.; crono = cronologia frequentazione (PI = Paleolitico Inferiore; PM= Paleolitico Medio; PS = Paleolitico superiore; M= Mesolitico; N= Neolitico; E= Eneolitico; BM= Bronzo Medio; BT= Bronzo Tardo; PF= primo Ferro. Ap/h= rapporto tra larghezza apertura e altezza; Cav= caverna; rip= riparo; gr= grotta.

5. Conclusioni

Considerato che l'intento è stato quello di cercare di avanzare una preliminare analisi di differenziazione tra le cavità prendendo in esame le caratteristiche morfometriche e prettamente geologiche e lo spazio caratterizzato dalll'attività antropica, il contributo proposto si configura come una prima riflessione sulla possibilità di sistematizzare i termini sia dal punto di vista speleologico che archeologico in tre categorie: riparo, caverna e grotta. Attraverso questo studio in corso, inoltre, si auspica di contribuire a sviluppare una sempre maggiore collaborazione tra archeologi e speleologi, al fine di ottenere un quadro sempre più esaustivo e interdisciplinare per la comprensione delle tracce del paesaggio antico.

Ringraziamenti

Si ringrazia la Soprintendenza Archeologia, Belle Arti e Paesaggio per le province di Salerno e Avellino nella persona della Dottoressa Adele Lagi, il Dottor Pierfrancesco Talamo, la Prof.ssa Annaluisa Pedrotti, Il Prof. Marco Pacciarelli, il Prof. Fabio Cavulli, la Federazione speleologica campana, il Gruppo speleologico Club alpino italiano, sezione di Napoli, in particolar modo Umberto Del Vecchio, Norma Damiano e Giuseppe Langella.

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3D geomorphology and landscape evolution of the Roc-aux-Sorciers site (Vienne, France).

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Abstract

The Roc-aux-Sorciers site (Vienne, France), is a rock shelter located in a meandering concavity. Sculpted bas-reliefs were attributed to the Magdalenian culture. To study of the morphological context, integrated geomorphological approach was conducted on the site. Beyond the 3D mapping, the geomorphological analysis transcribes the integrated approach methodological steps to which geomorphological, archaeological, and sedimentological insights can be added for depicting landscape evolution on open archaeological sites.

Résumé

Géomorphologie 3D and évolution du paysage au Roc-aux-Sorciers (Vienne, France). Le site du Roc aux Sorciers (Vienne) est un abri sous roche situé dans la concavité d'un méandre. Les bas-reliefs sculptés dans le calcaire oxfordien ont été découverts en 1927 et attribués au Magdalénien par la datation des niveaux archéologiques sous-jacents (environ 18.000 ans BP). Toutefois, au moment de sa découverte, le site présentait des morphologies différentes de celles du Magdalénien. Pour étudier le contexte morphologique et l'évolution du site, une approche intégrée a été conduite sur le site. Les reconstitutions 3D issues de cette étude recombinent les résultats des campagnes archéologiques antérieures, ceux de l'étude morphologique, auxquels s'ajoutent les données sédimentologiques qui rendent compte de l'évolution du paysage sur les sites archéologiques à ciel ouvert.

1. Introduction

In the Roc-aux-Sorciers site (Vienne, France), sculpted bas-reliefs carved in Oxfordian were discovered in 1927 and attributed to the Magdalenian culture by dating the underlying archaeological levels (around 18 ka cal. BP). However, when discovered, rock art was covered by slope sediments and so yielded morphologies different than during the Magdalenian frequentations. The archaeological excavations performed since 1927 also participated to change the local topography.

To study of the morphological context and evolution of the site (rock shelters at the foot of the walls, collapse and transformation by archaeological investigations), an integrated geomorphological approach was conducted on the site. The 3D reconstructions resulting from this study are a combination of the geomorphological approach with the results of previous archaeological excavations. Beyond the 3D mapping, the geomorphological analysis transcribes the integrated approach methodological steps to which geomorphological, archaeological, and sedimentological insights can be added for depicting landscape evolution on open archaeological sites.

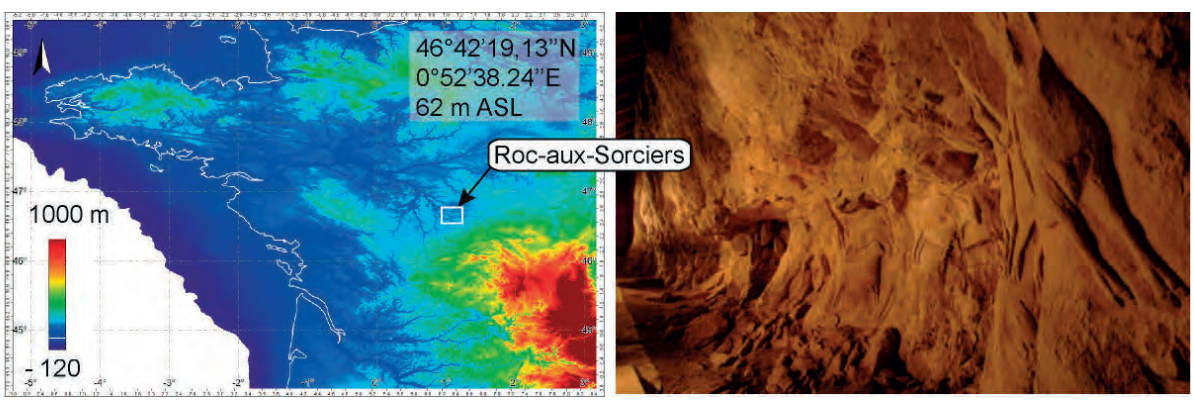

Figure 1: Location map of the Roc-aux-Sorciers site. The Anglin river than flows next to the archeological site is part of the Loire catchment (a). Parietal sculptures (b) visible in the Abris Bourdois were attributed to Middle-Magdalenian culture.

2. Materials and methods

In order to capture the site and its environment, 3D mapping was performed on the Roc-aux-Sorciers using a short-range Faro Focus 3D 360° (Fig. 2). Scans were registered with spherical targets and consolidated using the Faro Scene software. Survey covered the archaeological site and its direct physical environment (scarps, slopes and riverbank).
The obtained point-cloud was then filtered and classified in order to remove vegetation and protection infrastructures. The obtained point cloud was then meshed with Delaunay 3D triangulation method to obtain a final 3D model representing the current archaeological site's topographical setting. The soils were also rasterized in order to provide a reference 2D elevation map that can be directly exploited through GIS softwares. The Roc-aux-Sorciers site possesses different kind of reference morphologies that can be used to understand its landscape evolution since its occupation by the past societies. While the site is currently filled with plurimetric blocs and slope sediments (BOZET & MISKOVSKY 2010), it was different during its occupation and also when it was discovered in 1927 (ROUSSEAU 1933).

In order to reconstruct the site's aspect during its discovery in 1927, we used historical photographs taken during archeological excavations (GUILLIEN & de SAINT MATHURIN, 1976; de SAINT MATHURIN 1984) and cross-sections that were manually plotted in the 3D model (Fig. 3). This method allowed to reconstruct the original slope deposit's morphologies, before it was excavated for archeological purposes.
The Middle Magdalenian surface was interpolated from various parts of the site where it was recognized by previous works (both inside the Abris-Bourdois and the cave Taillebourg cellars). Interpolation was also performed using the bottom of the plurimetric blocs that are supposed to lie on the Middle Magdalenian layers (Pinçon, 1993 et 2009).
Because of the rockfall that occurred inside the site (ABGRALL, 2007) the current scarp morphology is different from the original one (Middle Magdalenian period). Measurements taken on the outcropping blocs visible in the 3D model provided an estimation of their size and so of the scarp retreat.

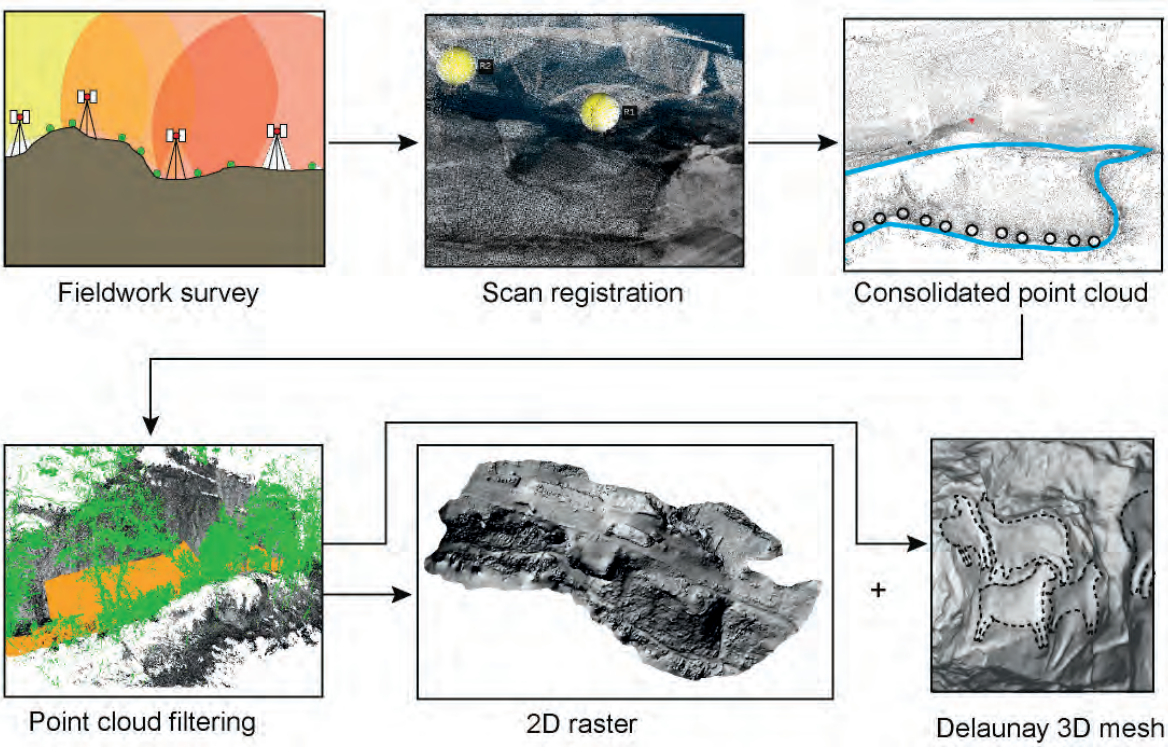

Figure 2: Methodological framework from fieldwork acquisition to 3D model building.

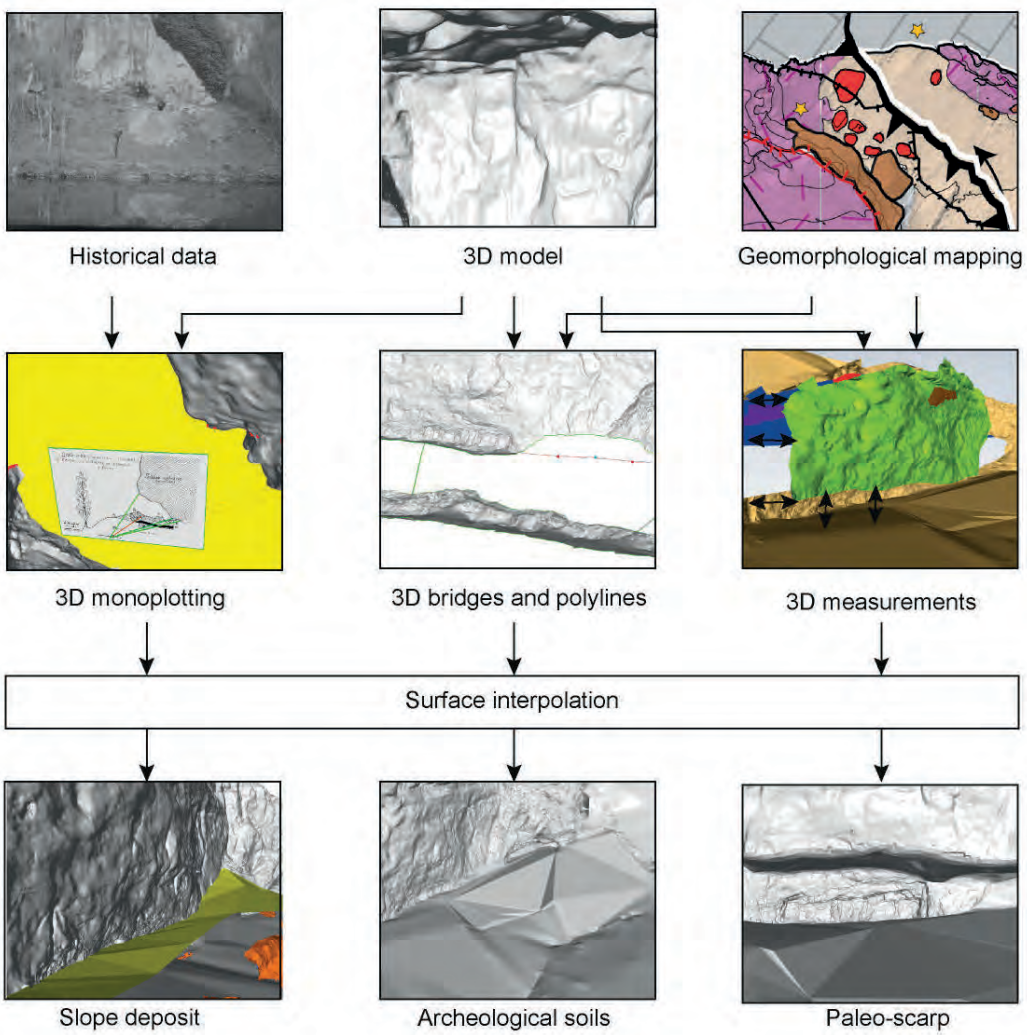

Figure 3: Methodological steps used on the Roc-aux-Sorciers site to reconstruct some of the past morphologies.

3. Preliminary results and interpretations

Integrated geomorphological analysis supplied by 3D model of the site and its surrounding allowed to reconstruct some steps of the site's landscape evolution before, during and after its frequentation by the Middle and Upper Magdalenian people (BOURDIER *et al.* 2017; FUENTES 2017). The Middle Magdalenian soil reconstruction reveals a more open paleo-landscape directed toward the river (Fig. 4, phase 1), with a light slope in place of the current plurimetric blocs that mask the river and the view to the exterior (Fig. 4, phase 5). The paleo-scarp was also forwarding a few meters more than the current one, especially upon the Abris Bourdois part. The Rockfall event that occurred inside the site deeply changed the general topographical setting of the site and of the scarp (Fig. 4, phase 2). Those blocs are still sealed in the deposit today, which means the river did not move them downward or eroded them sufficiently, either because it lacked the power to move them, or because the river level was lower than the blocs. Their presence may also have favoured the conservation of the sediments inside the site, where they were deposited continuously after the rockfall event. The Upper Magdalenian occupation that was registered inside the sediment sequence was above the rockfall deposits. That level is consequently higher in the sediment sequence (Fig. 4, phase 3). Because of that, the Upper Magdalenian people may not have seen as much of the rock art, that was partially sealed under the rockfall and the slope deposits. When the site was discovered, it was almost entirely filled with slope sediments, and thus presented a very different topography compared to the initial Middle Magdalenian one (Fig. 4, phase 4). The current conservation structures prevent any access and visibility to the site from the exterior (Fig. 4, phase 5).

Those different landscape evolution steps are reconstructed on the 3D model and provide a quantitative and visual assessment of those changes. Such integrated work illustrates the interest of conducting integrated approaches on archeological sites, and the possibility of registering and organize data acquired during previous works. The obtained survey also provides a new tool for the site's conservation and future archaeological works that can be directly positioned in the 3D spatial reference.

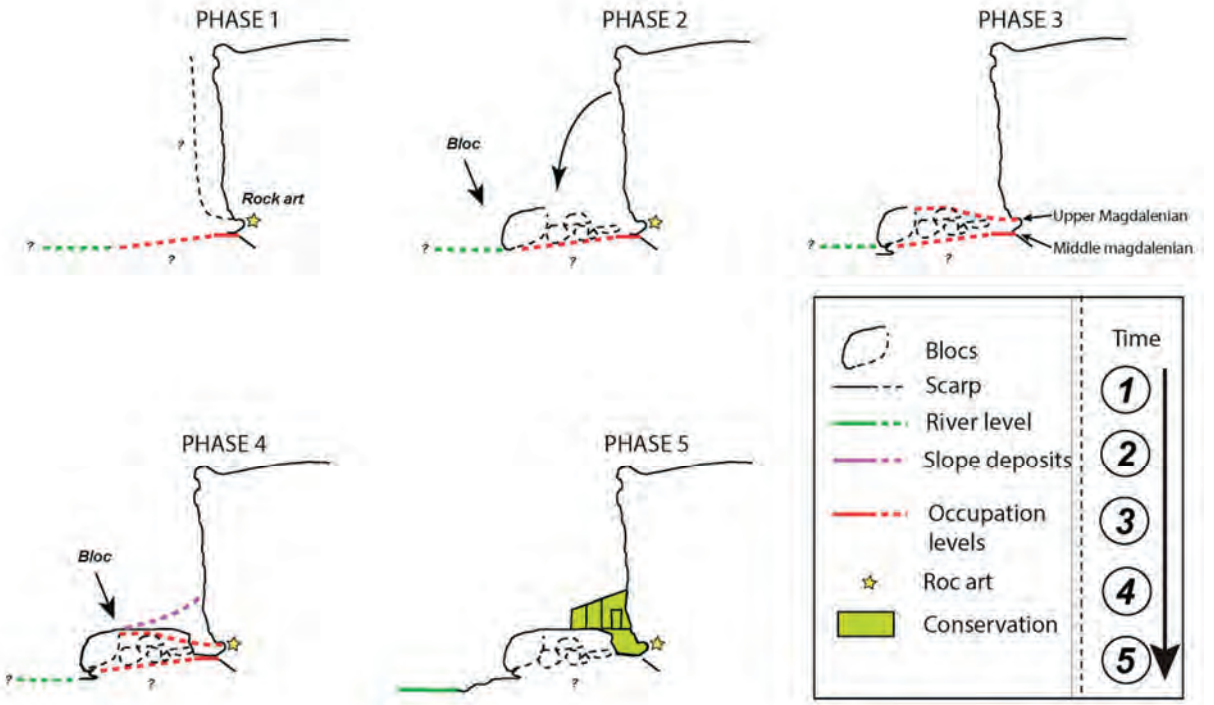

Figure 4: Landscape evolution phases of the Roc-aux-Sorciers site from the Middle Magdalenian occupation until today.

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La fortification médiévale de la Caune de La Valette (Véraza – Aude)

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Résumé

Une étude des vestiges médiévaux de la Caune de La Valette (Aude - FR) a eu lieu dans le cadre d'un Programme Collectif de Recherche. L'analyse du bâti et celle du mobilier de la grotte 1 semblent indiquer une édification à l'époque romane (entre la fin du XIe s. et le milieu du XIIe s.). L'abandon aurait pu intervenir assez tôt, peut-être dès la fin du XIIe s. La grotte 2 a aussi livré des mobiliers de chronologies diverses, de l'Antiquité à l'époque moderne, révélant la complexité et l'épaisseur chronologique des fréquentations de ce site.

Abstract

Medieval fortification of the Caune de La Valette (Aude - FR). A study of the medieval remains of the Caune de La Valette (Aude - FR) took place as part of a Collective Research Program. The analysis of the built and of the archaeological materials (cave 1) seems to indicate a construction in the Romanesque period (between the end of the 11th c. and the middle of the 12th c.). The abandonment could have occurred early enough, perhaps at the end of the 12th c. Cave 2 also delivered materials of various chronologies, from Antiquity to the modern era, revealing the complexity and chronological depth of the human frequentations in these caves.

Resumen

Fortificación medieval del Caune de La Valette (Aude - FR). El estudio de los restos medievales del Caune de La Valette (Aude - FR) se realizó como parte de un Programa de Investigación Colectiva. El análisis del marco y del mobiliario de la cueva 1 parece indicar una construcción en el período románico (entre finales del siglo XI y mediados del siglo XII). El abandono podría haber ocurrido lo suficientemente pronto, quizás ya a fines del siglo XII. La cueva 2 también arrojó muebles de diversas cronologías, desde la Antigüedad hasta la época moderna, revelando la complejidad y profundidad cronológica de las visitas a este sitio.

1. La Caune de La Valette

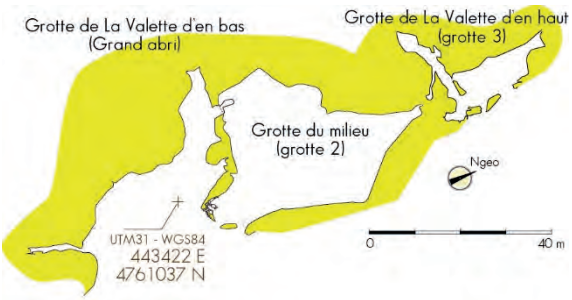

Figure 1 : Plan d'ensemble des grottes de la Caune de la Valette. Crédit Florence Guillot, Denis Langlois, Rodrigue Tréton.

La Caune de La Valette est un ensemble de trois grottes, aujourd'hui indépendantes l'une de l'autre, qui s'ouvrent sur le flanc nord de la vallée, en rive droite du ruisseau de Lavalette dans la commune de Véraza (Aude), à l'ouest du massif des Corbières (fig. 1 et 2).

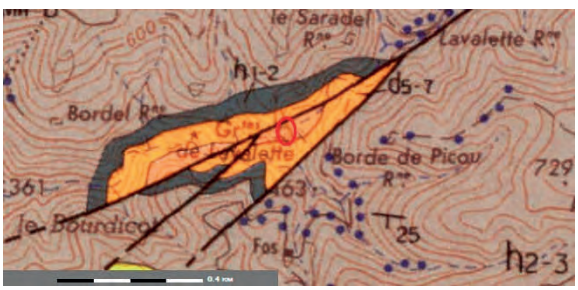

Figure 2 : Situation de la grotte sur la carte géologique au 1/50000e de Quillan. Crédit BRGM - Info Terre

La Caune est située géologiquement dans des formations d'âge dévonien moyen et supérieur (couleurs rosé et beige de la fig. 2) qui affleurent au sommet d'un anticlinal faillé au sein de terrains d'âge carbonifère (gris et gris rosé). Ces séries sédimentaires sont respectivement composées de *calcaires gris plus ou moins argileux à chailles surmontés par des calcaires gris à taches roses* et de *jaspes noirs, gris ou*

verdâtres surmontés de calcaires micritiques beiges fortement dolomitisés (notice carte BRGM). Les failles induisent une déformation importante de ces formations au niveau de la Caune (plissements, fracturations, basculements...). Elles sont à l'origine d'arrivées d'eau importantes qui, jointes à la déformation des roches, ont permis le creusement des cavités par dissolution. Ce sont les calcaires des deux formations dévoniennes qui ont été utilisés sous forme de blocs récupérés ou de moellons extraits pour l'érection des murs.

Un des objectifs du Programme Collectif de Recherche mené par Muriel Gandelin (INRAP – UMR 5608) « Milieu et peuplement en Languedoc occidental du Néolithique au Bronze ancien » était de rassembler des données pour la publication des fouilles de Jean Guilaine dans ce site éponyme du Vérazien. La présence d'un mur maçonné barrant le porche du Grand Abri a donné l'opportunité à quelques spécialistes de la période médiévale de réaliser une étude sur cette construction et son contexte. Les conclusions de l'étude sont limitées par l'absence d'opérations archéologiques, datations $_{14}$C sur les mortiers ou sondage associé au mur. Elles souffrent aussi de la carence documentaire liée à ce site.

2. Une grotte sans histoire ?

Cet ensemble de cavités dominant les petites gorges du ruisseau de Lavalette est situé en contrebas d'une ancienne voie de communication reliant la vallée de l'Aude aux Corbières. Qualifié de *Grand chemin* en 1594, puis de *chemin de Limoux à Missègre* au XIXe siècle, c'est vraisemblablement cet itinéraire qu'emprunta l'armée du roi de France à l'automne 1240 lors de l'expédition de répression de la rébellion du vicomte Trencavel (Tréton, Loppe *et al.* 2017). Il s'avère malheureusement que la quasi-totalité des archives médiévales se rapportant à ce secteur a été détruite au cours des guerres de Religion, conflit qui a très durement éprouvé l'ancien comté de Razès. C'est le cas notamment des archives de la puissante abbaye bénédictine d'Alet. Érigée en évêché en 1318, celle-ci était à la tête d'un vaste domaine temporel s'étendant du Couserans à la plaine du Roussillon. Situé à 4 km à l'ouest des grottes, ce monastère possédait le lieu de Saint-Salvayre, où subsistent les vestiges d'un rocher fortifié probablement édifié au cours de la période carolingienne à 1600 m au nord-ouest de la Caune. En l'absence de documentation écrite, il est impossible de savoir dans quel contexte la grotte de Lavalette fut fortifiée et par qui. On observe seulement qu'elle se situe sur le territoire de Véraza, lequel semble avoir constitué une seigneurie particulière jusqu'à ce que les moines d'Alet en fassent l'acquisition en 1283. L'absence d'information historique fiable se rapportant à l'occupation de la grotte de Lavalette au cours de la période médiévale a bien évidemment laissé le champ libre à toutes sortes d'hypothèses. Certains ont ainsi avancé qu'elle avait servi de refuge aux « Cathares » pendant la croisade contre les Albigeois, d'autres affirmant que les habitants de la cité épiscopale d'Alet s'y seraient fortifiés pendant les guerres de Religion, attribuant même à cette période l'édification du mur clôturant le porche (Gibert 1972). Mais force est de constater que ces spéculations demeurent jusqu'à présent totalement infondées. Quoi qu'il en soit, il importe de souligner qu'à ce jour la grotte fortifiée de Lavalette constitue une singularité dans le paysage castral du Razès médiéval où ce type d'aménagement ne semble pas avoir été très répandu, contrairement à ce qui a été observé dans les montagnes ariégeoises voisines (Guillot 2006). Dans le bassin supérieur de l'Aude, la seule grotte fortifiée évoquée par les sources médiévales est également située à proximité d'une ancienne abbaye bénédictine. Il s'agit de la Caune de Saint-Martin-Lys en Fenouillèdes qui est mentionnée dans des actes de la première moitié du XIIIe siècle. Mais cette dernière n'a pas encore été formellement localisée.

3. Un mur de facture aristocratique : fin XIe siècle — XIIe siècle ?

Le Grand Abri est constitué par un vaste porche dont les hauteurs sous plafond sont comprises entre 4 et 6 m (fig. 4). Il comporte des murs en pierres sèches, en l'état indatables et peut-être d'origines diverses. Les vestiges d'un grand mur barrent l'entrée de la cavité et délimitent un périmètre intérieur d'environ 40 x 10 m, pour une superficie potentiellement habitable de 440 m². Ce mur maçonné à la chaux (ép. 0,90 m) se compose de moellons calcaires en petit et moyen appareils formant des assises régulières, signe d'une réalisation soignée. Sa base est édifiée sur de gros blocs rocheux disposés pour servir de socle. Cette technique est observable dans plusieurs grottes fortifiées de la haute Ariège des XIIe-XIIIe siècles et à la base de murs castraux synchrones. Cette maçonnerie s'étirait du nord au sud sur environ 25 m de long répartis en pans coupés. Au sud, un premier pan pratiquement détruit s'accolait à la paroi et se liait à un autre d'une douzaine de mètres de long, actuellement conservé sur 2,5 m de hauteur (fig. 3). Il est percé de six ouvertures rectangulaires (de tir ou de jour ?) de petites dimensions disposées en quinconce. Pourvues d'un linteau, elles sont horizontalement espacées d'un à deux mètres, alors que leur écartement vertical est très faible (1,5 m). Deux d'entre elles sont grossièrement bouchées en parement externe. Hormis ces ouvertures, on ne distingue aucune trace d'aménagement dans la maçonnerie, ni dans la paroi rocheuse ouest qui lui fait face : ni trou de boulins, ni engravure, ni retraite d'étage. Si la fonction défensive peut-être ostentatoire comme dans tant de sites castraux, la qualité du bâti implique un commanditaire aristocratique, ce qui laisse par conséquent présumer que la grotte a pu avoir une fonction d'abord résidentielle. La typologie de l'appareil oriente nettement vers une datation médiévale que l'on serait tenté de cerner entre la fin du XIe et le milieu du XIIe siècle par comparaison avec d'autres maçonneries contemporaines observables dans la région, par exemple les villages castraux d'Albières et Nouvelles (Aude).

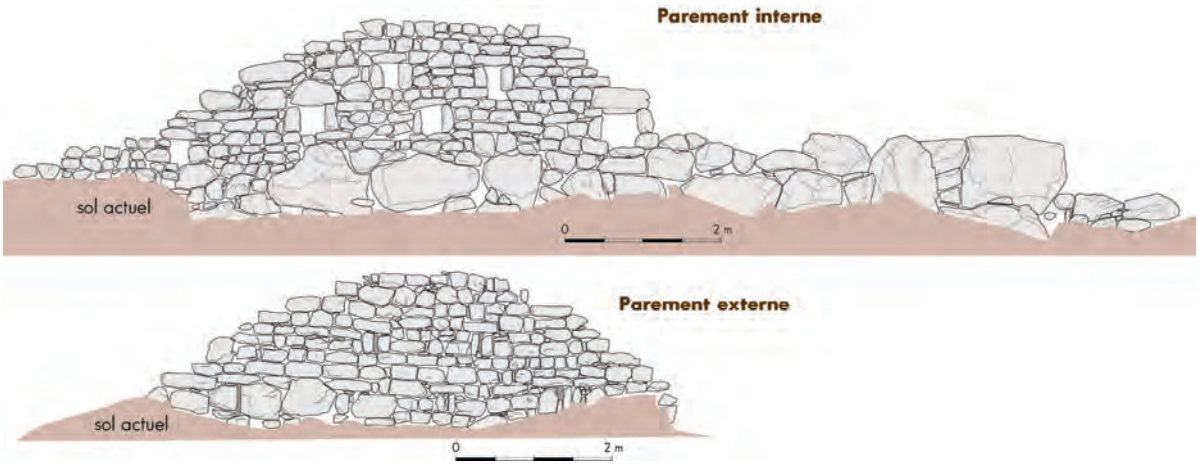

Figure 3 : Relevés développés du mur maçonné au mortier de chaux barrant le porche du Grand Abri de la Caune de La Valette (ou grotte n°1). Crédit Florence Guillot, d'après les images et levés de Denis Langlois.

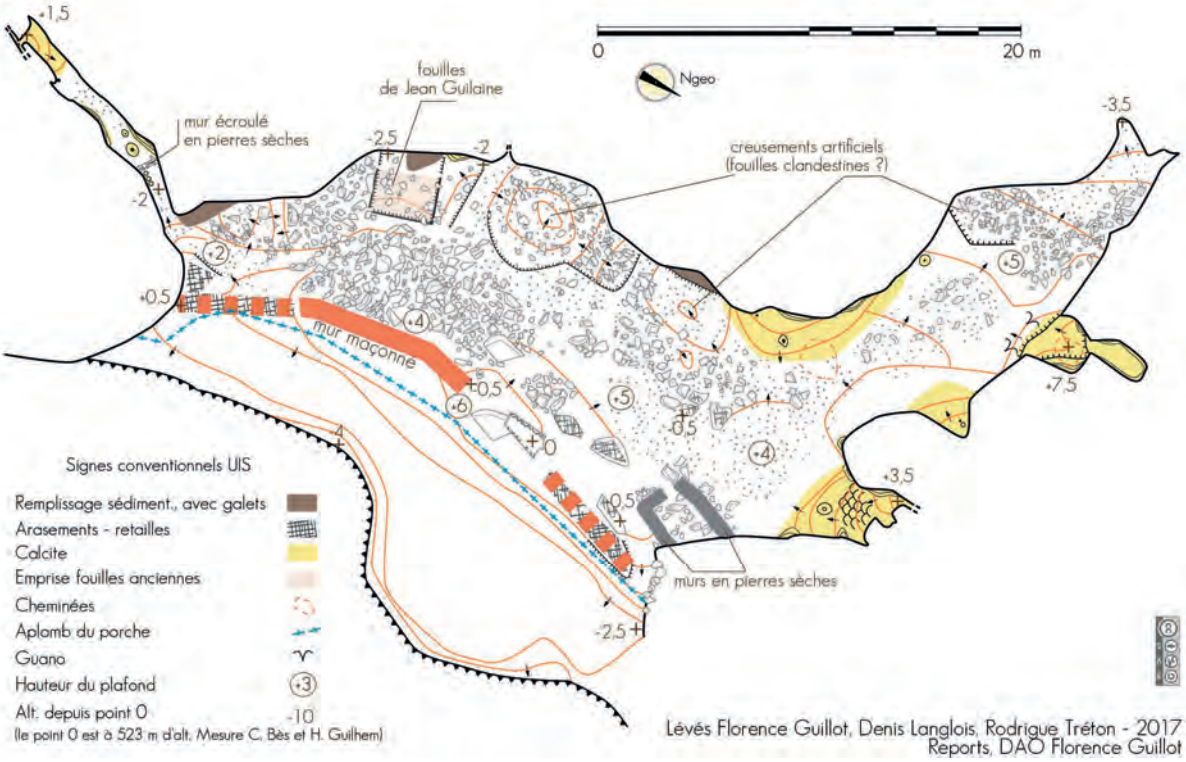

Figure 4 : Plan du Grand Abri ou grotte de La Valette d'en bas (Véraza – Aude).

4. Un petit lot mobilier postérieur à la Préhistoire[1]

Dans les années 1960, un ensemble de 174 objets postérieurs à la période préhistorique a été récupéré par l'équipe de J. Guilaine lors des fouilles et des prospections dans les cavités de Lavalette. Privé de tout contexte stratigraphique, ce petit lot confirme toutefois l'occupation discontinue de ces abris entre la Protohistoire et l'époque contemporaine.

La grotte 1 ou Grand Abri n'a livré que 8 tessons à cuisson réductrice, attribuables à une fourchette chronologique comprise entre le Xe et le XIIe siècle : quatre tessons de panse et trois bords d'oules à lèvres arrondies ou biseautées (fig. 5/1-3), la taille des fragments, plutôt importante, orientant vers un dépotoir. Dans la grotte 2, 115 objets répartis en plusieurs lots correspondent à diverses époques : dans la couche 1 du porche, 62 éléments ont été recueillis, dont 3 tessons en CNT – céramique non tournée – de l'âge du Bronze ou du Fer ornés de traces de peigne ou d'un décor imprimé de points (fig. 5/12, 13, 14).

[1] Avec la collaboration de Claude Raynaud.

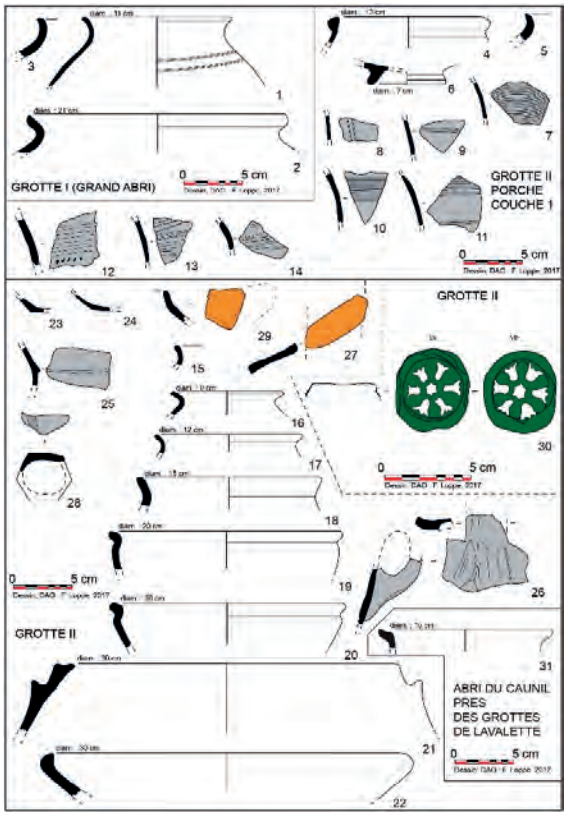

Figure 5

L'époque antique se signale par des tessons d'amphores, un bord d'urne à cuisson réductrice (fig. 5/4), un pied annulaire (fig. 5/7) et un fragment de DSP – dérivé de sigillée paléochrétienne – à pâte rouge (V^{e}-VIe siècles). Une quarantaine de tessons médiévaux à cuisson réductrice sont à signaler, par exemple des tessons de panse tournés (fig. 5/7-9) dont la surface est parfois polie (fig. 5/10, 11) et un bord d'oule ou de marmite à post-cuisson réductrice (fig. 5/5 ; XIe-XIIe siècles). Huit fragments de fer ont également été exhumés. Dans le reste de cette cavité, on note un tesson en CNT d'époque protohistorique et 3 fragments de DSP (V^{e}-VIe siècles) à pâte calcaire recouverte d'un engobe transparent : un tesson de panse à carène de profil triangulaire (fig. 5/25) et deux bords de bols (fig. 5/19, 20). Le reste du mobilier est attribuable à l'époque médiévale : un bord de pégau à cuisson oxydante, proche des productions orangées polies (IXe-Xe siècles ; fig. 5/29), quatre bords d'oules ou de marmites à cuisson réductrice attribuables aux XIIe-XIIIe siècles (fig. 5/15-18), un départ d'anse de marmite (fig. 5/26), une grande jarre (diam. : 30 cm) non tournée réalisée dans une pâte épaisse (ép. : 0,7 cm ; fig. 5/21), et une écuelle ou une jatte tournée (fig. 5/22). Enfin, on relève un fragment de trompe d'appel de section hexagonale dont la paroi externe présente un polissage décoratif comme c'est souvent le cas dans ce genre d'objets (fig. 5/28). Par ailleurs, 14 tessons de céramique à cuisson oxydante réalisés dans une pâte tendre orange vif (XIIIe siècle ?) ont une paroi extérieure rugueuse et des tranches émoussées, parmi lesquels 2 fragments d'anse plate (fig. 5/27) et 2 fonds plats dont un comporte une trace de glaçure vert olive mat (fig. 5/23, 24). Le mobilier métallique se signale par une applique ajourée en tôle de bronze (diam : 4,8 cm ; ép. : 0,7 cm ; poids : 4,7 gr. ; XVIe-XVIIIe siècle ? ; fig. 5/30).

Enfin, dans l'abri du Caunil, près des grottes de Lavalette, 50 objets ont été découverts, parmi lesquels 2 tessons en CNT d'époque protohistorique, une vingtaine de tessons à cuisson oxydante et post-cuisson réductrice (X^{e}-XIe siècles ?) dont fait probablement partie un bord de pot d'un diamètre de 15 cm (fig. 5/31). Enfin, un tesson à cuisson oxydante et glaçure jaune et verte (ép. : 0,8 cm) est attribuable à un bord à marli de plat ou de jatte (seconde moitié XVIe siècle-début XVIIe siècle).

5. Perspectives

Longtemps ignorée par la recherche archéologique et historique, la question de l'occupation, de l'aménagement et de la fortification des grottes au cours de la période médiévale est devenue depuis une vingtaine d'années un objet d'enquête scientifique à part entière, mais souffre encore du peu d'opérations de recherche autres que des inventaires. En cela, la Caune de La Valette est exemplaire. Probable résidence aristocratique du début du second Moyen Âge, elle expose un bâti de qualité et mériterait des études plus approfondies et une reprise des fouilles afin de mieux séquencer le contexte d'occupation de cette grotte fortifiée.

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Pre-Hispanic Rock Art Extraction from Geomorphological Cave Context in Puerto Rico

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Abstract

Continuous exploration of caves in Puerto Rico harboring rock art, enables an intimacy that exposes past human uses permanently evidenced in its morphology. Exploration together morphological analysis leads to identify the absence of pre-Hispanic human marks in the caves based in the context from where they were removed. This investigation focuses on the extraction of pre-Columbian rock art from its cavernous geomorphological spatial area context.

For speleology and archeology, petroglyphs constitute an object of study defined by cave context. Their physical location is an essential component in their examination. By case studying fifteen caves sheltering rock art in Puerto Rico, we will identify the subtraction of petroglyphs from walls and speleothems. As a result, another human mark subsists that demonstrates the diverse anthropogenic effects in the cave and indicates the withdrawal of the petroglyph.

This study establishes bases for further research incorporating more caves around the archipelago, methods of removal, and conservational education. The literature review mentions the traffic of pre-Columbian artefacts including petroglyphs obtained from caves in Puerto Rico and occasionally comments on rock art extractions, but no study has ever addressed it as a systematic practice in all caves with rock art around Puerto Rico mainland.

1. Introduction

Rock art extraction from geomorphological context is a well spread anthropogenic effect occurring in Puerto Rico, but barely documented. In this study a representative sample of caves harboring rock art are case studied to expose the general practice of removal around all mainland Puerto Rico and the impact it has in the interdisciplinary investigation of cave morphology. 15 inland and coastal caves were chosen considering their georeference, speleogenisis, dimension, recognition and amount of rock art sheltering.

Figure 1: Puerto Rico main island caves extraction location map. Prepared by Tamara González-Durán.

Continuous human use of caves in different historic moments perpetuates respective modifications to their natural morphology. Numerous examples of anthropogenic pre-Hispanic human evidence persist to date that suggests different practices within caves spaces. Puerto Rico main island registers around 2,000 caves where about 250 of them enclose rock art that are distributed among inland and coastal caves. Rock art expressions held in these sites signal the valorization and impact of pre-Columbian habitants within these natural spaces. Pre-Hispanic groups incorporated caves into their cultural valorization in relation with geographical settings as part of their social, political and mythological constructs. For example, caves were part of the Taino's origins myth of human life which underlines the cultural relevance of caves in their identity narrative.

Geomorphology and geographical settings played a role in the rock art placement in caves. During post-Hispanic times and the later creole peasantry development, the utilization of the underground transmuted because of the revalorization of the cavernous space. New cultural conceptions dazzled other objectives that transformed the use of rock art safeguarded in caves. In the 19th and 20th century, the collection of pre-Columbian archeological material extended the search to the floors, walls and speleothems of caves. The extraction of rock art from caverns, regardless the motive, disassociates the human expression of its ancestral and geographical valorization limiting the experience for interdisciplinary exchanges of future integrational studies.

Inside and outside of Puerto Rico, there are pre-Hispanic archeological collections in museums, universities, government agencies and private collectors that include rock art removed from caves. The archeological collections that began to spring in the Island since the 19th century responded to private collectors and funded expeditions by the institutions currently holding the material. All these inventories were not methodologically documented to rescue their backgrounds which will be challenging for their future analysis, since the archeological and geographical track of the petroglyph was lost. In some limited instances there had been official cave context extractions done by archeologists that recover information previous to the withdrawal. For example, there is data found on petroglyphs removed from caves that were going to be imminently affected by a natural or anthropogenic event.
The economic situation of 19th and early 20th century motivated by collectors, stands out as the leading factors for the removal of petroglyphs from Puerto Rico's mainland caves. The literature revision identifies *purchase* as one of the methods for the acquisition of archeological material that includes petroglyphs coming from Puerto Rican caves. Government agencies in the Island have in their custody petroglyphs removed from caves by independent local collectors for their sale. The municipality of Manatí has 12 speleothems with carved petroglyphs that were remove from their cave context for the purpose of being sold and have no knowledge of their geographical settings. Occasionally, specialized literature does mention the absence of speleothems presumed to harbor rock art, specially of caves that had been archeological or speleological documented.

Figure 2: Removed petroglyph displayed at the municipality of Manatí's inventory of extracted rock art from unknown caves. Photo by Tamara González-Durán.

2. Methods

The permanent exploration of coastal and interior caves harboring rock art enables to analyze the alterations in their morphology to identify the removal of petroglyphs from archeological contexts. The removal of the rock art embodies another anthropogenic modification to the cave space. Subtractions are rarely mentioned in professional investigations and there are no studies addressing the subject as a systematic practice in all Puerto Rico mainland caves.

With a geographical area of 8,896 km^2, a well distributed population throughout the Island and an abundant karst landscape, petroglyph extraction had many favorable elements to be a generalized practice present in various geomorphological contexts with different types of caves. Puerto Rico main island is composed of a volcanic core overlaid by carbonate deposits spread all around the territory. 27.5% of Puerto Rico's mainland total surface is limestone distributed geographically primarily in the North limestone while other carbonate deposits also flourish in the South Limestone and the Scattered limestone all over the remaining of the Island. This geomorphological composition has a geographical distribution of karst caves all around the main Island suitable for rock art placement. The research findings show that extractions occurred in notorious as unknown caves, in caves filled with petroglyphs as others barely harboring any and in accessible just like remote caves. The geomorphological and geographical distribution of the examples studied show that removals occurred in coastal caves 1m above sea level as well as interior caves with an altitude of 800m more than 20km from the nearest shore line, deep in the scattered karst of the interior center of Puerto Rico.

3. Results

The investigation identified 78 extractions in 15 caves at several geomorphological landscapes with their particular speleogenesis based in their georeference whether found in the interior or the coastal scenery. The availability of surfaces displayed in such a diverse morphological setting makes it suitable for rock art placement in relation to spatial cave area distribution and geographical ambient. The suggested petroglyph extractions were frequently found in stalactites, columns and rimstone pools. In this first approach, 43% of extractions were removed from cave walls and the rest 57% from stalactites, stalagmites, flowstones, columns, and rimstone pools. The morphology of the caves where rock art lies keeps being an element to consider optimizing the integrity of the speleothems while modifying the cave by the extraction. This suggests that cave surface and morphology in the samples studied have a connection with the practices of pre-Columbian habitants and continued determinizing post-Hispanic and modern uses with their respective variability on the cultural revalorization of cavernous spaces. Also, the remaining petroglyphs in the cave context where extractions took place show natural weathering that could help estimate the antiquity of the subtraction. In other instances, the natural weathering that develops in the section area or the remnant of a petroglyph extracted could help establish a minimum age of the removal.

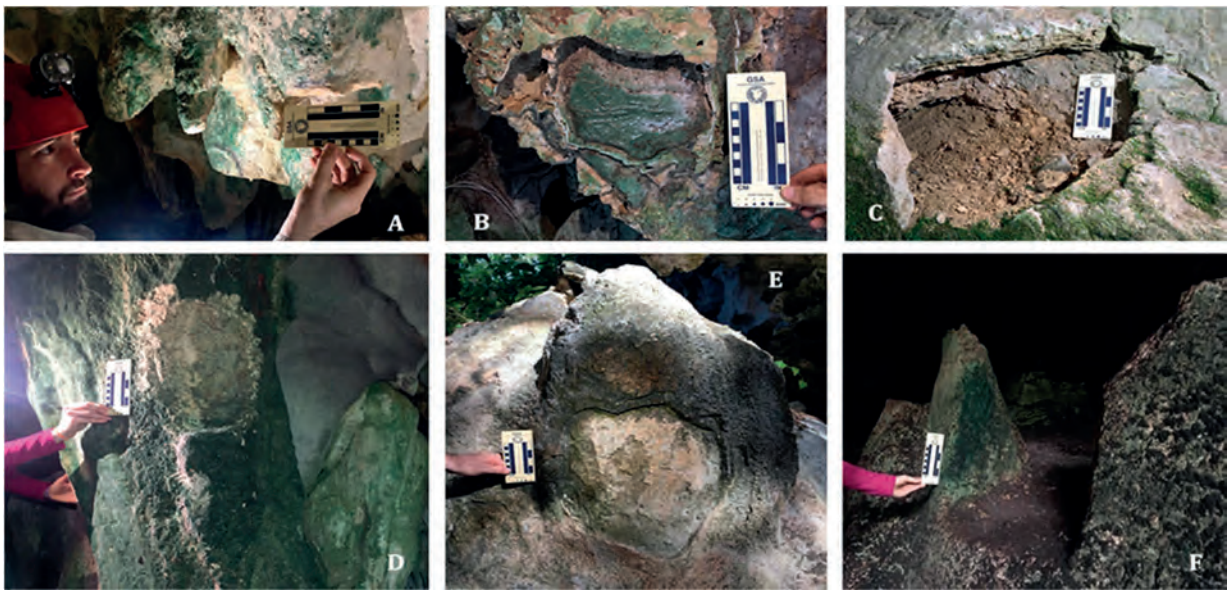

Figure 3: A- Cueva Golondrinas, Ciales; B- Cueva la Mora, Comerío; C- Cueva los Gemelos de Zamas, Jayuya; D- Cueva Clara, Aguas Buenas; E- Cueva el Guineo, Morovis; F- Cueva del Arco Superior, Utuado. Photos by Tamara González-Durán (A, B, C, E) and by Manuel Güivas (D, F).

4. Discussions

Among the studied cases, Cueva del Indio and Cueva Golondrinas are comparable caves with different speleogenesis that exhibit similar samples of petroglyph extractions. Cueva del Indio in the coastal municipality of Arecibo, is a flank margin cave of easy access harboring more than 120 petroglyphs and used as a tourist attraction nowadays. Its popularity is demonstrated in countless professional and amateur publications that highlight its rock art together with the continuous human use that this cave has been objected to in different historical periods and contemporary times. Cueva Golondrinas in the interior municipality of Ciales is an inland cave that displays similarities with Cueva del Indio in its recognition, dimensions, density of petroglyphs, and approachability. Located in the Lares Limestone, this cone cave presents 8 instances that suggest removal of petroglyphs. Cueva Golondrinas particularly shows subtractions of stalactites where the cut left out remnants of the contour of the removed petroglyph. Similar examples of petroglyphs remnants left out in the extraction are found also in the walls of Cueva del Indio.

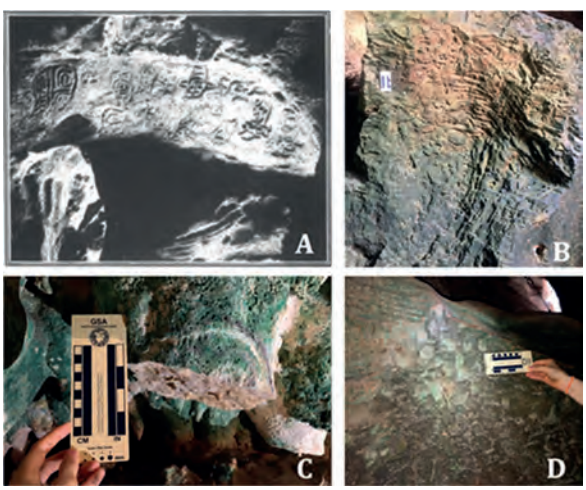

Figure 4: A- Photo published in the Puerto Rico Ilustrado showing a removed petroglyph panel from Cueva del Indio, 1910. B-Petroglyph extraction in Cueva el Indio. C-Petroglyph remnant from subtraction in Cueva Golondrinas, Ciales. D- Another removal in Cueva del Indio. Photos by Manuel Güivas (B, C & D)

Both caves present ordinary deterioration by natural weathering and anthropogenic factors that distresses the rock art.

Small caves with scarce rock art, limited divulgation and remote access are also examined to compare its particular patterns of extractions. With different karstic speleogenesis, Cueva Playuela in Aguadilla, Cueva los Pérez in Isabela and Cueva los Gemelos de Zamas in Jayuya exhibit subtractions of petroglyphs that extends the practice of removal to isolated caves with limited rock art expressions. Cueva Playuela is a sea cave and Cueva los Gemelos de Zamas is developed in the contact of limestone with volcanic rock at 800m above sea level that both present a small cave area with a minor density of rock art, but from the analyses of their respective morphologies the subtraction of petroglyphs is suggested from their interior contexts. Similarly, Cueva los Pérez located in the Aguada Limestone within a government natural reserve, registers 2 mutilated petroglyphs of a total of 3 and a removal in the entrance. Additional caves were analyzed and geographically distributed in the north, south, and disperse karst to outline this first phase of documenting the practice of petroglyph extraction in all mainland Puerto Rico.

5. Conclusion

The representative sample examined at this stage helps establish that the manifestation of petroglyph extractions was a practice well disseminated across all the main Island. The distribution of limestone rock, the economic situation, the high population density in rural areas together with collectors and the absence of laws to protect archeological material, were ideal conditions for a systematic extraction pattern all over mainland Puerto Rico.

Nowadays, as a result of population displacement from rural to urban ambients hundreds of caves are in uninhabited surroundings including caves sheltering rock art that helps in their conservation. Despite this, the majority of caves are located within properties with limited or no vigilance which represents a constant anthropogenic threat to the morphological integrity of the caverns. Since the 1980's legislation has been passed in Puerto Rico to protect caves and their biota, archeological material, morphology and everything they harbor inside. Contemporary hazards to the preservation of archeological contexts include the divulgation over the internet of the exact location of caves concealing rock art.

This study establishes the grounds for a systematic analysis of rock art extraction from cave contexts all over the main island and extend it to the rest of the Puerto Rican archipelago. Future chapters will expand the sample of caves with removals helping create an analytical and integral model to determine which geographical contexts and morphological aspects of caves are most affected and what kind of extraction methods are used. It is necessary a multisectoral approach of the community and the government to preserve caves bearing rock art because of its investigative and cultural relevance.

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La cavité sépulcrale de Laninca (Corse) : un témoignage unique d'une pratique funéraire en Méditerranée à l'âge du Bronze

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Résumé

La découverte fortuite en 2015 d'une grotte sépulcrale inédite lors de l'exploration de cavités perchées de la commune de Lano (Haute-Corse) a eu lieu dans le cadre des activités des associations de spéléologie I Topi Pinnuti et du Groupe Chiroptères Corse. Les spéléologues ont été interpellés par des éléments en bois de grandes dimensions et des ossements épars qui les ont conduits à stopper leur exploration. Les fouilles menées par des archéologues du ministère de la Culture et du CNRS en totale collaboration entre les spéléologues et les archéologues ont été conduites de 2015 à 2018. La situation du dépôt funéraire, la présence des coffres en bois très bien ouvragés et surtout leur conservation depuis plus de 3000 ans, confèrent à cette découverte un caractère absolument exceptionnel et témoignent de pratiques funéraires et artisanales totalement inconnues à l'Âge du Bronze dans le bassin méditerranéen.

Abstract:

Sepulchral cave of Laninca (Corsica), a unique testimony of a burial practice during Bronze Age around Mediterranean Sea. The fortuitous discovery in 2015 of an unprecedented sepulchral cave during the exploration of perched cavities in the village of Lano (Haute Corse) took place as part of the activities of the I Topi Pinnuti caving association and the Corsican Chiroptera Group. The speleologists were challenged by large wooden elements and scattered bones which led them to stop their exploration. The excavations carried out by archaeologists from the Ministry of Culture and the CNRS in full collaboration between speleologists and archaeologists were carried out from 2015 to 2018. The situation of the funeral deposit, the presence of very well crafted wooden chests and especially their conservation for more than 3000 years, give this discovery an absolutely exceptional character and bear witness to funerary and artisanal practices totally unknown for the bronze age in the Mediterranean basin.

1. Une découverte surprenante

Au cours de la prospection d'une corniche calcaire du massif de *Cima al Cuccu* à 835 m d'altitude, un porche perché a pu être exploré. Il est prolongé par une modeste cavité qui domine, à mi-hauteur du massif, la vallée encaissée de *Laninca* (Fig. 1). La grotte s'ouvre au milieu de l'escarpement rocheux et n'est accessible que par une descente de 20 m sur agrès depuis le sommet. Au cours de la première exploration, les spéléologues ont été interpellés par la présence en surface du conduit karstique, d'éléments ouvragés en bois de grandes dimensions et d'ossements épars. Ils ont alors informé le service archéologique de la DRAC de Corse de leur découverte. Deux prélèvements pour datation au radiocarbone, sur une pièce de bois et sur un des ossements humains, ont été réalisés par les spéléologues à la demande de la DRAC de Corse. Quelques semaines plus tard, les résultats inattendus sont arrivés : les deux dates réalisées sur des matériaux différents donnaient le même résultat, la fin de l'Âge du Bronze (1200-906 cal BC). Compte tenu du caractère exceptionnel de la situation des vestiges, de leur nature et de leur chronologie, une équipe d'archéologues spécialistes de plusieurs domaines de recherche a été organisée par la DRAC de Corse afin de conduire la première expertise du gisement. À la suite de ces travaux qui ont confirmé l'intérêt majeur du site (LEANDRI et *al*. 2015), trois autres campagnes de fouille ont été organisées pour conduire l'étude à son terme. Ces travaux ont bénéficié d'une équipe archéologique pluridisciplinaire qui a œuvré avec les spéléologues. Sans l'investissement mutuel de tous, ce projet n'aurait pas pu être mené à son terme et dans les meilleures conditions, comme ce fut le cas malgré les nombreuses contraintes techniques spécifiques à la situation et l'environnement de la cavité (Fig. 2).

Figure 1 : Situation de la cavité dans un escarpement rocheux de la vallée de Laninca (vue du sud-est).

Figure 2 : La grotte dans la corniche.

2. Des travaux révélateurs

Lors de sa découverte, le site présentait des éléments mobiliers significatifs de son usage comme grotte sépulcrale (Fig. 5). Néanmoins, les questions étaient nombreuses sur la forme initiale du dépôt funéraire, ainsi que de son évolution dans le temps. L'apport d'une telle découverte est important car il révèle de nouvelles pratiques et gestes funéraires pour des populations du début du premier millénaire avant notre ère. C'est donc en ce sens que la fouille des remplissages de la cavité devait permettre de faire évoluer la connaissance du site.

Figure 3 : Vue de la passerelle à l'avant de la grotte.

Outre les aspects purement techniques liés à la recherche archéologique, ces travaux ont été compliqués par la situation de la grotte et par son accès au demeurant très technique (Fig. 2 à 4). Il a également fallu faire installer une plateforme à l'avant de l'entrée afin que le travail puisse se faire dans les meilleures conditions et ce à la hauteur de l'intérêt du gisement. Tous les moyens humains, techniques et financiers ont été mis en œuvre par la DRAC de Corse afin de valoriser au mieux la découverte. Localement, l'appui de la commune de Lano représentée par son maire Pierre Leschi a été essentiel. Mais la grande particularité de cette opération, réside dans le fait que les archéologues, anthropologues et spéléologues ont chacun dans leurs domaines de compétences respectifs travaillé en commun, dans l'intérêt du site, sans ambiguïté et dans une amitié partagée.

Figure 4 : La via ferrata aménagée par les spéléologues pour faciliter l'accès au chantier de fouille.

L'approche purement archéologique du site a été conduite par une étude morphologique des remplissages qui contenaient les vestiges. Mais afin de bien comprendre le contexte du gisement et son évolution post-dépositionnelle, c'est l'intégralité des remplissages de la grotte qui a été fouillée. Une telle opération nécessite de nombreuses spécialités pour approcher la connaissance des gestes anciens : analyse archéologique ; archéo-anthropologie ; archéothanatologie ; archéozoologie ; xylologie ; palyno-

logie ; géologie ; géomorphologie ; topographie ; analyses physico-chimiques ; gestion des mobiliers et conservation préventive des vestiges. Les différents spécialistes de ces disciplines étaient présents sur le site.

Pour réaliser cette opération plusieurs aménagements techniques ont été nécessaires. Ce sont là les spéléologues qui ont œuvré : aménagement des accès (entretien de la piste carrossable, ouverture du sentier jusqu'à la grotte) ; équipement des voies d'accès sur corde à partir de la corniche ; aménagement des camps de base ; équipement et encadrement technique des intervenants ; conception, installation et mise en œuvre d'une tyrolienne de 200 m du chemin à la grotte ; installation d'une via ferrata pour l'accès à la cavité ; participation à la pose et au replis des chantiers ; contribution aux travaux de tris et de tamisage ; et tout le reste ! Un tel chantier nécessite réellement un engagement et un travail collectif.

Figure 5 : Aperçu des vestiges après le premier décapage.

Les campagnes de fouilles réalisées dans ce contexte particulier ont permis d'étudier la globalité du comblement de la cavité. Plusieurs phases sédimentaires ont été identifiées, liées au fonctionnement du karst et à l'évolution du site dans le temps. Le dépôt funéraire de la fin de l'Âge du Bronze a aussi été érodé. On peut dire qu'au moins deux coffres en bois d'if, parfaitement ouvragés, avec des techniques inconnues et notamment l'utilisation d'une scie, ont été déposés dans la cavité. Ces objets ont été naturellement déplacés et leur contenu semble avoir été répandu. Les vestiges humains retrouvés représentent un minimum de 6 individus (deux enfants, un adolescent et trois adultes). Une grande partie des pièces ostéologiques était absente, de même aucune trace de mobilier d'accompagnement. La géométrie de la cavité favorise une diffusion gravitaire des éléments vers l'extérieur. Une grande partie du matériel archéologique a donc dû être évacuée naturellement du site et se retrouver en pied de corniche. Les recherches conduites dans ces secteurs ont confirmé ce principe, néanmoins l'érosion a détruit avec le temps la quasi-totalité des vestiges issus du site.

Figure 6 : Dépose d'un des coffres monoxyles en bois avant son transfert à la base terrain via la tyrolienne.

La présence de plusieurs sujets déposés dans un même espace sur un temps relativement court suggère que cette cavité funéraire a fonctionné de manière collective, comme c'est le cas pour d'autres sépultures contemporaines. Toutefois, la préservation partielle de certaines données autorise d'autres hypothèses quant à son fonctionnement.

Figure7 : Le coffre en bois conditionné dans sa caisse.

Ce sont les conditions tout à fait exceptionnelles offertes par cette cavité qui ont permis la conservation de pièces de bois ouvragées depuis la fin de l'Âge du Bronze, mais également, dans ce même environnement, des vestiges humains. Les ossements, presque frais, présentent une quantité encore importante de matière organique. Chez certains d'entre eux, du cartilage apparaît sous la forme de fines pellicules brunes rigides. Un sacrum montre une conservation rarissime d'un résidu de moelle épinière. De même, un crâne conserve encore des fragments des tissus cérébraux.

3. Un site rare

La grotte de Laninca a offert des conditions environnementales tout à fait particulières qui ont permis la conservation de matériaux totalement inédits pour la période protohistorique de la Corse et même au-delà. Ce type de découverte est rare et un seul autre site proche pourrait y être comparé ; il s'agit de la grotte dite *Cova del Pas* découverte dans les îles Baléares (FULLOLA et *al*. 2007). Cette cavité qui comme la grotte de Laninca a son entrée située au milieu d'une corniche rocheuse, a livré lors de sa fouille un dépôt funéraire très bien organisé et surtout très bien conservé. Outre les différents aspects liés aux gestes funéraires, on notera plus particulièrement que les corps étaient transportés et déposés sur des brancards en bois. De même, de nombreux restes organiques humains ont également été découverts (PRATS-MUNOZ et *al*. 2013). De nombreuses traces d'objets d'accompagnement en matières périssables y ont été identifiées, expliquant probablement l'absence d'un tel matériel à Laninca.

La grotte sépulcrale de Laninca constitue donc un site majeur à l'échelle de la Méditerranée qui va apporter de nouvelles données sur les sociétés de la fin de l'Âge du Bronze. On a ici un très bel exemple de ce que peut apporter une découverte assez anodine au départ, maintenant promise à un bel avenir.

Figure 7 : Mis dans une civière, le coffre en bois est descendu par la tyrolienne au-dessus du ravin et jusqu'à un des camps de base situé 150 m plus bas.

4. Pour conclure

L'exploitation des données acquises lors de cette fouille nécessitera plusieurs années de travail pour pouvoir établir une synthèse du gisement. Néanmoins, on peut dès aujourd'hui conclure qu'un tel projet n'est réalisable, pour être à la hauteur des enjeux, que dans une approche qui fédère tous les intervenants. Comme toutes les grandes entreprises spéléologiques qui ont permis les grandes découvertes, l'œuvre collective doit être reconnue. Plutôt que de rendre un hommage forcément vibrant aux 67 autres participants, il nous semble plus important de tous les nommer ici en guise de conclusion… Jérôme Angeli, Anne-Marie Angot, Séréna Asti, Ludovic Bellot-Gurlet, Henri Bernard-Maugiron, Grégory Beuneux, Antoine Boschi, Gaël Brkojewitsch, Laurent Bruxelles, Michèle Caletti, Michèle Castagnoli, Jean-Baptiste Caverne, Carine Cenzon-Salvayre, Sophie Champdavoine, Sébastien Cluzet, Wanda Comparetti, Anne-Gaëlle Corbara, Rémi Corbineau, Aurélien De Ortoli, Valérie Deshayes, Jean-Claude Del Basso, Michaël Delasalle, Albert Demichelis, Dominique Descalzo, Jean-Noël Dubois, Audrey Eberle, Agnès Ferrand, Ana Ferraz, Henri-Pierre Fiocconi, Alain Gaulme, Marie Genevier, Olivier Gérald, Noémie Gil, Pierre Lacombe, Isabelle Lascroux, Anne-Sophie Laurent, Antoine Leandri, Livio Leandri, Pierre Leschi, Didier Liberale, Élise Maire, Sophie Manenti, Marjorie Mansier, Francis Maraval, Véronique Massa, Pierre-Jean Micaelli, Pierre-François Milles, Kewin Peche-Quillichini, Stéphane Perron, Régis Picavet, Bénédicte Quilliec, Jean Raffaldi, Jérôme Redon, Antonia Revel, Noël Ricoveri, Juan Rofes, Rémi Rossignol, Marie-Pierre Rozé, Maxime Seguin, Jean-Philippe Serres, Alexia Simian Buissonnet, Alain Touzet, Pascal Tramoni, Jean-Pierre Vergnon, Jean-Denis Vignes, Philippe Viti, Silvain Yart et Franck Zerli.

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Natural and cultural heritage as attractions in karstic areas: correlation between the municipalities of Maravilha - Alagoas and Iraquara - Bahia, Northeast of Brazil

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Abstract

The semi-arid region of north-eastern Brazil has a vast diversity of ecosystems with great geodiversity and biodiversity, associated with sites of world-renowned scientific and cultural value, such as paleontological and archaeological sites. In the state of Alagoas, a project was developed in 2008 to increase tourism activity in the region, through Pleistocene mammal fossils and rock painting sites made by Paleoindians about 5,000 A.P., developing tourism and protecting the local scientific and cultural heritage. The same research is being carried out in the municipality of Iraquara located in the Chapada Diamantina National Park region of Bahia. This site has a karst with dozens of caves, containing quaternary fossils, ceramic artefacts, lithics and rock graphics. In 2019, discoveries were made in the caves of Iraquara, which motivated the start of paleontological and archaeological research in these cavities, identifying the taxa and interpreting the tafonomical and sedimentary processes that formed these Pleistocentric fossil deposits with the megamammals and their geological ages, as well as the anthropic artefacts found. The research proposes the creation of a visitor centre in the municipality, for the permanent exhibition of the material discovered, a more attractive alternative, both from a scientific and cultural point of view.

Resumo

Património natural e cultural como atracções em zonas cársicas: correlação entre os municípios de Maravilha - Alagoas e Iraquara - Bahia, Nordeste do Brasil. A região semiárida no Nordeste do Brasil, possui uma ampla diversidade de ecossistemas com grande geodiversidade e biodiversidade, associadas aos sítios de valores científicos e culturais reconhecidos mundialmente, como exemplo, os sítios paleontológicos e arqueológicos. No estado de Alagoas, foi desenvolvido um projeto no ano de 2008 objetivando incrementar a atividade turística na área, através dos fósseis de mamíferos pleistocênicos e sítios de pinturas rupestres feitas por paleoíndios há cerca de 5.000 A.P., incrementando o turismo e protegendo o patrimônio científico e cultural local. Busca-se o mesmo no município de Iraquara localizado na região do Parque Nacional da Chapada Diamantina, Bahia. O qual possui um Cárste com dezenas de cavernas, contendo fósseis do Quaternário, artefatos cerâmicos, líticos e grafismos rupestres. No ano de 2019, descobertas foram realizadas em cavernas de Iraquara, motivando o início de pesquisas paleontológicas e arqueológicas nessas cavernas, identificando os táxons e interpretando os processos tafonômicos e sedimentares que formaram esses depósitos fossilíferos pleistocênicos com megamamíferos e suas idades geocronológicas, bem como, dos artefatos antrópicos encontrados. A pesquisa propõe a criação de um centro de visitação no município, para exposição permanente dos achados, uma alternativa a mais de atrativos, tanto do ponto de vista científico quanto cultural.

Résumé

Le patrimoine naturel et culturel en tant qu'attractions dans les zones karstiques : corrélation entre les municipalités de Maravilha - Alagoas et Iraquara - Bahia, Nordeste du Brésil. La région semi-aride du nord-est du Brésil, possède une vaste diversité d'écosystèmes avec une grande géodiversité et biodiversité, associées aux sites de valeurs scientifiques et culturelles mondialement reconnues, comme les sites paléontologiques et archéologiques. Dans l'État d'Alagoas, un projet a été développé en 2008 visant à accroître l'activité touristique dans la région, à travers les fossiles de mammifères pléistocènes et des sites de peintures rupestres faites par les paléoindiens il y a environ 5.000 A.P., en développant le tourisme et en protégeant le patrimoine scientifique et culturel local. La même recherche est effectuée dans la municipalité d'Iraquara située dans la région du Parc National de Chapada Diamantina à Bahia. Ce site connait un karst avec des dizaines de grottes, contenant des fossiles quaternaires, artefacts céramiques, lithiques et graphismes rupestres. En 2019, des découvertes ont été faites dans les grottes d'Iraquara, ce qui a motivé le début de recherches paléontologiques et archéologiques dans ces cavités, en identifiant les taxons et en interprétant les processus tafonomiques et sédimentaires qui ont formé ces dépôts fossilifères pléistocentriques avec les mégamammifères et leurs âges géologiques, ainsi que les artefacts anthropiques trouvés. La recherche propose la création d'un centre de visite dans la municipalité, pour l'exposition permanente du matériel découvert, une alternative plus attractive, tant du point de vue scientifique que culturel.

1. Introduction

The discovery of fossils in depressions of the crystalline basement, called Tanks, with Pleistocene mammals in the semiarid region of Alagoas, led the paleontology team at the Natural History Museum of the Federal University of Alagoas to develop a project aimed at the protection of the fossiliferous heritage, and its use as a scientific and cultural attraction, contributing to the economic development of the region. The discovery and beginning of paleontological research in the Lapa Doce Cave, in the municipality of Iraquara, Chapada Diamantina region, Bahia, northeastern Brazil, in the years of 2019/2020, motivated the implementation of a project with a partner between Lapa Doce Group, Bahia Speleology Society and the Natural History Museum of the Federal University of Alagoas (MHN-UFAL), similar to the one developed in the municipality of Maravilha, in the state of Alagoas, Northeast Brazil. The proposal consists of the implantation of a visitor center, with an exhibition of the fossils found inside the Gruta Lapa Doce, as well as of the installation of a paleontology laboratory, under the guidance of the Paleontology Sector of MHN-UFAL, which conducted the excavations and conservation of found fossils.

The visitor center will show the fossil specimens found, the taphonomic processes that led to the formation of the deposits, the sedimentological aspects of the deposit, the identification of the species, their paleoecology and the paleoenvironmental reconstitution of the area.

The laboratory will have a storage room for the collected material, a preparation room, a study office and a storage room for the collection not exposed in the visitation center. The monitors must be members of the local school-age community, who will be guided by the MHN-UFAL team. In Brazil, in the state of Piauí, municipality of São Raimundo Nonato, similar activities have been performed for more than twenty years, with the implantation of a visitor center, museum and an advanced campus of the Federal University of the São Francisco Valley (UNIVASF), however the objective of this research is to relate what is being developed in Alagoas through the Natural History Museum in the municipality of Maravilha with the partnership signed with the Lapa Doce Group in the municipality of Iraquara, Bahia.

2. Material and methods

The Lapa Doce Farm, in which the Lapa Doce Cave is located, is located at 12 ° 19’54” S and 41 ° 36’22” W, in the municipality of Iraquara, state of Bahia, Brazil. The cave has sum total of 46 km of surveyed passage. The Lapa Doce system has three large galleries open to tourists. The main gallery, open to tourism for about 30 years, has an extension of 900 m. In the middle of this passage, the authors found the first fossils, mainly of Pleistocene mammals (Fig. 1), together with reptiles, amphibians and birds.

The surface survey consists of walks along the gallery, observing the most favorable places for the accumulation of bioclasts by draining surface waters that penetrate the karst system.

After the location of the fossils, the site was demarcated and registered for further research intervention and adaptation for tourist observation in situ, when feasible. Taphonomic, sedimentological and geological features of fossiliferous concentrations are being observed. Most of the fossils found on the clay substrate are currently being removed, observing their position and orientation. After protection and conditioning, they are transported to the Integrated Laboratories of Paleontology and Speleology of the Natural History Museum of the Federal University of Alagoas (LIPE-MHN-UFAL), where they are cleaned, glued, prepared, identified and registered.

After the preparation of the fossils, they will return to the Lapa Doce Farm and will be on display at the Visitors Center, to be implanted for educational and tourist activities.

Taxonomic identification is being conducted from the analysis of the specialized literature, through the physical collection and the image bank of LIPE-MHN-UFAL and from research in collections of other institutions.

Adaptations of the literature are being used for basic taphonomic analysis (BEHRENSMEYER, 1991; HILL, 1980; SHIPMAN, 1981; LYMAN, 1994, 2008; ROGERS, 1994; EBERTH ET AL., 2007).

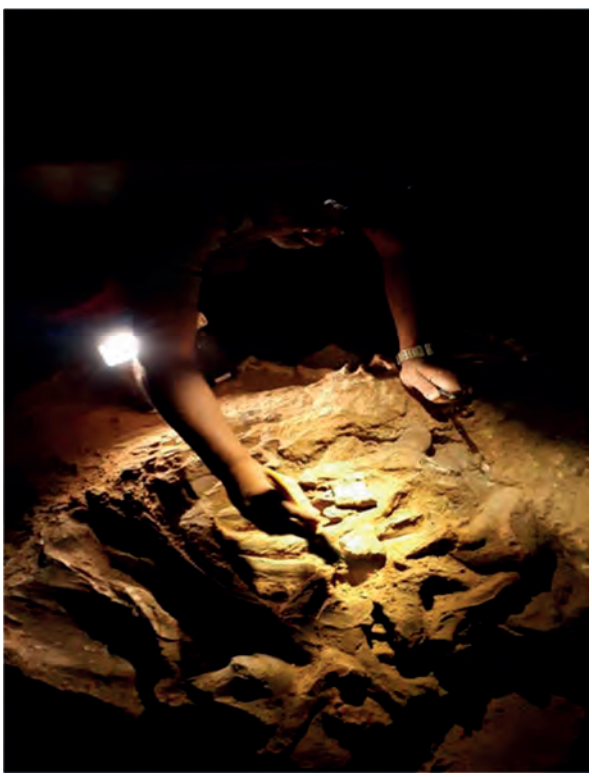

Figure 1: Block cemented by calcite containing part of the upper skeleton of the extinct land sloth, Glossotherium *sp. (Photo by Ana Paula LOPES, 2020).*

Observing the following macroscopic taphonomic features: (i) physical integrity (degrees of completeness of the skeletal elements - complete, partial and/or fragment; (ii) disarticulation (articulated/disarticulated); (iii) marks of desiccation, according to the stages weathering; (iv) abrasion stages; and (v) incrustation stages. We have not yet

observed human actions on the bones, as the work is in its initial phase.
Sediment samples are being collected for sedimentological analysis, mineral samples are also being collected for dating and geochemical analysis. In places where the fossils are in situ, sessions are being held to observe the stratigraphic profile.

On the surface, close to the Lapa Doce farm headquarters restaurant, a deactivated school is being converted into a paleontology center, with a preparation laboratory, collection room, office and material entry room coming from the field.

3. Results

To date, 221 whole or fragmented skeletal pieces of fossils and recent material have been found and collected, belonging to the classes Amphibia, Reptilia, ave and Mammalia. With at least twenty taxa, predominating the Mammalia class, being: three species of *Xenarthros*, the terrestrial sloths, *Eremotherium laurillardi*, *Glossotherium* sp. and a third species, possibly, *Catonyx curvieri*, of the camelid *Paleolama major*, of *Notoungulata Toxodon* platensis, of unidentified cats, giant armadillos, such as *Panochhtus* sp., two smaller armadillos, three rodents, including an extinct Coendou, the deer *Mazama* sp., Marsupials, reptiles, amphibians and birds, in the tourist section and in the area of fossiliferous occurrence (fig. 2). We observed a significant temporal mixture, with Pleistocene and Holocene specimens, mainly in the section formed by sedimentary deposition influenced by rainwater during periods of greater precipitation and which infiltrate through cracks and openings in the carbonate rock.
While research continues in the interior of the Lapa Doce Cave, an area was selected near the headquarters of the tourist attraction to install a visitor center that will tell the story of the speleological activities in the area, geology, the presence of human groups prehistoric in the region and the fossil organisms found in the paleontological research being developed. The visitation space project is under development and will be adapted to the environment where it will be inserted. A paleontology laboratory will be set up in the area, in order to facilitate research and preparation of fossil specimens for storage in collections and public exhibition at the Lapa Doce Cave visitor center. The activities of the visitation center and the laboratory will be developed with young people of school age in the municipality of Iraquara and neighboring municipalities, who will undergo training of specialists from the Integrated Laboratories of Paleontology and Speleology of MHN-UFAL. The museum team has been carrying out paleontological research will provide technical support in museum and research activities for the local community.

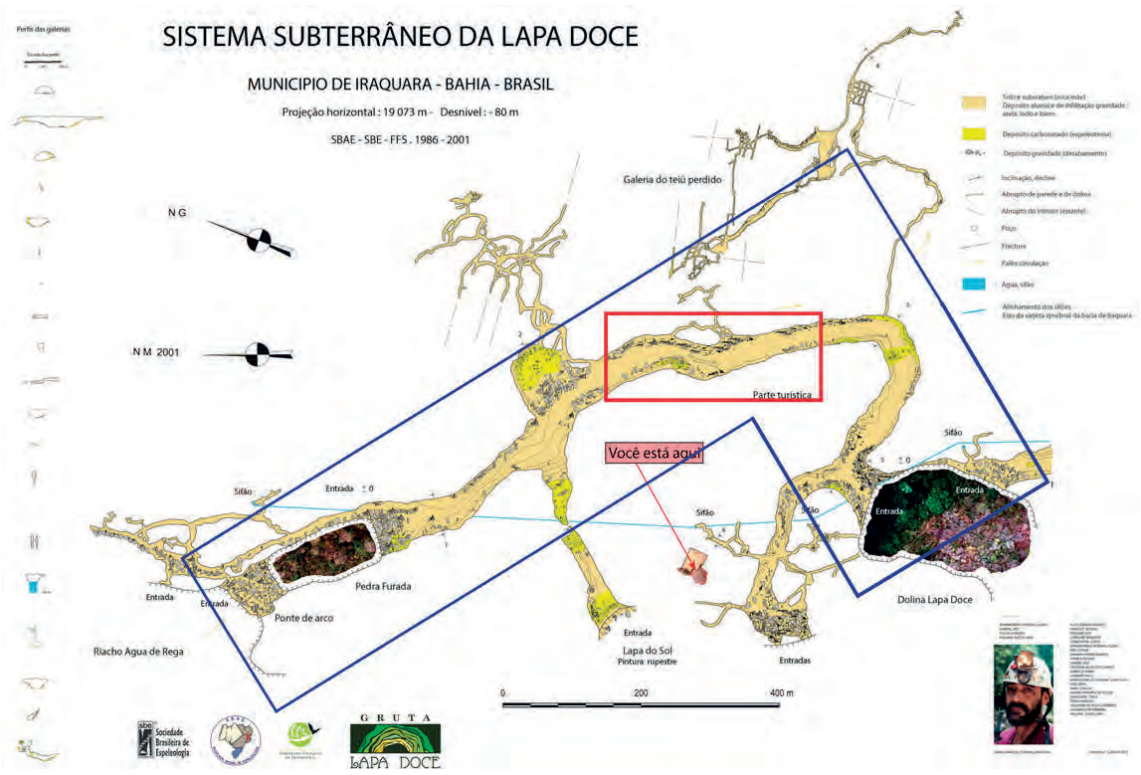

Figure 2: Map of Lapa Doce Caves System, in blue, traditional tourist section, highlighted in red for the area with the occurrence of fossils. Modified from Hez, G. (2001) by Nascimento, J.S.O. (2021).

4. Discussion

The municipality of Iraquara has one of the highest concentrations of natural cavities in Chapada Diamantina, the central region of the state of Bahia. Some of the cavities are already used in speleotouristic activities, which

guarantees a means of economic sustainability for the owners of these areas and the local community.

There is a need to associate this speleotouristic potential with the area's scientific and cultural heritage, adding greater value to the visits made. It is important to highlight that the scientific and cultural activities incorporated into the existing activities, will allow a greater involvement of the local community, schools and young people, motivating them to research, value and protect this heritage.

Research on fossils in the Lapa Doce Cave is in its initial phase, already revealing significant potential due to the diversity of taxa found, some are of first record in the area as *Toxodon* sp., possibly terrestrial sloth *Glossotherium phoenesis* and *Eremotherium laurillardi,* the most common of the terrestrial sloths found in Brazilian territory and registered now in Gruta Lapa Doce. Osteodermos of glyptodontidae, *Panochthus* sp., was collected and two other smaller armadillos not yet identified. The paleontological potential of Iraquara in Bahia is similar to the municipality of Maravilha in the state of Alagoas, Northeastern Brazil, which created a paleontology museum called "Paleontological Museum Otaviano Florentino Ritir" (Fig. 3, A and B), to expose the fossils found in the region by research carried out by paleontologists from LIPE-MHN-UFAL in 2001. Maravilha is a municipality with 10 thousand inhabitants and its small museum has already received about 30 thousand visitors from 26 different nationalities. The initiative resulted in the preservation of the area's fossil heritage, as well as bringing economic alternatives to residents of the municipality who developed economic activities aimed at scientific/cultural tourism.

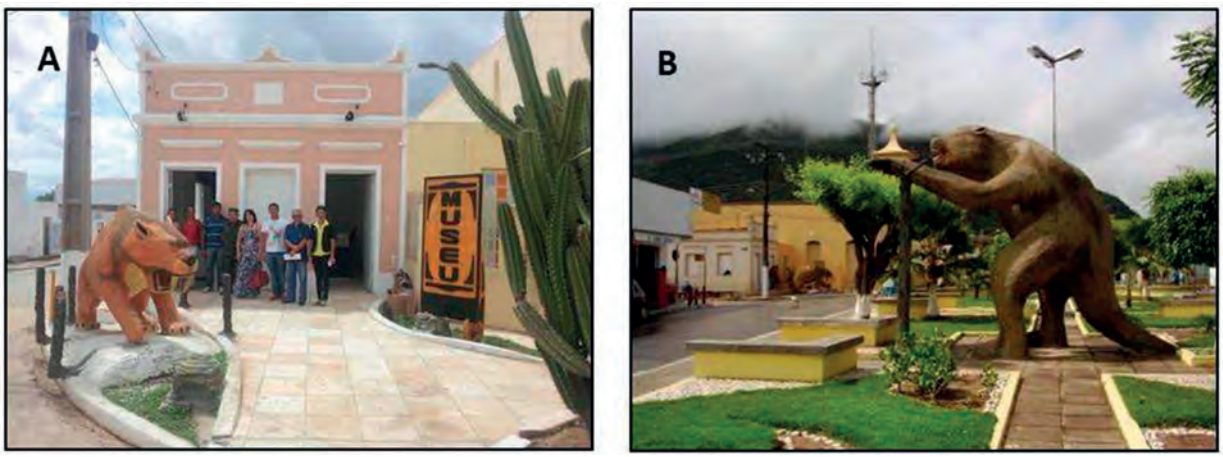

Figure 3: Image of the facade of the Maravilha, Alagoas (A) paleontological museum; in (B) reconstitution in the central square of the municipality of the land sloth Eremotherium laurillardi. Photo (A) Luciano Lemos, 2014, Photo (B) Ana Paula Lopes, 2005.

5. Conclusion

The rate diversity found in the surveys started in January 2020, demonstrates the relevance and the need for continuing studies in the Lapa Doce Cave and in the natural cavities of the municipality of Iraquara, BA. Excavations with taphonomic studies using judicious methodologies should reveal a substantial number of specimens and taxa inside the Lapa Doce Cave. The implementation of a paleontology laboratory in the area will facilitate and accelerate the work performed in the area. The construction of a tourist visitor center with an exhibition of the fossils found will give greater visibility to the real potential of the municipality and the region of the Chapada Diamantina National Park.

Acknowledgment

To Lapa Doce Group and Bahia Speleology Society *in the person of Cláudia Lima for the partnership in the work, to Gabriel Hez for the support in the topography, to the guides of Gruta Lapa Doce and to Johnson Sarmento for his help in the field activities.*

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Complejo de Cuevas Ventana: Estudiando el Arte Rupestre encontrado en las Cuevas Ventana Superior, Intermedia e Inferior (Puerto Rico)

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Resumen

Puerto Rico es una isla del Caribe que pertenece a las Antillas Mayores y es considerada como una de las de mayor contenido de arte rupestre en la zona. Siendo a su vez una isla relativamente pequeña cuenta con gran variedad de este arte, tanto en sus costas y ríos como en sus abrigos rocosos y cuevas. Entre los lugares registrados con este arte se encuentra el Complejo de Cuevas Ventana, la cual, por su localización geográfica demuestra ser única en nuestra isla. Este complejo de cuevas se comprende de tres cuevas: Superior, Intermedia e Inferior donde solamente se han realizado estudios en las primeras dos. La Gruta Troglodita Norman Veve se ha dado a la tarea de explorar estas cuevas con la intención de completar la documentación cartográfica de las tres cuevas. Como miembro de esta organización me he dado a la tarea personal de trabajar en la documentación de su arte rupestre y comenzar un estudio más abarcador entre las tres cuevas ya que en los estudios anteriores no se habla de la Cueva Ventana Inferior. Los estudios realizados y de dominio público datan del 1996 y el más reciente en 2017.

Abstarct

Studies of rock art observed in Cuevas Ventana Superior, Intermediate, and Inferior (Puerto Rico). Puerto Rico is an island of the Caribbean which is part of the Greater Antilles, also considered as one with the most rupestric art documented as well. Being also a small island, it holds a vast variety of this prehistoric art throughout its coasts, rivers, rock shelters and caves. Among the documented places with rupestric art in Puerto Rico there is one called “Cueva Ventana” or Window Cave which, because of its geographic location, is unique on the island. This cave system is formed by three caves: Superior, Intermediate, and Inferior. Only the rupestric art in the first two caves have been documented. The Norman Veve Grotto (Gruta Troglodita Norman Veve) have been exploring these caves to complete the cartography of the Cave System. As a member of this group, I have been working on the documentation of its rupestric art to start a deeper study of the caves since the “Cueva Ventana Inferior” has not being included in any of the studies being made. The documented studies of the first two caves date since 1996 being the most recent published in 2017.

Por años, la Cueva Ventana o “Window Cave” ha sido una de las principales atracciones turísticas de Puerto Rico. A diario miles de turistas locales e internacionales la visitan con el deseo de poder tomar la tan codiciada foto que solo este lugar puede brindar. Un paisaje de ensueño desde la misma cueva a todo el valle de Arecibo.

Pero Cueva Ventana es mucho más que una atracción turística. En su interior guarda las huellas de nuestros antepasados. El arte rupestre grabado en este lugar lo convierte en un baluarte histórico que cautiva la intriga paleontológica y arqueológica también.

Figura 1: Valle de Arecibo desde Cueva Ventana.

Figura 2: Petroglifo en Cueva Ventana Superior.

Este sistema de cuevas, al cual se le conoce localmente como el Complejo de Cuevas El Consejo se encuentra en la región del Karso Norteño de Puerto Rico. Una vasta región de la isla compuesta mayormente de roca caliza.

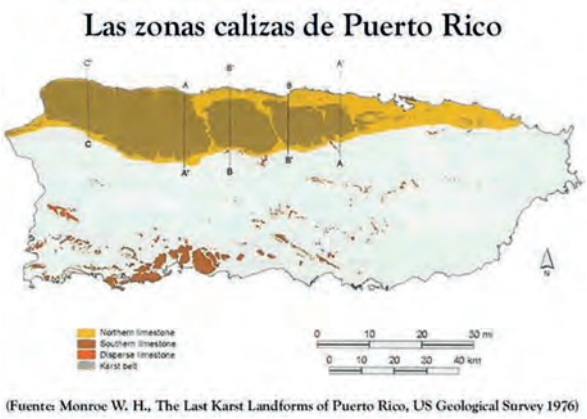

Figura 3: Mapa de las Zonas del Kárstica en Puerto Rico. Fuente MONROE, 1976.

En esta región, que comprende un 90% de la región caliza de Puerto Rico, se han identificado alrededor de 800 cuevas, pero ninguna se compara a estas tres dado a su posición geográfica. Esto se debe a que solamente Cueva Ventana Superior cuenta con acceso desde el bosque, sin embargo, Cueva Ventana Intermedia y Cueva Ventana Inferior solo cuentan con entradas verticales en el borde de su pared cársica a una altura cercana a los 220 MSNM y de un ángulo prácticamente de 90 grados.
A simple vista se podría asumir que el acceso a estas cuevas es estrictamente posible con sistemas modernos de ascenso y descenso vertical, sin embargo, los estudios arqueológicos realizados en la zona nos demuestran que nuestros antepasados habitaron estas cuevas. Esto obliga a preguntarnos: ¿Como lograban el acceso al lugar?
De las tres cuevas que comprenden este sistema, solamente las primeras dos han sido estudiadas y documentadas. Entre los estudios arqueológicos realizados, para el año 1996, el arqueólogo Roberto Martínez Torres encontró en Cueva Ventana Superior un depósito arqueológico prearahuaco fechado entre 2490 y 950 a.C.

Para el año 2017, el arqueólogo Reniel RODRÍGUEZ RAMOS (2017) realizó un estudio en Cueva Ventana Intermedia, también conocida como Cueva León (dado a una pictografía que ha sido comúnmente asociada con este felino en su interior). En su estudio encontró que las pictografías tanto abstractas como zoo y antropomorfas en la cueva dataron fechados entre 730 y 390 a.C.

Como resultado de estos estudios, RODRÍGUEZ RAMOS nos dice en su informe que: *"El panel principal de pictografías de esta cueva fue articulado por diversos grupos que, durante muchos siglos, mantuvieron continuidad en su uso para reflejar sus conocimientos, ideas, eventos y/o creencias."* (RODRÍGUEZ RAMOS *et al.*, 2019).

Figura 4: Cueva Ventana Superior, Intermedia e Inferior.

Figura 5: Pictografías en Cueva Ventana Intermedia.

Con la evidencia encontrada en Cueva Ventana Superior e Intermedia de arte rupestre, vasijas, caracoles terrestres, peces marinos y de río, aves y crustáceos, entre otros se demuestra que estas cuevas fueron sin lugar a duda refugio para nuestros antepasados por generaciones.
Pero todo lo que hasta la fecha se ha documentado de esta zona comprende estudios realizados en Cueva Ventana Superior e Intermedia, dejando en el olvido a Cueva Ventana Inferior.
Con el propósito de explorar esta última cueva, un grupo de espeleólogos decidimos coordinar un descenso en marzo del 2020. Para ello coordinamos acceso al lugar a través del personal que administra los recorridos turísticos a Cueva Ventana Superior.

El propósito de este viaje inicial era solamente para explorar la cueva y como sabíamos que el acceso era vertical nos enfocamos en conseguir la ruta que nos facilitara el descenso y ascenso vertical.

Para ello, logramos encontrar una vereda que nos permitía llegar dese Cueva Ventana Superior hasta la Ventana Intermedia. En medio de este camino logramos identificar un punto de anclaje que nos permitiría el descenso hasta la Ventana Inferior.

Figura 6: Descenso Vertical a Cueva Ventana Inferior.

En nuestra primera visita logramos explorar la cueva y apreciar las pictografías que se encuentran en su interior. A mi entender, el arte rupestre en Ventana Inferior es mucho más elaborado que el documentado en Ventana Superior e Intermedia, por lo que decidí entonces comenzar un proyecto de documentación en esta cueva.

Figura 7: Pictografías en Cueva Ventana Inferior.

Es entonces donde La Gruta Troglodita Norman Veve coordina en el mes de julio, 2020 una segunda exploración con el propósito de:

1. Analizar rutas de acceso alternos al lugar
2. Documentar el arte rupestre digitalmente
3. Trabajar en la cartografía de la cueva

En nuestro esfuerzo logramos conseguir una vía de acceso alterna, pero aun así requiere la utilización de equipo vertical.
En cuanto a las pictografías encontradas logramos identificar 10 con medidas desde 6 pulgadas hasta 24 pulgadas de longitud.
Mientras un grupo se dedicaba a inventariar el arte rupestre, otro grupo se dedicó a tomar las medidas de la cueva para su cartografía. El mapa de esta tercera cueva ya está en desarrollo y prontamente tendremos su mapa digitalmente, aunque esperamos poder en un futuro contar con la tecnología LIDAR para crear un modelo tridimensional también.
Aunque al momento logramos identificar dos rutas de acceso vertical para la Cueva Ventana Inferior, contamos con un inventario digital de su arte rupestre y el mapa de la cueva esta en proceso, cabe destacar que nuestro estudio aun está en sus comienzos.

Figura 8: Miembros de GTNV cartografiando la cueva.

En viajes futuros se pretende explorar posibles veredas por donde en tiempos pasados pudiesen lograr acceso al lugar. Al momento no se ha podido localizar ninguna ruta prexistente hasta esta cueva, pero según las personas que residen ese sector existen historias de que en el siglo pasado existían veredas ancestrales que les permitían acceso desde el valle de Arecibo hasta la montaña donde están las cuevas. Próximamente se estarán coordinando viajes con los residentes de la zona para explorar estas veredas con el propósito de aprender mas del lugar y de ser posible encontrar algún camino que llegue hasta estas cuevas.

Por otro lado, aunque ya hemos documentado fotográficamente las pictografías de esta cueva, necesitamos que se realicen pruebas en las mismas para determinar su antigüedad y poder relacionarlas con las documentadas en Cueva Ventana Superior e Intermedia.
Debido a la situación de la pandemia que el mundo vive actualmente con el COVID-19, solamente hemos logrado realizar tres viajes a este lugar en el 2020, siendo el tercero uno meramente de exploración en busca de alguna ruta de acceso alterno al lugar.

Esta exploración es sumamente importante para nuestro proyecto ya que de eso depende, primeramente, el obtener un mejor entendimiento del comportamiento de nuestros

antepasados en estas cuevas como también nos daría una ventaja con un acceso más seguro tanto para nuestro grupo como para que nuestros colegas científicos puedan acompañarnos y de esta manera completar las pruebas necesarias de fechado en las pictografías.

De esta manera se facilitaría una exploración más abarcadora en el futuro donde se puedan realizar investigaciones arqueológicas y paleontológicas por igual que nos ayude a asociar estas tres cuevas entre sí.
Nuestra meta principal para el ano 2021 será encontrar un mejor acceso a esta cueva y capacitar nuestros científicos en técnicas verticales para así lograr el fechado de estas pictografías y poder tener un mejor entendimiento del panorama de nuestros antepasados en esta zona.

Entendemos la importancia de estudiar el arte rupestre en su lugar de origen ya que, tal y como nuestros colegas espeleólogos cubanos explican: *"el estado deseado de la contrastación teórica puede y debe asumirse desde la observación, documentación, y recuperación, las cuales nos deben asegurar o, al menos, intentar asegurar, la recuperación del sistema, en la mayoría de las partes que lo integran; esclarecer y decodificar los niveles, relaciones, jerarquías, interacciones y retroacciones, entre cada uno de los símbolos y entre ellos y el entorno."* (GUTIÉRREZ CALVACHE & GONZÁLEZ TENDERO, 2016).

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Quaternary fauna of the Aguas Buenas cave system, Aguas Buenas municipality (Puerto Rico)

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Abstract

The "Sistema de Cuevas de Aguas Buenas" (SCAB) was developed in Cretaceous limestone bounded by insoluble volcanic rocks, located in northern Puerto Rico. The initial collection of fossils in SCAB was carried out at four localities within the system. The fossils were recovered in the sediments from topsoil or by sieving but were not found in a layer horizon per se. The mammal fauna found in SCAB can be used to establish a minimum age of 33,670 ± 370 years before the present (Pleistocene) for the semi-arboreal sloth (*Acratocnus odontrigonus*). Other fossils found were the large hutia (*Elasmodontomys obliquus*) and smaller hutia (*Isolobodon portoricensis*), as well as birds such as the crow (*Corvus* sp.), Audubon shearwater (*Puffinus lherminieri*), the Antillean cave rail (*Nesotrochis debooyi*), and reptiles such as the giant anole (*Anolis cuvieri*), the land iguana (*Cyclura* sp.) and amphibians such as the coqui (*Eleutherodactylus* sp.) and the toad (*Peltophryne* sp.). SCAB provides new information relating to the distribution of Quaternary fossils in northern Puerto Rico. Although most of the fauna found in this deposit have already been collected from other localities, the encrusted bones of the anuran *Peltophryne* sp. and other data are evolutionary and paleobiogeographical clues.

Resumen

Fauna cuaternaria del sistema de cuevas de Aguas Buenas, municipio de Aguas Buenas (Puerto Rico). El "Sistema de Cuevas de Aguas Buenas" (SCAB) se desarrolló en la caliza del Cretáceo unida por rocas volcánicas insolubles, localizadas al norte de Puerto Rico. La colección inicial de fósiles en SCAB se llevó a cabo en cuatro localidades en el sistema. Los fósiles fueron recobrados de los sedimentos en la capa superficial del suelo o mediante tamiz, pero no se encontró un horizonte como tal. La fauna mamífera obtenida en SCAB puede ser usada para establecer una edad mínima de 33,670 ± 370 años antes del presente (Pleistoceno) para el perezoso semi-arbóreo (*Acratocnus odontrigonus*). Otros fósiles encontrados fueron la jutía mayor (*Elasmodontomys obliquus*), y la jutía menor (*Isolobodon portoricensis*), de igual manera que aves como el cuervo (*Corvus* sp.), el pamperito (*Puffinus lherminieri*), el rálido de cueva antillano (*Nesotrochis debooyi*), y reptiles como el chipojo (*Anolis cuvieri*), la iguana terrestre (*Cyclura* sp.) y anfibios como el coquí (*Eleutherodactylus* sp.) y el sapo (*Peltophryne* sp.). SCAB provee nueva información respeto a la distribución de los fósiles del Cuaternario en el norte de Puerto Rico. Aunque la mayor parte de la fauna hallada en estos depósitos ha sido colectada de otras localidades, los huesos incrustados del anuro *Peltophryne* sp. y otros datos son pistas evolutivas y paleobiogeográficas.

1. Introduction

The Aguas Buenas Cave System (in Spanish "Sistema de Cuevas de Aguas Buenas" or SCAB) is located in what is now a natural reserve in northern Puerto Rico. In this reserve, 42 cave entrances to the system and nearby caves have been detected thus far, all located in the municipality of the same name. SCAB limestones dates from the Early Cretaceous during the Albian (113-100.5 million years ago). The dominant geology includes volcanic material deposited under a predominantly marine environment during the Early-Late Cretaceous, with plutonic incrustations or late intrusions (magmatic rocks of slow cooling under the soil surface) and recent landslides (BECK *et al.*, 1976; LUGO *et al.*, 2001; RICHARDS, 2002). This entire surface is highly weathered or altered by the pluvial precipitation of the area. The whole system consists of several kilometers of galleries and passageways. The Río Caguitas is a tributary stream of the Río Grande de Loíza and has its origin in this cave system (BECK *et al.*, 1976; RICHARDS, 2002).

In 1976, the National Speleological Society (NSS) and the Sociedad Espeleológica de Puerto Rico, Inc. (SEPRI) published a geological, hydrological, and biological report in SCAB that was compiled by several specialists, including one of the mentors of the third author of this report, Nicaraguan Prof. Juan R. Carvajal Zamora (BECK *et al.*, 1976). Prof. Carvajal Zamora was a limnologist and mycologist who undertook the first scientific studies relating to the existence and ecology of the ascomycete microfungus *Histoplasma capsulatum*, which causes the disease known as histoplasmosis (BECK *et al.*, 1976). SCAB has caused an ancestral fear to all speleologists of the old guard because it brings ungrateful reminders of histoplasmosis and its consequences. Indeed, we must not underestimate the

etiological capability of the fungus and its danger, particularly if a person is ill and irresponsibly visits caves, since we assure you that it could be lethal (at least in a 14% of the cases), but not all persons who explore SCAB or other caves in Puerto Rico develop symptomatology. But in this regard, the third author will treat cave histoplasmosis in Puerto Rico in another publication.

Through the years there have been explorations of SCAB by different local speleological groups, but recently the Gruta Troglodita Norman Veve (GTNV) has thus far have recorded 20 additional entrances, increasing the total known to 42 entrances of the caves, which are related to a net of caverns interconnected by their hydrology or physically, a set extended by several kilometers. Although scientific explorations of SCAB began at the turn of the 19th Century, Pre-Columbian evidence is still embodied in the rock art of the walls and entrances of the system, like the Post-Columbian art. In 2003-2006, systematic archaeological excavations in Cueva Clara (SCAB) found no fossil material (Carlos AYES SUÁRES, pers. comm., 12 November 2020). Studies and documentation of the system still continue in the 21st Century.

2. Paleofauna of SCAB

The study of SCAB and the initial collection of fossils were carried out in four localities within the system with particular characteristics. These were visited as follows: Site 01 (9 September 2010; 4 January 2011), Site 02 (16 April 2017), Site 03 (6 August 2016) and Site 04 (19 October 2016). Fossils were deposited in the Paleobiology Collection of the Smithsonian Institution tentatively (NMNH, uncatalogued). The fossils were recovered in the sediments from topsoil or by sieving, but there was no layer horizon per se. This highlighted the possible internal collapses, runoffs, or landslides inside the cave. The mammal fauna was represented by the semi-arboreal sloth (*Acratocnus odontrigonus*), the plate-toothed giant hutia (*Elasmodontomys obliquus*) (Figure 1), an undetermined rodent, and an undetermined bat. The term undetermined does not mean a new species but that these bones lack the anatomical elements for their taxonomical identification.

During the Pleistocene (between 2.59 mya to 11,700 years ago) in SCAB there existed the sloth (*A. odontrigonus*), giant hutia (*E. obliquus*), and smaller Puerto Rican hutia (*Isolobodon portoricensis*), as well as birds such as the crow (*Corvus* sp.) (Figures 2, 3), Audubon shearwater (*Puffinus lherminieri*) (Figure 4), the Antillean cave rail (*Nesotrochis debooyi*) (Figure 5), and reptiles such as the giant anole (*Anolis cuvieri*) (Figure 6), the land iguana (*Cyclura* sp.) and amphibians such as the coqui (*Eleutherodactylus* sp.) and the toad (*Peltophryne* sp.).

Figure 1: Right proximal femur of plate-toothed giant hutia (Elasmodontomys obliquus)

Figure 2: Right humerus of a crow (Corvus sp.)

Figure 3: Left carpometacarpus of crow (Corvus sp.)

Figure 4: Left tarsometatarsus of Audubon's shearwater (Puffinus lherminieri)

Figure 5: Distal tibiotarsus of Antillean cave rail (Nesotrochis debooyi)

Figure 6: Lingual view of lower jaw of a giant anole (Anolis cuvieri)

In early vertebrate paleontological studies of SCAB, there are collections made by the National Speleological Society and the Smithsonian Institution at the end of the 1970s, showing new records. At present, GTNV has identified four paleontological sites inside SCAB, extending to unsurveyed sections of the cave system. Although paleontologists are always looking for novel discoveries, much is what we should comprehend regarding our prehistory. A fossil hutia tooth (*Isolobodon portoricensis*) was collected by U.S. speleologist Barry F. Beck and the sloth *A. odontrigonus* in "one of the new portions" of this cave system was reported in 1976 in the NSS Bulletin (BECK *et al.*, 1976). Pleistocene fauna (Quaternary) of Puerto Rico has been studied by many paleontologists during the course of the early and late twentieth century, making use of comparative anatomy as well as more recently with molecular biology. More recent studies have been carried out, as well as discoveries and relationships of the extant and extinct fauna with respect to the rest of the Quaternary fauna on Puerto Rico and nearby Caribbean islands (ITURRALDE-VINENT, 2006; VÉLEZ-JUARBE & MILLER, 2007, FABRE *et al.*, 2014). This fauna includes toads, frogs, geckos, lizards, crocodilians, birds, insectivores, rodents, bats, and sloths. Puerto Rico currently has no taxa related to some of these fossils, as in the case of mammals, which the extinction could be accounted to 100%. Some of these organisms had representative taxa present in Puerto Rico since the Oligocene and Miocene (PREGILL, 1981; PREGILL *et al.*, 1988; MACPHEE & WYSS, 1990; ITURRALDE-VINENT, 2006; DELSUC *et al.*, 2019).
SCAB brings additional data relating to Quaternary fossils in the north of Puerto Rico. Although most elements of the fauna found in the SCAB deposits have been collected in other localities, we did document an unusually large tibiofibular, calcanium and talus of a *Peltophryne* sp. The age of the deposit is Pleistocene, based on the set of fossils found in this locality. The mammal fauna found in this cave can be used to establish a minimum age of 33,670 ± 370 years before the present (Pleistocene) according to the latest data reported for *A. odontrigonus* (MCFARLANE, 1999). The fossil bird record in SCAB included a carpometacarpus, a humerus, and six ulnae probably of crow (*Corvus* sp.), tarsometatarsus of Audubon shearwater (*P. lherminieri*), and the distal tibiotarsus of an Antillean cave rail (*N. debooyi*) (Figures 2-5) (Storrs L. OLSON, pers. comm., 10 March 2011). *Puffinus lherminieri* has been reported from both paleontological and archaeological sites in the West Indies (PREGILL *et al.*, 1988).
From the Barahona Caves in Morovis [today the Reserva Las Cabachuelas], McFARLANE (1999) via radiometric dating found the last occurrence dates for *Nesophontes*, *Elasmodontomys* and *Heteropsomys* to be in the mid-Holocene and thus overlap with Amerindian occupation of the island. *Acratocnus* is known only from the Late Pleistocene. However, *Acratocnus* and *Elasmodontomys* in middens or another anthropogenic context has never found, and *Acratocnus* has not been found in superficial context as reported by McFARLANE (1999). DELSUC *et al.* (2019) reported that Caribbean sloths have a single origin and two divergence lineages and not related to the two-fingered sloth.

The fossil herpetofauna collected in SCAB is represented by the lower jaw of *A. cuvieri* from SCAB fossil material. This lower jaw is of the correct size and displays the heavy sculpturing laterally (Gregory K. PREGILL, pers. comm., 30 March 2011). In 1996, archaeologist José Muñoz Vázquez also recovered the lower jaw of a fossilized *A. cuvieri* during an exploration of Cueva Matos, near Cueva Ventana in the municipality of Arecibo, that is similar to the one recovered from SCAB. Also in SCAB, the fossilized vertebrae of a frog was unearthed, possibly an *Eleutherodactylus* or *Leptodactylus*. Additionally, an anuran tibiofibula was found although the species could not be established. Similar findings were identified by Storrs L. Olson (Smithsonian Institute, Washington. D.C.), he mentioned to us that many other bones clearly showing bats, other mammals, and a great anuran. However, Olson noted an anuran bone to be well embedded in the substrate, so he suspects that it must have been of a native species. He also considered that this anuran to be *Peltophryne* sp., but he did not know that they grew so large (Storrs L. OLSON, pers. comm., 10 March 2011). The appearance of *Peltophryne* sp. in SCAB is important due to its paleobiogeographical distribution and reduced populations of today due to anthropogenic depletion. The paleoenvironment seems to have been characterized by xeric conditions such as today in karst fringes in southern Puerto Rico.

3. Conclusions

SCAB provides new information relating to the paleobiogeography of Quaternary fossils in northern Puerto Rico. Although most of the fauna found in this deposit have already been collected from many other caves in northern Puerto Rico, the unusual size of the encrusted bones of the anuran *Peltophryne* sp. is noteworthy with regards to the appearance of some of the fossils in this cave. Paleontological studies in SCAB are just beginning, with many surprising findings yet to be reported.

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Les espaces sépulcraux en milieu karstique dans les Alpes nord occidentales : synthèse des chaînes opératoires et approche des pratiques de gestion de l'espace funéraire du Paléolithique à l'âge du Bronze

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Résumé

La géologie influence les pratiques funéraires au cours de la préhistoire. Tumulus ou sépultures en silos se trouvent en plaine, les hypogées sont nombreux dans les collines gréseuses, enfin les grottes et les karsts prennent des dimensions sépulcrales. L'environnement se lit dans les variations des chaines opératoires et la gestion des espaces sépulcraux. Du Paléolithique à l'âge du Bronze, les pratiques funéraires évoluent de manière non linéaire. Cette synthèse montre un passage progressif de la tombe individuelle vers des sépultures collectives, associé à une pluralité de chaines opératoires ou les différents degrés de préservation de l'intégrité squelettique des défunts vont de pair avec les inégalités sociales. L'espace funéraire des sépultures individuelles est limité, tout en n'empêchant pas des aménagements. Pour les sépultures collectives, l'implantation est d'autant plus forte que le temps d'utilisation est long. Vont apparaître des espaces de circulation, d'autres de dépôt, des cloisonnements afin de condamner des espaces familiaux. Le génie des hommes de la Préhistoire s'attache à rendre les dépôts funéraires stables dans le temps en parant à toutes éventualité de flux sédimentaires. Murets de soutènement, obturation de conduit en sont les résultats. Ainsi grotte, puits, diaclases ou fissures seront investis de façon appropriée.

Abstract

Graves in a karst environment in the north-western Alps: synthesis of the operating chains and approach to practices of the funerary space from the Palaeolithic to the Bronze Age. Geology influence funeral practices during prehistoric times. Tumulus or silo tombs are found in the plain, hypogeums are numerous in sandstone hills, and finally karsts take on sepulchral dimensions. The environment can be read in the variations of the operating chains and the management of sepulchral spaces. From the Paleolithic to the Bronze Age, funeral practices evolved in a non-linear fashion. This synthesis shows a gradual passage from the individual tomb to collective burials, associated with a plurality of operational chains where the different degrees of preservation of the skeletal integrity of the deceased go hand in hand with social inequalities. The burial space of the individual burials is limited, while not preventing improvements. For collective burials, the implantation is stronger as the time of use is long. There will appear circulation spaces, other storage areas, partitions to condemn family spaces. The genius of prehistoric men strives to make funerary deposits stable over time by dealing with any eventuality of sediment flows. Retaining walls, duct sealing are the results. Thus cave, wells, joints or fissures will be appropriately invested.

1. De la contrainte géologique

C'est peut-être un truisme de dire que la géologie influence les constructions humaines et de fait les modalités funéraires au cours de la préhistoire. Un regard sur une carte archéologique nous apprend que la répartition des nécropoles, tumulus ou sépultures en silos se trouvent en plaine, que les hypogées sont nombreux dans les collines gréseuses, et enfin que les grottes et les karsts prennent des dimensions sépulcrales. L'environnement se lit dans les variations des chaines opératoires et la gestion des espaces sépulcraux. Une approche diachronique permet un croisement des données d'anthropologie et d'archéologie funéraire.

2. Les chaines opératoires funéraires en résumé

Du Paléolithique à l'âge du Bronze, les pratiques funéraires évoluent de manière non linéaire. Trois modes se détachent clairement en fonction des pratiques et des degrés de conservation de l'intégrité squelettique des sujets inhumés, (MILLET, 2018).

• Mode 1
Du Paléolithique au Mésolithique, cette période ancienne concerne essentiellement des sépultures individuelles, doubles voire triples, très rarement multiples. D'une manière générale, le squelette est conservé dans son intégrité, déposé dans une fosse. Dans le cas de sépultures multiples les squelettes sont déposés en périphérie de la zone d'habitat avec parfois des manipulations (CAUWE, 1996). À partir du Mésolithique, les sépultures restent majoritairement individuelles, mais il n'est pas rare d'observer des sépultures collectives. Ici les squelettes sont conservés dans leur intégrité et déposés dans une fosse. Mais il peut arriver que des pièces choisies, des crânes, soient réunies pour être inhumées (JEUNESSE, 2012).

• Mode 2
À partir du Néolithique, les sépultures multiples et collectives deviennent la règle, alors que les sépultures individuelles se font plus rares. Le squelette reste bien conservé dans son intégrité osseuse, bien que des manipulations soient observées et des éléments squelettiques viennent à manquer. Ces derniers peuvent être enterrés dans une autre sépulture voire à l'intérieur de l'habitat. Les dépôts sont faits dans des espaces funéraires pas toujours délimités. Au cours de la deuxième partie du Néolithique, les sépultures collectives perdurent. Cependant, l'intégrité du squelette n'est plus conservée. Les restes deviennent de plus en plus fragmentaires et mélangés. Leurs dépôts se font dans des fosses ou dans un espace funéraire défini. Bien que le phénomène de crémation existe déjà depuis le Mésolithique, il n'est pas rare qu'il soit pratiqué sur les mêmes lieux. Ainsi peuvent cohabiter plusieurs chaînes opératoires. Ce qui donne des espaces funéraires mixtes.

• Mode 3
À l'âge du Bronze, de nouveaux comportements funéraires se font jour. Les sépultures individuelles sont à nouveau plus fréquentes, souvent associées en nécropole. Les sépultures collectives existent toujours. L'intégrité squelettique est respectée.
Un passage progressif de la tombe individuelle vers des sépultures collectives est observé, associé à une pluralité de chaines opératoires, où les différents degrés de préservation de l'intégrité squelettique des défunts vont de pair avec les inégalités sociales (MILLET, 2018). L'espace funéraire des sépultures individuelles n'est pas limité, et des aménagements sont possibles. Pour les sépultures collectives, l'implantation et leur développement sont d'autant plus forts que le temps d'utilisation est long.

3. Du génie des hommes : aménagements et gestion de l'espace funéraire

Il apparaît que l'aménagement de l'espace funéraire et sa gestion, soient des notions associées aux sépultures collectives. Avec l'émergence de cette complexité et celle due au collectif, vient s'ajouter la délimitation de l'espace sépulcral. Ainsi la problématique posée par le lieu de dépôt funéraire sera son ouverture, son utilisation et sa clôture.

• Des aménagements d'ouverture
La délimitation de l'espace funéraire, dans un espace ouvert, concernera la mise en place de la chambre funéraire. Des nécropoles aux constructions mégalithiques, une ou plusieurs chambres funéraires seront intégrées dans des dispositifs monumentaux : allées couvertes, tumulus ou structure de type Passy. Se pose ici la question de l'accès à la chambre funéraire divisée ou non par cloisonnements en plusieurs caveaux (MASSET, 1997).
Dans un espace fermé, en grotte, et c'est le cas développé ici, avec l'exemple du trou du Renard, à Ribiers, Hautes-Alpes (MILLET, 2018), Figure 1, les hommes vont aménager la zone funéraire en n'omettant pas d'obturer les conduits pouvant être à l'origine de fuites de sédiments et d'ossements. Ainsi de petites dalles, des murets de pierre sèches serviront à colmater et construire l'assise des dépôts funéraires (grotte du Chatelard, BLAZIN, 2003). Une aire de crémation peut être associées aux dépôts (Hypogée des fourneaux, BROCHIER *et al*., 1987).

• Des aménagements progressifs liés à l'utilisation
La délimitation de la zone de dépôt, reflète toutes les possibilités de la grotte. Les aménagements permettront de mettre en place les axes de circulation, l'entrée et la sortie. Suivant la configuration, l'entrée sera aménagée de manière à rendre stable la zone de dépôt, évitant toute vidange possible. Nous pourrons observer alors des murets d'enrochements comme des murs de soutènements. Les pierres seront taillées sur place, comme en témoignent les éclats de calcaires et seront posées sur les voies de circulation permettant aux fossoyeurs d'éviter le piétinement des dépôts. Sinon, les osselets seraient fragmentés, or ce qui n'est pas le cas.

• Gestion de l'espace funéraire
Au fur et à mesure de l'utilisation de l'espace funéraire, les dépôts deviennent conséquents. Ainsi les hommes vont gérer les volumes. Les espaces complets seront fermés par des cloisons de pierres.
Concernant les dépôts eux-mêmes, il y a plusieurs possibilités : dans un premier cas, l'espace au complet servira à déposer les ossements des défunts (abri Fontabert, BOCQUET, 1969a et b, MILLET 2014), avec ou sans manipulations, les restes reposant pêle-mêle ou de manière organisée (grotte des Sarradins, BLAZIN, 2000). Des puits de réseau karstique sec, peuvent être utilisés à ces fins (La grotte de la Balme, Locus III, MILLET & TACUSSEL, 2008). Dans un deuxième cas, des fosses ou des coffres composés de quatre dalles de pierre seront construits. Ces coffres

recevront un ou plusieurs individus (grotte de Souhait, GATTO, 2010). Une dernière possibilité, connue depuis longtemps mais souvent éludée, présente des restes osseux choisis en petits nombres souvent fragmentaires, représentant plusieurs individus, déposés dans de petites fosses ou espaces délimités par quelques pierres. C'est le cas de nombreuses grottes, dont le Trou du Renard, mais aussi la beaume Courdeau (LALLEMENT com. pers., 2020). Ils peuvent avoir été déposés dans un contenant végétal. Ces petites structures peuvent finir par remplir tout l'espace disponible, comme une sorte de colombarium avant la lettre (ROUGE, com. pers., 2015). Leur répartition peut-être plus ou moins aléatoire, ou séparée par de petites cloisons. Certains de ces compartiments se distinguent par la présence de restes d'animaux domestiques (chèvres, moutons, vaches, chiens) ou d'animaux chassés (sangliers, cerfs, loups) et d'armatures. Les animaux seront traités de manière significativement différente selon leur nature domestique ou sauvage. Les inégalités au sein du groupe se traduiront dans le recrutement des défunts et dans l'organisation de leurs dépôts. Enfin si la totalité de l'espace funéraire est remplie, des travaux de terrassement et de nouveaux aménagements vont être réalisés (MASSET, 1997). Généralement une couche de quelques centimètres de sédiments stériles va recouvrir les premiers dépôts et une deuxième étape funéraire pourra alors commencer.

- **Aménagements de clôture**

L'abandon ou l'arrêt de l'utilisation de l'espace funéraire peut donner lieu à des aménagements divers. Les dépôts funéraires vont être recouverts soit par des restes végétaux comme une litière végétale ou du bois, soit par une couche de sédiments stériles ou constituée de déchets domestiques et de restes alimentaires. Enfin l'ensemble pourra être recouvert de petites dalles (La grotte de la Balme, BOCQUET & RAYMOND, 2007).
Cet aménagement de clôture n'est pas toujours visible. Souvent à l'âge du Bronze, l'arrivée tonitruante des hommes de cette époque vont parfois donner lieu à des terrassements nouveaux sans ménager les dépôts funéraires anciens (grotte de l'Aiguille Muret 2006, Grotte du Chatelard, BLAZIN, 2003). Ainsi sur des restes osseux humains d'une autre époque en mode 2 vont reposer des squelettes du Bronze en mode 3 (Les Râcles, BOCQUET, 1963).

Des restes de crémation peuvent être intégrés à ces différents modes funéraires. Ils sont soit simplement déversés dans de petites fosses, soit mis dans des urnes funéraires. À l'âge du Bronze, ces urnes peuvent être déposées en grand nombre dans les cavités, et ainsi constituer des champs d'urnes (BOCQUET & RAYMOND, 2007).

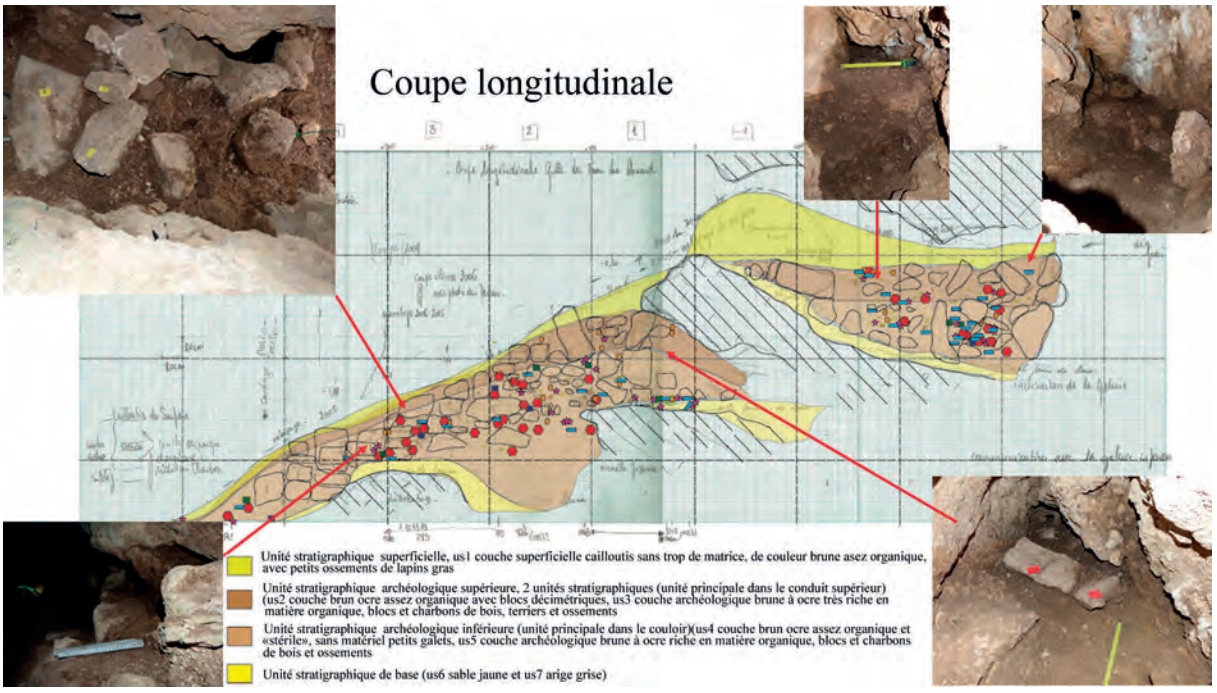

Figure 1 : Stratigraphie du trou du Renard, à Ribiers (Hautes-Alpes) : éléments construits, alvéole, boyau aménagé avec cloison, muret longitudinal et muret transverse devant une niche.

4. Conclusion

L'exemple du Trou du renard, à Ribiers, Hautes-Alpes, montre combien est complexe l'approche de l'archéologie funéraire en grotte. Cette grotte qui s'ouvre par un large porche se resserre très rapidement sur une fine diaclase de 80 cm de largeur et se termine par de petits conduits dont le plus grand mesure 1,42 m de hauteur, une fois vidé. À l'entrée, un mur de soutènement accueille les premiers dépôts. À droite, un crâne ou plus exactement une calotte crânienne retournée comme une coupe est déposée entre trois pierres, et à gauche, de manière symétrique, un bassin.

En montant vers la diaclase, les alvéoles, où sont disposées de petits amas osseux, recouvrent le sol et cela se poursuit dans toutes les directions qu'offre la grotte, dans la diaclase, de même que dans les petits espaces latéraux. Des cloisons colmatent les espaces funéraires pleins. Entre trois pierres sont déposés quelques ossements, des vertèbres, des dents, des phalanges ou quelques fragments d'os longs. Dans le boyau du fond, les restes humains sont plus robustes (correspondant probablement à des individus de sexe masculin). Les os sont bien conservés quoique toujours fragmentaires, et associés à quelques restes d'animaux : du cerf chassé et du chien domestique, du mouton ou de la chèvre et du bœuf. En tout, rien de spectaculaire pourtant toute l'organisation de l'occupation de cette grotte répond à une pensée préhistorique (TESTART, 2016).

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Middle Jurassic sauropod tracks in the Castelbouc cave N°4 (Lozère, France)

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Abstract

Over the last decades, collaborations between speleologists and palichnologists revealed the preservation of theropod dinosaur footprints inside several natural cavities from the Causses Basin (southern France). More recently, we discovered the first trackways of sauropod dinosaurs from this area in the Castelbouc cave N°4. This cavity is located 500 m under the surface of the Causse Méjean plateau, in the «Calcaires à Stipites» Formation which is Bathonian in age (Middle Jurassic). These tracks are up to 1.25 m long, and show impressions of digits, digital pads and claws. Some of the tracks correspond to a new ichnotaxon called *Occitanopodus gandi*. The sediments exposed in the Castelbouc cave N°4 were deposited in a shallow bay or lagoon bordered by conifer-dominated forests. The latter were probably an attractive source of food for Titanosauriformes. This discovery demonstrates the importance of palichnological prospecting inside deep karsts that can offer large roofs preserved from the erosion.

Résumé

Des empreintes de sauropodes dans le Jurassique Moyen de la grotte de Castelbouc n° 4. Au cours des dernières décennies, les collaborations nouées entre spéléologues et palichnologues ont révélé la préservation d'empreintes de dinosaures théropodes à l'intérieur de plusieurs cavités naturelles du Bassin des Causses (Sud de la France). Plus récemment, nous avons découvert de premières pistes de sauropodes dans la grotte de Castelbouc n° 4. Cette cavité est localisée près de 500 mètres sous la surface du Causse Méjean, dans la Formation des Calcaires à Stipites qui est d'âge bathonien (Jurassique Moyen). Ces traces mesurent jusqu'à 1,25 m de long, et montrent des marques de doigts, coussinets et griffes. Certaines de ces empreintes correspondent à un nouvel ichnotaxon nommé *Occitanopodus gandi*. Les sédiments affleurant dans la grotte de Castelbouc n° 4 ont été déposés dans des lagunes et des baies bordées par des forêts de conifères. Ces dernières ont probablement été une source d'alimentation attractive pour les Titanosauriformes. Cette découverte démontre l'importance de mener des prospections palichnologiques à l'intérieur des karsts qui peuvent offrir de larges plafonds préservés de l'érosion.

1. Introduction

Several dinosaur footprints have been mentioned in mines, underground quarries or tunnels from diverse areas throughout the world (e.g. PETERSON, 1924; PARKER & BALSLEY, 1989; COOK *et al*., 2010). However, vertebrate fossil tracks are extremely rare in natural and deep cavities. Up to now, only the Causses Basin (southern France) yielded dinosaur tracks inside karsts. Historically, the first dinosaur tracks were discovered by one of us (M.W.) in the Bramabiau cave in 1977 (Gard; ELLENBERGER, 1988). Since that date, footprints were observed in several galleries of the long karstic network of the Bramabiau cave (e.g. Grand Tunnel gallery; Félix Mazauric galleries; MOREAU *et al*., 2019a; WIENIN, 2019). In 2006, the first dinosaur tracks in the Malaval cave (Lozère) were discovered by the speleologists Daniel André and Jean-Pierre Malafosse. Between 2013 and 2019 several palaeontological prospections were co-organised by the Association Paléontologique des Hauts Plateaux du Languedoc (Mende) and the Association Malaval (Ispagnac) in this karst. They led to the discovery of tracks in diverse parts of the "Super-Blanches" galleries (MOREAU *et al*., 2018). Later, a few dinosaur footprints were mentioned in the Boissière cave, in Gard (ANDRE *et al*., 2019). Tracks from the Bramabiau, Malaval and Boissière caves (Fig. 1) were all found in the Dolomitic Formation which is Hettangian in age (Early Jurassic; ca. 201-199 Ma). They are all tridactyl and some of them are ascribed to the ichnogenera *Grallator*, *Kayentapus* and *Eubrontes* (MOREAU *et al*., 2018). The trackmakers are

hypothesised to be theropods. Recently, a study published in *Journal of Vertebrate Paleontology* (MOREAU *et al.*, 2019b) revealed the discovery of Middle Jurassic megaherbivorous dinosaur trackways in the Castelbouc cave N°4 (Fig. 2). They represent the first occurrence of sauropod tracks preserved inside a natural karstic cave.

2. The Castelbouc Cave N°4

The entrance of the cave is located near the small village of Castelbouc, in the Gorges du Tarn, 30 km South of Mende (Lozère). The cavity which is developed 500 m under the surface of the Causses Méjean plateau is 880 m long and shows 102 m of difference in elevation (ANDRE, 1992). All tracks are located on the roof of the Tunnel gallery (Fig. 2). This gallery is 76 m long, up to 22 m wide and up to 11 m high. From the cave entrance, the Tunnel gallery is accessible after crawling along a 100 m long and very narrow conduit.

The Castelbouc cave N°4 is developed in the «Calcaires à Stipites» Formation which is Bathonian in age (c.a. 170-168 Ma.; CHARCOSSET, 2000). In the Gorges du Tarn this formation is 30 to 150 m thick (CHARCOSSET *et al.*, 1996; CISZAK *et al.*, 1999) and mainly consists of oolithic or bioclastic limestone alternating with thin layers of lignitic marl yielding abundant plant remains (PHILIPPE *et al.*, 1998).

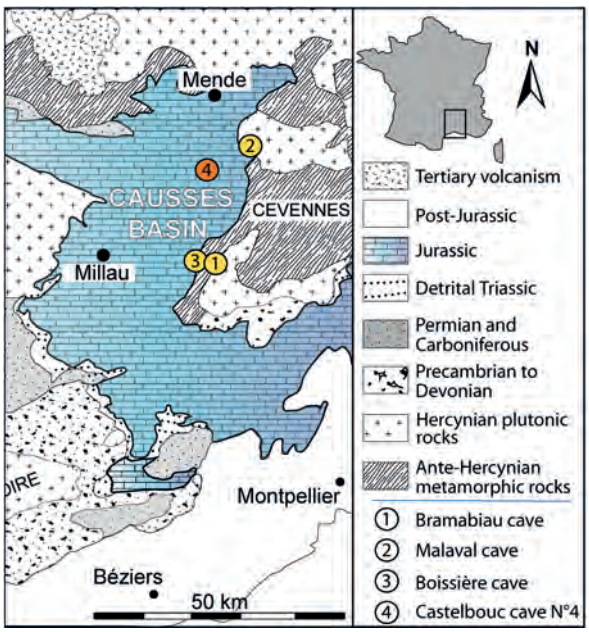

Figure 1: Location of the karsts yielding dinosaur footprints and geological context of the Causses Basin.

Figure 2: Roof of the Tunnel gallery bearing large dinosaur tracks. Photograph by Rémi Flament

3. The trackways

The tracksite was discovered during a speleological trip organised by the Association Paléontologique des Hauts Plateaux du Languedoc in December 2015. Then, three consecutive missions were organised in 2016, 2017 and 2018. They allowed us to identify 3 trackways composed of 33 large dinosaur tracks in the Tunnel gallery. All tracks are located on a single stratigraphic surface and are preserved as convex hyporeliefs. The longest trackway is 18 m long and 2.6 m wide. Trackways are composed of pes and manus tracks (Fig. 3A-E). Pes tracks are up to 1.25 m in diameter, subcircular to oval in shape and pentadactyl. Manus tracks are smaller, D-shaped and convex forward. Some of the tracks are exquisitely preserved, showing impressions of digits and claws. Although some of the tracks remain undetermined, the biometric analysis led to the erection of a new ichnotaxon: *Occitanopodus gandi* (see MOREAU *et al.*, 2019b in Journal of Vertebrate Paleontology for detailed description).

4. The trackmakers and their environment

The morphology and dimensions of tracks from the Castelbouc cave N°4 are characteristic of herbivorous, quadrupedal and long-necked sauropods (Fig. 3F). The trackmakers were probably Titanosauriformes. They are known from the Middle Jurassic to the Upper Cretaceous, measured more than 30 m and weighted more than 50 tons (PAUL, 2010). The biometric analysis reveals that Titanosauriformes from Castelbouc had a hip height of 2.5 m and a locomotion speed of 7 km/h.

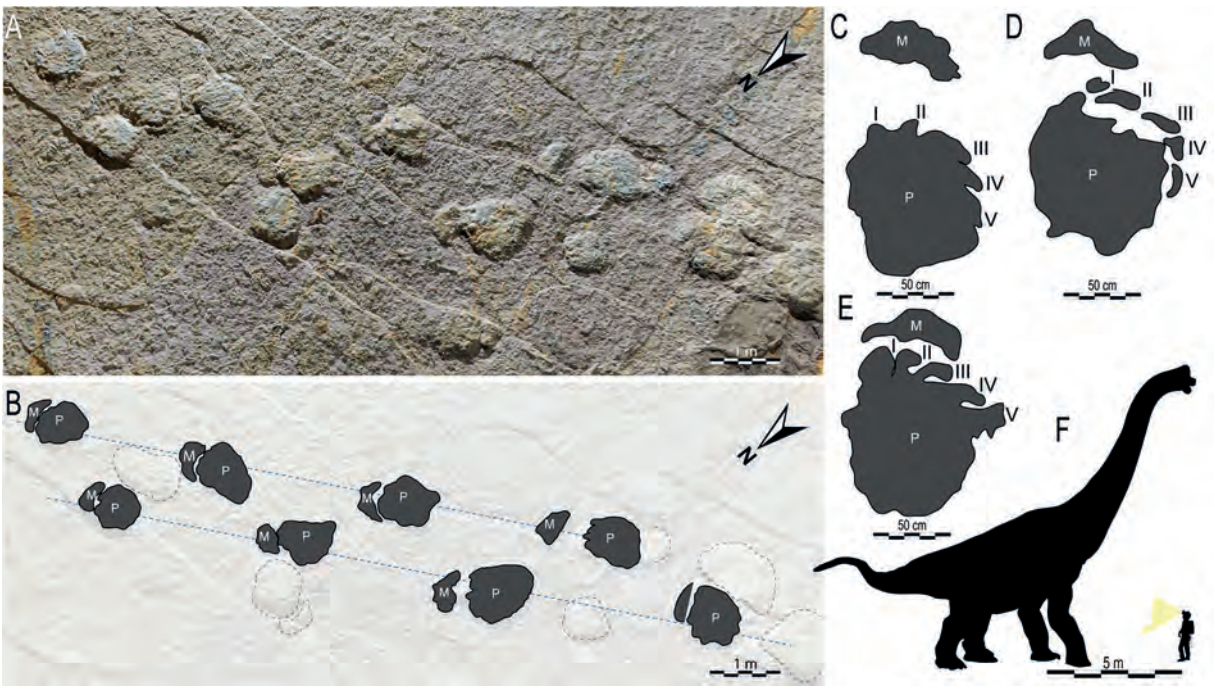

*Figure 3: A-B, Photograph (A) and interpretative sketch (B) of a sauropod trackway (*Occitanopodus gandi*) preserved on the roof of the Tunnel gallery (photograph by Rémi Flament). C-E, three pes track-manus track sets F, silhouette of a sauropod. M = manus tracks; P = pes tracks.* C-E were modified after MOREAU *et al.* (2019b).

Sedimentological, petrological and mineralogical analyses of the stratigraphic section from the Tunnel gallery (see MOREAU *et al*., 2019b for details) demonstrated that sauropods from Castelbouc walked on the border of a shallow and restricted environment such as a bay or a lagoon periodically emerged and open to the sea. The presence of wood remains and conifer cuticles suggests that these littoral environments were bordered by conifer-dominated forests that were probably an attractive source of food for these megaherbivorous dinosaurs.

As demonstrated by other tracksites from the Causses Basin and stratigraphically located in the «Calcaires à Stipites» Formation (e.g. SCIAU *et al*., 2006; MOREAU *et al*., 2012; GAND *et al*., 2018), as well as bone microremains (e.g. KRIWET *et al*., 1997; KNOLL & LOPEZ-ANTONANZAS, 2014), these ecosystems were also inhabited by other dinosaurs such as theropods and ornithopods as well as amphibians and crocodylomorphs.

5. Conclusions

Since body fossils of sauropods remain hitherto unknown in the «Calcaires à Stipites» Formation, these tracks represent the first evidence of such dinosaurs in the Bathonian ecosystems from the Causses Basin. They also represent the first evidence of Titanosauriformes in the Middle Jurassic deposits from France.

The recent collaboration between speleologists and palichnologists led to major discoveries inside karsts from the Causses Basin. It demonstrated that some cavities from this area offer large roofs preserved from the erosion and that occasionally yield theropod or sauropod tracks.

In France, many natural cavities are developed in sedimentary formations which are Mesozoic in age and that were deposited in marginal-littoral or terrestrial environments. Palaeontological prospecting in these karsts could yield new underground vertebrate tracksites.

Acknowledgments

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Le paléokarst quercinois, des millions d'années d'archives environnementales

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Résumé

De façon quasi continue, le Quercy est soumis à la karstification depuis la fin du Crétacé avec, pour sa partie la plus méridionale, une ablation superficielle limitée depuis la fin de l'Oligocène. C'est ainsi que coexistent de multiples remplissages karstiques, dont les phosphatières, exploitées à l'articulation XIXème/XXème siècle. Leur contenu paléontologique est exceptionnel, tant en diversité (mammifères, oiseaux, squamates, amphibiens, arthropodes et végétaux) qu'en qualité (conservation en 3D, momies). À l'échelle géologique, chaque gisement permet de documenter précisément la biodiversité et les conditions environnementales ; ce sont aujourd'hui près de 200 « instantanés » répartis sur plus de 30 millions d'années (Ma), entre 52 et 18 Ma. Plus remarquable encore, cet intervalle de temps comprend un événement majeur d'aridification et de refroidissement global du climat lors de la transition éocène-oligocène avec de profondes conséquences biogéographiques dues à une baisse importante du niveau de la mer résultant de la formation d'une calotte glaciaire antarctique. En Eurasie, on observe un important renouvellement de la faune appelé "Grande Coupure", où environ la moitié des espèces européennes de mammifères placentaires disparaissent, tandis que de nombreux clades d'origine asiatique ou nord-américaine immigrent. Une telle archive sédimentaire est unique en contexte continental.

Abstract

The Quercy paleokarst, millions of years of environmental archives. Since the end of the Mesozoic, Quercy has been almost continuously exposed to karstification, with limited superficial ablation in its southernmost part since latest Oligocene times. This is why multiple karstic fillings now coexist, including "phosphatières", which were exploited in the late 19th and the early 20th century. Their paleontological content is exceptional, both in terms of diversity (mammals, birds, squamates, amphibians, arthropods, and plants) and quality (3D-preservations, mummies). On a geological scale, each deposit makes it possible to accurately document biodiversity and environmental conditions: today there are nearly 200 "snapshots" of past biodiversity spread over thirty million years (Ma), between 52 and 18 Ma. Even more remarkable, this time interval includes a major event of aridification and global cooling at the Eocene-Oligocene transition, with profound biogeographical consequences due to a significant drop in sea level related to the onset of the Antarctic ice sheet. In Eurasia, a drastic renewal of the fauna called "Grande Coupure" coincides with the disappearance of about half of the endemic European species of placental mammals, while many clades of Asian or North American origin immigrate. Such a sedimentary archive is unique in a continental context.

1. Introduction

Les Causses du Quercy comptent près de 200 localités fossilifères cénozoïques formées dans un contexte continental. Ces dernières se concentrent sur la terminaison sud des Causses du Quercy, à cheval sur le Lot et le Tarn-et-Garonne, avec quelques autres sites en Aveyron et dans le Tarn. Ils constituent un élément géopatrimonial majeur et occupent la moitié sud du territoire du Géoparc mondial UNESCO des Causses du Quercy.

Trois facteurs expliquent l'originalité de cet ensemble fossilifère : **i)** Même si le substrat carbonaté du Jurassique a connu une érosion karstique depuis la fin du Crétacé (environ 70 millions d'années [Ma]), l'ablation superficielle y est restée limitée, permettant la conservation et la juxtaposition de remplissages paléokarstiques étagés entre l'Éocène inférieur (52 Ma) et l'Holocène, et comprenant une série continue, très fossilifère, de la fin de l'Éocène moyen à l'Oligocène terminal (39-24 Ma) ; **ii**) Les cavités karstiques constituent des pièges sédimentaires enregistrant des témoignages uniques de la biocénose environnante ; **iii**) Le phosphate, omniprésent dans les remplissages karstiques quercinois, a permis, dans certaines circonstances encore énigmatiques, une fossilisation « éclair » d'une qualité exceptionnelle. En témoigne la conservation de crânes en 3D (aussi délicats que ceux des chauves-souris) ou la présence de momies d'amphibiens, d'arthropodes, de graines et de fleurs phosphatisées.

Le caractère hautement fossilifère des karsts quercinois en font un Konzentrat-Lagerstätte multi-sites enregistrant des assemblages de fossiles locaux sur un intervalle de temps de plus de 30 Ma (52-18 Ma). Par le caractère extrêmement dense, presque continu, du registre fossile, les localités du Quercy donnent accès à une image dynamique des faunes vertébrées, avec une diversité taxonomique inégalée d'amphibiens (grenouilles et tritons), de squamates (lézards et serpents), de tortues, de crocodiles, d'oiseaux (avec notamment des perroquets et des rapaces), et surtout de mammifères (marsupiaux, pangolins, carnivores, insectivores, ongulés à doigts pairs et impairs, chauves-souris, rongeurs et primates (PELISSIE & SIGE 2006).
En tant que tel, cet assemblage de fossiles offre une fenêtre unique sur la biodiversité de l'Éocène-Oligocène en Europe (LEGENDRE 1989 ; ESCARGUEL *et al*. 2008 et 2011), d'un intérêt tout particulier puisque l'intervalle de temps couvert par les localités du Quercy comprend un événement majeur d'aridification et de refroidissement mondial lors de la transition Éocène-Oligocène [Eocene-Oligocene Transition : EOT ; autour de 33,9 Ma].
Cet événement est lié à l'apparition d'une calotte glaciaire en Antarctique (ZACHOS *et al*. 2008). Ce changement climatique a de profondes conséquences biogéographiques engendrées par une nette baisse du niveau marin et l'apparition de voies terrestres entre l'Asie et l'Europe, jusqu'alors isolée. En Europe, l'EOT correspond à un important renouvellement faunique appelé "Grande Coupure" (STELHIN 1910), où environ la moitié des espèces européennes de mammifères placentaires disparaissent, tandis que de nombreux clades d'origine asiatique ou nord-américaine immigrent (LEGENDRE & HARTENBERGER 1992). Dans ce contexte, les archives fossiles du Quercy offrent une perspective intégrée unique sur la dynamique évolutive et écologique des communautés de vertébrés, locale à régionale, dans le contexte d'une crise mondiale.

2. Matériel et méthodes

Le Quercy a connu une intense exploitation des phosphates pendant la seconde moitié du XIXème siècle. Le phosphate, comme à l'heure actuelle en Afrique littorale, était exploité pour son rôle fertilisant. Identifié en 1865 dans un champ près de Caylus par M. Jean-André Poumarède, docteur en médecine et en pharmacie, le phosphate contenu dans les poches de remplissages argileux a très rapidement représenté une manne financière pour les paysans du Quercy. En l'espace de cinq ans seulement, plus de 300 gisements de phosphate sont repérés dans le Quercy. L'activité minière a consisté en le vidage/curetage des poches karstiques remplies d'argiles et contenant le phosphate, à la pelle et à la pioche. L'exploitation industrielle du phosphate, qui a débuté en 1870, emploiera un temps plus de 2000 ouvriers. Pendant les 16 ans que durera l'exploitation « industrielle », plus de 300 000 tonnes de minerai seront extraites dans le Quercy et des milliers de fossiles découverts par les mineurs. Une part était directement broyée et exploitée pour le phosphate, mais certaines des plus belles pièces étaient revendues à des collectionneurs et à des scientifiques, parmi lesquels Henri Filhol. Ces « anciennes collections » se sont ainsi retrouvées dispersées dans de nombreux musées dans le monde (MNHN-Paris ; Musée de Bâle ; *Natural History Museum*, Londres ; *American Museum of Natural History*, New York). Des centaines de poches karstiques d'âges différents étant exploitées simultanément, les fossiles des anciennes collections n'ont malheureusement pas de provenance géographique ou stratigraphique identifiée avec précision.
En 1965, plus d'un demi-siècle après la fin de l'exploitation minière, les fouilles scientifiques commencent à l'initiative des équipes des laboratoires de paléontologie de Paris et de Montpellier (aujourd'hui CR2P et ISE-M, respectivement), rapidement rejointes par des paléontologues des Universités de Poitiers et de Lyon. Les fouilles se poursuivent depuis en collaboration avec différentes institutions françaises. Cinquante années de terrain ont permis de constituer une nouvelle collection riche de plusieurs centaines de milliers de spécimens, avec provenance et contexte biostratigraphique identifiés, en grande partie conservés à l'Université de Montpellier. Il est à noter que des opérations de lavage-tamisage ont longtemps été menées en parallèle par l'Université d'Utrecht et de nombreux paléontologues amateurs (de manière variablement concertée).
Les fossiles sont d'abord étudiés à des fins systématiques (description, mesures, comparaisons et détermination) par les spécialistes des groupes d'organismes identifiés. Ces fossiles permettent ensuite l'établissement d'une échelle biochronologique où chaque phosphatière – un « barreau » de l'échelle – est située de façon relative (plus ancienne/plus récente) et finalement numérique (datation en Ma). De fait, plusieurs phosphatières quercinoises constituent aujourd'hui des niveaux de référence biochronologique à l'échelle de l'Europe entière pour la période Paléogène.
Ainsi ordonnées dans le temps, telles les pages d'un roman dont on aurait retrouvé l'ordre grâce à leur contenu, ces phosphatières racontent une partie de l'histoire des êtres vivants en Quercy. Cette histoire est très précisément consignée entre 52 et 18 Ma, et restreinte à quelques bribes éparses pour l'intervalle temporel menant à l'Actuel – une histoire évolutive, c'est-à-dire faite d'adaptations et de transformations, d'apparitions et d'extinctions, mais aussi de migrations, au gré des fluctuations géographiques et climatiques de la Terre. Différentes analyses quantitatives du registre fossile, telle l'analyse de cénogramme développée par Serge Legendre dans les années 1980, permettent de visualiser et d'interpréter l'évolution du spectre de distribution de taille des espèces de mammifères au sein d'une communauté locale (LEGENDRE 1989), ou encore l'analyse de prénaissance et de survie des espèces constitutives d'une métacommunauté régionale (ESCARGUEL & LEGENDRE 2006 ; ESCARGUEL *et al*. 2008, 2011).
S'appuyant sur les énormes corpus de données disponibles, le projet de recherche "Deadender", financé par l'Agence Nationale de la Recherche (ANR), vise actuellement à caractériser et à mettre en contraste les caractéristiques biologiques et la dynamique de l'évolution des clades endémiques européens "archaïques" de l'Éocène et des

clades asiatiques "modernes" dispersés en Europe pendant la "Grande Coupure". Deadender se concentre sur les artiodactyles (ongulés à doigts pairs) de la fin de l'Éocène et du début de l'Oligocène, pour lesquels un exceptionnel registre fossile existe dans les localités du Quercy.

L'avènement récent de l'imagerie 3D, notamment par le biais des microtomographies à rayons X (CTscan) ou des faisceaux Synchrotron, a entraîné une véritable révolution en paléontologie, en donnant accès aux structures internes des fossiles, de manière non-destructive et avec une résolution de l'ordre du micron (Fig. 1B). Le registre fossile des phosphorites s'y prête admirablement, notamment pour l'étude des structures crâniennes (os de l'oreille, moulages endocrâniens) (Fig. 1F). De même, la phosphatisation précoce de micro-restes (momies d'insectes, graines, fruits et fleurs) (Fig. 1C, D, E) ouvre de nouvelles perspectives de recherche, en permettant par exemple de caractériser finement les étapes du développement de nombreux organes et organismes, habituellement décomposés avant fossilisation.

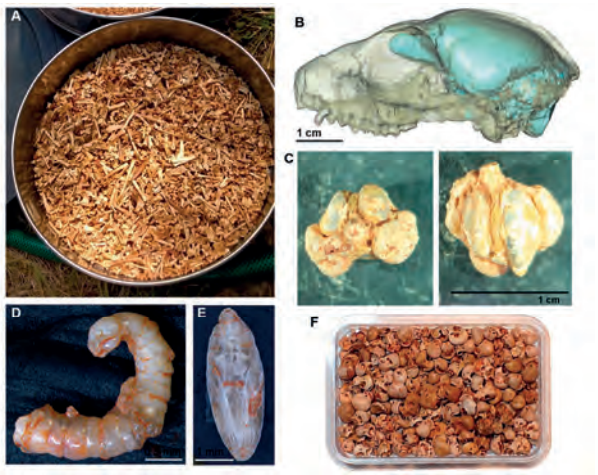

Figure 1 : Fossiles phosphatisés de l'Éocène-Oligocène quercinois. A) résidu de lavage de la localité de Dams, Éocène supérieur ; B) crâne du petit primate Microchoerus eracinus *montrant le moulage de sa boite crânienne ; C) Endocarpe non identifié (provenance inconnue) ; D) myriapode et E) chrysalide de papillon (Sindou D, Éocène supérieur) ; F) collection d'os pétreux de chauve-souris (Sainte-Néboule, Éocène supérieur).*

3. Résultats

Après plus d'un demi-siècle et plusieurs centaines de milliers d'heures de travail sur le terrain et en laboratoire – prospection, levés topographiques et sédimentologiques, prélèvements, lavage et tamisage des sédiments, puis tri et identification – près de 700 espèces distinctes de vertébrés fossiles ont été reconnues. Si les mammifères dominent, le registre disponible inclut aussi des oiseaux, des reptiles (lézards, serpents, tortues et crocodiles) et des amphibiens (grenouilles, salamandres et tritons) ainsi que différentes familles d'insectes et de plantes (Fig. 1). Ces restes, exhumés de près de 200 phosphatières fossilifères distinctes, constituent l'un des registres fossiles continentaux les plus longs, denses et continus disponibles à ce jour à l'échelle globale.

1) Dynamique des faunes

Les travaux pionniers réalisés par Serge Legendre dans les années 1980-90 ont montré à l'aide d'analyses de cénogrammes combien les communautés locales de mammifères étaient profondément affectées par le refroidissement global de l'EOT, en matière de richesse et de composition (LEGENDRE, 1989). Par ailleurs, ce même EOT a entraîné une plus grande hétérogénéité écosystémique en période plus froide et sèche (ESCARGUEL & LEGENDRE, 2006 ; ESCARGUEL *et al*. 2008 et 2011).

Concernant l'étude des artiodactyles endémiques d'Europe, la dynamique de la diversité des Cainotheriidae a pour l'instant focalisé notre attention. La phosphatière de Dams découverte en 2017 (Caylus, Tarn-et-Garonne) a en effet livré des remplissages fossilifères très riches datés de part et d'autre de la Grande Coupure et enregistré une diversification locale des *Cainotheriidae*, après la Grande Coupure (ASSEMAT *et al*. 2020 ; WEPPE *et al*. 2020a et b). Les analyses de diversité fondées sur les mentions de cette famille révèlent un pic de diversification post-EOT et permettent d'identifier la température, la fragmentation continentale, et la compétition intra-clade comme facteurs principaux de la dynamique de leur diversité. L'étude morphologique des taxons de part et d'autre de l'EOT révèle également des différences significatives en lien avec les changements environnementaux.

2) Préservations exceptionnelles et investigations 3D

Les momies d'amphibiens sont parmi les fossiles les plus exceptionnels découverts dans les phosphatières. L'étude de leur structure interne à partir de données synchrotron (LALOY *et al*. 2013 ; TISSIER *et al*. 2017) indique que la préservation des tissus en trois dimensions est exceptionnelle (squelette, poumon, moelle épinière, muscles, organes uro-génitaux et tube digestif). Les organismes phosphatisés comprennent également nombre d'arthropodes dont les tissus mous et structures internes fournissent des données sans précédent sur leur paléobiologie (SCHWERMANN *et al*. 2016 ; VAN DE KAMP *et al*. 2018). Concernant les mammifères, la préservation exceptionnelle a permis la collecte de dizaines d'osselets de l'oreille moyenne, minuscules et particulièrement fragiles, de plusieurs espèces de *Cainotheriidae*. Leur étude a montré la pertinence des caractères de l'oreille moyenne pour reconstruire les relations de parenté au sein du groupe (ASSEMAT *et al*. 2020).

4. Conclusions et perspectives

Depuis leur découverte vers 1870, les phosphatières du Quercy ont livré un matériel fossile paléogène exceptionnel (vertébrés, mollusques, arthropodes et plantes). 150 ans de recherches paléontologiques ont démontré l'extrême richesse et l'intérêt de premier plan de ce véritable Konzentrat-Lagerstätte multi-sites (200 gisements). De nouvelles localités sont découvertes et échantillonnées chaque année, en association avec l'étude géologique et sédimentologique des remplissages. Ainsi, les phosphatières du Quercy permettent-elles une analyse diachronique des communautés terrestres locales-régionales, de leur dynamique et de leur environnement, dans un contexte de changements climatiques et biogéographiques majeurs (autour de l'EOT). Fondé sur les résultats scientifiques antérieurs et les projets de recherche en cours, le potentiel scientifique à long terme de cette zone est incontestable et les futures études de la dynamique de la faune et de la flore seront certainement d'une aide considérable pour comprendre l'évolution des organismes dans un contexte de changements globaux drastiques. Les projets à venir pourraient aborder des questions liées à la datation radiométrique absolue des fossiles et des sédiments afin d'améliorer la résolution biochronologique de l'ensemble des séries chronologiques, de la dynamique karstique et des processus de phosphatation. D'autre part, l'étude de clades ou de niveaux trophiques spécifiques permettra de mieux comprendre la dynamique de la diversité et les interactions entre les organismes dans les paléobiocénoses concernées.

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Bats (Chiroptera) from the Archaeological Site of the Lichtenstein Cave, Harz Mountains, Germany

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Abstract

Bat finds from the archaeological site of the Lichtenstein Cave (Lower Saxony, Germany) induced this research. The Lichtenstein is situated in the gypsum karst area at the SW margin of the Harz Mountains. The cave served as a burial place in the late Bronze Age, from 950 to 850 BC. Bats (Chiroptera) hibernated there contemporary. Since bats have very differentiated habitat requirements, the association allows palaeoecological conclusions. Though large parts of the Harz Mountains were covered with old growth forests, stenoecious bat species of primeval forests, such as *Myotis bechsteinii* were rare. Euryoecious species or species living synanthropic, such as *Plecotus auritus* and *Rhinolophus hipposideros* were the most abundant species. In the cultural landscape of the late Bronze Age for the first-time forests were dominated by beech (*Fagus*). Beech forests replaced primeval mixed oak forests (*Quercus*), which had been predominant since the early Holocene. To the present Central European beech forests show a lower biodiversity and biomass compared to mixed oak forests, which indicates reduced biotope continuity and a brief habitat tradition. The research highlights the relevance of beech and oak for contemporary bat conservation attempts relating to current forest restructuring measures due to present climate change.

Résumé

Chauves-souris et sites archéologiques, la grotte du Lichtenstein (massif du Harz, Allemagne). Les os de chauves-souris trouvés dans le site archéologique de la grotte du Lichtenstein (Basse-Saxe, Allemagne) font l'objet de ce travail. Le Lichtenstein est situé dans la région karstique du gypse du SW-Harz. La grotte a servi de lieu de sépulture à la fin de l'âge du Bronze, de 950 à 850 avant J.-C. environ. Des chauves-souris, contemporaines de cette époque, ont hiberné dans cette cavité. Les exigences différenciées en matière d'habitat des chauves-souris permettent de faire des déductions paléoécologiques. Bien que de grandes parties du Harz aient été couvertes de forêts, des espèces de chauves-souris sténoïdes des forêts primaires, comme *Myotis bechsteinii*, étaient rares. La faune est dominée par l'espèce euryécienne *Plecotus auritus* et l'espèce synanthropique *Rhinolophus hipposideros*. Dans le paysage culturel de la fin de l'âge du Bronze, les forêts étaient dominées par le hêtre (*Fagus*) pour la première fois, déplaçant les forêts de chênes mixtes (*Quercus*) qui avaient prédominé depuis le début de l'Holocène. Aujourd'hui, les hêtraies d'Europe centrale présentent une biodiversité et une biomasse inférieures à celles des chênaies mixtes, ce qui indique une continuité réduite du biotope et une brève tradition d'habitat. Cela doit être pris en compte pour les mesures de conversion des forêts en rapport avec le changement climatique ainsi que pour la protection des chauves-souris.

1. Introduction

Bats (Chiroptera) comprise more than 1,300 species and represent one-fifth of extant mammal species (SIMMONS et al. 2008). Current studies elucidate cryptic diversity in bats by genetic analyses and evidence is provided for new species also in Central Europe. However environmental degradation causes dramatical population declines. Thus, many bat species are critically endangered and the research of habitat requirements of new and rare species requires high effort. Furthermore, the fossil record of new cryptic species has not been analyzed yet, due to misidentification in former studies.

Findings of subfossil bat bones in anthropogenic deposits from the late Bronze Age discovered during archaeological excavations at the Lichtenstein cave site induced this research. The Lichtenstein (Fig. 1) is situated in the gypsum karst area near Osterode am Harz (Lower Saxony, Germany) at the SW margin of the Harz Mountains. Quarrying for gypsum and anhydrite destroyed parts of the landscape irretrievably, raising constant threat to nature and archaeological sites (Fig. 2) (KNOLLE et *al*. 2017). The Lichtenstein cave was discovered in 1972 and protected by law since 1974, so that this part of the Lichtenstein could be preserved from quarrying. The archaeological site was found only in 1980 behind an extremely constricted passage (Fig. 3) (FRICKE 1999). Excavations were carried out between 1993 and 2011. The cave served as a burial place during the Urnfield Period (Hallstatt B_1 to $B_{2/3}$), approximately from 950 to 850 BC (Fig. 4) (FLINDT et al. 2013, FLINDT & HUMMEL 2015). Contemporary bats used it as winter habitat. The focus of the research is elucidation of Chiropteran diversity as well as its palaeoecological evaluation.

Figure 1: Northwestern slope of the Lichtenstein. Photo Wolfgang Rackow.

Figure 2: Gypsum quarry at the eastern slope of the Lichtenstein in 2008. Photo Stephan Röhl.

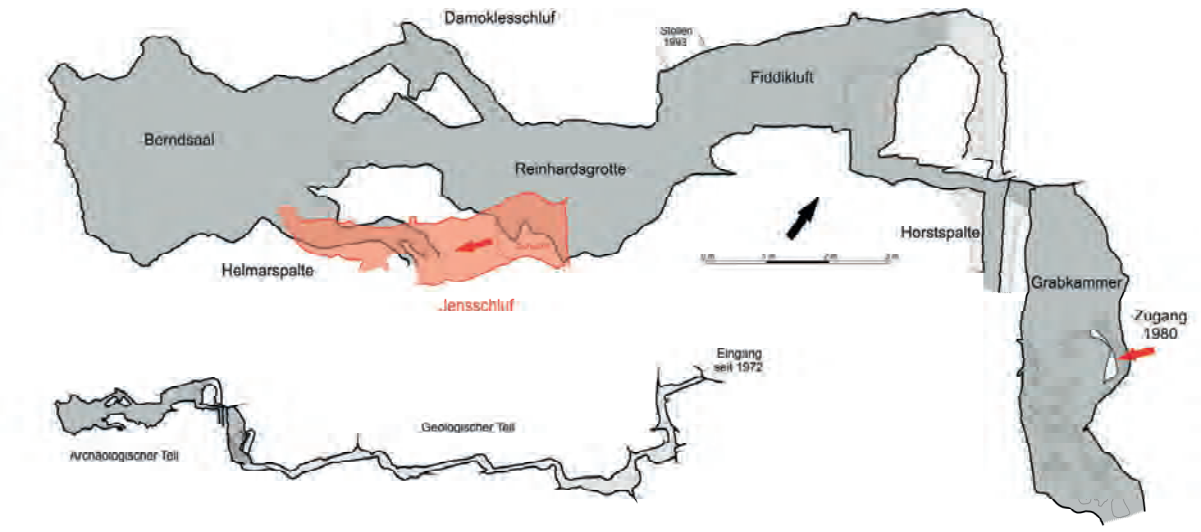

Figure 3: Map of the archaeological site of the Lichtenstein cave; the overview map of the whole cave is shown below. Graphics by Stefan Flindt.

2. Materials and methods

The processed material comprises determinable fragments of 187 skulls, 410 lower jaws and 696 humeri. They are assigned to twelve species: *Plecotus auritus*, *Rhinolophus hipposideros*, *Myotis brandtii*, *M. alcathoe*, *M. mystacinus*, *M. daubentonii*, *M. bechsteinii* (Fig. 5), *M. nattereri*, *M. myotis*, *M. dasycneme*, *Barbastella barbastellus* and *Eptesicus serotinus*. Morphometric determinations of humeri of the species *M. brandtii*, *M. alcathoe* and *M. mystacinus* were verified by aDNA analyses (RUPP 2016a, 2020, HAFFNER 2019).

Palaeoecological conclusions are inferred from changes in relative frequency patterns of the species spectrum in comparison to the regional recent fauna. They are interpreted against the background of palaeoecological developments derived from frequency diagrams of pollen types from lake sediments and bogs in the gypsum karst area.

3. Results

The most frequent bat species from the Lichtenstein cave site is Brown Long-eared Bat (*Plecotus auritus*) followed by Lesser Horseshoe Bat (*Rhinolophus hipposideros*). Together they represent 52 % of the fauna. Alcathoe Whiskered Bat (*Myotis alcathoe*) was more common in the late Bronze Age species spectrum than its cryptic species Whiskered Bat (*M. mystacinus*). While the latter is extremely seldom, Alcathoe Whiskered Bat as well as Brandt's Bat (*M. brandtii*) each represent almost 10 %. All other species are rarer.

Remains of Bechstein's Bat (*M. bechsteinii*) comprise approximatly 7 % of the fauna (RUPP 2020). It had been the dominating species in early Holocene subfossil cave

assemblages (NIELBOCK 1987, RUPP 2016b, HUTTERER 2013). Its habitat requirements comprise old growth woodland, especially oaks (*Quercus*) (GÜTTINGER & BURKHARD 2013). *M. alcathoe* likewise is adapted to old full-grown mixed oak forests adjacent to water bodies (DIETZ et *al*. 2016). In late Bronze Age alluvial forests of river Söse and its tributaries were suitable habitats, whereas in present industrial landscapes they both belong to the rarest bat species. *M. mystacinus*, on the other hand, today occurs in open habitats in the vicinity of human settlements and contemporary forms larger populations (DIETZ et *al*. 2016).

Figure 4: The Lichtenstein cave served as a burial place during the late Bronze Age, ca. 950-850 BC. Photo Landkreis Göttingen.

In the cultural landscape of the late Bronze Age for the first-time shady forests dominated by beech (*Fagus*) replaced primeval mixed oak forests, which had been predominant since approximately 10,000 years BP at the beginning of the Holocene (VOIGT et *al*. 2008, BEGEMANN 2003). The widespread dispersal of the beech caused changes of frequency patterns of bats. The first beech forests were colonized mainly by euryoecious species like Brown Long-eared Bat. Lesser Horseshoe Bat in Central Europe lives synanthropic. As early as the late Bronze Age it probably was able to use anthropogenic summer roosts and open hunting grounds in the vicinity of human settlements. Thus, it was prevalent in the proximity of its late Bronze Age winter habitat in the Lichtenstein cave (RUPP 2017a, b, 2020). It had been abundant until the 20th century. In Lower Saxony it became extinct in the 1960s due to pesticide usage and habitat destruction (RÜHMEKORF & TENIUS 1960, SCHILLAT & MEYER 2001).

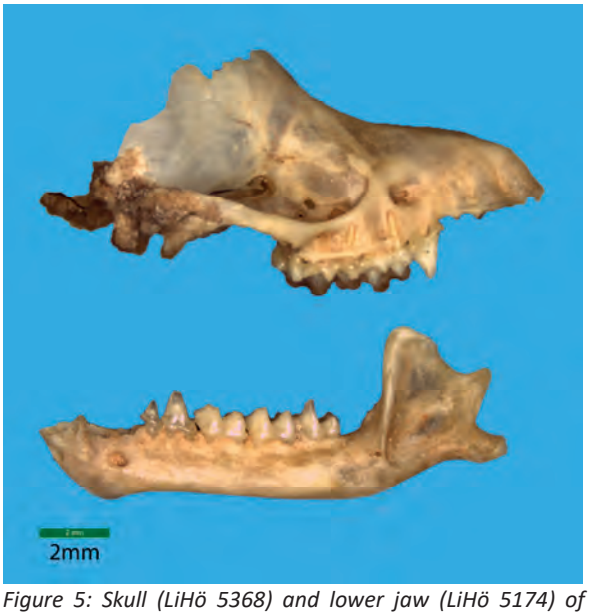

Figure 5: Skull (LiHö 5368) and lower jaw (LiHö 5174) of Bechstein's Bat (Myotis bechsteinii) from the Lichtenstein cave site. Photo Hildegard Rupp.

4. Discussions

The widespread dispersal of the beech during the Bronze Age induced a profound ecological change. 3,000 years ago, large parts of the Harz Mountains and its foothills were covered with beech forests, in which old wood was preserved until the phase of decay. Nevertheless, beech forests are less diverse and provide habitats especially for euryoecious species. Thus, Brown Long-eared Bat dominates the fauna of the Lichtenstein cave and stenoecious Bechstein's Bat declined. To the present Central European beech forests show a lower biodiversity and biomass compared to mixed oak forests, which indicates reduced biotope continuity and a brief habitat tradition (WALENTOWSKI et *al*. 2013).

Today beech forest associations are regarded as potential natural vegetation in the Harz Mountains up to upper montane regions. They play an important role for landscape planning and management. Oaks on the other hand are considered a relic of historical forest management, nonetheless it was an essential component of primeval forests in Central Europe.

5. Conclusion

All indigenous bat species are protected by law. The use of bats as bioindicators not only allows a better understanding of palaeoecological conditions. It also highlights the relevance of beech and oak for contemporary bat conservation attempts. Oak should be given greater importance in current forest restructuring measures due to present climate change.

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3D scanning tools for paleontological studies in caves

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Abstract

Caves are places where palaeontological and archaeological discoveries are common. Sometimes these remains/artefacts may be of fundamental importance for understanding the evolution of life or the human history. Some examples are the rock art paintings in Lascaux cave in France or the Altamura Neanderthal skeleton in Italy, just to mention a few of many fossils discovered in caves over the centuries. There is often a need to preserve these discoveries in the site where they have been found. In these cases, performing *in situ* surveys and studies becomes essential. Three-dimensional surveys with laser scanner or photogrammetry techniques are increasingly applied to achieve a high-level characterization without removing the fossils or archaeological material from their original location in the caves. This paper focuses on two different technologies used for 3D scanning of two palaeontological remains: the 20-million-year old mermaid fossil of the Puerto Princesa Underground River cave in Palawan, Philippines, and a 5-thousand-year old ocelot skeleton discovered in the Imawarì Yeuta quartz-arenite cave in Venezuela. The mermaid fossil was 3D scanned using the DPI Products-8 (a handheld portable laser scanner) whereas the feline skeleton was documented through photogrammetry. The potential of 3D scanning technologies for the preservation, *in situ* characterization of archaeological and palaeontological discoveries in caves will be outlined.

1. Introduction

Caves are perfect places for the conservation of archaeological and palaeontological remains because of their relatively stable climatic and environmental conditions. In some cases, especially where the geological, archaeological or palaeontological material is endangered by natural or anthropic processes, traditional scientific excavations are carried out. In other circumstances, where fossils are embedded in the rock itself and their removal would cause severe damage to the findings themselves and to the surrounding environment, it is often wise to carry out microsamplings, and study the material *in situ* without removing it (VACCA & DELFINO, 2004; SUBSOL *et al.,* 2015; RIGA *et al.*, 2020). In these circumstances the findings must necessarily be studied and documented with non-invasive technologies capable of giving as much information as possible to scientists (MOREAU *et al.*, 2018). Three-dimensional scanning techniques and instruments as photogrammetry or LIDAR technologies have therefore become increasingly important in the field of research and documentation.

In the recent past there have been several examples of important discoveries inside natural caves which have been analyzed and studied through the use of 3D scanning technologies, which in some cases have led to the faithful artistic reproduction of these important finds, such as in the case of the paintings found inside the caves of Lascaux, or in Chauvet Cave (Ardèche, France), and subsequently physically reproduced (DUVAL *et al.*, 2020). Digital tools associated with dating methods can provide a powerful aid for reconstructing past environments and events.
These reconstructions are not only necessary to prove and improve the scientific value of cultural karst geosites but also to provide contents for promotion to a general public (HOBLÉA *et al.*, 2014). Karst geosites are increasingly recognised as being of great scientific interest as well as providing opportunities for developing geotourism.
The Italian La Venta Association, which for over 25 years has been involved in exploration and research in some of the most important underground cave systems of our planet, collaborating with institutions and universities, has since several years adopted the use of new technologies for three-dimensional survey particularly for the study of palaeontological finds, discovered and documented during recent expeditions.

With this paper, we want to focus on two different technologies used for 3D scanning of two palaeontological remains: the 20-million-year-old mermaid fossil of the Puerto Princesa Underground River cave in Palawan, Philippines, and a 5-thousand-year-old ocelot skeleton discovered inside the Imawarì Yeuta quartzite cave in Venezuela. In addition to describing the methodologies, the data obtained and how they were subsequently used, we want to discuss the different methods and approaches possible according to the different logistical scenarios.

2. Case study (A): the mermaid fossil of the PPUR

The Natuturingam cave (better known as Puerto Princesa Underground River) is a cave complex of more than 36 km of passages in limestone that make it the longest cave of the Philippines, with several areas currently being explored. This cave hosts a unique natural ecosystem due to its exceptional peculiarities from the climatic, environmental and faunistic point of view including huge colonies of bats and swiftlets (AGNELLI *et al.*, 2018). Because of all these extraordinary features the cave has been listed by UNESCO since 1999 and has been recognized as one of the New Seven Wonders of Nature in 2011.
As part of a project financed by the Philippines-Italy debt for the support of sustainable eco-tourism inside this cave and the Park area and managed by La Venta, several parts of this cave were mapped using photogrammetry and Terrestrial Laser Scanning (TLS) techniques during two expeditions realized in 2016 and 2017. One of the most beautiful features of this cave is represented by the presence of the remains of a 20-million-year old Halitherium (extinct genus of Sirenia) fossil exposed on the wall along the main course of the underground river at a height of about 3 meters from the water level (Fig. 1).

Figure 1: Scanning operations of the mermaid fossil inside the Puerto Princesa Underground River

Halitherium is a Dugongidae that lived between Eocene and the Miocene, and is thought to be a distant relative of the dugong (a mammal known as "sea cow" for its algae grazing habits from shallow sea bottoms). All along the Philippines, colonies of dugongs were quite abundant up until mid 20th century, especially along the coasts of Palawan Island, but then their numbers decreased (mostly because of anthropic causes).
Since the fossil bones, embedded in the Eocene limestone, are located along the river at a height of about 3 meters from the water level (Fig. 1), it is necessary to use a boat to move near the site. For this reason, data acquisition was not particularly simple to carry out. The survey phases were carried out using a handheld scanner and photogrammetry techniques performing the operations with a ladder from the boat. The handheld scanner used is a DPI-8 model from DOT Products company which is generally used for onsite capture of medium sized objects and work environments. This device is a clever combination of an Android tablet and a PrimeSense 3D Sensor with an 8MP camera that can be easily held in one hand (with a total weight of less than a kg). It is able to acquire point clouds and textures and export the 3D models in various file formats (or directly on the cloud) via USB or Wi-Fi connection. Its sensor operation range moves from 60 cm to 4 m with a horizontal FOV of 57.5 degrees and because of this it was not possible to scan from very close range.
For this reason, photogrammetry was used to obtain greater detail measuring from closer distances (less than 50 cm) taking about 50 photographs around the exposed bones using a Pentax K30 camera with 18-55 lens.
Data obtained were subsequently processed separately in order to create two different models, one derived from the DPI-8 data and another one merging these data with the photographs and processing with Reality Capture photogrammetry software to obtain a single more accurate three-dimensional model (Fig. 2).

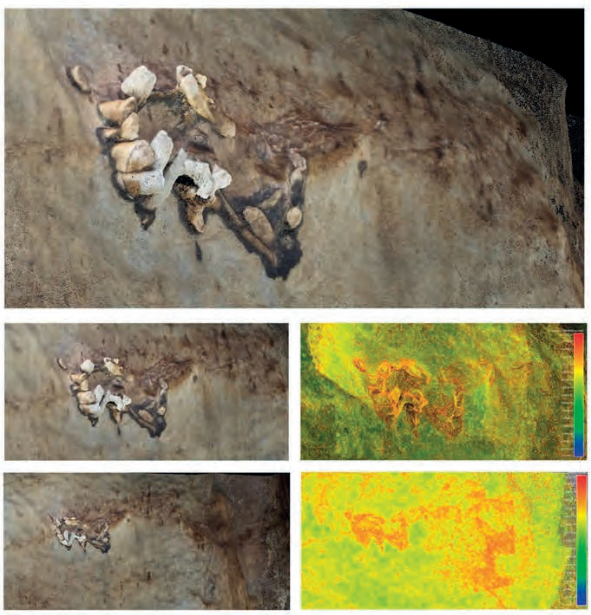

Figure 2: The fossil in the wall (above). Picture (left) and point cloud of the scanned fossil in RGB colours (Right,) and picture (left with intensity scale view to the right.

The final result is a point cloud with 1-2 mm resolution from which a 3D mesh model was subsequently obtained, creating a unique surface through the triangulation of the individual points. This model allows to obtain additional information such as measurements, identification and distinction of bones and can also help to define which are the most compromised parts that could be lost forever by falling into the river.
An interactive model was created to allow viewing this important palaeontological finding: https://skfb.ly/6RoUA

3. Case study (B): the ocelot skeleton in Imawarì Yeuta

Caves carved in Tepui quartz-sandstone table mountains (Venezuela) are among the less explored and most remote caving areas on Earth. For example, the ~20 km-long Imawarì Yeuta cave has been discovered and explored only in 2013. Hosted in the Precambrian rocks of the Auyan Tepui massif, it is now considered one of the longest quartz-sandstone cave systems in the world (SAURO *et al.*, 2013).
In addition to the characteristics that make this cave so interesting from the genetic and mineralogical point of view, this cave has preserved also important palaeontological remains. During the expedition realized in 2014, an intact skeleton of an ocelot (*Leopardus pardalis*) was discovered lying on the floor of a side passage. This discovery is particularly important as this species has never been documented on Tepuis before and for the exceptional state in which the bones were found in terms of composition and arrangement and silica speleothems deposited on the bones (Fig. 3).
Considering the need to acquire as much information as possible and due to the difficulties to reach these places with laser scanning equipment, photogrammetry was used to realize a detailed 3D model of the bones. In order to obtain a three-dimensional model in correct scale, a set of four target of 10 x 10cm were used to have metric references on the photographs taken. Photogrammetric survey was performed taking about 90 photographs from different angles and heights near the skeleton with a Pentax K30 camera with 18-55 lens.
This process allowed to realize a 3D model with 0.5-0.8 mm resolution depending on the area scanned. The set of photographs were processed with Reality Capture photogrammetry software and several types of models were exported to be used for scientific and outreach purposes.

Figure 3: The intact skeleton found in a secondary gallery.

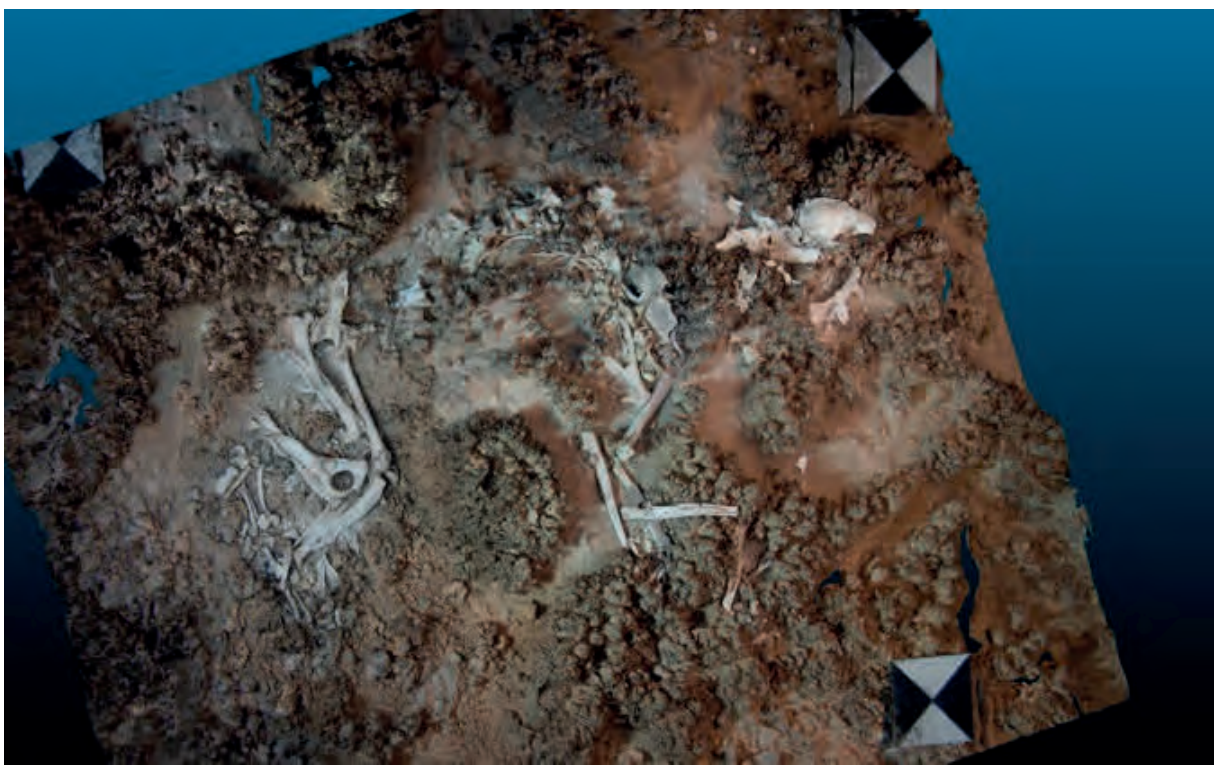

Figure 4: The photogrammetric 3D model and the 10x10 cm targets used during the survey phases.

4. Discussions and conclusion

In recent years, paleontological studies have been revolutionized by the emergence of powerful methods for the digital visualization and analysis of fossil material. This has included improvements in both computer technology

and in tomographic techniques, which have made it possible to image a series of 2D sections or slices through a fossil and to use these to make a 3D reconstruction of the specimen (CUNNINGHAM *et al.*, 2014). As they are rapidly evolving, digital tools seem to have a promising future in the field of geoheritage management. Laser scanning and photogrammetry techniques provide a precise and objective methodology to digitally document and study palaeontological objects *in situ* in a non-destructive manner. The potential for developing and applying these tools is still very high as they can provide a powerful aid for reconstructing past environments and events or to study palaeontological finds, and also to show the results to the public through interactive 3D models.

This paper reports two different methodologies and approaches which have been used to carry out three-dimensional surveys on palaeontological findings in cave, depending on the logistical problems of the site of discovery, and technological constrains. One of the main differences between these two types of works is that the 3D scanning of the Halotherium in the PPUR was planned and well organized, and therefore performed with dedicated instruments, while the feline found in Imawarì Yeuta, being an occasional and unplanned discovery, coupled with the difficulty of reaching the site in a near future, was documented with the technologies available at the moment of the explorations.

The rapid diffusion of technologies and knowledge will allow to use 3D scanning techniques on fossils much more easily in the next future and this can only represent an important change in the documentation of palaeontological finds even in difficult environments like caves.

Acknowledgements

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L'art pariétal des cavités de la craie de Normandie (France) et sa survivance

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Abstract

The parietal art of the underground cavities of the chalk of Normandy (France) and its survival.
The best examples of Norman parietal art known to prehistorians are the decorated cave of the Cheval de Gouy and the decorated cave of the Catelier d' Orival, both dated to the Upper Palaeolithic, around 12,000 years ago. These rare treasures are all located in the Seine Maritime Department. Much less studied, the walls of some caves but especially of underground quarries and marls exploitations present thousands of graffiti created more recently, especially from the post-medieval period to the present day. The representations cover a very varied panel, from the religious, to the accounts of quarrymen, from artistic symbols to the testimonies of visitors, or even the messages left during troubled periods, especially during the Second World War. Since the end of the 20th century, graffiti or esoteric paintings have been added, left rather by idle youth.
This hidden heritage is rich and undoubtedly constitutes an inexhaustible subject of study for archaeologists and historians who will quickly have to take an interest in it, this heritage being strongly threatened by the security policy which promotes the closure or destruction of underground establishments.

1. Introduction

En Normandie, la Seine a entaillé le plateau crayeux pendant les périodes froides du Quaternaire, laissant pour témoins des falaises dans lesquelles se développent de nombreuses grottes, le plus souvent sur le mode paragénétique. L'art pariétal des cavités de la craie normande peut se résumer aux ornementations paléolithiques des grottes de Gouy et d'Orival. Une bonne dizaine de millénaires s'est écoulée avant que les hommes ne se remettent à orner les parois des cavités normandes. Exception faite de quelques précurseurs (GRATTÉ, 1985), cette survivance de l'art pariétal a longtemps été négligée. Tantôt gravés ou sculptés, tantôt dessinés au crayon ou au fusain, parfois même réalisés à la peinture en bombe aérosol, des milliers de graffiti et d'illustrations méritent pourtant qu'on s'intéresse à cet héritage, tant il est riche d'informations. Ce patrimoine captivera à n'en pas douter les archéologues et les historiens des siècles ou des millénaires à venir (STAIGRE et *al*. 2019).

2. L'art pariétal préhistorique

L'art pariétal de la craie normande se résume à 7 cavités en amont de Rouen : Gouy I à Gouy V pour la rive droite de la Seine, grotte ornée du Catelier (MARTIN, 2001) et grotte n° 1 de la Roche Fouet d'Orival pour la rive gauche (STAIGRE et *al*. 2019). La plus connue d'entre elles est sans conteste la Grotte du Cheval (Gouy I), avec ses dix-huit figures et ses nombreux palimpsestes (GRAINDOR et MARTIN 1972 ; MARTIN 1973). Parmi ces dessins remarquables, nous ne pouvons pas faire moins que de citer les représentations les plus célèbres comme le magnifique Cheval de Gouy (Fig. 1), le rapace, les bovidés, les triangles pubiens et une silhouette féminine en bas-relief (MARTIN, 2007). Durant l'été 2019, lors d'une énième et difficile recherche que nous avons effectuée dans l'Eure pour retrouver une petite grotte oubliée, un certain nombre de figures énigmatiques ont été repérées par le premier auteur de ces lignes (STAIGRE & WATTE 2021). Interprétées un peu rapidement comme un nouveau témoignage de l'art azilien, les experts du Centre National de la Préhistoire sollicités par le S.R.A. de Normandie n'y ont reconnu que des griffades d'animaux. Cette grotte étant encore en cours d'étude, nous ne donnerons aucune information de localisation. Cependant, il nous a semblé judicieux de profiter du 18éme Congrès international de spéléologie pour présenter quelques-unes des griffades les plus suggestives (Fig. 2 à 5).

Figure 1 : le Cheval de Gouy (© Bernard Lefebvre, dit Ellebé).

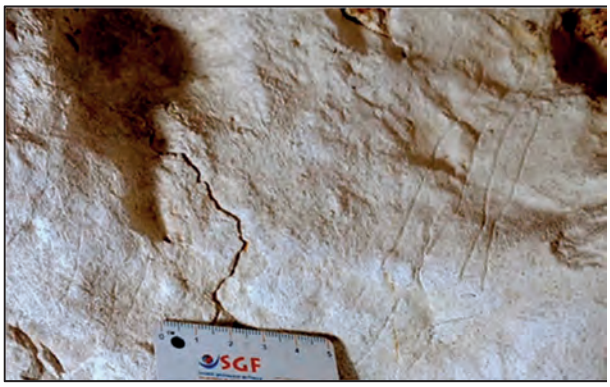

Figure 2 : Griffades anthropomorphes (© J.C. Staigre 2019).

Figure 3 : Griffade anthropomorphe et symbole pubien récent (© J.C. Staigre 2019).

Figure 4 : Griffades bifides et symétriques (© J.C. Staigre 2020).

Figure 5 : Des lignes courbes, bifides et parallèles pouvaient faire penser à des bois de cervidé (© J.C. Staigre 2020).

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3. L'art pariétal récent

Mis à part les cavités naturelles citées ci-dessus et dans lesquelles se trouvent parfois des inscriptions plus récentes (Fig. 6), l'art pariétal récent concerne exclusivement les carrières souterraines et les marnières.

Figure 6 : Située dans la grotte N° 1 de la Roche Fouet, à Orival, Cette faucille jouxtant un symbole pubien pourrait être antérieure au Moyen Age (© J.C. Staigre 2011).

Figure 7 : Vestiges d'oratoire dans la carrière souterraine n° 1 du Transformateur à Oissel (©J.-C. Staigre, 2015).

Bien que l'exploitation de certaines carrières ait commencé il y a environ un millénaire, on ne rencontre guère d'inscriptions ou de dessins antérieurs au XVII éme siècle. Cela s'explique surtout par le fait que les carriers étaient le plus souvent des serfs ignorant tout de l'écriture.

Les premières ornementations ont été surtout d'ordre religieux, destinées sans doute à protéger les travailleurs de l'ombre. Nous citerons en exemple les rares oratoires des carrières souterraines d'Orival et de Oissel (Fig. 7) et des représentations du Christ comme c'est le cas dans la carrière souterraine n°1 du Sanglier, à La Londe (STAIGRE et *al*. 2019), et dans la carrière souterraine des Pigaches à Surtauville (AUDAM, 2010 – fig. 8).

Figure 8 : Christ sculpté de la carrière souterraine *des Pigaches (© J.-L. Audam, 2000).*

Bien que peu courants, d'autres symboles religieux comme les différentes croix gravées du trou d'Enfer de Vatteville (Eure), ou l'étoile de David de la marnière Morvilliers, à la Haye-du-Theil (Eure) sont vraisemblablement attribuables aux périodes troubles que sont la Révolution française et la seconde guerre mondiale (Fig. 9)

Figure 9 : Les croix de Vatteville, probablement gravées par les réfractaires de la Révolution française (© J.-C. Staigre, 2019).

À Orival, la carrière souterraine n° 4 du Sentier des Roches, connue sous le nom de Grotte Sculptée présente tous les attributs d'une chapelle ainsi que la date de 1895 suivie de 3 points en triangle, symbole de signature maçonnique.
Pour le profane, les dessins ou les écritures témoignent des périodes pendant lesquelles elles ont été réalisées. À Orival par exemple, on trouve de nombreuses signatures laissées par de « vaillants explorateurs », des messages codés ou des symboles datant de la seconde guerre mondiale (Fig. 10), une sculpture d'idole des années yéyé, une soucoupe volante et même une feuille de cannabis (STAIGRE et *al*. 2019). Des œuvres uniques méritent qu'on les cite. C'est le cas pour la reproduction de fresques des catacombes romaines dans la carrière souterraine Glatigny à Auberville-la-Renault, de l'Arlequin de la carrière souterraine de la vallée de l'Aulnay à St Hélier, des marnerons de la carrière souterraine de la Bérangerie à Fourmetot (AUDAM, 2010), ou encore des silex ornés précisant le nom des chambres de la marnière du Reposoir à Venon.

Figure 10 : Dans la carrière souterraine *n°7 du Sentier des Roches, à Orival, une francisque gallique jouxte curieusement le symbole de la Résistance (© J.-C. Staigre & J.-L. Audam, 2017).*

Les ponctuations, dessins ou sculptures ésotériques ainsi que des textes incompréhensibles figurent dans certaines cavités artificielles, attendant que des experts viennent en comprendre le sens (Fig. 11 & 12). C'est le cas à Orival et Oissel mais aussi dans de nombreuses carrières souterraines et marnières de la craie normande.

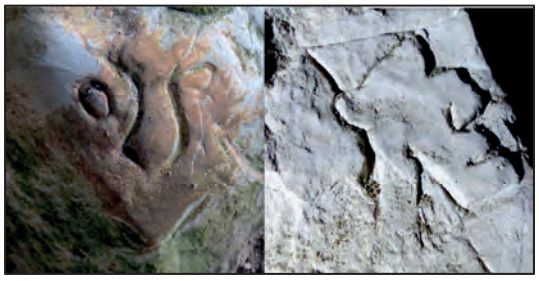

Figure 11 : Deux des sculptures insolites du porche d'entrée de la grande carrière souterraine du Roule Caron, à Oissel (© J.-C. Staigre & J.-L. Audam, 2015).

Figure 12 : Les incompréhensibles ponctuations de la carrière souterraine supérieure du Grand Talweg de la Roche Foulon (Orival) (© J.-C. Staigre, D. Sayaret & J.-L. Audam, 2016).

Enfin, pour illustrer de façon magistrale l'impact des découvertes des authentiques chefs-d'œuvre paléolithiques sur notre sensibilité et notre conscience, des artistes de la seconde moitié du XX éme siècle se sont inspirés de dessins

animaliers pour orner quelques carrières de façon très réaliste (Fig. 13 à 16). Nous en montrons ci-dessous quelques superbes exemples.

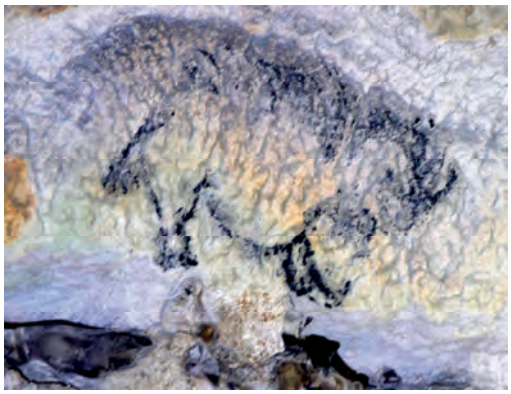

Figure 13 : Représentation animale dans la carrière souterraine n° 3 des Roques, à La Londe. (© J.-C. Staigre, D. Sayaret & J.-L. Audam, 2016).

Figure 14 : Animal percé de flèches. Grande C. S. du Four à Chaux, Saint-Pierre-lès-Elbeuf. (© J.-C. Staigre, 2017).

Figure 15 : Vue partielle d'une fresque pastorale. Grande Carrière souterraine du Four à Chaux, Saint-Pierre-lès-Elbeuf. (© J.-C. Staigre, 2017).

Figure 16 : Ces peintures rupestres, dans une carrière souterraine de la craie normande, ont été exécutée par Régis Fareu pour la chaîne de télévision FR3 Normandie, à l'occasion du 1er avril 1995 (© J-C. Staigre, 2012).

4. Conclusion

Si l'art pariétal de la craie normande a fait et fait toujours l'objet de nombreux travaux scientifiques, tout reste à faire sur sa survivance. Nul doute que les archéologues et historiens à venir s'y intéresseront d'ici quelques temps, à condition bien sûr que ces cavités ne soient pas détruites ou rendues inaccessibles par la politique sécuritaire qui règne en France depuis ces dernières décennies.

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État de surface du panneau orné des chevaux sur argile de la grotte d'Oxocelhaya (Pyrénées-Atlantiques, France)

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Résumé

La cavité d'Oxocelhaya s'ouvre à 140 m d'altitude sur le versant sud de la colline calcaire de Gaztelu (Saint-Martin-d'Arberoue, Pyrénées-Atlantiques, France). Découverte en 1929, elle présente environ 300 m de développement selon une orientation générale sud-nord. Sa renommée, dès 1955, tient à la découverte d'œuvres pariétales dans la galerie Laplace. Parmi les différentes ornementations, les chevaux sur argile (galerie Larribau) ont une place à part en raison de leur bon état de conservation. Afin de discriminer le travail de l'Homme et les évolutions naturelles ultérieures, les états de la surface de la paroi ornée sont décrits. Ce relevé permet de comprendre les processus naturels passés en jeu et d'expliquer ainsi l'état actuel de l'œuvre ; ce relevé constitue aussi, un outil pertinent pour le suivi de l'œuvre pariétale dans un but de conservation.

Abstract

Conservation state of the decored canvas of *chevaux sur argile* in Oxocelhaya Cave (Pyrénées-Atlantiques, France). The Oxocelhaya cave open at 140 m above sea level, on the south limestone slopes of Gaztelu hill (Saint-Martin-d'Arberoue, Pyrénées-Atlantiques, France). The cave was discovered in 1929; it develops over 300 m length, along a south-north direction. The cave paintings that were discovered, notably in 1955 in Laplace gallery, made it very famous. Among its various images, the *chevaux sur argile* are particularly well preserved. In order to differentiate artefacts from the later natural evolutions, the authors concentrated on the precise description of the decorated wall and its preservation state. This assessment contributed to a better understanding of past natural processes and to the explanation of the current conservation of the works of art; it also provides relevant analysis tools for future preservation follow-up.

1. Introduction

La colline de Gaztelu est un éperon rocheux long de 500 m, large de 300 m et haut de 209 m qui appartient au croissant sédimentaire de l'Arberoue, vallée aveugle située au nord-est du massif de l'Ursuya dans les Pyrénées occidentales françaises. Ce relief comporte quatre galeries étagées : Aldabia (175 m), Isturitz (150 m), Oxocelhaya (138/140 m) et Erberua (100 m). Les niveaux les plus élevés marquent les stades d'enfoncement progressif du niveau de base ; le niveau le plus bas correspond à la percée hydrologique active de la rivière Arberoue (Figure 1).

Découverte en 1929 par J.-O. Etchegaray, l'étage d'Oxocelhaya présente un développement cumulé d'environ 300 m de galeries selon une orientation générale sud-nord (Figure 2). Sa renommée tient à la découverte d'œuvres pariétales (LAPLACE, 1960) dont les chevaux sur argile (LARRIBAU, 1982). Dans cet article, les auteurs décrivent l'état de surface du panneau orné en distinguant le travail de l'artiste et les évolutions naturelles et en proposant une chronologie relative des faits.

2. Objet et méthode

Les deux entrées naturelles de la cavité d'Oxocelhaya s'ouvrent respectivement à 138 et 140 m *asl* sur le flanc sud de la colline calcaire de Gaztelu. L'encaissant est constitué de calcaires crétacés à faciès urgonien. Orientée sud-nord, la galerie Larribau prolonge la galerie Haristoy 2 et se situe en amont de la galerie des Bauges. Elle domine la salle de la Pagode dont elle représente la terminaison ouest (Fig. 2). Sa forme générale est celle d'un canyon souterrain à section asymétrique. Entrée et sortie exigent un franchissement en escalade sur des zones concrétionnées qui correspondent à des venues d'eau, désormais inactives au nord, mais toujours actives au sud : elles alimentent alors des gours. Le panneau orné se situe dans la partie nord de la paroi ouest de la galerie Larribau, sur un pan incliné de roche ; il est

constitué de deux chevaux, tournés vers le sud, qui se suivent (Figure 3).

L'étude a été réalisée en trois temps : 1/ acquisition photogrammétrique et déclinaison en ortho-image, 2/ typologie des états de surface du panneau orné, report cartographique et interprétation des processus en jeu, 3/ classement de ces observations dans le cadre chronologique préalablement établi à l'échelle du réseau.

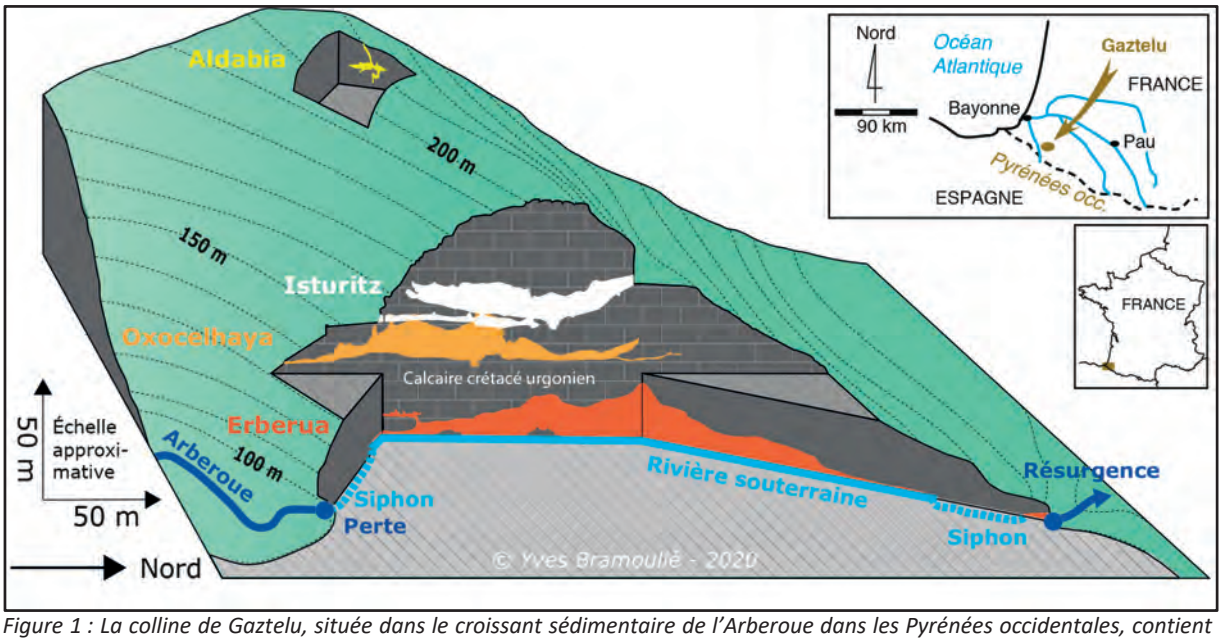

Figure 1 : La colline de Gaztelu, située dans le croissant sédimentaire de l'Arberoue dans les Pyrénées occidentales, contient quatre réseaux dont celui d'Oxocelhaya. La représentation d'Erberua est indicative (non topographiée).

3. Résultats

Les chevaux sur argile sont rattachés au Magdalénien moyen ; outre le travail des artistes (GARATE, 2017), les caractéristiques de l'œuvre sont fonction de deux paramètres : les états du support lors de sa réalisation et les évolutions ultérieures conditionnées par les dynamiques actives de la galerie (Figure 3).
1/ Le pan incliné correspond à la forme initiale de la galerie, il s'inscrit entre deux niveaux de conduits et pendants. 2/ Les conduits sont colmatés par des argiles jaunâtres à enduit noirâtre à l'interface remplissage/encaissant tandis qu'une altération entraîne un ameublissement de 1 à 4 mn (pseudo-mondmilch) du calcaire au niveau du pan incliné ; 3/ Le remaniement des argiles dans les conduits supérieurs forme des coulures sur le plan incliné ; 4/ Les hommes repèrent cette surface à la fois plane et meuble et inscrivent deux chevaux sur le pseudo-mondmilch et les coulures ; 4bis/ Des taches noirâtres, à l'intérieur et dans le prolongement des tracés, et des fines stries, uniquement à l'intérieur des tracés, complètent l'œuvre. On peut, sans certitude, rattacher les boulettes d'argile à cette époque ; 5/ Une période plus humide permet des arrivés d'eau avec mise en place de gours et de coulées qui viennent masquer respectivement le sol et la paroi surtout au nord du panneau. On observe un décapage de la paroi au sud et l'effritement des coulures d'argile au niveau de l'oreille, de l'encolure et du garrot du cheval de tête, tandis que l'œil et le chanfrein résiste à la desquamation. Les naseaux et la bouche du cheval de tête, la tête du cheval de queue sont figés par un film de calcite (réactif aux UV) tandis que, sous le ventre du cheval de queue, ce film de calcite s'agrémente de petits picots pointés vers le plafond. Les phénomènes de néoformation sont aussi marqués par la mise en place de cristaux radiaires de calcite pris dans l'épaisseur du pseudo-mondmilch en avant et au niveau des sabots du cheval de queue.

4. Discussion sur la chronologie des événements

La forme en canyon de la galerie Larribau est à rattacher au fonctionnement d'Oxocelhaya lors de l'évolution de la paléo-Arberoue en percées hydrologiques au Pliocène et Pléistocène inférieur, le niveau de base régionale étant à +30 m par rapport à la situation actuelle. Les datations par isotopes cosmogéniques des formations, situées dans la partie amont de la cavité, ont livré des dates de 4,66 (±1,2) et 3,7 (±0,8) Ma. Ces dates sont à prendre avec prudence. Les barres d'erreur pourraient laisser envisager un fonctionnement concomitant. Or faciès et stratification permettent de distinguer une terrasse alluviale séparée d'un dépôt remanié par une surface de ravinement scellée par un plancher stalagmitique ancien. On date, certes, un enfouissement mais pas forcément contemporain du fonctionnement de la rivière souterraine. Les flots pouvant reprendre à leur charge des altérites soutirées lors de

périodes antérieures de la karstification sous couverture (phénomène de relais). Les conduits et pendants, qui encadrent le panneau orné sont caractéristiques d'un creusement paragénétique (RENAULT, 1966). Chenaux et lapiaz de voûte attestent d'un colmatage complet de la galerie (Figure 2). Le décolmatage laisse les parois nettes.

Après abandon des circulations noyées au Pléistocène moyen, la cavité est investie par la faune terrestre (dès 300 ka pour les ursidés). L'occupation importante par les chauves-souris (période éémienne probable) expliquent : 1/ que les rares sédiments restants soient enrichis par le guano (les enduits noirâtres sont interprétés comme étant de l'apatite ; 2/ que du pseudo-mondmilch investisse le pan incliné. Ce matériel est jaunâtre, meuble, poreux et pulvérulent en cas de dessiccation ; il est constitué en partie d'argiles phosphatées et de calcaire altéré avec substitution de la calcite sparitique et micrite de la roche par des cristaux aciculaires de gypse en structures radiaires.

Au Pléistocène supérieur, le refroidissement du climat chasse les chauves-souris mais favorise les ours des cavernes qui parcourent la galerie avant les hommes ; pour preuve les griffades repérées sous les tracés de l'œuvre Cheval noir (Figure 2). Les hommes du Magdalénien moyen adoptent leur technique aux différents supports que leur propose la galerie Larribau : sur la paroi nue, ils optent pour la gravure (Cheval au licol, Figure 2) alors que le pseudo-mondmilch et les coulures sont travaillés par écrasement (tracés digités probables) et les stries au fond des tracés sont obtenues à l'aide d'un outil lithique.

À l'Holocène, l'adoucissement du climat permet le concrétionnement (coulées et gours). Les morphologies passées contraignent la position, l'extension et la récurrence de phénomène de condensation-corrosion plus récents. Ces derniers sont marqués par des limites franches au-delà desquelles agissent les processus d'évaporation-précipitation. Avec l'augmentation du lessivage dû aux imbibitions de la paroi, le gypse est localement remplacé par la calcite. Les ruissellements aboutissent à l'évacuation de la partie meuble du mondmilch, laissant localement apparaître des picots ou des cristaux radiaires de calcite (Figure 3).

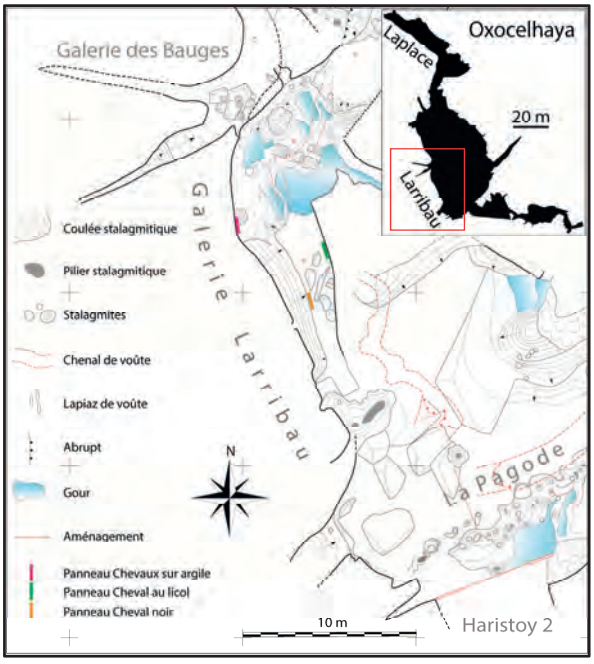

Figure 2 : Plans d'Oxocelhaya et de la galerie Larribau (Y. Bramoullé, M.-J. Lhuillier, G. Parent et E. Tixier, 2013).

5. Conclusion

Les relevés réalisés au cours de cette étude, en soutien du relevé d'art pariétal, constituent un état des lieux de la paroi. Il ne s'agit pas simplement d'une mise en mémoire photographique mais d'une description circonstanciée et analysée permettant de réaliser des interprétations morphologiques des états de paroi et de leurs évolutions dans le temps. En identifiant les processus en jeu, cette approche constitue, par voie de conséquence, un outil pertinent pour le suivi des supports des œuvres pariétales en vue de leur conservation.
Des visites d'inspection régulières, à une fréquence adaptée, pour la comparaison de l'évolution des états de paroi avec le relevé existant (Figure 3) seront donc à prévoir pour déceler d'éventuels désordres. En parallèle, la mise en place d'une instrumentation pour l'étude aérologique de cette partie de la cavité serait souhaitable pour comprendre au mieux les conditions de ces évolutions. Enfin, il sera aussi nécessaire de prendre en compte le rôle de la faune cavernicole, notamment des chiroptères (études éthologique, biogéographique et de la biocénose bactérienne associée). L'installation de chauves-souris dans une niche au droit du panneau orné pourrait avoir des conséquences délétères très rapides comme on peut déjà le constater au sud et au nord de la galerie avec le retour (période historique) de quelques chauves-souris.

Remerciements

Le financement de cette étude a été assuré par la DRAC Nouvelle-Aquitaine. Les auteurs tiennent à remercier M. Olivier Ferullo (DRAC Nouvelle-Aquitaine) pour ses conseils lors des montages administratifs et financiers des dossiers, la famille Darricau (association Isturitz-Oxocelhaya) pour les autorisations accordées et le suivi toujours bienveillant de nos travaux et MM. Jean-Baptiste Fourvel et Christophe Galant (relecteurs) pour leurs commentaires constructifs.

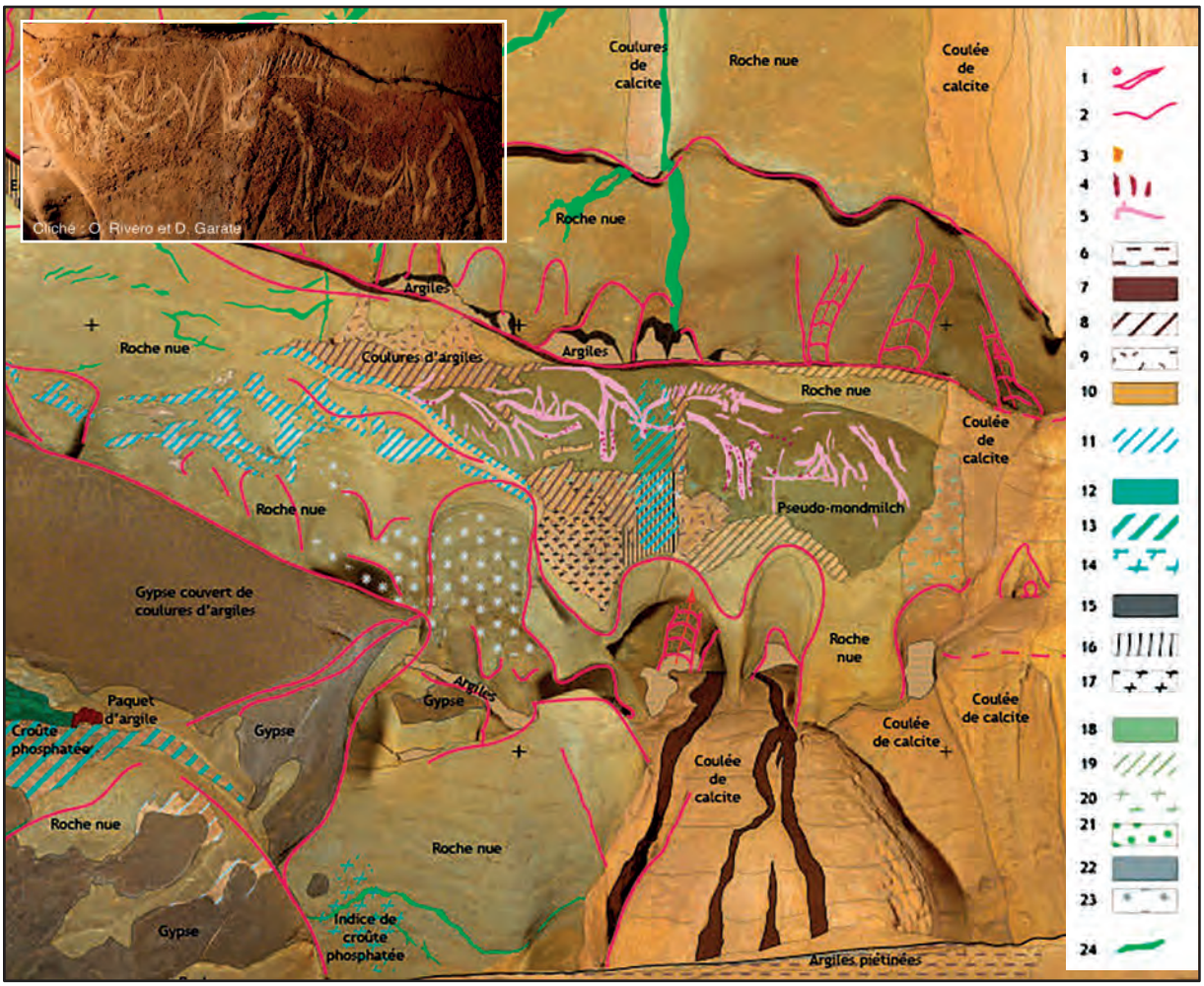

Figure 3 : Cartographie des états de paroi centrée sur le panneau des chevaux sur argile.
Topographie et morphologies : 1- Micro-conduits ouverts, 2- Morphologies de creusement par l'eau en régime noyé ou épinoyé. Artéfacts archéologiques et paléontologiques : 3- Boulettes d'argile projetées sur paroi, 4- Taches ponctuelles de pigments noirs, 5- Traces digitées. Sédiments : 6- Argiles piétinées, 7- Argiles remaniées, 8- Argiles remaniées en coulures, 9- Argiles mouchetées, 10- Argiles litées en place. Enduits et croûtes : 11- Calcite réagissant aux UV d'épaisseur faible et discontinue, 12- Enduits phosphatés d'épaisseur faible et régulière, 13 - Enduits phosphatés d'épaisseur pelliculaire, 14- Indice de présence d'enduits phosphatés sous coulée de calcite, 15- Enduit noirâtre d'épaisseur faible et régulière en arrière des croûtes phosphatées, 16- Enduit noirâtre d'épaisseur faible et discontinue en arrière des croûtes phosphatées, 17- Enduit noirâtre résiduel en arrière des croûtes phosphatées. Paroi corrodée : 18- Pseudo-mondmilch d'épaisseur millimétrique, 19- Pseudo-mondmilch de très faible épaisseur, 20- Pseudo-mondmilch résiduel, 21- Calcite aciculaire radiaire néoformée dans le pseudo-mondmilch, 22- Gypse en enduit épais, 23- Gypse en cristaux épars. Calcaire encaissant : 24- Filon de calcite blanche dans l'encaissant calcaire crétacé à faciès urgonien.

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Initial Geoarcheological Survey of Caves at Chichén Itzá, Yucatan, Mexico

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Abstract

Maya Mesoamerica extends across Belize, Guatemala, and parts of El Salvador, Honduras, and Mexico. Approximately 70% of this area is karst. With most access to water being through caves, springs, and cenotes, the importance of caves to ancient Maya culture has long been recognized. The archaeological site of Chichén Itzá, in Yucatan, Mexico, is famous for human sacrifices in one cenote, but until this study, a systematic study of caves in the area was lacking.

This initial investigation geoarcheologically examined five caves, three cenotes, three sascaberas, and two chultuns within and as far as 4.5 km from Chichén Itzá. None of the caves were used as water sources, since cenotes are locally abundant, but ritual use is clear in most caves. One was probably mined for medicinal clay. A stalactite from a cenote was placed in one cave. The chultuns were also found as ritually important than as practical water sources. Potential caves and extensions of known caves, hidden behind constructed walls or under structures, were identified for future evaluation.

1. Introduction

The Maya Mesoamerican region extends across Belize, Guatemala, and parts of El Salvador, Honduras, and Mexico. Approximately 70% of this area is karst, characterized by caves and little to no surface water (VENI 1990). With most access to water being through caves and related features like cenotes (large sinkhole collapses that expose the water table) and springs, the importance of caves to ancient Maya culture has long been recognized (e.g., THOMPSON 1959).

Caves were used by the Maya as sources of water and for religious, calendric, ascension, and other rituals (e.g. STONE 1995). Especially sacred areas of caves were frequently hidden or obstructed by constructed walls. The most famous such cave is Grutas de Balankanche near the archaeological site of Chichén Itzá, in Yucatan, Mexico (ANDREWS 1970).

Caves have also been identified as significant elements in the sacred symbolic geography and layout of major structures in Mayan communities, even to the extreme degree that some communities have excavated tunnels to create the cultural equivalent of caves where natural caves do not exist (e.g., BRADY & VENI 1992; BRADY 2004). Further, studies of some chultuns, constructed cavities initially envisioned for water storage, found them impractical or unable to hold water and are reinterpreted as another form of artificial cave—even in cavernous areas—for the sacred value they give to a site (e.g., BRADY & LAYCO 2018).

In August 2019, Projecto Gran Acuífero Maya (GAM) invited Dr. George Veni of the US National Cave and Karst Research Institute to conduct a preliminary geoarchaeological investigation of known and newly found caves and karst and archaeological sites in and around Chichén Itzá. Dr. Veni was assisted by his long-time colleague and Maya cave expert Mr. Allan Cobb. Their work and access to field sites was facilitated by GAM directors Dr. Guillermo de Anda and Dr. Jim Brady, with assistance from Ana Celis, Karla Ortega, and other GAM members.

This project was funded by GAM to geologically investigate several sites and their potential for subsequent, more detailed study. Following is an alphabetical listing of some of the sites visited, and the preliminary findings.

2. Sites Investigated

Balamku. This newly re-discovered cave contains multiple caches of incensarios and other ceramic vessels (STEFFENS 2019). Within a horizontal distance of about 15 m from the entrance, the cave reaches a depth of about 12 m and maintains that approximate depth throughout its surveyed length of about 500 m. The passages range from 0.5 to 3 m high and wide and are phreatically formed. Elevated levels of carbon dioxide occur throughout the cave, which Allan Cobb measured at 3.1-3.2%, nearly 100 times greater than normal atmospheric levels.

The primary reason for investigating this cave was to assess the potential for additional sacred passages hidden by the Maya. The considerable effort and difficulty to carry the large ceramic vessels throughout the known small passages with high levels of carbon dioxide, and with relatively little resulting damage, requires the consideration of a possible hidden entrance. While all passages were not examined, the cave's morphology and descriptions and map of unvisited areas suggest no additional entrances are likely. Much of the area over the cave was walked and two depressions were discovered aligned just south of the current limit of exploration, but excavation by GAM did not reveal entrances. Allan Cobb observed that the floor of white rocks leading from the entrance is artificial and likely represents a sacbe (literally "white road," which were built on the surface by the Maya for commerce and to connect sacred sites), further suggesting this is the only entrance into the cave.

Geologic observations indicate that the stone staircase leading down and south from the entrance may hide a continuation of the entrance passage to the north. Additionally, the weathering pattern on a probably roughly-carved 1-m long stalactite in the entrance room was not native to the cave and was brought in from a cenote or rejollada (a large collapsed sinkhole like a cenote, except with dry floor) where the stalactite grew in an environment open to surface weathering.

Two depressions found by the GAM team are located near a sacbe and a roughly 20- by 20-m square by 2-m high structure. Given this proximity, if they cover cave entrances, they seem likely to hold notable cultural materials. At least one depression is almost certainly a natural sinkhole. Excavation is needed to determine if it was filled naturally or by the Maya. Even if filled naturally, an underlying cave could exist that the Maya may have entered through another, currently unknown open or buried entrance.

Cueva del Osario. One of the longest known caves in the area, this cave was first reported in 1897 (THOMPSON 1938). This study was its first examination by a karst hydrogeologist. The cave's entrance is covered by El Osario, a 9-m tall flat-topped pyramid, and is accessed through a 1-m square shaft at the top of the pyramid that drops through the core of the structure to the cave.

The natural entrance is a 2-m deep pit with steps built into one side to give access into a space about 1.5 m in diameter and high. In the floor is the 0.4-m diameter top of a vadosely-formed pit that widens quickly to a diameter of 3-4 m and drops about 12 m to the bottom of the cave. The room at the bottom is about 18 m long by 5 m wide by 0.5 m high. It appears phreatic in origin. A slightly anastomotic network of small passages extending from the room suggests they were created by low-velocity groundwater conditions. High levels of carbon dioxide are also common in this cave.

Some of the small passages in the pit and room show airflow corrosion. Weak but detectable air movement was felt, especially from inaccessibly small holes in the room about 2 m southeast of the bottom of the entrance pit and 4 m northwest of the pit. Minor excavation of the floor in the area to the northwest should reveal if the cave can be explored in that direction or if significant additional excavation may be needed. A small passage heads east into the pit wall about 3.5 m above the floor. Its morphology indicates it will become impassably small within a short distance, which needs to be confirmed.

Most of the floor is covered with an estimated 0.3-m thick layer of rock and sediment, debris from the original archaeological investigation of the cave. This debris might cover currently unknown passages, but this seems unlikely given the morphology of the room and that the archaeologists probably would not have deliberately filled any passages.

Cueva Xtoloc. Drs. Jim Brady, Kevin Thuesen, and George Veni surveyed this cave in 1992, which was revisited during this study. The cave is in the wall of Cenote Xtoloc, about 20 m down from the top of the cenote and 6 m above its lake. The depth of the cenote's lake is not known. The cave averages 1 to 1.3 m high by 2 m wide. The entrance passage goes west 5 m to a "T" intersection. In each direction the cave extends about 80 m, to the southwest and northeast. The 1992 survey was extended overland to the lake, the top of the cenote, and to some exposed structures within the cenote.

The cave's origin predates the collapse of the cenote. The direction of groundwater flow that created the cave is not clear. The cave's map-scale morphology indicates northeast to southwest flow while smaller features in the southwest passage suggest northeast flow. This may suggest a flow reversal when the cenote collapsed, allowing water to drain from the entrance. The entrance passage was probably initially a tributary to the main passage and became a spring for a short while as flow from the cave discharged from the newly created cenote wall. Later, the entrance passage was enlarged by the Maya to gain access to the main part of the cave.

Given the historic long-time easy access to the cave, any significant cultural materials left in the cave were probably looted long ago. What may be a partial constructed wall exists in the southwest part of the cave and may have once blocked access to a short side passage. A small pit, 1.3 m long by 0.6 m wide by 0.3 m deep, was found dug into the sediment floor of the side passage. It was not possible to assess the age of the excavation. Many excavations of cave sediment by the ancient Maya cannot be visually distinguished from modern excavations.

Throughout the cave, and especially in domes in its northeast section, is a gray-green clay that is not found in most caves. It appears to be attapulgite, also known palygorskite, a magnesium aluminum phyllosilicate clay known for use by the Maya for "Maya Blue" pigment and medicinally for its anti-diarrheal properties; it is an active ingredient is several modern medicines (e.g. ARNOLD 2005). It is possible this clay was more abundant and excavated from the cave, but there is no direct evidence to support this hypothesis at this time.

Grutas de Balankanche. A short visit was made to this show cave for comparison to Balamku. Morphologically, the caves are similar, except that passages in Balankanche are much larger. Both caves have high levels of carbon dioxide and drain to the south, suggesting a subtle structural control of cave development in the area that would require detailed geologic mapping to confirm. At its southern limit, Balankanche turns along an east-west trend, suggesting Balamku may also turn and drain to the east beyond its current limit of exploration.

Like Balankanche, Balamku becomes wet at its southern end. At this point Balamku is only muddy and no significant pools are known. The description of the end of Balamku is conflicting; it is not clear if the cave ends or continues small and can only be traversed with difficulty. If it is physically passable, it should be explored. Pools that would have been sacred to the Maya probably exist beyond the current limit of exploration. If they are humanly accessible, then notable cultural materials may be present.

San Felipe Nuevo Chultun. This chultun was visited twice during its excavation by Dr. Jim Brady's student, Christina Iglesias. Our evaluation confirmed that the chultun was not

a natural pit but a constructed, plaster-walled feature in a small platform structure. We also noted the chultun could accept drainage from an area probably no more than 25 m^2, suggesting its water was more for ceremonial use than as a domestic water supply.

San Felipe Nuevo Sascabera. A 0.4-m diameter by 1.8-m deep pit drops into this feature. The room at the bottom is approximately 5 m long north-to-south, 4 m wide, and up to 1.8 m high. Its west wall is bedrock with small tool marks, apparently from mining sascab (a poorly cemented limestone and marl used by the Maya for mortar and related purposes). The east wall is loosely stacked stones.

The purpose of investigating this feature was to confirm it was a sascabera (a sascab mine) and if excavation of sascab occurred through the pit entrance. A conclusive answer about the entrance is not currently possible. Preliminarily, the sascabera may have been a small, naturally occurring cave with a larger entrance that opened eastward. It appears that the loosely stacked rocks may have filled the entrance area to create a slope up to the pit entrance, which seems natural or slightly enlarged. Marks from large excavation tools were not observed, which may indicate that only small-scale ceremonial excavation was conducted through the pit entrance and the larger east-facing entrance, if it in fact existed, was sealed to create a sacred cavernous space. In contrast and in support of this hypothesis, an open pit sascabera in the vicinity of Takbilha was likely excavated for larger volumes of material for construction needs.

Takbilha. The entrance to this cave is a 10-m long by 6-m wide by 5-m deep pit on a hillside. The pit is oriented on a north-south axis and enlarges to about 16 m long by 10 m wide at its base. To the south its floor slopes down into the cave's second room, which is on a northeast-southwest axis and approximately 22 m long by 11 m wide. The floor of the second room slopes down to the southeast to a 0.5-m diameter by 0.2-m deep pool at an elevation roughly 16 m lower than the entrance.

Breakdown covers much of the cave floor. Much if it is historic in age with some covered by recently deposited white flowstone. The second room contains several ceramic sherds which could not have occurred in their locations unless rocks fell on them. Undoubtedly, excavation of the rocks would yield more ceramics, but the effort and hazardous excavation conditions, especially near the pool where the concentration of ceramics is greatest and the rocks are boulders with no safe or stable location to place them, is probably not worth the effort—especially considering the unknown quantity and quality of mostly crushed materials that would be retrieved.

Sascab is visible in the west wall of the entrance pit about 1-1.5 m above the floor. The wall extends almost a meter west along this bed. Small conduits are evidence of groundwater seepage from the wall, that may be responsible for eroding the wall back about a meter. The wall could have also been cut back by sascab mining, although any evidence of that has been lost to subsequent erosion.

Figure 1: Allan Cobb examines a cache of incensarios and other ceramic vessels at Offering 2 in Balamku.

4. Conclusions

The following is a summary conclusion of some of the results of this project, discussed in the context of recommended additional or continued research.

Continued Exploration. The recent discovery of Balamku spectacularly illustrates the value of the continued archaeological exploration and study of caves in the Chichén Itzá area. Discoveries like these need to continue through searches for additional caves and exploration of all passages. Cave entrances and passages may be filled by natural and artificial means to hide cultural materials. Excavation, coupled with detailed geological observations, will result in more accurate predictions for finding new caves and passages.

Geophysical Studies. The potential extent of Maya cave use and importance is currently understood by systematic exploration and fortuitous discoveries, usually in known and open caves. The caves and passages hidden beneath structures, filled sinkholes, and behind walls are almost certainly poorly and only partly studied. The most effective and least invasive means of investigating if such caves or passages are present is through near-surface geophysical methods. A variety of geophysical methods are available for conducting such studies. Of these, electrical resistivity surveys are generally the most effective tool for identifying subsurface void space, whether air or water filled.

Three specific applications for geophysics are recommended: 1) determine if open passages exist prior to excavation of passages or possible cave entrances; 2) enhance characterization of chultuns and sascaberas; 3) ascertain if caves exist below Mayan structures. Expanding that third application, BOOT (2005) provides a detailed study of the iconography of Chichén Itzá and identifies several structures with text that refer to water and gods often associated with caves. A geophysical study that includes those sites would determine if such iconography likely indicates the presence of an underlying cave, which then could be targeted for exploration and study in excavations of those structures.

Hydrogeologic Mapping. The Yucatán Peninsula karst aquifer is extensive and needs additional detailed study. Precision mapping of the local hydrostratigraphy, structure, and elevations of hydrologically active and inactive cave passages, as well as the water chemistry and flow patterns in caves, will provide important insights into groundwater movement and cave development in the area. Such research would contribute to a better understanding of groundwater resources in Yucatan and may provide important insights to more successfully identify where cultural materials may occur underground.

Mineralogical Analyses. Geological samples collected for analysis from four locations await analysis to better characterize local karst geological conditions and Maya use of karst resources. Those samples will be studied as soon as possible.

Acknowledgments

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Symposium 08 - special session

Paleospeleology

Paleospeleology

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English

From the beginning, archaeology has always considered the underground domain as a conservative space where the density of remains justified the search for traces of the past. It very quickly became apparent that the cave domain showed an often-rapid sedimentation closely linked to human occupations. From then on, "stratigraphy" was seen as the key to reading human evolution, fixing it both in relative time and in absolute space through dating, both on the archaeological levels and on the surrounding natural contexts.

The evolution of archaeological research has brought to light the need to better perceive the natural environment in order to better understand the problems caused by the impact of humans on sites. It is through the karst and its often rapid evolutionary processes that the geomorphological approach has entered the debate. It has also allowed us to go beyond the sites by looking at the periphery of the places of occupation, and even into more distant spaces. Versatile researchers, among whom Paul Ambert played a major role, crossed the analysis of the natural with that of the anthropic. This is how the geoarchaeological approach came about. Through a very detailed analysis of natural contexts and the analysis of their disturbances, it is possible to perceive, understand and discover completely innovative and unsuspected aspects concerning the knowledge of ancient human societies.

Very quickly this approach produced very surprising results in underground environments. A few speleologists who were very curious about these facts, like François Rouzaud as a pioneer, revealed the major interest of this approach. It was thus possible to measure that natural contexts and their disturbances play an essential role in understanding anthropic events. This new approach makes it possible to perceive unexpected, often unique and exceptional gestures. The multiplication of these recordings makes it possible to characterise specific behaviours and to reveal things that are obvious but never presented as such. Thus the notion of ancient speleological explorations, an essential prerequisite for discovering the underground environment and perceiving its interests, comes to light. Humans dominated the surface but in the karst they also dominated the underground domain! The impact of human activity on the development of the caves in relation to their uses has now been revealed in aspects that were as monumental as they were unknown until now.

It thus appeared essential to present in this colloquium a long series of these new works in the framework of a specific sub-session of the symposium on the archaeology of the underground environment, such is the specificity of this approach and so essential its contributions, to perceive the human attitude in the deep karst under a new glance. In these recent studies, we perceive the impact of cavers by the quality of their views and the major role they have by their very fine knowledge of this environment so exceptional in many ways.

Français

Dès son origine, l'archéologie a toujours considéré le domaine souterrain comme un espace conservateur où la densité des vestiges justifiait la recherche des traces du passé. Très vite il est apparu que le domaine des grottes montrait une sédimentation souvent rapide et en lien étroit avec les occupations humaines. Dès lors, « la stratigraphie » a été perçue comme la clé de lecture des évolutions humaines, les fixant à la fois dans le temps relatif mais également dans l'espace absolue au travers des datations, tant sur les niveaux archéologiques que sur les contextes naturels encadrant.

L'évolution de la recherche archéologique a fait apparaitre la nécessité de mieux percevoir l'environnement naturel pour mieux comprendre les travers induits par l'anthropisation des sites. C'est par le karst et ses processus d'évolution souvent rapides, que l'approche géomorphologique s'est invitée dans le débat. Elle a également permis de sortir des sites en portant un regard périphérique aux lieux d'occupations, voire dans les espaces plus lointains. Des chercheurs polyvalents, parmi lesquels Paul Ambert a joué un rôle majeur, ont croisé l'analyse du naturel avec celle de l'anthropique. Ainsi est apparue la démarche géoarchéologique. On peut alors, au travers d'une analyse très fine des contextes naturels et l'analyse de leurs perturbations, percevoir, comprendre et découvrir des aspects tout à fait novateurs et insoupçonnés portant sur la connaissance des sociétés humaines anciennes.

Très vite cette démarche a produit des résultats très étonnants dans les milieux souterrains. Quelques spéléologues très curieux de ces faits, comme l'a été François Rouzaud en pionnier, ont révélé l'intérêt majeur de cette approche. On a pu ainsi mesurer que les contextes naturels et leurs perturbations jouent un rôle essentiel pour comprendre les faits anthropiques. Cette nouvelle approche permet de percevoir des gestes inattendus, souvent uniques et exceptionnels. La multiplication de ces enregistrements permet de caractériser de véritables comportements spécifiques et de révéler des choses pourtant évidentes mais

jamais présentées telles qu'elle. Ainsi la notion d'explorations spéléologiques anciennes, préalable incontournable pour découvrir le milieu souterrain et en percevoir ses intérêts, se montre au grand jour. L'homme dominait la surface mais dans le karst il dominait également le domaine souterrain ! L'impact des faits anthropiques dans l'aménagement des cavités en lien avec leurs utilisations se révèle sous des aspects tout aussi monumentaux qu'inconnus jusqu'alors.

C'est ainsi qu'il est apparu indispensable de présenter dans ce colloque une longue série de ces travaux nouveaux dans le cadre d'une sous-session spécifique du symposium sur l'archéologie du milieu souterrain, tant la spécificité de la démarche est forte et ses apports essentiels, pour percevoir l'attitude humaine dans le karst profond sous un nouveau regard. Dans ces recherches récentes on perçoit tout l'impact des spéléologues par la qualité leurs regards et le rôle majeur qu'ils ont par leur connaissance très fine de ce milieu si exceptionnel à bien des titres.

A human footprint (Aldène cave in Cesseras, Hérault, France), a direct witness to prehistoric cave exploration. The history of these remains can be reconstructed through a geoarchaeological approach. Photo: Ministry of Culture - DRAC Occitanie.

L'empreinte d'un pas humain (Grotte d'Aldène à Cesseras, Hérault, France) est un témoignage direct de l'exploration spéléologique préhistorique. Grâce à une approche géoarchéologique de ces vestiges on peut en restituer l'histoire. Photo : Ministère de la Culture - DRAC Occitanie.

Speleo-archeology, or the search of historic and prehistoric constructions in the caves of Southern France

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Abstract

The scientific study of the human frequentation clues in caves started with the work of François ROUZAUD (1978), entitled *"La paléospéléologie"*. Since that time, other archeologists have continued research, developing a real specialty, the speleo-archeology, defined as the study of human frequentation in caves prior to modern speleology. Clues of human incursions have already been examined by karst scientists or geomorphologists in well-known prestigious caves, which access is regulated. However, many open-access caves have not been yet studied through the point of view of speleo-archeology. Only one example of caves containing anthropogenic constructions is presented here to illustrate speleo-archeological research: the Mas-d'Azil Cave (Ariège), which keeps old traces of a clay mining.

1. Introduction

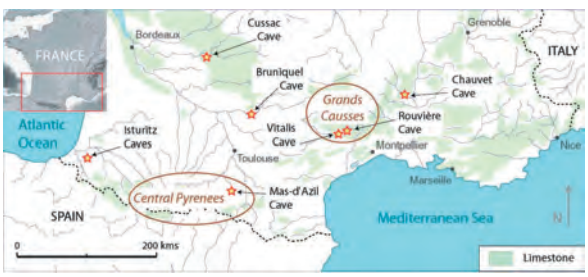

Figure 1: Location of the caves in the South of France quoted in the text.

In France (Fig. 1), the search for traces and constructions in caves formally began in the 1970s with the work of François ROUZAUD (1948-1999), published in 1978 and entitled: *« La paléospéléologie »*. The study of human traces (footsteps, hands imprints, etc.), which took place in the caves of the Central Pyrenees, continued to be practiced in the Grands Causses and the Mediterranean garrigues with the investigation of the caves used during the Late Neolithic (GALANT & HALGAND, 2004).

In the early 2010s, the arrival of karstologists in archeological research programs shed additional light. Since a collaboration was imposed in the study of the Chauvet cave, teams of archaeologists have sometimes called on the services of karstologists, in particular to map prehistoric caves of national interest (caves of Bruniquel, Cussac, Isturitz, etc.). Access to these prestigious caves being limited and regulated, it was necessary investing in other caves, open and free in access, to refine our sense of observation. This is what we have been doing in the caves of Southern France in order to develop new investigation methods.

2. The Speleo-archeology: a new discipline?

Speleo-archeology was practiced by few enlightened precursors who laid the foundations of a specific discipline of cave environment. After having stated the advances of archeologists and their followers, the detection of anthropogenic traces will be the subject of a brief presentation.

a) The choice of the word speleo-archeology

The word speleo-archeology contains the root of two key words borrowed from ancient Greek: *spelaion* which means "cave" and *arkhaiologia* which means "history of antiquity", ended by the suffix -logy or study of. This word is built on the same bases as the word geoarcheology proposed by the Anglo-Saxons and then gallicized in "géoarchéologie".

If we had to sum up the speleo-archeological activity in one sentence: "recognize in caves what is natural and what is not".

The speleo-archeological approach is a new discipline in the sense that it is based on a good knowledge of karst and cave formation possessed by all good speleologists or karstologists, geomorphologists specialized in karst. Indeed, a perfect knowledge of the "cave without man", that is to say before his passage, allows identifying with certainty what is natural and what is not. Discrimination between natural and man-made forms constitutes the essence of the speleo-archeological approach.

The word “paleospeleology”, literally “old speleology”, proposed by François Rouzaud in 1978 is limited to the search for traces left by prehistoric man in the remote parts of the caves. He does not apprehend the container, that is to say the cave, but only certain types of traces left by the Upper Paleolithic people during their underground forays into the Central Pyrenees.
The word "paleospeleology", speleology practiced by prehistoric men in the sense of Rouzaud, cannot have the meaning of the word speleo-archeology, which applies to a much larger field of research.

b) A pioneer: François ROUZAUD

François ROUZAUD is a pioneer in the search for anthropogenic traces in cave environments. In 1978, he laid the foundations of a specialty that was struggling to emerge. He was a precursor of this type of archeology, which he practiced mainly in the ancient Midi-Pyrénées region, SW of France. It is only much later, when the cave has been considered a « crime scene » that the methods of observation had changed. These new methods are inspired by the « forensic principle of exchange during contact between two agents and the traces that this contact produces » (MONTELLE, 2012).
In 1997, ROUZAUD proposed an inventory of all human traces (beyond footprints); this inventory « most often takes as a starting point the observations made by the inventor speleologists ». Indeed, ROUZAUD was a speleologist who specialized in the archeology of caves. He built the foundations of « paleospeleology » and specified that the progress of the speleologists should be dictated by the detection of « anomalies, of all kinds, observable on the surface of the soil and walls ».
The new discipline practiced by ROUZAUD implicitly implies a practice of caving. Like him, speleologists are perfectly familiar with the gestures and situations in which their predecessors (the « paleospeleologists ») were confronted. This is also the main theme of his work published in 1978: *« La paléospéléologie. L'homme et le milieu souterrain pyrénéen au Paléolithique supérieur »* (« The paleospeleology. Man and the Pyrenean underground environment in the Upper Paleolithic »). As a pioneer, he advanced alone for years creating this new discipline, whose name will not really be repeated.
In 1989, the methods and relationships that ROUZAUD developed with speleologists were used as good practices during the discovery of an extraordinary cave: the Bruniquel Cave (Tarn-et-Garonne), that appeared several years later as a unique milestone of Neanderthal culture (JAUBERT *et al.*, 2016). The measures taken in favor of conservation made it possible to preserve prehistoric structures, made up of an accumulation of speleothems, in a state of conservation close to the original. At that time, the ^{14}C dating on charcoal only indicated an age beyond the limit of the method (ROUZAUD *et al.*, 1996). Obviously, F. ROUZAUD was ahead of his time, however he was followed by some disciples in the Grands Causses area.

c) Followers in the Grands Causses

In the 1980s, the archeologist Philippe GALANT set out to study the caves of the Causses, in the south of Massif Central. However, in Prehistory, the fashion is still for outdoor archeology. The confined environment of caves is still considered to be an outdated subject, even an archaism comparable to the excavations of the 19th century, where nothing remains to be discovered...
On the Causse de Blandas, the discovery of the Rouvière Cave (Rogues, Gard), justified rescue excavations in 1989 and 1992. The identified remains and constructions dated from the end of the Neolithic presented unusual character. Alerted, those in charge of the excavation then decided to review a certain number of sites of the same period. Actually, these sites reveal several previously unidentified constructions, and the authors wrote that « *the old studies, too focused on the stratigraphic analysis of the fillings, and without a global geomorphological approach of the caves and their contexts, are the cause of this very reductive vision of underground environment* » (GALANT & HALGAND, 2004). From this moment, the cave, as a site recording traces, became an archeological specificity which methods frankly differ from those used by traditional archeologists, focused on the stratigraphy of sedimentary deposits, and parietal ornaments when existing.

d) Historical speleologists

In France, a few speleologists started research about the uses of caves and decided to inspect the clues left by their occupants. Christophe GAUCHON (1997) is one of them, but deliberately excluded prehistoric periods, which fall outside his competence, he considered as the prerogative of archeologists. GAUCHON's approach was based on observations and documents related to local history. On the field, the search for traces and evidences results from the documentation of observed facts that initially motivated the visit of caves. His book *« Des cavernes et des hommes »* (1997) offers a very innovative perspective, but never crossed that of archeologists, most of whom remaining in a logic of excavations.

e) Evolution of archeological sciences

Since the recognition of prehistoric cave art in 1902, ideas have evolved for the archeologists in charge of the conservation of the decorated caves; the cave is no longer considered only as a deposit of prehistoric objects, it was gradually assimilated into its archeological context. However, it is initially beyond the Atlantic that « geoarcheology » appeared and suggested integrating geoscience specialists into archeological excavation teams.
In France, the archeological authorities became aware of such a delay and reacted positively after the discovery of the Chauvet Cave in 1994, which study had to be exemplary. New obligations were imposed to cave researchers, whether they are speleologists or geomorphologists.
While the specialty initiated by ROUZAUD struggled to impose its name, the study of the Chauvet Cave begun.

f) First observations in the Chauvet Cave

The Chauvet Cave (Vallon-Pont-d'Arc, Ardèche) is an exceptional cavern; for those in charge of its study, it was important not to repeat the former mistakes made in other caves and to avoid the destructive excavations. From the outset, researchers were asked first to observe while reducing the number of excavations, in order to limit the impact on the cave. Archeologists were looking for the development of new methods that were imposed on them, thus the karstologists of the EDYTEM laboratory in Chambéry were entrusted with the mission of expertise in geomorphology, a discipline supporting the mission of archeologists at the beginning of the 2010s (DELANNOY *et al.*, 2012). They identified an artificial pool made by prehistoric men that was completely unnoticed by archeologists who did not realize its anthropogenic origin. Their knowledge of cave features and landscapes was decisive in recognizing the mark of Man. Their experience allows them practicing a real specialty, which does not yet have a name, but which in fact belongs to geomorphology.
However, despite a long presentation aimed at justifying "The integrative geomorpho-archeological approach" (DELANNOY *et al.*, 2012), no reference was made to the work of ROUZAUD and his disciples of the Grands Causses who have yet practiced the paleospeleology for several years. While this approach was efficient, it was however not new since the study of anthropogenic traces in caves began more than thirty years before.

3. The detection of old visits: the example of the Mas-d'Azil Cave

a) Classification of anthropogenic traces

There are several ways of classifying the traces left by human frequentation; ROUZAUD (1978) proposed a classification into three large groups.
The first group contains traces of progression left by men (prints of feet or hands, slips, broken speleothems); the second checks the traces corresponding to the end of the penetration (bodily prints, charcoals and torch-wipes, broken speleothems). A third group gathers the traces of construction in underground sites (hearths, soil, blackening, cave art).
According to MONTELLE (2012), there is another group of traces, those that escape us and « that we cannot yet identify, for lack of not having thought of them ».
However, a good knowledge of caves and some specialization can reduce the limits of undetectable tracks. We tried to push these limits by carefully observing the caves from all points of view: karstological, speleological, and archeological.

b) Between doubts and certainties

When entering a cave known to be prehistoric, we are trying to search by any tangible means signs of human frequentation. Sometimes it is possible to immediately recognize traces of the prehistoric passages; but the numerous visits through history could have erase any trace. It is then necessary to seek and in particular to analyze, then to decipher the underground landscapes in order to distinguish what is natural from what is not.
Unfortunately, this analysis is not accessible to everyone; but it will be more spontaneous for those who study caves and know well their speleogenesis. An archeologist claimed, evoking Easter Island: « If you understand geology, you understand culture ». The quote can be transposed to caves and karstology.
Despite a good knowledge of cave formation, it can happen that a single visit in a cave is not sufficient. Indeed, sometimes it takes only a second to identify a first decisive clue that will allow « pulling the thread » and resolving a situation. Thus, a minor clue can lead to the discovery of a major archeological interest. There is a brief moment when you completely change your mind from perplexity to certainty. When the first clue appears, it brings intense emotion. Speleo-archeological research is part of a police investigation, and it is carried out using the same methods.
Only one example will illustrate our methodology and shed light on a discipline that has remained obscure for a large number of archeologists who are not so familiar with cave environment.

c) Speleo-archeology in the Mas-d'Azil Cave

Caves remained regularly open to men during successive prehistoric periods. Indeed, one can find their traces as well from Paleolithic, Neolithic, and even historical periods. Of course, revealing these traces requires a trained eye and special conditions.

Figure 2: Large pebble in place used to break the calcite flowstone in the Mas-d'Azil Cave (Ariège). Scale: 20 cm. Photo D. Cailhol.

A practical case occurred in the Mas-d'Azil Cave (Ariège) in 2017, when Marc JARRY, researcher at INRAP (French institute of preventive archeology), brought together six karstologists to identify signs of biocorrosion linked to the presence of bats. He was aware of his « blindness », however since only the result counts for him, he knows that others could see. The concentration of karstologists in the cave was an opportunity to gain a new vision of it. Thus, the detection of hidden clues in the underground landscape was at the origin of the discovery of an old clay quarry, which had never been identified previously, despite its front of about 20 m in length.

The first clue was tenuous and based on the observation of the slope of a clay deposit, almost vertical. Indeed, any rock can be characterized by a natural slope which can extend from vertical (hard rocks like limestone) to a subhorizontal slope (loose rocks like sand). Here, since the clay was not affected by natural subsidence, another explanation was necessary.
Once the first clue discovered, it was easy “getting to the bottom of things" and discovering a large pebble, still in place (Fig. 2). It has been used for a methodical cutting of the calcite flowstone. This flowstone originally covered the coveted clay deposit. Nearby were standing enigmatic small, rolled clay balls, about 2.5 cm in size and flattened by pressure onto the soft clay. Strokes printed in the clay were observable on surfaces which miraculously remained intact. All material remained sealed by an old patina. Further on, overhanging calcite flowstone have preserved a hollowed-out area that showed traces of a pick (tool): it was a clay quarry mined by sapping, a type of mining also known in the Cave of Vitalis (Hérault).

5. Conclusion

We have seen that archeologists practicing caving played a determining role in the identification of human traces in caves. Pioneers, like François ROUZAUD, and followers like Philippe GALANT, took an innovative look beyond classical excavation methods, by carefully observing the volumes that contain human traces. The awareness of the destructive action of archeological excavations was understood in the Chauvet Cave, where officials recommended a non-destructive archeological approach carried out with specialists from other disciplines (geoarcheology). In caves, the constructions can be obvious or very discreet; they are only accessible, that is to say visible, by those who know the caves and their speleogenesis. Karstologists, from speleology circles, have a real skill, they are able to distinguish what is natural from what is not.
Thus, a team of specialists of underground environment and experts in speleogenesis, trained in speleo-archeology, are able to detect anthropogenic constructions more easily.

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Speleothems break and regrowth testifying past visits in some caves of Southern France

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Abstract

Various causes can be invoked to explain the anthropogenic broken speleothems: the exploration of caves, which sometimes requires the enlargement of passages, breakage by awkwardness, as a game, for different uses, profane or cult, and for many other reasons that still remain unknown. For scientist, the advantages of speleothems are multiple and are justified by a relative durability of the flows at the origin of their formation. This allows deducing a relative chronology recorded in the growth laminated layers. Paradoxically, the fragility of speleothems, very sensitive to destruction and collection, is a very good clue for the identification of past human frequentation.

1. Introduction

Figure 1: Location of the cited caves in the south of France (base map according Maps-for-free.com).

Although the break of speleothems is an excellent indication of human frequentation, it is not yet recognized as an indisputable element of the passage of man in caves. For most archeologists, ceramic that were abundantly produced from the Neolithic, and more generally artefacts, remain the undisputed element. Since 2010, a karstological approach was carried out to identify broken speleothems, especially fragments which lie on the ground in an unnatural position. Breakages from a natural cause are not as widespread as generally considered and the causes of their fall can often be easily elucidated. Falls and natural ruptures of speleothems in caves can be attributed to various phenomena such as earthquakes, subsidence, decompression, creep of ice or sediment (GILLI, 2005).
From the observations made in caves of southern France (Fig. 1), we developed a new speleo-archeological approach centered on the breakage of speleothems. We discuss here some example of speleothem human breakage that could be explained by different motivations.

2. Breakage and speleothems: paradoxes and margins for progress

There are a number of causes and paradoxes that can justify the weakness of archeological investigations about broken speleothems. Likely, a too weak knowledge of caves and karstic processes in general did not allow speleothems reaching a better status in the clues of human frequentation recognized by the archeologists. After an attempt at explaining the reluctances regarding the recognition of broken speleothems as a proof, the various causes of their artificial breakage will be inventoried.

a) Recognition of intentional breakage: Bruniquel Cave

From the 1970s onwards, broken speleothems were considered as traces of the passage of man (ROUZAUD, 1978). In his study (« La paléospéléologie ») François ROUZAUD considered these « breakage of speleothems » resulting of at least two physical actions classified among the traces of progression and stoppage.
Admittedly, the subject was not very developed in his study, however ROUZAUD continued to be interested in underground archeology throughout his career before being confronted with an accumulation of speleothems in the Bruniquel Cave (Tarn-et-Garonne).
Since he was in charge of the conservation of this exceptional archeological site, he was able to identify the very ancient age of the constructions made up of broken stalagmites. Dating of the structures allowed him to obtain a ^{14}C age beyond the limits of the method (> 47,600 years) (ROUZAUD *et al.*, 1996). The Bruniquel site was indeed too old to be dated to ^{14}C...

Twenty years later, improved dating technics have revealed an age of 176,500 years (JAUBERT *et al.*, 2016) to these construction, made of speleothems broken and arranged in the cave. When writing their article, the team of scientists first had to demonstrate that structures made up of stalagmite fragments could not be natural, before they could eventually present their results.
However, archeologists are generally not requested to provide such evidence when using ceramics as an anthropogenic product. Obviously, the recognition of broken speleothems, as clues of human frequentation, remains full of pitfalls and additional difficulties for researchers trying to interpret them.

b) The paradox of the karstologist
It is a well-known fact that karstologists hardly appreciate speleothems, especially when their abundance covers and hide other features, making difficult the identification of the original type of flow and thus the type of speleogenesis that produced cave passages.
However, karstologists are familiar with geomorphic methods integrating speleothems, whatever their environment. Their experience enables them to interpret more precisely the underground landscapes. Thus, their skills in speleogenesis allow them contributing to speleo-archeology (BIGOT, 2015).

3. Possible reasons of anthropogenic speleothems breakage

Anthropogenic speleothem breakage can be distinguished into two main categories. The first is linked to underground progression, and the second to the constructions and exploitation of a site. The other cases could be games, awkwardness and, of course, motivations that are still unknown or for which interpretation still remains uncertain.

a) The underground progression
Broken speleothems in caves are first linked to the progression. In fact, before exploiting a cave, it must be first explored. The most common causes of breakage are related to the digging or widening of narrow passages. The Grosse Marguerite Cave (Gard) and the Sot Manit Cave (Hérault) show attempts to open passages between speleothems (BIGOT, 2018; BIGOT & BRUXELLES, 2019). Sometimes it is just a matter of cutting down stalagmites that get in the way. The stalagmites, lying and sealed on the floor of the Serre des Périers Cave (Hérault), show that men removed the speleothems that grew along their path (BIGOT & CAUMONT, 2019).

b) Constructions in exploitation site
The development of an underground site can sometimes be significant, in particular to allow collecting drink-water (BIGOT, 2018). The most remarkable identified developments are in the Mas de Rouquet and Sot Manit caves (Hérault).
The Fage Cave (Gard) also conceals a huge stalactite acting as a gutter, well wedged between two impressive stalagmites (Fig. 2). This stalactite, difficult to handle due to its weight, was broken from the vault just a few meters from its final destination.
Clay quarries are sometimes spectacular and require opening calcite flowstones first to gain access to the underlying clay deposit. In the Mas-d'Azil Cave (Ariège) the opening of a trench in a flowstone, in order to mine the clay, was done by hammering the calcite flowstone. A large pebble, still in place, was used as a hammer, and shows traces of percussion.
Accessibility always requires a special care. Similarly, when current cavers have to take the same route repeatedly, they alter it to make it more convenient. Elsewhere, steps or even ramps, made up of an accumulation of speleothems, have been built, such as in the Sot Manit Cave (Hérault). Steps were also carved in an inclined slippery flowstone in the Besses Cave (Hérault).

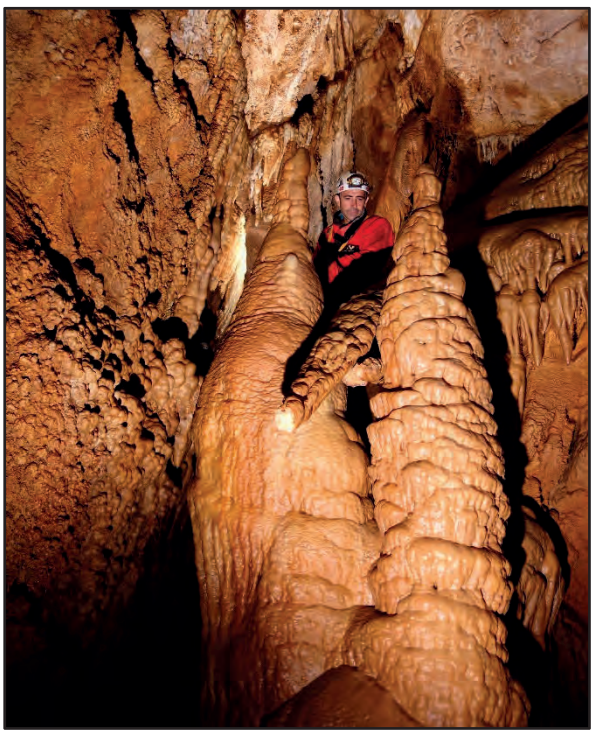

Figure 2: The stalactite-gutter of the Fage Cave (Gard) was stuck between two large stalagmites to collect and concentrate the dripping water from ceilings.

c) Game, awkwardness and unknown causes
In caves, waiting places often exhibit finger holes in clay or fingerprints, the probable result of games meant to stave off boredom. Sometimes balls of clay are stuck to the walls; we know that the throw of dumplings is attested since the Paleolithic. Stalactites located 5 or 6 m high in the roof of the Fées Cave (Gard), were broken for no apparent reason, probably by throwing stones. Indeed, the points of those stalactites, sealed on the calcite soil, indicate that they have not been used. It underlines the gratuitous and destructive intention.

The breakages may or may not be intentional. It happens that speleothems were broken without apparent intention. A stalagmite which dominates a rimstone pool in the Radar Cave (Alpes-de-Haute-Provence) was broken by clumsily resting a hand on its apex. However, the person responsible for the breakage balanced the stalagmite back on its base, and it has since been naturally re-sealed.
Unexplained constructions have been identified in the Portalerie Cave (Aveyron). A piece of a 20 cm-long stalagmite, about 8 to 10 cm in diameter, was planted vertically in a small pool. In the water of this pool, since the breakage, a ring of calcite crystals grown around the stalagmite, attesting to the antiquity of the anthropogenic composition. It is possible that this composition was intended to mark a route, further research must be undertaken to check this hypothesis.

4. Use of speleothems indicators

Speleothems often cover walls and floor of caves, especially in the late stages of speleogenesis. The growth of speleothems is rarely continuous and depends in particular on the presence of seepage and plant cover on the surface. However, the speleothems offer a relative chronology that can attest to a certain antiquity. Speleothems have other characteristics such as their fragility: their breakage is easy, and their growth laminas are clearly visible. In addition, they can be dated by various methods, notably by uranium/thorium (U/Th).

a) Relative chronology and sustainability of the flows

Examination of the fragments of speleothems sealed by calcite makes it possible to reconstruct the different actions that took place underground, since calcite authenticates the relative chronology of events. It is sometimes possible to deduce a gesture, or even an intention. The deposition of secondary calcite is a determinant fact in the recognition of the antiquity and the relative age of traces and clues.

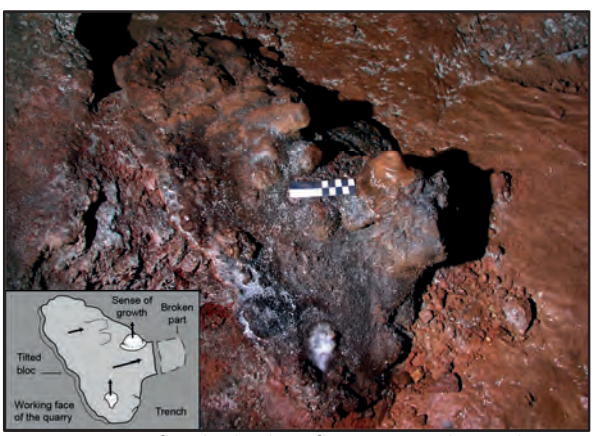

Figure 3: Part of a tilted calcite flowstone in the Vitalis Cave (Hérault). After the mining, new stalagmite regrowth appeared on the tilted flowstone. Scale: 10 cm.

Speleothems can cover the entire surface of the underground voids and constitute the last « coating » of the cave. The water supply, at the origin of calcite growth, often presents a relative continuity (at the scale of human visits duration), and above all, it is totally independent of human action.

Stalagmitic regrowth after an intentional breakage or an abandonment of the site are often visible (Fig. 3). The durability of the seepage allows the calcite to seal constructions or exploitation sites, like in the Vitalis Cave (Hérault) (BIGOT, 2020).
Indeed, calcite tends to cover everything, including artefacts (ceramic, charcoal, flint, etc.), making traditional techniques for identifying archeological sites entirely unsuitable. Other methods of investigation must therefore be considered to detect past human frequentation.

b) Fragility of speleothems

By nature, speleothems are fragile, while the host rock is generally harder. The fine stalactites therefore appear more exposed to the breakage. Natural breakages are well known, such as the tilting of stalagmitic pillars on a ground gradually undermined. However, the repeated passage of humans can even be more destructive. This overexposure of speleothems to human frequentation is the reason that today motivates cavers to set protection markings in the most fragile caves.
Paradoxically, the fragility of the speleothems is a boon for the search for traces of past frequentation, because they will first be broken to manage a place or enlarge a passage. In addition, in an environment where everything is sealed by calcite and where no free pebbles are lying on a calcified ground, a fine stalactite protruding from the ceiling can be easily broken by man.

c) Advantage of growth laminated calcite

Speleothems provide indications of their growth and reveal the conditions under which they developed. Cave speleothems have a specific morphology which provides information on their evolution, whether vertical (stalactite, stalagmite) or horizontal (rimstone, flowstone).
By comparison, the limestone host rock does not offer such advantages: it is much more difficult to find the anthropic origin of a displaced stone block than a broken speleothem. Indeed, speleothems have a certain traceability (laminated calcite growth) which can be easily exploited, for instance stalagmitic regrows following a breakage.
In addition, it is possible to sample and date speleothems, in particular by using the U-Th method.

Figure 4: laminated calcite eroded by a stream in the Portalerie Cave (Aveyron).

d) Alternation of calcite laminations in speleothems

The alternation of dark and light laminations in the speleothems sections can be an indication of human frequentation.

Eroded and laminated speleothems showing such alternation of colors can be of anthropogenic origin (Fig. 4). Numerous caves, assiduously frequented at different periods, keep traces of past incursions. Some caves may have been visited for possible cult reasons (BIGOT, 2014), as in the sanctuary of Rajal del Gorp Cave (Aveyron), Mounios Cave (Hérault), or Auguste Cave (Hérault). However, the motivations for the incursions remain unknown in the Baumes-Chaudes Cave (Lozère) and in the Portalerie Cave (Aveyron). Dark laminated calcite often originates from torch soot trapped in the calcite; a new approach by the fuligino-chronology (VANDEVELDE, 2019) allows us to better understand the frequency of visits.

5. Conclusion

Broken speleothems did not always attract the attention of cavers or archeologists; very few ancient incursions were reported from the sole clue of broken speleothems, because of the too common consideration that destruction is due to the current frequentation. Nobody is no longer astonished to see devastated underground landscapes, which are often wrongly attributed to modern cavers.

However, for the men who frequented the caves, speleothems were just a practical and standard material that could easily be collected and used to build systems for collecting and redirecting water, to mark out a route, or simply to open a path.

Today, there is a conservative relationship between the cavers and the speleothems, which is at the origin of this misinterpretation. In reality, in the past, men were thoroughly insensitive to cave conservation, because their goal was completely different: they simply included the caves to their living environment, for surviving.

Consequently, the constructions made of broken speleothems must deserve the same respect as the stalactites or stalagmites protected by the cavers.

Identifying such an archeological heritage is already contributing to the protection of the world heritage of caves, whether natural or human.

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Le feu, vecteur d'appropriation de l'endokarst par Néandertal et Homo sapiens - Étude des altérations thermiques et apports des expérimentations

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Résumé

La présence d'oxydes de fer, sous forme de gœthite, dans les calcaires et la calcite, est un excellent traceur qui nous renseigne sur les températures auxquelles ont été soumis les matériaux puisque le changement de phase minéralogique de la gœthite en hématite s'opère à partir de 250°C. Ce seuil de température est largement atteint et dépassé lors d'une combustion et se traduit notamment par un changement de couleur (rubéfaction). À partir de l'observation des altérations thermiques visibles sur les vestiges archéologiques, la démarche expérimentale permet de tester des hypothèses mais aussi de restituer les dispositifs d'éclairage et de combustion (emplacement des foyers, puissance, éclairement, contraintes liées aux gaz toxiques). Associées à des études archéométriques et au développement de la simulation numérique, cette démarche a produit des données nouvelles pour les structures de combustion des sites de Bruniquel (Tarn-et-Garonne) et de Chauvet-Pont d'Arc (Ardèche). Les dispositifs d'éclairage mobile ont également été réétudiés à partir des thermo-altérations de certains des spéléofacts de la grotte de Bruniquel et des lampes de la grotte de Gabillou (Dordogne).

Abstract

Fire, vector of appropriation of endokarst by Neanderthal and Homo sapiens - Study of thermal alterations and contribution of experiments. The presence of iron oxides, in the form of gœthite, in the limestones and calcite is an excellent tracer that gives us information on the temperatures to which the materials were subjected, the mineralogical phase change from gœthite to hematite taking place from 250°C. This temperature threshold is largely reached and exceeded during combustion and results in particular in a change of color (rubefaction). From the observation of the thermal alterations visible on the archaeological remains, the experimental approach allows to test hypotheses but also to restore the lighting and combustion devices (location of the hearths, power, lighting, constraints related to toxic gases). Associated with archaeometric studies and the development of digital simulation, this approach has produced new data for the combustion structures of the sites of Bruniquel (Tarn-et-Garonne) and Chauvet-Pont d'Arc (Ardèche). The mobile lighting devices were also re-examined using thermo-alterations of some of the caving artifacts in the Bruniquel cave and the lamps in the Gabillou cave (Dordogne).

1. Introduction

L'utilisation et la maîtrise du feu ont permis à l'homme préhistorique de pénétrer profondément dans les grottes et d'explorer le monde souterrain. La découverte de la grotte de Bruniquel a démontré que cette fréquentation, qualifiée de « paléospéléologie » (ROUZAUD, 1978), était une pratique déjà en cours au Paléolithique moyen (JAUBERT *et al.*, 2016). Les moyens d'éclairage nécessaires à la progression et aux activités réalisées dans les espaces profonds, où la lumière du jour n'arrive pas, correspondent aux lampes et aux torches, dont les vestiges ont été retrouvés dans les cavités fréquentées au Paléolithique supérieur (BEAUNE, 1983). Des expérimentations ont été menées et continuent de l'être pour mieux comprendre les matériaux nécessaires à l'optimisation de ces dispositifs. Les grottes profondes ont également livré des foyers dont la fonction est identifiée ou fait l'objet d'hypothèses : foyers domestiques, foyers destinés à l'éclairage, au balisage du

cheminement, à l'allumage de torches ou à la production de matières colorantes (charbon de bois par exemple).

L'objectif de cet article est de présenter les résultats d'études intégrant une approche géoarchéologique, archéométrique et archéoexpérimentale portant sur les lampes de la grotte de Gabillou et sur les feux réalisés dans les grottes de Bruniquel et de Chauvet-Pont d'Arc. Dans le premier cas, se pose la question de la relation entre les altérations thermiques visibles sur les objets et le fonctionnement des lampes. Pour les foyers, il s'agit d'identifier la nature et la quantité de combustible à l'origine des altérations thermiques, les contraintes générées par la combustion, pour *in fine* discuter de la fonction des feux.

2. Matériel et méthodes

La démarche repose sur :
- Le lien établi entre température et changement de phase minéralogique. Les oxydes de fer présents dans les calcaires et les argiles piégées lors de la formation des spéléothèmes, notamment sous forme de gœthite, constituent d'excellents traceurs puisque la transformation vers l'hématite s'opère à partir de 250°C lorsque les matériaux sont déshydratés. Ce seuil de température, facilement atteint voire largement dépassé lors d'une combustion, se traduit par un changement de couleur du matériau (rubéfaction) visible à l'œil nu. Par ailleurs, des essais de chauffe en laboratoire ont permis de montrer que la coloration évolue vers le gris à partir de 375°C (BRODARD *et al.,*2014). La typologique de la thermo altération, de par sa couleur et son extension, constitue une signature qui nous renseigne sur la puissance relative du feu qui en est à l'origine.

- L'établissement d'un corpus des thermo-altérations visibles sur les matériaux étudiés, à partir d'observations à l'échelle macroscopique et d'analyses par des méthodes non invasives. Cet inventaire comprend la description de l'extension et de l'organisation spatiale des impacts thermiques ainsi que celles des d'altérations thermomécaniques associées (fissures, écailles). Les carbonisats et leur position relative par rapport aux surfaces thermo altérées sont également enregistrés.

- La réalisation d'expérimentations prenant en compte les données archéologiques. Pour déterminer les facteurs variables et non variables des protocoles, des essais préliminaires ont été effectués en extérieur. Les expérimentations se sont ensuite poursuivies dans une ancienne carrière souterraine d'extraction de calcaire (Oligocène, Rupélien) située dans l'Entre-deux-Mers en Gironde. Différents paramètres ont été mesurés : températures (°C) au sein du foyer, températures (°C) des matériaux (calcaire ou calcite suivant le cas) à différentes profondeur, températures (°C) de l'air à différentes distances de la source de chaleur (foyer ou lampe) à l'aide de thermocouple de type K, perte de masse pour le calcul de la puissance des foyers grâce à une balance placé sous les foyers, concentration (ppm) des gaz CO et CO_2 par analyseur de type Servomex et luminance (lux) avec un luxmètre de type Chauvin Arnoux C. A. 1110. Afin de s'assurer de la répétabilité des résultats, chaque essai a été effectué à trois reprises (FERRIER *et al.*, 2017a).

Les recherches ont porté :

- Sur les lampes de la grotte ornée de Gabillou (Dordogne). Sur l'une d'elles, des traces de rubéfaction sont visibles dans le fond et sur les bords de la cupule en association avec un revêtement noir correspondant probablement à des carbonisats (Fig. 1).

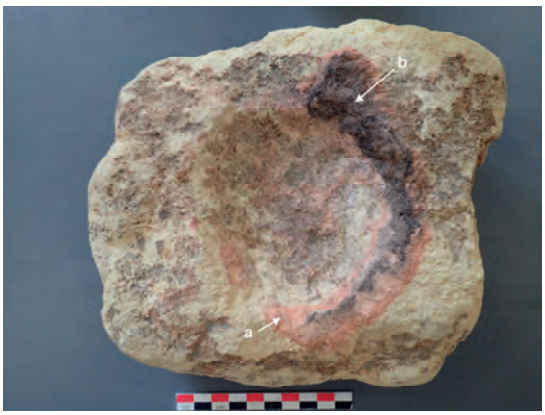

Figure 1 : Lampe provenant de la grotte de Gabillou. a : rubéfaction, b : carbonisat.

À partir des données bibliographiques et de tests en extérieur, des choix ont été opérés sur la nature de la roche, les dimensions de la cupule, la graisse utilisée comme combustible ainsi que le type et la taille des mèches. Les lampes ont été confectionnées dans du calcaire du Rupélien afin d'obtenir une cupule de 6 cm de diamètre pour 2 cm de profondeur dont le volume correspond à 50 ml. La graisse provient du tissu adipeux de la cuisse d'un bœuf (*Bos taurus*) âgé de 7 ans. Elle réunit les avantages suivants : point de fusion à 70°C et indice de viscosité élevé (17 centipoises à 60°C). Elle a été broyée et épurée manuellement des parties fibreuses. Les mèches ont été taillées dans la partie sous-jacente de la cuticule de l'amadouvier. Celle-ci est constituée par la juxtaposition de tubes qui assurent une excellente capillarité de l'huile lors du fonctionnement de la lampe. Deux mèches de 5 x 2 x 1 cm ont été utilisées et positionnées côte à côte sur le bord de la cupule. La combustion s'est opérée avec une seule charge de 50 ml de graisse.
- Sur le foyer intégré dans la structure principale de la grotte de Bruniquel (Tarn-et-Garonne) (JAUBERT *et al.*, 2016). D'un diamètre de 30 cm, il a été aménagé avec un parement constitué de concrétions brisées. Sur celles-ci, des thermo-altérations de couleur rose et grise, des fissures thermiques et des carbonisats ont été observés. La présence de

fragments d'os brûlés suggère l'utilisation de l'os comme combustible, sans pour autant exclure celle du bois (FERRIER *et al.*, 2017b).

La reproduction expérimentale du foyer en extérieur a eu pour objectif de valider la masse de combustible nécessaire à l'apparition des thermo-altérations. Celle-ci correspond soit à 9 kg de bois de pin sylvestre répartis en six charges, soit à 7,5 kg d'épiphyses entières d'os frais de bœuf adulte correspondant à une seule charge et dont la combustion doit être initiée avec 1,5 kg de bois. Les essais menés en contexte souterrain ont permis de comparer le potentiel de chacun de ces combustibles.
- Sur les feux de la galerie des Mégacéros de la grotte Chauvet-Pont d'Arc. Des thermo-altérations (rubéfaction, coloration grise, écailles thermiques) situées à des hauteurs pouvant atteindre 3 m ont été observées à dix endroits de la galerie. Des revêtements résiduels de suie ont également été identifiés sur la partie supérieure des parois.

Le combustible utilisé pour les expérimentations correspond à du Pin sylvestre (*Pinus sylvestris)*, en accord avec les données de l'étude anthracologique des charbons de la grotte. Le bois a été conditionné en fagots dont la taille et le poids a été défini par des tests de collecte manuelle dans une parcelle d'arbres de 35 ans dont les branches situées à hauteur d'homme n'ont subi aucun élagage. Celles-ci, d'un diamètre compris entre 1 et 4 cm, ont pu être directement cassées sur l'arbre sans outil.
Les résultats acquis lors des expérimentations dans la carrière ont été utilisés pour mettre au point et valider le code numérique permettant la simulation des feux, à partir du relevé 3D de la galerie (SALMON, 2020).

3. Résultats et discussion

- Expérimentations de lampes à graisse : la durée de la combustion, a été de 44 mn. La valeur de la luminance, mesurée à 1 m de distance, est en moyenne de 1,7 lux avec un maximum à 4,5 lux. Elle augmente progressivement après l'allumage et atteint un palier compris entre 2 et 3 lux lorsque l'ensemble de la graisse est totalement fondu et que le corps de la lampe est suffisamment réchauffé par la combustion (35°C au maximum à 1 cm sous la cupule). L'utilisation simultanée de deux mèches en amadou a permis d'obtenir des valeurs plus élevées que celles données dans la bibliographie, généralement inférieures à 2 lux. Il n'a pas été observé de rubéfaction nette, que ce soit sur les bords ou le fond de la cupule. La présence de carbonisat a été constatée.

L'apparition de la rubéfaction ne peut se produire que lorsque le calcaire est chauffé au-delà de 250°C, et après qu'il a été totalement déshydraté. Dans le cas des lampes, la présence de la graisse, qui maintient le matériau hydraté, empêche ce phénomène de se produire. Il est donc impossible d'obtenir une rubéfaction dans le fond et le bord de la cupule durant le fonctionnement. La rubéfaction observée sur l'objet provenant de la grotte de Gabillou n'est donc probablement pas liée au fonctionnement de la lampe. En revanche, d'autres pièces, qui ne présentent pas de thermo-altération sont conformes aux résultats expérimentaux.

- Le foyer de la structure principale de la grotte de Bruniquel : à partir des expérimentations, une comparaison a pu être établie entre les des deux types de combustible (bois et os). Les résultats soulignent l'intérêt de l'utilisation de l'os. En effet, la durée de la combustion est plus longue, la production de gaz toxique est moindre et la recharge n'est pas nécessaire. A contrario, le bois donne une puissance plus importante et des températures plus élevées car la combustion est plus rapide. La luminance produite par chacun des deux combustibles suffit à éclairer l'ensemble de la structure (avec le bois : 115,05 lux à 1 mètre, 1,67 lux à 7 mètres ; avec l'os : 34,62 lux à 1 mètre, 0,34 lux à 7 mètres). Cependant, la combustion du bois étant rapide, pour éviter les fortes variations de l'éclairement, une alimentation régulière du foyer est nécessaire. Par contre, à partir d'une seule charge, l'os offre un éclairement beaucoup plus stable.

- La galerie des Mégacéros de la grotte Chauvet-Pont d'Arc : les simulations numériques apportent des résultats sur la position et la quantité de combustible employé. Seule la disposition du bois en tipi, qui produit une flamme haute et étroite, permet d'obtenir la reproduction des thermo-altérations, tant au niveau de leur présence en hauteur que de leur extension spatiale. La masse de bois nécessaire, à minima, varie entre 10 et 15 kg suivant les feux. La masse totale correspondante est estimée à environ 170 kg. Les tests de collecte de bois montrent qu'elle peut être obtenue à partir de l'élagage manuel de 15 arbres.
En raison du phénomène de convection de l'air et de la morphologie de la galerie, les fumées et les gaz toxiques étaient évacués en directions de la salle Hillaire où ils étaient dilués en raison de son volume important. En revanche, les simulations montrent que la salle du Fond située à l'extrémité de la galerie était épargnée, ce qui est concordant avec l'absence d'indice de suie sur le terrain. La stratification de l'air permettait de circuler dans la galerie, près du sol, à une hauteur comprise entre 0,90 et 1,40 m de hauteur, jusqu'à approcher le foyer à une distance de 1,50 m. Ces indications sont valables pour chaque feu pris individuellement. Il n'y a pour l'instant aucune donnée nous indiquant si plusieurs ont fonctionné en même temps.
Parmi les diverses hypothèses formulées pour la fonction de ces feux, la production intentionnelle de charbon de bois a été évoquée. Celle-ci ne peut être compatible avec la puissance de ces feux que si la masse thermique des braises a été rompue par dispersion avant combustion totale.

	9 kg de bois	7,5 kg d'os et 1,5 kg de bois
Durée de la combustion	1h15mn	2h
Puissance max (kW)	130	55
CO max (ppm)	900	100
Nombre de charges	6	1
Luminance à 1 m	115,05	34,62
Luminance à 7 m	1,67	0,34

Figure 2 : comparaison du potentiel des combustibles à charge égale. Expérimentations portant sur le foyer de la structure principale de la grotte de Bruniquel.

5. Conclusions

Les expérimentations portant sur les lampes à graisse montrent qu'il est nécessaire de mieux comprendre l'origine de la rubéfaction observée sur certains objets archéologiques. Il est ainsi indispensable de poursuivre les essais pour tester d'autres dispositifs, par exemple en augmentant le nombre de mèches, ce qui est possible pour des cupules de grande taille, et en évaluant les impacts thermiques d'une utilisation prolongée. La présence de zones rubéfiées sous plusieurs des objets interprétés comme lampe suggère par ailleurs qu'elles ont pu être chauffées avant utilisation, pour en optimiser le fonctionnement. Dans la grotte de Bruniquel, seule une investigation archéologique nous semble pouvoir apporter de nouvelles données pour discuter de l'utilisation de l'un ou l'autre des combustibles possibles. Par ailleurs, les recherches se poursuivent pour mieux cerner l'utilisation probable de torches pour le cheminement mais aussi pour la collecte des spéléothèmes ayant servi à l'aménagement des différentes structures. Les simulations numériques devront être appliquées dans la grotte Chauvet-Pont d'Arc aux autres secteurs où les thermo-altérations sont visibles, notamment dans la zone correspondant à l'entrée paléolithique où elles occupent des surfaces de plusieurs mètres carrés sur des plafonds situés à 3 m de hauteur.

Les résultats déjà acquis démontrent l'intérêt d'une démarche interdisciplinaire intégrant les données géoarchéologiques et archéométriques, couplées à des expérimentations et des simulations numériques, pour mieux comprendre l'appropriation du domaine endokarstique, que ce soit au Paléolithique moyen ou au Paléolithique supérieur.

Remerciements

Nous remercions Christian Bouchet, propriétaire de la carrière de Lugasson, où les expérimentations en domaine souterrain ont été réalisées. Celles-ci ont bénéficié de la collaboration avec le Laboratoire Central de la Préfecture de Police de Paris et du SDIS 33. Les recherches ont été financées par le ministère de la Culture (PCR LAsCO porté par M. Langlais et S. Ducasse, UMR PACEA) et la région Nouvelle Aquitaine (programme CarMoThaP porté par C. Ferrier, UMR PACEA).

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Caractérisation d'une exploration spéléologique préhistorique dans la grotte d'Aldène (Cesseras, Hérault, France)

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Résumé

La grotte d'Aldène est un important réseau spéléologique du Minervois. Une galerie découverte en 1948 par l'abbé Cathala a révélé des indices préhistoriques. Des empreintes de pas humains et des traces de torches indiquent que des hommes ont fréquenté anciennement une partie du réseau. L'analyse récente de ces traces, dans leur contexte avec une prise en compte des données géomorphologiques et archéologiques, permet de restituer une exploration spéléologique vieille de 8000 ans, dont les gestes et vicissitudes ont pu être identifiés.

Abstract

Characterisation of a prehistoric speleological exploration in the Aldène cave (Cesseras, Hérault, France). The Aldène cave is an important speleological network in the Minervois. A gallery discovered in 1948 by Father Cathala has revealed prehistoric clues. Human footprints and traces of torches indicate that men formerly frequented part of the network. The recent analysis of these traces in their context, taking into account geomorphological and archaeological data, makes it possible to reconstruct an 8000-year-old speleological exploration, whose actions and vicissitudes have been identified.

***À la mémoire de Paul Ambert et d'Albert Colomer**… pour tout ce qu'ils m'ont appris dans une amitié partagée.*

1. Une grotte exceptionnelle.

La grotte d'Aldène constitue le réseau spéléologique le plus important du Minervois. Elle offre aux visiteurs plus de 10 km de galeries qui se répartissent sur quatre niveaux hydrogéologiques. Seuls les deux premiers sont fossiles et ont livré d'importants vestiges paléontologiques et archéologiques (GALANT et HOLWOET 2001). Le premier étage est connu de tout temps et a fait l'objet d'études dès la fin du 18ème siècle principalement pour son intérêt paléontologique. Plusieurs dizaines de chercheurs ont abordé ce site qui a fait l'objet de plus de 700 publications en presque deux siècles ! (BESSET et MARTY à paraître). Pour l'archéologie, le premier étage d'Aldène renferme les vestiges de plus de 400 000 ans d'histoire. Mais ces trésors ont aussi été victimes de la richesse de la caverne : dans ses entrailles elle renfermait les traces de phosphates dont certains ont convoité la richesse. Une exploitation s'y est développée dès 1890 jusqu'en 1950. La presque totalité des remplissages des galeries a été passée au concasseur, réduisant tous les vestiges multimillénaires en poussière dans l'espoir de faire grandir les vignes ! À chaque chose malheur est bon… en vidant les galeries, les mineurs ont dégagé deux accès spéléologiques. Le premier, ouvert en 1927 a permis à Marcel Guerret d'identifier des gravures préhistoriques (GUERRET 1927), œuvres originales qui ne seront datées avec certitude que presque 80 années plus tard (AMBERT et *al*. 2005). Le deuxième passage a été indiqué par un mineur à l'abbé Dominique Cathala en 1948 : un trou souffleur de quelques centimètres qui propulsait un violent courant d'air. Sa désobstruction révélera le deuxième étage de la caverne avec ses nombreux vestiges paléontologiques et préhistoriques (CATHALA,1949). C'est plus particulièrement une des galeries de ce second étage qui renferme au sol des empreintes de pas humains et sur ses parois des tracés charbonneux. Malgré l'ancienneté de cette découverte, ce n'est que récemment que ces vestiges ont commencé à être étudiés dans un cadre scientifique global (AMBERT et *al*. 2001. GALANT et *al*. 2008).

Figure 1 : Empreintes de pas de la galerie Paul Ambert.

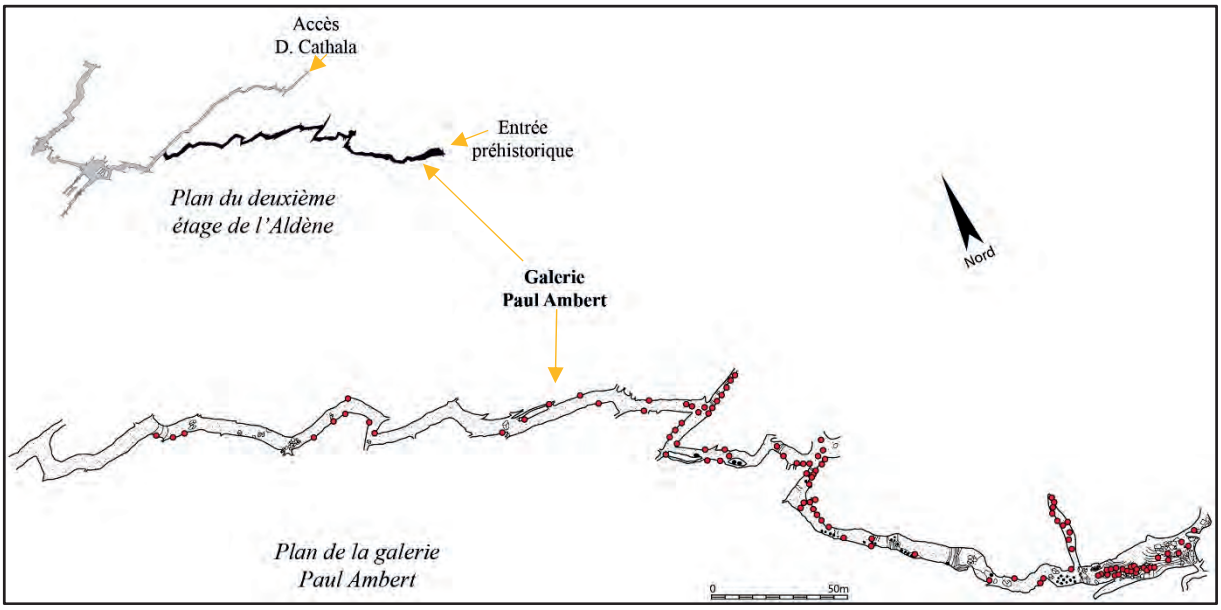

Figure 2 : Répartition des traces de torches dans la galerie Paul Ambert.

2. Les traces de torches.

Les traces de torches se matérialisent par des impacts charbonneux sur les parois et des concentrations de charbons de bois au sol. Ces vestiges sont uniquement localisés dans la galerie Paul Ambert (Fig. 2). L'étude de l'entrée effondrée, qui permet l'accès à cette galerie, a montré qu'elle constituait l'accès préhistorique au réseau (GUENDON et *al*. 2004). La répartition topographique de ces vestiges indique le circuit emprunté par les préhistoriques, depuis l'entrée jusqu'à leur terminus supposé, soit plus de 500 m d'un parcours souterrain présentant plusieurs obstacles. L'entrée, par un porche effondré, se prolongeait sur plusieurs mètres dans un couloir étroit qui débouche dans une grande salle. Celle-ci est suivie par une galerie de belle section (3 x 4 m). Une zone concrétionnée complexe précède un passage bas de 0,5 m de haut, 1,5 m de large et long de 4 m ; il faut obligatoirement ramper pour franchir ce laminoir. Il débouche sur un lac d'environ 45 m de long entrecoupé d'un passage bas, dont le fond est constitué d'une argile liquide profonde ; plusieurs éléments indiquent que ce lac était en eau lors du passage des visiteurs préhistoriques. Après une remontée, la galerie débouche sur un deuxième lac similaire au premier et de 30 m de long. Au-delà, la galerie de 3 à 4 m de large et d'une hauteur minimale de 5 à 6 m, développe un sol plan et argileux, au long d'un parcours qui ne semble jamais s'arrêter !

Outre leur répartition, ces vestiges d'éclairage ont fait l'objet d'une étude détaillée. Il apparaît qu'en un point de la cavité, ils ont pu être mis en relation directe avec les empreintes de pas humains ; il est donc certain que ce sont les mêmes visiteurs qui ont laissé les empreintes de pas et les traces de leur moyen d'éclairage. Ainsi, le fait qu'il n'y ait eu qu'un seul aller-retour, comme le montrent sans aucune ambiguïté les empreintes de pas, permet d'aborder ces traces de torches avec une réelle perspective analytique.
Dans un premier temps, la caractérisation de ces vestiges a permis de mieux comprendre la forme de ce système d'éclairage : les torches étaient composées de 10 à 15 brandons, qui en brûlant donnent une lumière assez puissante (Fig. 3). La qualité du dispositif repose en partie sur celle du bois utilisé : du genévrier, un bois à essence. Suite à ce constat, une phase expérimentale a permis de vérifier la faisabilité du dispositif, de constater sa qualité et découvrir ses commodités d'usage : il se porte facilement avec très peu de fumée ; lorsqu'il y a un obstacle on pose la torche qui continue d'éclairer et on la récupère après ; si elle tombe au sol et s'éteint, l'extrémité rougeoyante des brandons permet de la récupérer et en la secouant plusieurs fois elle se rallume seule. Plusieurs essais contre les parois nous ont permis de reproduire les gestes dont résultent les traces observées dans la caverne. L'étude fonctionnelle a aussi permis de définir les sens de réalisation de ces traces (à l'aller ou au retour).

Figure 3 : Reconstitution d'une torche préhistorique.

Ces données permettent d'identifier deux types de traces : les impacts accidentels et les marques volontaires. Pour le premier, les impacts sont liés au cheminement du porteur de torche qui, à la faveur d'un obstacle ou d'une trajectoire,

va involontairement heurter la paroi avec son dispositif. La conséquence en est un tracé de 3 à 4 lignes parallèles qui représentent le frottement latéral de la torche (Fig. 4). Pour le deuxième, il y a une volonté de balisage en réalisant une marque contre la paroi. Elle concerne un écrasement volontaire de l'extrémité de la torche perpendiculairement à la paroi. De fait, l'extrémité des brandons se matérialise par une dizaine à une quinzaine de points répartis sur une surface subcirculaire (Fig. 5). Ce type de trace est observé au niveau d'un obstacle, en fin de galerie et dans la zone présumée d'arrêt de l'exploration. Dans ce schéma, les traces d'impacts involontaires reflètent la progression des visiteurs préhistoriques ; on peut individualiser celles faites à l'aller de celles réalisées au retour. Ainsi, on constate qu'à l'aller les impacts sont liés à de vrais obstacles (saillies de rochers, passages bas) ; alors qu'au retour on a plus le sentiment d'erreurs de trajectoires, comme si les visiteurs étaient pressés de sortir, moins attentifs au parcours. Ces traces nous ont également permis de constater que toutes les galeries connexes à la galerie principale, ont été visitées lors du passage aller. Au contraire, les traces volontaires signalent les obstacles et semblent marquer les points terminaux de la visite.

Comme nous l'avons déjà signalé, l'ensemble de ces traces charbonneuses nous indique le cheminement suivi par les visiteurs préhistoriques. Les vestiges le plus éloignées de l'entrée sont à plus de 500 m ; au-delà, il n'y en a plus. Y-a-t-il un problème de conservation différentielle des vestiges ? Les visiteurs se sont-ils abstenus de réaliser des traces dans cette partie ? N'y sont-ils jamais allés et donc, ont-ils rebroussé chemin avant ? Les réponses aux deux premières questions sont négatives. Alors comment expliquer un arrêt sur rien au milieu d'une galerie sans obstacle, si ce n'est la remontée, au demeurant très facile, d'un simple talus peu pentu ? Il semble qu'il ne faut prendre en compte qu'une seule donnée, celle de la lumière. On admet forcément que les visiteurs sont partis avec un nombre de torches définis, et lorsque plus de la moitié de cette provision a été consommée lors de l'aller de la visite, il leur a fallu envisager le retour ! Ainsi, le fait d'avoir utilisé plus de torches que la moitié théorique explique, un balisage du point d'arrêt et une marche plus rapide sur le retour, moins d'attention à la configuration des passages et donc plus de heurts des torches contre les parois. Tous les éléments induisent l'hypothèse d'un arrêt de cette exploration sur autonomie de l'éclairage.

Figure 4 : Impact accidentel de torche contre la paroi.

Figure 5 : Marquage volontaire à l'aide d'une torche.

3. Les empreintes de pas humains.

Dans le monde, moins d'une quarantaine de sites contient des empreintes de pas humains préhistoriques. Parmi eux, l'Aldène est un des rares à présenter autant d'empreintes (plus de 500) et surtout d'une telle netteté (Fig. 1 & 6). Ces vestiges complètent les observations réalisées à partir des traces de torches. Par exemple, les différents recoupements permettent d'affirmer qu'elles correspondent au passage d'un groupe de personnes qui n'a fait qu'un simple aller-retour dans la caverne. Depuis, plus personne n'était venu avant que l'abbé Cathala ne les découvre !

L'observation détaillée de ces traces nous renseigne sur leurs auteurs : les différentes tailles permettent d'estimer que le groupe était principalement composé d'enfants accompagnés de quelques adultes : image parfaite d'une famille ou d'un clan de la Préhistoire dans laquelle, et comme dans toutes les sociétés traditionnelles, il n'y a pas de contrôle des naissances et une forte mortalité infantile jusqu'à l'âge adulte. En l'absence d'un inventaire précis, les premiers comptages permettent d'estimer la composition de ce groupe à une vingtaine de personnes. Les visiteurs ont préférentiellement marché au centre de la galerie, quelques individus circulant au long des parois ; mais cela reste un déplacement collectif avec des personnes qui se déplacent en groupe. Les séquences d'empreintes indiquent, qu'à l'aller, la marche est régulière avec des foulées ni trop courtes ni trop longues ; sûrement prenaient-ils le temps de regarder, d'explorer.

La structure des empreintes indique une plasticité variable du support, d'un mètre à l'autre. Bien que le sol argileux de la galerie soit présent sur plusieurs centaines de mètres, les empreintes ne se sont conservées que sur un secteur de 30 m de développement. Ceci confirme le caractère très exceptionnel de la conservation d'empreintes en milieu souterrain. On pourrait presque dire qu'entre le passage d'un être humain préhistorique jusqu'à la découverte de l'empreinte à notre époque, il faut une succession de miracles pour que la trace nous parvienne. Et il en est ainsi

pour chacun des sites qui renferment de tels vestiges. On ne mesure pas assez l'aspect rare et unique de ces traces.

Depuis leur découverte, ces empreintes n'ont pas fait l'objet d'une étude exhaustive. Il est certain que les conditions d'une telle recherche sont complexes. Bénéficiant des avancées technologiques de notre époque, un programme de recherche spécifique à ces empreintes vient d'être engagé. Il regroupe une quinzaine de chercheurs dont les compétences vont de la modélisation numérique jusqu'à l'ichnologie en passant par l'anthropologie, la géoarchéologie et la spéléologie. Ainsi, un plan général a pu être réalisé grâce à la modélisation tridimensionnelle et à la photogrammétrie. Le travail d'inventaire systématique a été engagé ; il permet d'identifier chaque trace individuellement et de la caractériser au travers de 18 critères relevés. Ce travail va surement nécessiter plusieurs années à cause du nombre d'empreintes et de la complexité du site ; mais c'est là la seule voie qui permette d'interpréter plus finement cet ensemble tout à fait exceptionnel.

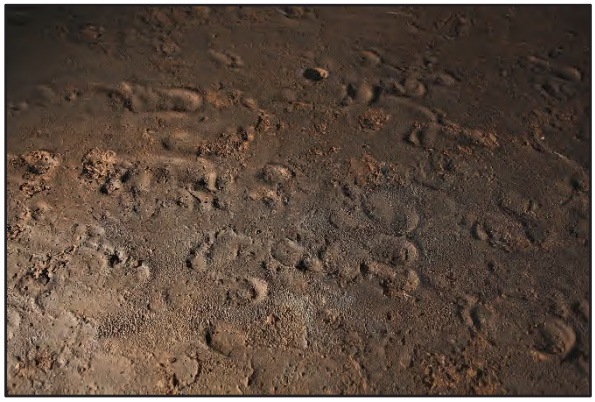

Figure 6 : La densité des empreintes est liée au passage d'un groupe composé de plus d'une vingtaine personnes.

4. À l'arrivée, une belle image…

Les empreintes de pas humains et les traces de torches découvertes dans la grotte d'Aldène, constituent un ensemble tout à fait exceptionnel, quasiment unique à l'échelle mondiale. La nature et la situation de ces différents vestiges s'explicitent dès lors qu'on en a une approche pluridisciplinaire prenant en compte au premier rang les données de la géomorphologie. En effet, la connaissance de l'évolution du site depuis ce passage d'un groupe humain préhistorique, permet d'expliquer et/ou justifier un certain nombre de situations spécifiques pour les vestiges. Grâce à ce regard, on peut dire que les vestiges identifiés dans cette partie du réseau de l'Aldène, sont à associer à une exploration spéléologique familiale voici quelque huit millénaires…

Le comportement du groupe semble pouvoir se comparer au comportement des spéléologues actuels : envie de découverte collective, respect du site et parfaite adaptation technique. Il est fort probable que les nouvelles recherches engagées nous permettront d'en savoir plus…

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Pister les spéléologues de la Préhistoire

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Résumé

L'utilisation des cavités naturelles durant la Préhistoire est un fait que révèlent de façon de plus en plus précise les fouilles archéologiques. Mais pour utiliser une grotte ou un aven, faut-il encore savoir ce qu'il y a dedans, quelle en est sa topographie, quid de son accès… On doit donc admettre que nos ancêtres ont préalablement visité les cavités, ne réservant à leur usage que celles correspondant à leurs nécessités. De fait, la spéléologie d'exploration préhistorique est une réalité. Mais comment la caractériser ? Pouvons-nous en trouver les traces ? Une cavité visitée mais non utilisée peut-elle nous révéler les indices d'une exploration spéléologique préhistorique ? On se trouve là dans un jeu de piste qui doit se construire à partir d'observations originales rendues possibles grâce aux découvertes spéléologiques.

Abstract

Tracking prehistoric cavers. The use of natural cavities during Prehistory is a fact that archaeological excavations reveal more and more precisely. But to use a cave or a sinkhole, one have previously to know what is inside, what is topography, what about its access ... We must therefore admit that our ancestors have previously visited the cavities, keeping for their own use only those corresponding to their needs. Prehistoric exploration caving is a reality. But how to characterize it? Can we find evidences of these first surveys? Can we imagine that a cavity visited but not used can yielded clues of prehistoric speleological explorations? It is a real treasure hunt, a detective investigation, built from original observations made possible thanks to speleological discoveries.

1. Introduction

Dès la naissance de l'archéologie, les grottes ont été des sites de prédilection pour connaître la vie de nos ancêtres. L'évolution des recherches a bien changé notre perception du site troglodytique, passant du concept « d'habitat de populations sauvages » à celui de réceptacle sédimentaire enregistrant de nombreuses activités anthropiques et variations naturelles. Il est indéniable que de tout temps, et largement encore aujourd'hui, les cavernes ont attiré et ont interrogé. Depuis que l'Homme est Homme, le domaine souterrain a été visité, utilisé. Aujourd'hui, les fouilles archéologiques vont très loin dans l'analyse de ces types de gisements au travers d'approches pluridisciplinaires très complètes et au prix de lourds investissements en temps et en moyens. Là aussi, l'évolution des disciplines est notable et une démarche collective permet de prendre en compte l'environnement et les données naturelles qui présentent un rôle majeur tant d'un point de vue géomorphologique que taphonomique au niveau des artéfacts (LAROCHE et *al*. 2019). Ainsi, l'analyse des différentes utilisations des cavités naturelles livre de nombreux détails quant à la perception de l'espace souterrain et son utilisation au cours des temps.

Pourtant, pour qui s'intéresse à cet espace et à cette thématique, une question est récurrente : comment savoir qu'une cavité répond au besoin attendu ? Comment imaginer que la première grotte investie va contenir l'eau recherchée ? Comment savoir que l'argile nécessaire aux vases se trouve dans cette partie du réseau ? On pourrait multiplier ce type d'interrogations pour chaque nature d'utilisation préhistorique d'une caverne. Mais comment répondre à ces questions ?

Figure 1 : Sur le Causse de Blandas, un passage découpé dans une draperie au Néolithique en vue d'explorer, puis d'utiliser, la suite d'un réseau.

2. Un constat en guise de première réflexion

Au sein des patrimoines souterrains, l'art pariétal du Paléolithique pose de nombreuses interrogations. Les recherches actuelles, qui utilisent souvent les dernières technologies, s'attachent à décrypter les grottes ornées. La connaissance avance, mais de nombreuses questions restent et resteront sûrement en suspens pour très longtemps. Cependant, il est des constats simples qui interrogent. Nous citerons l'exemple de la Baume Latrone (Sainte-Anastasie, Gard, France). Cette cavité renferme une série d'œuvres pariétales très particulières au premier abord dans son style pictural, mais qui dans le détail donne une image assez classique de la composition d'un sanctuaire souterrain paléolithique. On peut également s'interroger sur la localisation de ces œuvres là où le réseau semble s'arrêter. Comme si on avait cherché le point ultime de la caverne pour y réaliser des dessins. Toujours dans les gorges du Gardon, une vingtaine de kilomètres plus en aval, se trouve la grotte Bayol (Collias, Gard, France). On y observe la même configuration que dans la Baume Latrone, à savoir, la présence d'un panneau qui concentre une assez grande partie des œuvres connues, dans la partie terminale de la cavité.

Les gorges du Gardon, où se situent ces deux grottes, constituent un secteur investi par les spéléologues depuis très longtemps. De nombreux inventaires des cavités naturelles ont été réalisés par ces derniers et d'autres sont en cours. Il résulte de cette avancée des connaissances une assez bonne vision de la répartition des cavités et surtout de la description de leur morphologie. On constate que les deux seules grottes ornées qui y sont actuellement connues se trouvent dans des secteurs où le nombre de cavités est assez élevé. De même, si on considère les grottes situées dans un périmètre de 5 km autour (correspondant approximativement à une heure de marche), on constate que ces deux cavités sont les plus importantes, en termes de développement et de volume. Comme dans beaucoup de cavités ornées paléolithiques, on a le sentiment que la recherche de l'espace de réalisation des œuvres contribue à l'intérêt du sanctuaire. Dès lors, il est difficile d'admettre que l'intérêt spécifique de ces deux cavités ait été identifié dès leur première visite et ce, d'autant plus que leurs entrées ne sont pas forcément celles qui sont les plus visibles dans le paysage. Il est vrai que ces populations de chasseurs-cueilleurs parcouraient ce territoire et donc connaissaient les entrées de toutes les cavités. Il faut donc envisager qu'ils ont réalisé des explorations systématiques, parfois répétées, avant de retenir le site idéal correspondant à leur besoin. On est là dans une vraie démarche d'explorations spéléologiques qui consiste à connaître un milieu avant de l'utiliser. Il y a là une évidence difficile à prouver mais encore plus malaisée à nier !

Figure 2 : Sur le Causse de Blandas, dans une cavité très pentue utilisée à la fin du Néolithique, une concrétion porte une perforation où des traces d'usure témoignent de son utilisation pour l'amarrage d'une corde en main courante.

3. Percevoir la spéléologie préhistorique

Si l'on admet ce principe de la nécessité de « *connaître avant d'utiliser* », on doit aussi accepter que de nombreuses cavités aient été visitées au cours de la Préhistoire sans pour autant faire l'objet d'utilisation. On peut pousser plus avant cette approche du point de vue chronologique : une cavité visitée et non utilisée par un groupe du Paléolithique a pu être visitée et utilisée par un groupe du Néolithique ; les besoins variant au gré des périodes. Mais au-delà de cette approche « sémantique », le plus important concerne les traces liées à ces explorations.

Il faut en effet s'interroger sur les différentes catégories de traces engendrées lors d'une visite ancienne de caverne. Il semble qu'en premier lieu il faille considérer celles qui ne sont pas volontaires : passage (frottement et appui contre paroi, empreinte au sol) ; utilisation de dispositif d'éclairage (impact involontaire contre paroi, charbon de bois au sol). Dans un deuxième temps, celles engendrées pour les besoins de l'exploration : ouverture de passage pour circuler (bris de concrétions, déblaiement d'un remplissage – Fig. 1) ; aménagement d'un franchissement (accumulation de matériaux, agencement de prises – Fig. 3) ; installation

d'agrès en lien avec la progression (fixation de cordage, calage de support rigide – Fig. 2). Bien sûr, la nature des traces d'exploration peut être multiple ou unique selon les sites et les conditions taphonomiques. Outre la difficulté du repérage et de l'identification de tels indices (Fig. 4), leur datation reste un point majeur. Dans tous les cas, leur reconnaissance nécessite à la fois une observation très minutieuse du site, selon la règle du « *cinquante mètres à l'heure* », mais également une bonne connaissance du contexte karstologique et géomorphologique, d'où la nécessité d'une approche collective et pluridisciplinaire.

La présence d'éléments fonctionnels dans un site utilisé demeure un point important car il permet de documenter et donc de valider les types de traces que l'on peut associer aux explorations. Il n'en demeure pas moins qu'il faut rester très prudent dans les interprétations formulées au cours d'une telle étude de cavité. De fait, nous prônons plus l'approche « *catalogue* » qui permet d'identifier les éléments dans leur contexte et donc de garder un esprit d'objectivité dans la présentation des faits observés, que l'approche « *interprétative* » trop marquée par les sentiments souvent exacerbés du rédacteur ou de l'état de ses connaissances…

4. Une approche raisonnée, la Paléospéléologie

La démarche proposée ici a déjà été envisagée. En effet, à la fois spéléologue et archéologue, François Rouzaud s'était interrogé sur les conditions d'accès au domaine souterrain dans le cadre de ses recherches sur les grottes ornées pyrénéennes (ROUZAUD 1978). Le spéléologue et archéologue Albert Colomer avait, en plus de sa prise en compte spécifique de la relation archéologique entre l'homme et les cavernes, poussé ce paroxysme jusqu'à justifier le recours au creusement de grottes sépulcrales artificielles dans les régions dépourvues de cavités naturelles (COLOMER 1979). On constate que très tôt dans la recherche archéologique moderne, les archéologues ayant une très grande sensibilité spéléologique ont fait le lien entre ces deux disciplines, mais surtout dans la façon d'en percevoir les traces et leurs approches.

La notion de Paléospéléologie, telle qu'elle a été définie par François Rouzaud, repose sur le fait de rechercher la perception du milieu souterrain qu'avaient nos ancêtres. Dans son travail, il a organisé cette recherche autour de l'art pariétal et surtout des traces non figuratives, définissant entre autres les notions d'espaces éclairés et du milieu souterrain profond dans l'organisation des sites. Il en découle une spécificité des utilisations. Dans cette approche, François Rouzaud insistait beaucoup sur la reproductibilité des recherches, les vestiges étant laissés en place et non détruits, chaque prélèvement devant être raisonné, minimaliste et fiable avec donc un recours aux méthodes d'analyses les plus modernes. Outre le sujet de l'étude, il y a surtout une philosophie de cette recherche (GALANT et MAKSUD 2005).

Aujourd'hui, il est possible d'élargir cette démarche pionnière à d'autres chronologies et à bien d'autres contextes. L'approche est beaucoup plus globalisante car elle ne se réalise plus au travers d'un type de site et d'une chronologie donnée, mais elle se fonde sur la caverne, objet premier de l'intérêt. En évoluant dans cet espace, on part à la recherche d'indices et de faits qui attestent d'un impact anthropique. Il s'agit d'une sorte de puzzle dont il faut chercher les pièces qui nous sont inconnues, alors qu'on n'en connaît pas le nombre et qu'il sera fondamentalement incomplet. Il faudra donc se contenter de ce qui reste pour comprendre ce qu'il s'est passé. Évidemment, il y a dans cette approche beaucoup de pièges, principalement ceux tendus par la nature, mais aussi ceux de nos esprits trop formatés ! C'est souvent dans cette situation que le regard du spéléologue est important, car il ramène aux choses rationnelles, généralement les plus représentatives.

Figure 3 : Sur le Larzac, des marches taillées dans une coulée permettent de remonter une cheminée qui a livré à son sommet des indices de l'exploration de la fin de la Préhistoire.

Concernant l'interprétation c'est un tout autre domaine. Une globalité de paramètres demande alors une prise en compte raisonnée où la part du phénomène naturel et du geste anthropique doit être pesée à chaque instant. Cette analyse demande beaucoup de temps et souvent plusieurs visites collectives et pluridisciplinaires du site, pour finalement définir un concept parfois original (GAUCHON et GALANT 1997). C'est là aussi que s'applique la règle, humoristique mais tellement vraie, du « *cinquante mètres à l'heure* ». Il faut prendre son temps, observer analyser, comparer, chercher ce qui n'est pas « normal » au sens

naturaliste ; et souvent s'appliquer la règle du « *je ne sais pas* » ! C'est dans cette démarche, ô combien simpliste mais satisfaisante, que progressivement l'assemblage des données se met en place. Ainsi, on parviendra peu à peu à énumérer et conclure les différents modes opératoires de la fréquentation ancienne d'une caverne.

5. Une méthode à développer

Cette méthode, qui consiste à rechercher de nouveaux indices des fréquentations anciennes du milieu souterrain karstique, apporte des données inédites ; leur datation est parfois envisageable après l'étude exhaustive et pluridisciplinaire d'un site. Les résultats renouvellent notre perception du comportement de l'Homme face à la caverne, on constate une prise en compte des contraintes mais avec une recherche destinée à en tirer avantage.

La reprise systématique de plusieurs cavités caussenardes enrichi le corpus des observations ; elle augmente aussi les interrogations. La confrontation directe sur site permet aux intervenants d'exprimer un avis en fonction de leurs compétences. L'échange de points de vue permet de valider une hypothèse ou d'émettre un doute, mais incite toujours à avancer plus avant dans l'expertise.

Tous ces éléments, montrent qu'on peut réellement parler d'une spéléologie préhistorique. Ces explorations anciennes ont apporté aux groupes humains de la Préhistoire une connaissance du milieu, fournissant parfois un élément vital du quotidien ; les grottes citernes des Grands Causses en sont le plus bel exemple. Outre le fait de permettre la collecte et la conservation de l'eau, ces cavités ont fixé les points d'habitats et ainsi contribué à la définition des territoires, prenant également en compte le monde des vivants et celui des morts (GALANT 2015). Alors que l'archéologie des paysages permet d'ouvrir de très grands champs d'observations qui sont autant de terrains d'analyses, la paléospéléologie permet à une autre échelle d'établir une nouvelle perception du milieu souterrain karstique.

Figure 4 : Dans le Minervois, une empreinte de pas humain préhistorique est la preuve incontestable d'un passage ancien, mais elle ne ressemble pas toujours à ce que l'on pourrait en attendre ; c'est là que commence le jeu de piste…

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The relationship between use of ice from a lava tube in El Malpais (New Mexico) and drought events in the southwestern USA

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Abstract

The droughts are believed to have influenced settlement and subsistence strategies, agricultural intensification, demographic trends, and migration of the complex Ancestral Puebloans societies that once inhabited the American Southwest. Using precisely radiocarbon dated charcoal from an ice deposit preserved in a lava tube from El Malpais National Monument of New Mexico, we conclude that the population in the region used melted ice for drinking as early as 2000 years ago. The need of constant domestic water supply, especially during major drought events, forced Ancestral Puebloans people to venture into lava tubes and look for ice. Water availability in an already harsh environment may have influenced migrations across the landscape and caused repetitive depopulation-repopulation of some settlement locations.

Résumé

Les relations entre l'exploitation de la glace dans un tube de lave d'El Malpais(Nouveau-Mexique) et les épisodes de sécheresse dans le Sud-ouest des USA. Les sécheresses ont probablement influencé les stratégies de peuplement et de subsistance, l'intensification de l'agriculture, les tendances démographiques et les migrations des sociétés complexes des anciennes populations Pueblos qui occupaient le Sud-ouest américain. En utilisant des charbons de bois provenant d'un dépôt de glace préservé dans un tube de lave du Monument national d'El Malpais au Nouveau-Mexique, et bien datés par la méthode du radiocarbone, nous concluons que la population de la région utilisait depuis 2000 ans la glace fondue comme sources d'approvisionnement en eau. Les besoins constants en eau pour la consommation domestique, surtout pendant les grandes sécheresses, ont obligé les anciennes populations Pueblos à s'aventurer dans les tubes de lave à la recherche de glace. La disponibilité en l'eau dans un environnement déjà rude a pu influencer les migrations à travers le territoire et provoquer un dépeuplement-repeuplement répétitif de certaines régions.

1. Introduction

The Southwest United States has had a history of droughts and climatic hardship long before the occurrence of large scale anthropogenic related climate changes (GRISSINO-MAYER, 1995; CARRILLO *et al*., 2017). Better understanding the climate of the past few thousand years in this region not only sheds light on the struggles faced by the Native Americans and early settlers of the Southwest but may also give us insight into the problems affecting our society in the present and near future. Paleoclimate reconstructions are generated using proxies preserved in biological or inorganic archives that maintain evidence of past climate conditions. New archives are continually sought out by researchers to obtain a more complete picture of our planet's climatic past (LOWE & WALKER, 2015). Ice cores from glaciers and ice sheets have long been a source of paleoclimate data, with oxygen and hydrogen analysis having the potential to reveal temperature records and paleo-moisture sources (GAT, 2010). The isotopic composition of cave ice was first examined by ŞERBAN *et al*. (1967), and later in more detail and using modern calibration techniques by YONGE & MACDONALD (1999), LUETSCHER *et al.* (2005), PERSOIU *et al.* (2017), among others.

El Malpais National Monument (ELMA) is located on the southeast edge of the Colorado Plateau (Fig. 1) and is dominated by basalt flows originating from the Zuni-Bandera volcanic field. The Zuni-Bandera volcanic field has one of the longest spanning volcanic histories in the United States, estimated to range from 700,000 to 3,000 years ago (LAUGHLIN *et al*., 1994).

A lava tube can be described as a type of cave that forms in lava flows where the roof solidifies faster than the middle section, allowing it to empty out and leave a system of tube-shaped cavities (ROGERS & MOSCH, 1997). There are 453 documented lava tubes in ELMA, of which 94 have seasonal and/or perennial ice or have had ice at one time, as indicated by bathtub ring deposits of calcite along the lava tube walls and breakdown piles.

While oxygen isotopes in cave ice in El Malpais have been examined by DICKFOSS (1996), a full paleoclimate record based on isotopic composition of ice has yet to be examined in New Mexico. Here, we contribute to this line of research by documenting five drought events over an 800-year period using well-dated charcoal fragments preserved in an ice core recovered from a lava tube (Cave 29) in the ELMA.

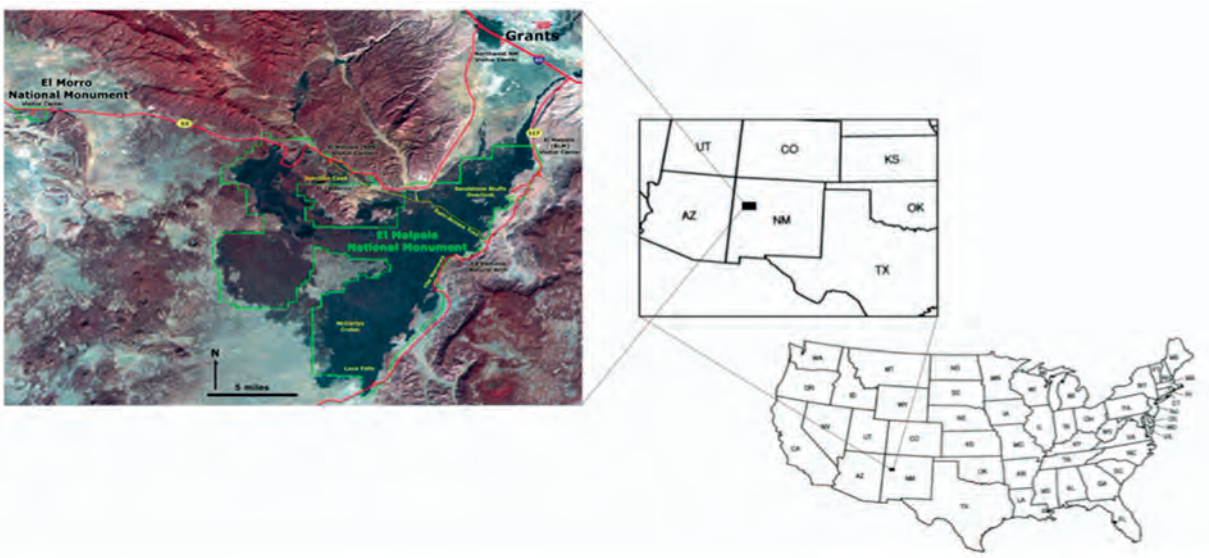

Figure 1: Map of the El Malpais National Monument and its location in the continental USA.

2. Ice and charcoal

Cave 29 opens at an elevation of 2268 m and is a single 171 m long lava tube that splits in two small passages at its very end. The access into the cave is through a large collapse area. The ice block is located in the deeper part of the tube in an alcove and is surrounded by thick (30 to 50 cm) charcoal deposits (ONAC *et al.* 2019). The charred material is only present in the inner part of the tube, beyond a narrow passage that occurs in its middle section. A 59-cm long ice core was recovered from the ice block, photographed, described, and sampled for isotopic analysis (1-cm interval) and radiocarbon dating (whenever charcoal particles existed) were collected while still in the cave.

The ^{14}C ages obtained suggest charcoal was deposited in the ice between AD 167 and 933 (ONAC *et al.*, 2019).

Corroborating the presence of charcoal in the ice core with available paleoclimate evidence, it became obvious that Ancestral Puebloans entered deep into the lava tubes during prolonged periods of droughts to harvest ice that they will use for medicinal rituals and also as a source for drinking water.

The *in-situ* discovery of the corrugated Cibola Gray Ware ceramic sherd, its position in relation to the top of the ice deposit, and the presence of charcoal residue coating its interior surface provides insights on the method employed by Ancestral Puebloan people (after ceramic was introduced in the area ~AD 800) to obtain water from the cave ice. Such pots or even sherds could have been used as a platform to support hot coals and/or contain a small fire.

3. Conclusion

Using precisely radiocarbon dated charcoal from a 59-cm long ice core recovered from Cave 29 in ELMA, we unambiguously identified five droughts events between AD 150 and AD 1100. Our findings suggest that the Ancestral Puebloans people ventured into the lava tube and harvest ice. It appears that water availability in an already harsh environment (high elevation lava fields), may have influenced migrations across the landscape and caused repetitive depopulation-repopulation of some settlement locations.

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Mesures acoustiques dans la grotte du Déroc (Vallon Pont d'Arc - Ardèche)

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Résumé

Si nous sommes habitués à topographier, photographier ou décrire les grottes, quid de leur dimension sonore ? Pour pallier ce manque d'informations nous avons investi la grotte du Déroc à Vallon-Pont-d'Arc afin d'y appréhender la dimension acoustique. À partir d'observations à la voix et à l'oreille, nous avons repéré les zones de résonance ; soit sur une fréquence isolée, soit sur une partie du spectre vocal, ou encore les zones où une réverbération du son est remarquable. Ensuite, pour étudier ces espaces acoustiques repérés, nous avons mesuré leur réponse en fréquence et leur temps de réverbération. Pour cela nous utiliserons la méthode de déconvolution, qui consiste à émettre et enregistrer un bruit bien choisi, puis à comparer le signal émis au signal reçu. Cela donne une identité acoustique propre à l'espace étudié. Dans notre cas, nous émettons tour à tour un son continu dont la fréquence varie de 20 à 20 000 Hz, et une impulsion de bruit blanc produite par l'éclatement d'un ballon de baudruche. Cette étude acoustique au Déroc nous amène à nous interroger sur l'approche archéoacoustique déjà réalisée par le passé.

Abstract

Acoustical measurements in the Déroc Cave. If we are used to topographing, photographing or describing caves, what about their sound dimension? To overcome this lack of information, we visited the Déroc cave in Vallon-Pont-d'Arc in order to understand the sonic dimension of the place. From observations with the voice and the ear, we located zones of interest regarding the acoustics. Then, to study these identified acoustic spaces, we measured their frequency response and their reverberation time. The idea is to give parameters delimiting the acoustical identity to the space studied. This acoustic study at Déroc leads us to question the archaeoacoustic approach already carried out in the past.

1. Introduction

Récits, observations écrites, témoignages, métrages, mesures des pentes, des directions, photographies, dessins... depuis toujours, les spéléologues ramènent de nombreuses informations de leurs explorations souterraines. Mais quel explorateur n'a pas un jour émis un "boh" derrière une étroiture pour écouter l'écho, la résonance souvent signe d'une suite prometteuse… ?

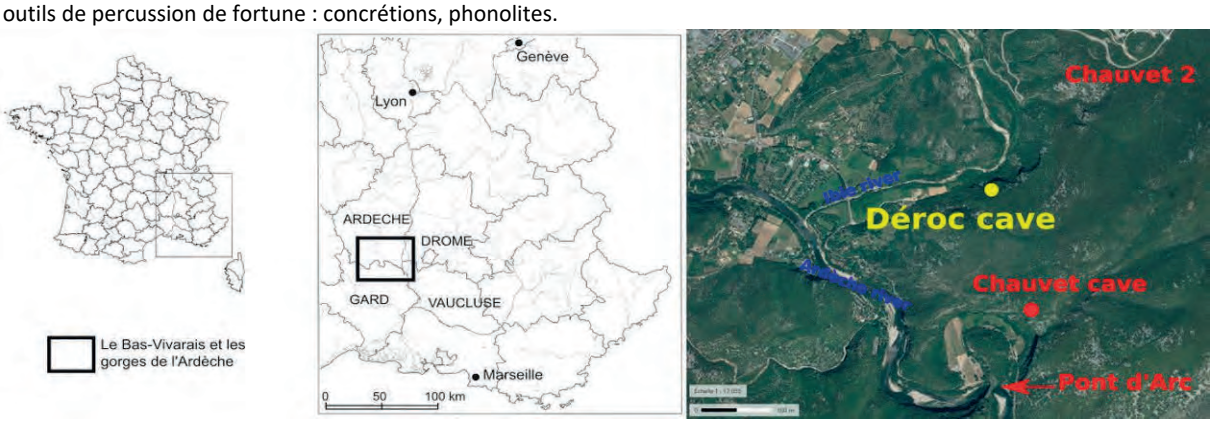
L'architecture des espaces souterrains ne pourrait-elle pas être représentable comme espace sonore ? L'acoustique ne pourrait-elle pas nous aider à appréhender cet objet qu'est la grotte ?

Réverbération du son, fréquence de résonance, nous avons tous fait l'expérience, en grotte, de ces conditions acoustiques remarquables avec la voix, mais aussi avec des outils de percussion de fortune : concrétions, phonolites.

De plus, si nous devions progresser sans lumière dans un réseau, en plus du toucher, une appréhension sonore de l'espace pour retrouver une paroi, repérer un vide nous paraît incontournable. Nos ancêtres préhistoriques n'ont-ils pas eux aussi appréhendé la grotte à l'oreille... ? Mais à quoi correspondent ces espaces acoustiques ? Comment pourrait-on les mesurer ?

C'est en nous aventurant dans ces problématiques que nous avons réalisé quelques expériences acoustiques dans la grotte du Déroc à Vallon Pont d'Arc (Ardèche, fig. 1) et nous vous présentons ici quelques éléments d'analyse et des perspectives pour donner suite à ces expériences.

Figure 1 : Situation de la grotte du Déroc.



2. Matériel et méthode

Une fois la localisation des trois stations de mesure déterminée (sur critères perceptifs puisque nous recherchions des espaces acoustiquement remarquables), nous allons émettre un signal connu et reproductible à l'identique. Simultanément à l'émission, nous allons enregistrer ce signal dans son espace sonore, c'est-à-dire son espace de mesure. En comparant le signal émis et le signal reçu, nous aurons alors la capacité de déterminer les spécificités acoustiques de l'espace sonore étudié.
Nous utiliserons ce qu'on appelle un « Sweep » audio, c'est-à-dire un fichier audio balayant quasi continuellement l'ensemble des fréquences audibles avec la même dynamique.
Pour émettre ce signal, nous utilisons une enceinte « Bluetooth Bose Revolve II+ ». Cette dernière nous permet donc de lire le « Sweep ». Le système d'acquisition est composé d'une paire de microphones statiques AKG P170, le signal est transmis au logiciel d'acquisition par la carte son YAMAHA AG06. La distance émetteur-récepteur est de 1m50 environ pour toutes les mesures.
Le matériel utilisé pour les mesures acoustiques a été choisi pour convenir de manière optimale aux conditions souterraines et de transportabilité, tout en restant performant au maximum. Nous avons donc testé le système au préalable en laboratoire. Étant donné que la réponse en fréquence du système de mesure n'est pas parfaite (réponse en fréquence non linéaire des microphones et de l'enceinte), nous comparons les courbes obtenues *in situ* avec la courbe de réponse en fréquence « neutre » du système de mesure que l'on obtient dans un espace acoustique neutre (chambre anéchoïque), en respectant exactement la configuration et les conditions de mesure (fig. 2). Lors de ces tests préliminaires, nous avons également testé l'enceinte et vérifié ainsi qu'elle est bien omnidirectionnelle (à 2 dB près).
Notons que lors du traitement des données, on effectue pour toutes les courbes présentées ci-dessous un lissage psychoacoustique, c'est-à-dire à hauteur des capacités perceptives maximale de l'oreille humaine, et on choisit une échelle logarithmique pour l'axe des fréquences en Hz afin de mieux observer la zone 50-6000 Hz qui correspond aux fréquences les plus audibles par l'oreille humaine.

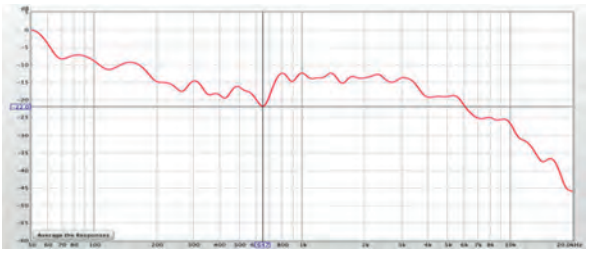


Figure 2 : Sonagramme de l'amplitude des fréquences du Sweep en fonction du temps (Échantillon neutre).

Pour espérer expérimenter la réponse de nos "boh" d'explorations, nous avons enregistré l'explosion de ballon de baudruche, dans le but de mesurer le temps de réverbération. Dans ce cas, l'enceinte était simplement remplacée par un ballon dont on enregistrait l'explosion. Le temps de réverbération sera donné à la norme RT60.

3. Résultats

Il a déjà été étudié que l'oreille humaine est suffisamment sensible à ces phénomènes de résonances des espaces architecturaux [SHENHUY, 2015]. Nous nous basons donc sur cette exploration à l'oreille avec l'utilisation de la voix et du logiciel FAcAT développé pour l'occasion, pour choisir les lieux les plus atypiques, reflétant un temps de réverbération remarquable et/ou des résonances particulières et ainsi caractériser des espaces à l'acoustique marquante.

Première station (Galerie Gauche proche de la zone du cervidé gravé (fig. 10)) : Dans cette zone, on repère à l'oreille une amplification des basses-fréquences. Pour un premier relevé, nous disposons l'enceinte au milieu de la galerie entre les micros et la paroi (fig. 3).
Le sonagramme semble confirmer cette amplification des basses-fréquences de 65 Hz à 700 Hz, avec un maximum à 128 Hz. Le reste de la courbe montre une faiblesse des aigus entre 2 et 18 kHz (fig. 4).

Nous mesurons aussi un temps de réverbération de 3,7 s (fig. 5).

Figure 3 : Mise en place du matériel (Photo Ph. Monteil).

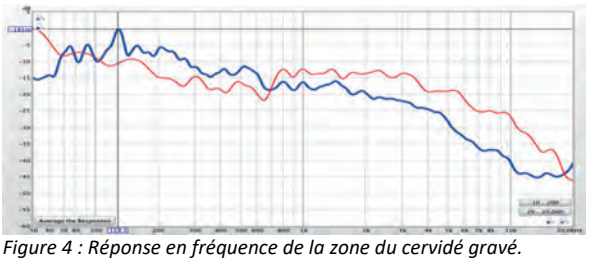


Figure 4 : Réponse en fréquence de la zone du cervidé gravé.

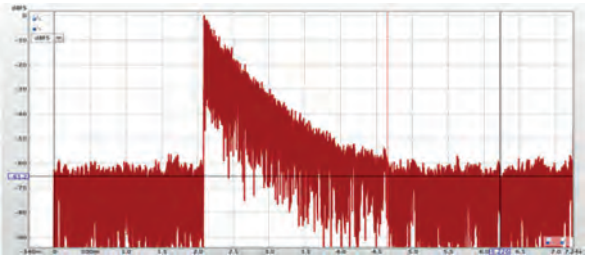


Figure 5 : Impulsion pour la mesure du temps de réverbération RT60, première station.

Pour un deuxième relevé, nous disposons l'enceinte proche d'un trou circulaire en hauteur sous le cervidé gravé (fig. 6). À la voix et à l'oreille, le phénomène acoustique nous semblait très intéressant.
Les ondes vocales émises dans cette niche ellipsoïdale présentent la particularité d'entrer très facilement en résonance dans les fréquences graves, le son se diffuse ensuite dans la grotte et produit un effet très impressionnant de bourdonnement.
Le temps de réverbération de la niche est de 4,9 s.

Figure 6 : Niche sous le cervidé gravé (Photo Ph. Monteil)

Là encore, le relevé confirme notre impression auditive. La réponse en fréquence de cette niche est l'une des plus remarquables de ce qui a été mesuré au Déroc, avec une résonance unique à de 63 Hz (fig.7).

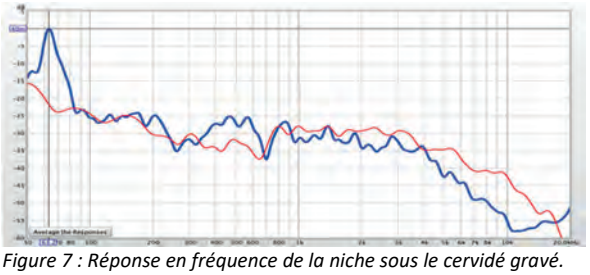


Figure 7 : Réponse en fréquence de la niche sous le cervidé gravé.

Ce phénomène acoustique est un résonateur de Helmholtz [INGARD, 1953]. Le résonateur de Helmholtz est constitué d'une cavité dans laquelle l'air entre en vibration et émet une fréquence précise proportionnelle à son volume. Cette relation de Helmholtz se vérifie au regard des dimensions estimées de la niche.

Deuxième station (Grande galerie, après l'embranchement vers l'entrée 2, à proximité du départ de la galerie du Puits (fig.10)) :
Le temps de réverbération mesuré est de 3,2 s.
Cette zone présente une amplification particulière à l'oreille. C'est ce qu'on retrouve au sonagramme : une fréquence fondamentale à 58 Hz et des résonances secondaire localisées sur les fréquences de 68, 79, 117, 141 Hz et 1 kHz principalement (fig. 8).

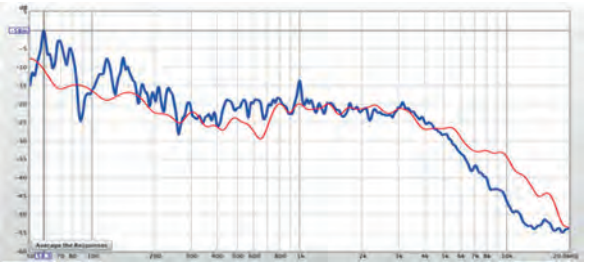


Figure 8 : Réponse en fréquence de la zone de la galerie de la peinture.

Troisième station (Extrémité ouest de la Grande Galerie dans un grand volume vers les sondages (fig.10)) :
Cette zone, repérée à l'oreille présente une acoustique assez neutre mais tout de même repérable par une légère amplification des fréquences graves sur une bande assez large. Au sonagramme, on observe une réponse en fréquence quasi neutre, mais on repère aussi sensiblement cette prédominance des fréquences graves (maximum d'amplification à 135 Hz). On mesure un temps de réverbération de 2,7 s. On repère de légers phénomènes d'écho sur les analyses acoustiques, toutefois difficilement perceptibles à l'oreille.

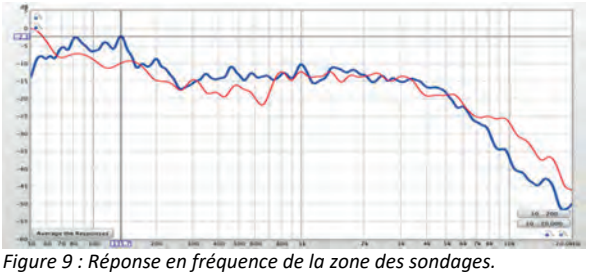


Figure 9 : Réponse en fréquence de la zone des sondages.

4. Discussion

Si nous avons ainsi pu mettre en lumière que cette grotte présente des particularités acoustiques mesurables et perceptibles, cette succincte étude aura surtout permis de mettre en lumière la difficulté d'étudier l'acoustique dans ce type de milieu. En effet, on se retrouve face à une architecture à la géométrie très complexe et on a ici les résultats pour une localisation émetteur/récepteur en seul point. Cette expérimentation reste bien sûr très insuffisante pour comprendre le fonctionnement physique de la grotte face aux ondes sonores : quels volumes entrent en résonance, comment circule le son… ? Il faudrait une quantité de relevés acoustiques pharaoniques pour espérer répondre aux questionnements sur l'ensemble des phénomènes liés aux réverbérations et volumes / réflexions et surfaces.
C'est pourquoi la modélisation acoustique même localisée, nous semble un défi ambitieux. Les volumes, les matières, la complexité du problème persiste. Aussi, en plus de la

réponse sonore de la roche, il restera à prendre en compte les différents remplissages ; zones concrétionnées, des zones argileuses… Une série de tests reste à faire pour ces situations.

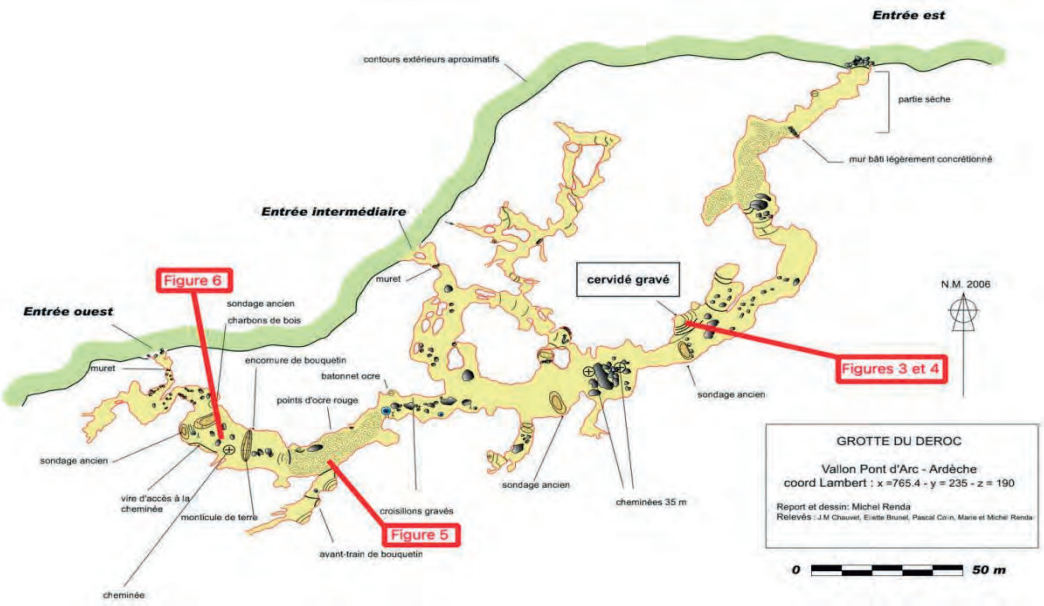


Figure 10 : Topographie de la Grotte de Déroc avec pointage des lieux de mesure [Brunel, 2007].

5. Conclusion

Même si l'étude sonore des grottes est un immense défi à relever, il serait dommage de négliger les potentielles applications de cette recherche, notamment dans le domaine de l'archéologie. En effet, si les études archéoacoustiques des grottes françaises telles que menées par Reznikoff et Dauvois semble aujourd'hui reposer sur des fondements assez subjectifs, une étude acoustique plus systématique et pragmatique pourrait permettre de mettre à jour nos connaissances de l'univers sonore des hommes de la préhistoire.

Lors de notre modeste expérience, nous avons mesuré des temps de réverbération de 2,7 à 4,9 s (norme RT60) soit un temps de réverbération supérieur à nos salles de concert, et comparable à certaines de nos Cathédrales.

Cette propriété acoustique que nous avons démontrée à certains endroits n'est pas présente dans l'intégralité de la grotte du Déroc, c'est donc bien une caractéristique acoustique majeure et localisée. Nous avons aussi montré que ce que l'on pouvait repérer à l'oreille (phénomènes de résonance ou de prédominance de certaines fréquences) se retrouvait explicitement à la lecture des sonagrammes. Ainsi il ressort des caractéristiques acoustiques intéressantes de certains lieux de nos grottes.

Il conviendrait aussi d'évoquer les phénomènes d'écho, que nous n'avons pas rencontrés au Déroc mais qui font également partie des paramètres acoustiques remarquables.

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Human presence in the Salle de la Structure of the Bruniquel cave, France, inferred from speleothem studies

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Abstract

The Bruniquel cave in the Aveyron Valley in France contains strange built structures of broken stalagmite pieces at approximately 300 meters from the entrance. The structures were dated at 176.5 ± 2.1 ka, which indicates that the authors of the constructions were ancient Neanderthals, the only *Homo* species known in Europe at that time. New investigations invest other areas of the room and the numerous broken stalagmite bases and pieces present on the floor. The inner area of the largest construction is totally covered with calcite which makes the access to the 'archaeological floor' difficult. Careful sampling by coring the calcite floor revealed char pieces at the base of the calcite cover. U-series dating give additional indications for the timing of the calcite deposition that seemed to start approximately at the same period than the constructions and continued to spread during the last Interglacial period around 120 ka. The calcite floor therefore gives indications on the local environment in the room at the time of the first cavers.

Résumé

La présence humaine dans la salle de la Structure de la grotte de Bruniquel, d'après l'étude des spéléothèmes. La grotte de Bruniquel, dans la vallée de l'Aveyron en France, contient d'étranges structures constituées de morceaux de stalagmites brisées à environ 300 mètres de l'entrée. Une structure a été datée à 176,5 ± 2,1 ka, et a donc été construite par des Néandertaliens anciens, seule espèce du genre *Homo* attestée à ce jour en Europe durant cette période. De nouvelles investigations reprennent dans d'autres zones de la salle où de nombreuses bases et morceaux de stalagmites brisées sont présents au sol. La zone intérieure de la grande construction est entièrement recouverte de calcite, ce qui rend l'accès au "sol archéologique" difficile. Un échantillonnage minutieux par carottage de la calcite a révélé des vestiges carbonisés à la base de la couverture de calcite. La datation uranium-thorium donne des indications supplémentaires sur la chronologie du dépôt de calcite qui semble avoir commencé à peu près à la même période que les constructions et qui s'est poursuivi au cours de la dernière période interglaciaire, autour de 120 ka. Le sol en calcite donne donc des indications sur l'environnement local de la salle au moment de ces 'premiers spéléologues'.

1. The Bruniquel cave - introduction

The Bruniquel cave, situated in Tarn-et-Garonne, France, was discovered in the early nineties and is known for its surprising constructions of broken stalagmites at 300 meters from the entrance. The cave opens in front of the medieval Bruniquel village in Bajocian limestone at approximately 50 meters above the Aveyron river. The cave was discovered in the early nineties by the Société Spéléo-Archéologique de Caussade (SSAC), a local caving club. Several roughly circular structures of broken stalagmites were discovered at 300 meters from the entrance. A main sub-circular structure (A) is 6.7 meters long and 4.5 wide, while a smaller adjacent one (B) has a diameter of ~2 meters. Two smaller accumulation structures are present inside the main structure (D, E) (Fig. 1) and two similar structures are situated at each side out of the main structure (C, F). The cave seems also very rich in animal traces, bear nests, bears footprints and claw traces, ungulate traces etc. (L. Ledoux in progress). Several animal bones were discovered in the entrance area but most of them were poorly preserved. A first archaeological study, led by F. Rouzaud and M. Soulier (ROUZAUD *et al.,* 1995 and 1997) followed by a second study since 2016 directed by the authors, revealed an age for the structures of 176 500 years with an uncertainty of ± 2 100 years (JAUBERT *et al.,* 2016), indicating they were most probably the work of early Neanderthals, the only human species known in Europe at the end of the Mid Pleistocene.

The structures are covered for an important part by more recent calcite. The floor in both roughly circular structures and partly around them are covered with a calcite flowstone, blocking the access to the archaeological floor. Therefore, it is uncertain if the archaeological floor is situated underneath or inside the calcite. In other words, did the Neanderthals stand on calcite or on the underlying clay when building those structures? The surrounding area of the

room displays clayey deposits, and several broken stalagmites and broken bases of stalagmites are present.
Gaining insight in the local environment of the structures and their surroundings in the room is a logical further step in the archaeological study and crucial to get more information about possible functions of the structures.
The function of these structures is still unknown. The discoverers thought of a dam, while rapidly the hypothesis of a basement for the installation of a tent was put forward (ROUZAUD *et al.* 1995 and 1997). Since the structure today holds the dripping and seeping water inside, causing the formation of a large rimstone basin, visitors are tempted to see some of the structures as former water reservoirs. However, the discovery of several fireplaces on the structures does not seem in agreement with the tent or water-basin hypotheses. A social, socio-cultural or ritual function has been proposed by B. Hayden, an anthropologist of U-Canada (HAYDEN, 2012) but evidence is still lacking to test this interesting hypothesis.
New data from insight and outside the structures give us first insights on the direct environment of the structures and source of the building material. The larger cave environment is treated in another contribution in these proceedings.

Figure 1: Bruniquel cave. The Structure chamber – Large structure A with the accumulation structures D (left) and E (right - covered by recent stalagmites) situated inside structure A. Today the structure A retains the seepage water inside its structure leading to deposition of a rim all around the pool visible as a thin white margin at the base of the stalagmite wall on the back.

2. The calcite floor in and around the structures

Two cores were taken in the calcite floor inside the structure A at two different locations (Fig. 2 and 3), one in the northern part (BR-PL-L11) and another in the southern part of the structure (BR-PL-P13). A third sample, a broken piece of the covering flowstone (BR-PL-2), was taken outside the structure along the pathway further south in the room (Fig.3).
All three cores revealed a calcite layer of between 1.5 to 5.0 cm thick. Outside the structure, along the pathway the calcite started its growth around ~140 ka. Inside the calcite cover started around 180 ka at the southern part, while it started at ~130 ka in the northern part of the structure. Currently, the calcite is deposited by seepage water flowing over a ~2 meters high stalagmite spreading further over the floor.
The results, including dating by H. Cheng, indicate that the calcite floor is oldest in the southern part of the structure, nearby the stalagmite and seemed to spread northwards and eastwards, in agreement with current topography and display. The calcite covered the floor nearby the nowadays pathway only ~36 ka after the construction of the structures, at first warming signs of the Last Interglacial Period (MIS 5).
The calcite at the southern part inside the A structure started to cover the area around ~180 ka which, by considering the age and sampling uncertainties, can be considered as approximately the age of the constructions

themselves (MIS 6). It is therefore difficult to conclude if a starting calcite floor was present or not when Neanderthals came into the cave and constructed these structures.

The BR-PL-L11 core taken at the northern side inside the A structure contains a small char, a piece of heated carbon piece as proven by Raman measurements at the bottom of the calcite (D.Deldicque, JN. Rouzaud and C. Burlet, ongoing work). The age of the calcite indicates that this char piece is at least 130 ka years old and most probably a piece of the burnt bones inside the structures, previously dated as contemporaneous of the construction of the structures. The small char piece was most probably remobilised and finally incorporated in the calcite at ~140 ka.

Under the calcite, the clay is deposited in thin layers over ~5.0 cm thickness, under which a layer of 'hardened' carbonated clay is observed. It seems unlikely that a thin lamination would have been preserved in the case humans walked around. Therefore, the question raises if the archaeological floor is located between the layered clay and the calcite or (more probably) under the laminated clay in the northern part of the structure. In this case, the 'hardened' carbonated clay is a possible indication for the archaeological floor. At the southern part of the structure, it is still uncertain whether the calcite was there or started just after the construction of the structures.

These considerations have their importance to prepare a test-pit of 30 by 30 centimetres during a next field campaign in order to explore the archaeological level inside the structure A, which remains a challenge without any indications of the possible location of this level inside the stratigraphic profile.

Figure 2: Bruniquel cave – the 'Salle de la Structure'– Coring of the calcite floor inside structure A. May 2019.

Finally, a breakage of the flowstone is visible underneath the recent calcite (Fig. 3). 'Whether this flowstone was broken; by bears, humans or natural processes, remains an open question.

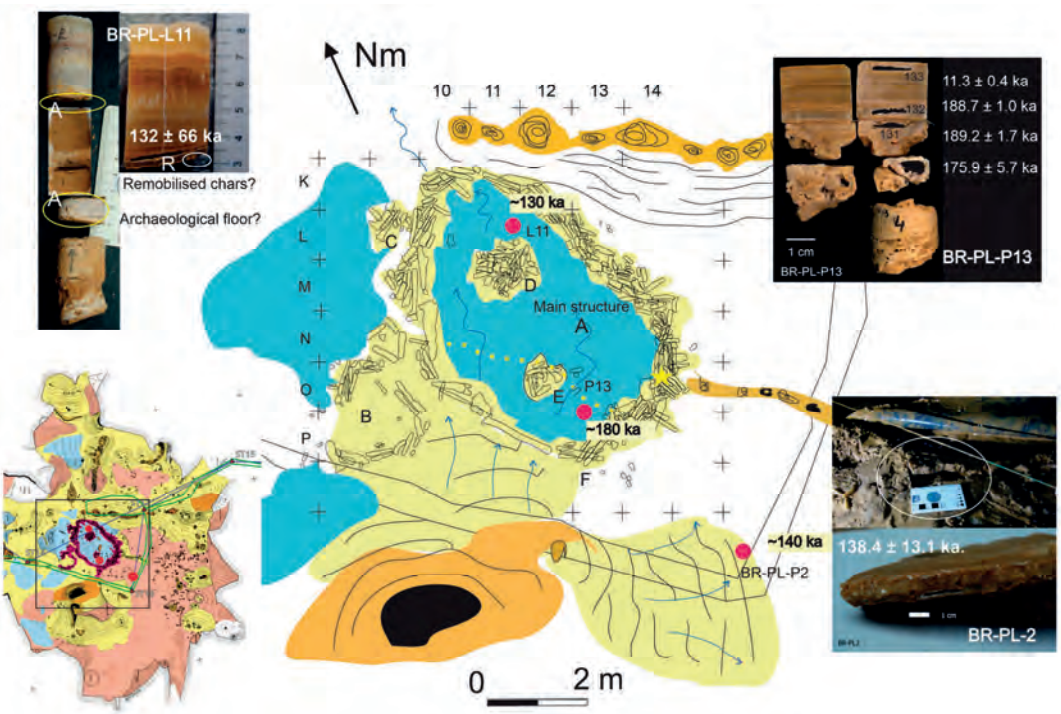

Figure 3: The Salle de la structure in the Bruniquel cave – The BR-PL-L11 and BR-PL-P13 cores, taken in the calcite flowstone inside the structure A (largest structure) are overlying partly calcified detrital deposits inside the large structure A. Dating of the calcite indicates different steps of calcite deposition that seems to originate from a southern stalagmite. The calcite covered the clayey soil in front of several stalagmites (P13) at around 180 ka, and later around ~140 and ~130 ka the calcite reached point 2 (BR-PL-2), nearby the sideway and point L11, at the northern side of the structure, respectively. A probably re-mobilised millimetric char particle at the interface between the calcite and the underlying clay is observed in the BR-PL-L11 core.

3. Location of the stalagmite 'quarry' – source of the building material.

The structures are made of 420 pieces named 'speleofacts'. These pieces are essentially identified as stalagmite pieces. Broken stalagmite bases, broken stalagmite pieces lying on the floor, and negative prints left by wrenching stalagmites out of the clayey deposits of the surroundings in the chamber, are indications of the collection of stalagmites as raw material by humans. To prove the source of the building raw material, we need to confirm the contemporaneity of the collection of stalagmites with the construction of the structures, or to confirm that the bases remaining in the chamber are those of the stalagmites used in the structures (spéléofacts), and ideally work on both approaches.
The inventory of each stalagmite piece, stalagmite base and wrenching trace in the room was made. A 3D (LIDAR) and high-resolution photogrammetry of the structure and surroundings is ongoing to permit the individualisation of the stalagmite pieces and bases and of the broken surface of the stalagmites in order to elaborate and test recognition software enabling to find back positive and corresponding negative surfaces of the same broken stalagmite, or to bring together a broken stalagmite and its base (X. Muth in progress).
In the meantime, new U-Th dating of calcite enabled us to identify a small stalagmite that started its growth at ~174 ka on a broken stalagmite base in the surroundings of the structures. The new results suggest that the direct surroundings of the structure were used as a source for the building raw material.

4. Conclusions and perspectives

The Neanderthal broken-stalagmite structures in the Bruniquel cave are unique human constructions without any reference possible. The unravelling of the site is only starting. Up to now, we know the age of ~176 ka of the structures, we know that they are composed of only stalagmite pieces and that the construction is rather complex. Several fireplaces are present. New data now reveal a probably rather clayey floor and suggest that building material came from the direct surroundings of the structures, demonstrating the important potential of the systematic mapping and dating of the different deposits in the cave.
Future research will focus on the direct surroundings to confirm the new results, as well as on the exploration of other parts of the cave.

Acknowledgments

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Did Neanderthals visit the Mishin Kamik cave, western Stara Planina, Bulgaria, 200 000 years ago (MIS7)?

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Abstract

The Balkans are known as the Danubian corridor, one of the three routes for Human migrations into and dispersal from SE Europe. The Mishin Kamik cave opens at 463 m asl and ~30 m above a small tributary of the Ogosta River, a tributary of the Danube. It developed in Upper Jurassic to Lower Cretaceous limestones. The discovery of several peculiar deposits questions the potential of human involvement and thus the visit of the cave by humans. In particular, a strange bear structure made of four skulls, two long bones and two lumps of yellow clay catch the attention. The structure show similarities with previously found peculiar arrangements. Up to now it was not possible to determine the human origin. However, a natural origin for the Mishin Kamik structure is not straightforward neither. Unfortunately, the structure was dismantled and cannot be studied anymore. Regarding the intense debate concerning bear symbolism among Neanderthals, the site, and its potential human involvement, may have important consequences on our knowledge about Neanderthal behaviour. Since the main evidence is dismantled, the site is discussed in terms of cave environment and remaining sedimentary indications and at least questioned by taking into account other related discoveries in Europe.

Résumé

Les Néanderthaliens ont-ils visité la grotte Mishin Kamik (Bulgarie) il y a 200.000 ans (MIS 7) ? Les Balkans sont l'une des trois voies de migration et de dispersion des êtres humains vers l'Europe du Sud-Est. La grotte Mishin Kamik s'ouvre à 463 m d'altitude et à environ 30 m au-dessus d'un petit affluent du fleuve Ogosta, lui-même affluent du Danube. La grotte creusée dans les calcaires du Jurassique supérieur au Crétacé inférieur a révélé des indices de passage humain. En particulier, un étrange dispositif composé de quatre crânes d'ours, de deux os longs et de deux morceaux d'argile jaune. La structure présente des similitudes avec des arrangements particuliers découverts précédemment. Jusqu'à présent, il n'a pas été possible de déterminer l'origine humaine. Cependant, l'origine naturelle de la structure du Mishin Kamik n'est pas non plus tellement évidente. Malheureusement, la structure a été démantelée et ne peut plus être étudiée. L'éventuelle implication humaine ou non a des conséquences importantes sur nos connaissances du comportement des Néandertaliens et en particulier sur la symbolique liée aux ours chez les Néandertaliens, sujet très controversé. En l'absence des ossements, le site est discuté en termes d'environnement karstique et de contexte sédimentaire. Il est intéressant de mettre le site en relation avec d'autres découvertes en Europe.

1. Archaeological findings in the Mishin Kamik Cave

The Balkan Peninsula is known as the 'Balkan' or 'Danubian' corridor, one of the routes known for SE-NW Human migrations and dispersal. In Bulgaria, twelve known palaeolithic sites are located at cave sites, mainly situated in the northern Stara Planina mountain range. The Mishin Kamik cave is located to the west of known human occupation sites such as Kozarnika, Temnata and Bacho Kiro (Fig 1). The cave (Fig 2) is well-known to local 'treasure' hunters and is of increasing interest for prehistorians.

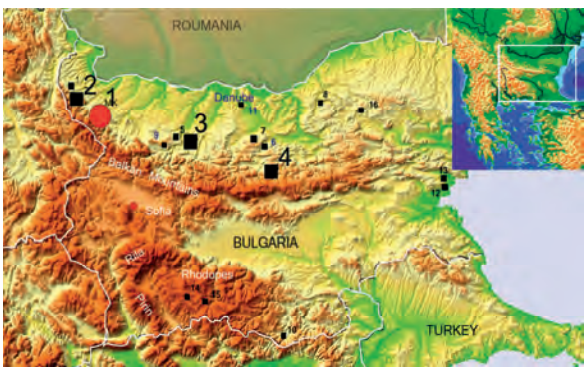

Figure 1: Bulgaria orographic map with indication of the main Palaeolithic sites. 1.Mishin Kamik Cave, 2. Kozarnika Cave, 3. Temnata Cave, 4. Bacho Kiro Cave.

Besides a rich paleontological content (SPASSOV, 2016) with several bear bones, mainly of *Ursus savini*, the excavations of 2013-2017 revealed several bones displaying linear traces, pointed or rounded edges and cut marks suggesting human presence in the cave according to GUROVA et *al*. (2018). In trench 4 (T4) (Fig. 2), ~1 meter deep, a weathered hollow stalagmite, positioned upside-down along the limestone wall, was found just above a 'pavement-like' layer of flat, decametric limestone pieces. The base of trench 1 (T1), shows calcite rimstones filled with centimetric pieces of limestone debris, so-called gelifracts under 0.8 meter of sediments.

However, what impressed most the excavators was a remarkable structure of four bear skulls (Fig. 3) in a nearly cruciform-like display located in T1. Adjacent to the structure, a fifth one lying upside down near the four others with several less well-preserved calcified bones. In the structure, flat limestone and flowstone pieces and two lumps of yellow clay accompanied the skulls and raised the question of an anthropogenic origin among the discoverers. All findings come from sediments that are typically unsorted material filling-up the cave. The paleontological content attributed the sediments to a Late middle Pleistocene up to Eemian age (SPASSOV et *al*., 2017)

However, this chronological constraint is too large to be pertinent for the chronology of the different sedimentary units and their related archaeological findings. Therefore, we studied and dated a speleothem and other calcite levels in the cave, to clarify the chronology in the Mishin Kamik cave and meanwhile illustrate the added value of speleothem studies to archaeological investigations. Moreover, since all findings and surrounding sediments are excavated, it is difficult to have the necessary information to attribute a human involvement in the bear structure, while this information is crucial and has important consequences for our knowledge on human behaviour.

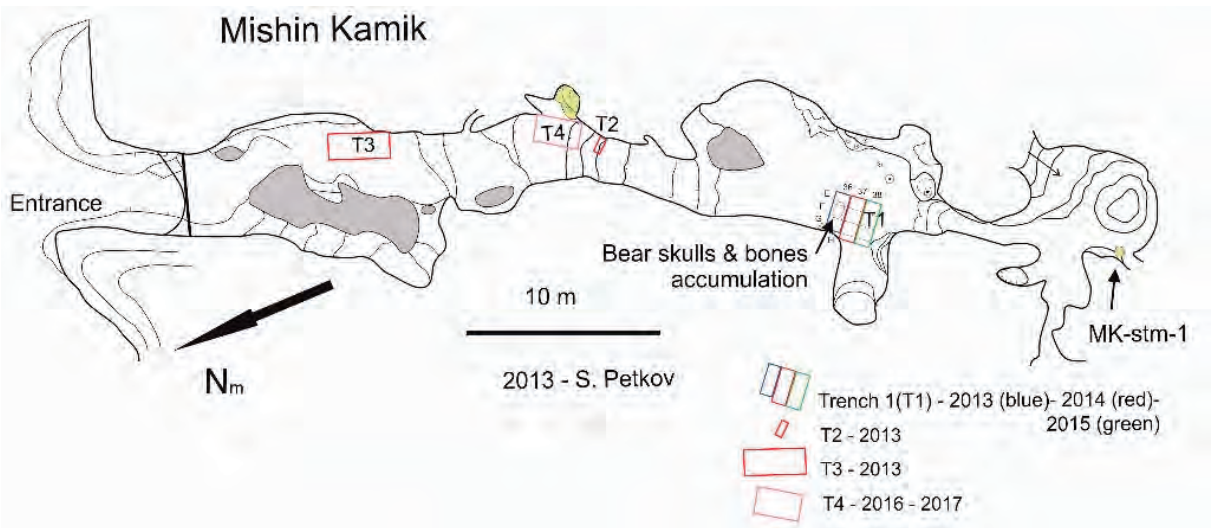

Figure 2: Map of the Mishin Kamik Cave, Bulgaria.

2. Speleothems to constrain the age of the findings – Methods and results.

Seven different carbonated flowstones and one stalagmite were sampled with permission of the Bulgarian Academy of Sciences for U-series dating. The stalagmite MK-stm-1 (Fig. 4) was taken from the third room (Fig 2). It was growing on the calcite floor but continued in the sediments underneath. The stalagmite is 66 cm long and clearly displays different growth phases. Other samples were taken from the flowstones covering trenches 1, 2 and 4 and from calcite layers in trench 1 for uranium-thorium dating by mass spectrometry (MC-ICP-MS) at the Isotope Laboratory at Xi'an Jiaotong University.

Raman analyses were performed to investigate black deposits and discriminate between Mn-oxides and burnt organic material.

Figure 3: Mishin Kamik Cave, Bulgaria. Archaeological findings in trench 1. The so-called 'bear-structure' is the part located at the right, i.e., the four skulls with flat limestone, long bones and yellow clay.

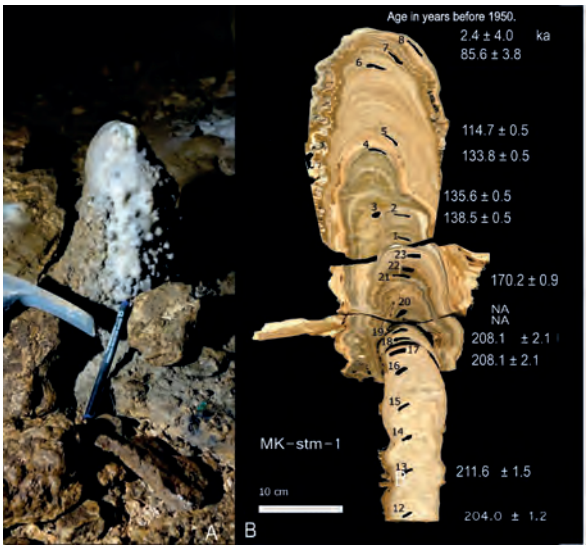

Figure 4: The MK-stm-1 stalagmite in the Mishin Kamik Cave, Bulgaria

The MK-stm-1 calcite stalagmite (Fig. 4) is composed of white-yellow to dark-brown calcite. It clearly displays several important sedimentary changes. The stalagmite grew between ~210 ka (most of the lower candle shaped) and ~80 ka (top of the stalagmite), with a thin Holocene layer on top.

The stalagmite recorded two periods of sedimentary infilling, with the presence of ~1 cm thick clay layers between ~208 ka and ~170 ka. The lower part of the stalagmite, i.e., the candle-shaped stalagmite is surrounded by detrital sediments. After 135.6 ± 0.5 ka, the upper part of the stalagmite completely covered the detrital sediments surrounding the lower part.

At least two layers of a yellowish powdery carbonate like dry moonmilk are deposited. A first one between 133.8 ± 0.5 ka and 114.7 ± 0.5 ka and a second one after 85.6 ± 3.8 ka. These layers can be followed along the stalagmite down to the cave floor and correspond to the floor covering the stalagmite room but also covering T1, ~15 meters away. This is confirmed by the ages of the T1 flowstone of 78 ± 29 ka, 80.1 ± 16.0 ka and 113 ± 78 ka from top to base.

Closer to the entrance, the flowstones covering T2 and T4 are dated of 124.1 ± 3.3 ka and 128.6 ± 0.9 ka, respectively.

The bear skulls structure buried in ~50 cm cave sediments under the T1 flowstone, was lying on a flat calcite piece that was dated 257.6 ± 2.7 and 252.2 ± 5.0 ka. Underlying calcite rimstones, under another ~20 cm of cave sediments are dated ~375 ka, but with only one date. Finally, three dates from calcite layers covering the skulls and from the surrounding sediments give ages between ~130 and ~220 ka.

4. Chronology of the cave deposits and evolution – Discussion.

The determination of a natural versus anthropogenic origin of the bear skulls structure is difficult. The bones and skulls of the bears were disarticulated, excluding an in-situ death. Vertebrate bone beds are relatively common in the cave environment. Most of the time these accumulations result from gravity fall-down, i.e., sinkhole or 'aven' type. However, no nearby pit can explain a bone accumulation in the Mishin Kamik Cave. Inside the cave, natural processes such as creep, water infiltration or debris flow mostly tend to disperse bones and lithic material resulting in a longitudinal distribution from the entrance further into the cave. Accumulation of the bones by bears or other carnivores is also common in caves and is regularly invoked to explain remarkable bone structures. However, recent open-air experimental series (CAMAROS et al., 2017), clearly demonstrated that bears and other carnivores tend to destroy spatial connections and the structured space resulting in a radial and linear dispersion rather than concentrating materials from different composition, such as the accumulation of skulls in the middle of the gallery in the Mishin Kamik cave. The absence of any gully structure discards the transportation and settlement by river flow. Seepage water may have come from several columnar speleothems fed by thin and larger cracks in the ceiling on the side of the room. The underlying rimstones of ~375 ka, underneath the 'bear structure ', are probably related to this water source.

The cave infillings are chronologically well-constrained by the calcite dating. The MK-stm-1 stalagmite suggests that the cave was filled up with detrital sediments before 135.6 ± 0.5 ka. A tilting of the stalagmite, *cf.* the change in axis, can be related to it.

The ages of the flowstones making the cave floor, indicate that the cave is in its present state since 113 ka, and probably even since ~125ka as indicated by the T2 and T4 flowstones.

Therefore, the bear structure and surrounding sediments are older than at least 113ka. The ages obtained from the different calcite levels underneath and above the bear structure confirm this since they give older ages that are in stratigraphic order for most of them. The ages suggest deposition of the structure between ~250 ka and ~220 - 113 ka. An arbitrarily stacking, such as deposition of the bear structure together with the sediments, *i.e.,* debris flow, is therefore less probable. Therefore, the question remains if instead, the calcite embedding the structure and its chronostratigraphic coherence could be in place before a final cave infilling occurred that buried it.

Clearly, further microstratigraphic studies of T1 surroundings and taphonomic studies of the bones are needed before a conclusion on an anthropogenic or natural origin of the bear structure can be drawn. The black deposits analysed so far by Raman techniques were all identified as Manganese oxides. No burnt organic material was found so far in the cave, neither in the hollow upside-down stalagmite. Finally, the rimstones filled with gelifracts may be explained by the natural process of washing out the fine material between the gelifracts. However, the question remains to know why the Last glacial period did not bring the same layer of gelifracts into the cave.

From the contextual information available today it is impossible to give strong arguments for an anthropogenic origin of the 'bear structure' but, meanwhile, a straightforward natural origin is also difficult to give.

5. Relation with the bear-cult debate and concluding remarks

The question of the existence of symbolic behaviour related to bears during the Middle Palaeolithic (e.g., in Neanderthal communities) is part of a long-lasting debate. Today, symbolism related to bears is more easily accepted for the Upper Palaeolithic, when anatomically modern humans are present in Europe, while for the Middle Palaeolithic very contrasting positions exist among researchers. However, recent evidence of symbolic behaviour in the Middle Paleolithic with the use of red ochre, ornaments and Golden Eagle feathers, as well as the discovery of complex structures of broken stalagmites of ~176ka, deep in the Bruniquel cave, continuously push back in time evidence for symbolic behaviour. D'ERRICO et *al*. (2009) even raise the question if some symbolic behavioural features could have been lost by environmental changes and reinvented by humans around 40ka. Poor excavation techniques often throw an everlasting doubt on their symbolic value. For example, the potential of Drächenloch cave in Switzerland, of Regourdou cave and Grotte des Furtins in France and of Rece Cave in Romania (LASCU et *al*., 1994), for their expression of symbolism are all heavily criticised. However, it appears useful to report structures with symbolic behaviour *potential* as much as possible (although with a critical view), to enable a geographically based comparison.
For the Mishin Kamik cave, as for most 'bear structure' sites, an in-situ study of the bear structure and bone accumulation is not possible anymore and proving an anthropogenic origin remains difficult, but a natural origin is not obvious neither. Comparing with other potential Middle Palaeolithic 'bear symbolism' sites, suggests that some points, such as the combined presence of skulls, long bones and flat decametric pieces of calcite/limestone is peculiar, as well as the surprising similarity between the Mishin Kamik 'bear structure' and the one of Cold cave (Rece cave) in Romania dated ~80 ka and only 400 km away.
The additional difficulty remains of course, even if anthropogenic origin is recognised, to distinguish between symbolic and/or utilitarian use by humans or the degree of both behaviours.
The Mishin Kamik study demonstrated the important potential of further interdisciplinary studies in the cave to investigate the human occupation of the site. It moreover demonstrates the important added value of speleothem studies in this context (VERHEYDEN et *al*., 2021).

Acknowledgments

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Symposium 08 - special session

Karst Paleoecology

Karst Paleoecology

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English

Few species of mammals penetrate the underground environment nowadays. According to the observations made by naturalists, most of them are chiropterans, but also rodents, medium-sized and small carnivores. For the latter, a great deal of research is still needed to improve our knowledge and to understand the reasons why these animals frequent the underground environment.

The picture is quite different when we look at the paleofauna. Indeed, numerous species frequented and/or occupied the karst during the Pleistocene to the beginning of the Holocene. The climatic changes linked to the end of the last glacial cycle and, at the same time, increasing anthropic pressure on the habitats have disrupted the animal communities and made their presence in the cavities scarce, at best.

Karst palaeoecology seeks to understand the importance of the underground world for these animals and the reason for their presence underground. It constitutes a vast field of research in paleontology (evolution of living forms), which combines biology, ethology (behavior), ichnology (trace fossils, such as footprints) or taphonomy, in all the vastness of this last discipline (evolution of accumulations, impacts of biotic and abiotic agents, etc.). In short, it forms a multi- and trans-disciplinary field of study, reflecting the relationships and entanglements that can exist between the different components of natural systems, considering the environment, habitat, resources and interspecific relationships.

Applied to the karst context, palaeoecology allows us to see the underground world in a completely different way, for those who regularly visit it: much less empty than it appears today - even if this is only an appearance. It is fascinating because it allows us to shed light (a head-torch, of course) on environments that have no equivalent today, in which animals that no longer exist or that no longer live side by side, due to changes in their geographical distribution or behavior, interacted.

Karst paleoecology is also fascinating given the nature of the remains it studies. In absolute terms, karst palaeoecology can encompass all animal species that have penetrated the karst. Unfortunately, the possibilities of research are inevitably conditioned by the conservation of palaeontological remains, and these preferentially - if not exclusively - concern the remains produced by the biological activity of vertebrates: bones and teeth, coprolites, imprints, polishes, claws, grooves.
The role of cavers in this context is essential. If they are the discoverers, they are also the first preservers of these remains, which are often tenuous and always fragile. Their knowledge of the underground environment and the specificities of these testimonies allows a multiplication of occurrences and thus the creation of a solid reference system to develop research on these species for which the karst constitutes an extension of the territory of the habitat.

The contributions offered in this sub-session reflect the different issues addressed in palaeoecology, from knowledge of the chronological and geographical distribution of species to their behavior in the underground environment. They also highlight the evolution of recording and analysis methods, which combine the classical approach of the naturalist and paleontologist with the use of digital tools.

Français

Peu d'espèces de mammifères pénètrent de nos jours le milieu souterrain. À l'aune des observations dont on dispose de la part des naturalistes, il s'agit dans la plupart des cas de chiroptères bien sûr, mais aussi de rongeurs, de moyens et de petits carnivores. Pour ces derniers, de nombreuses recherches sont encore à mener pour améliorer nos connaissances et saisir les raisons qui poussent ces animaux à fréquenter le milieu souterrain.

Le panorama est tout autre dès qu'on s'intéresse aux paléofaunes. En effet, de nombreuses espèces ont fréquenté et/ou occupé le karst au cours du Pléistocène jusqu'au début de l'Holocène. Les changements climatiques liés à la fin du dernier cycle glaciaire et, parallèlement, une pression anthropique de plus en plus forte sur les habitats ont bouleversé les communautés animales et raréfié, dans le meilleur des cas, leur présence dans les cavités.

La paléoécologie karstique cherche à appréhender l'importance qu'a pu revêtir le monde souterrain pour ces animaux et à saisir la raison de leur présence sous terre. Elle constitue un vaste champ de recherches de la paléontologie (évolution des formes du vivant), qui mêle entre autres la biologie, l'éthologie (comportement), l'ichnologie (empreintes) ou la taphonomie, dans tout ce que cette dernière discipline peut avoir de vaste (évolutions des accumulations, impacts des agents biotiques et abiotiques, etc.). En somme, elle forme un domaine d'étude pluri- et transdisciplinaire, à l'image des relations et des intrications qui peuvent exister entre les différentes composantes des

systèmes naturels, en considérant l'environnement, l'habitat, les ressources, les relations interspécifiques.

Appliquée au contexte karstique, la paléoécologie permet d'entrevoir le monde souterrain de manière tout à fait différente, pour celles et ceux qui le fréquentent régulièrement : bien moins vide qu'il n'y paraît aujourd'hui – même s'il s'agit bien là que d'une apparence. Elle a ceci de fascinant qu'elle permet d'éclairer (à la frontale, naturellement) des environnements sans équivalents actuels, dans lesquels ont interagi des animaux qui n'existent plus ou qui ne se côtoient plus, du fait de changements dans leur distribution géographique ou dans leur comportement.

Elle fascine aussi par la nature des vestiges qu'elle étudie. Dans l'absolu, la paléoécologie karstique pourrait s'intéresser à toutes les espèces animales qui ont pénétré le karst. Malheureusement, les possibilités de recherches sont fatalement conditionnées par la conservation des vestiges paléontologiques, et ceux-ci concernent de manière préférentielle – si ce n'est exclusive – les restes produits par l'activité biologique des vertébrés : ossements et dents, coprolithes, empreintes, polis, griffades, bauges.

Le rôle des spéléologues dans ce contexte est essentiel. S'ils en sont les inventeurs, ils sont aussi les premiers conservateurs de ces vestiges souvent ténus, toujours fragiles. Leur connaissance du milieu souterrain et des spécificités de ces témoignages permet une multiplication des occurrences et par là même la création d'un référentiel solide pour développer les recherches sur ces espèces, pour lesquelles le karst constitue une extension du territoire, de l'habitat.

Les contributions offertes dans cette sous-session traduisent bien les différentes problématiques abordées en paléoécologie, de la connaissance de la distribution chronologique et géographique des espèces, en passant par leur comportement en milieu souterrain. Elles mettent aussi en lumière l'évolution des méthodes d'enregistrement et d'analyse, qui couplent l'approche classique du naturaliste et du paléontologue à l'utilisation des outils numériques.

Grotte des Deux Ouvertures (Saint-Martin-d'Ardèche, Ardèche, France): A limestone wall with a large cave bear polish. Bioglyphs provide important information for understanding the use of karst networks by large Pleistocene carnivores. They may also reflect a particular ethology of certain species, which has no current equivalent. Photo: Nicolas Lateur.

Grotte des Deux Ouvertures (Saint-Martin-d'Ardèche, Ardèche, France) : Paroi calcaire présentant un important poli d'ours des cavernes. Les bioglyphes apportent des informations importantes pour appréhender la fréquentation des réseaux karstiques par les grands carnivores pléistocènes. Ils peuvent par ailleurs traduire une éthologie particulière de certaines espèces, sans équivalent actuel. Photo : Nicolas Lateur.

Les Grottes d'Azé : de la spéléologie à la paléontologie, en passant par les ours

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Résumé

La grotte touristique d'Azé (Saône-et-Loire) se situe en Bourgogne méridionale, au nord-ouest de Mâcon. La grotte supérieure Azé 1 abrite un site préhistorique, le plus ancien de Bourgogne, et de nombreuses accumulations de fossiles d'ours des cavernes jusqu'à 300 m de l'entrée. À l'origine, en 1963, la cavité connue ne dépassait pas 60 m. Grâce à Maurice Bonnefoy et à différentes équipes, au prix d'un gigantesque travail de désobstruction pendant plus de 57 ans, cette cavité atteint maintenant 400 m de galeries. Les différentes études montrent un cloisonnement en trois tronçons fermés successivement par d'importantes formations stalagmitiques. Les datations U/Th de ces blocages prouvent que les ours des cavernes les plus anciens parcouraient la cavité jusqu'au fond, les ours du Pléistocène moyen récent (OIS 6) ne pouvaient pénétrer que jusque dans le tronçon 2, médian. La fermeture à 60 m réduit l'usage à la partie antérieure de la cavité et de la galerie des Aiglons en contrebas aux ours de la période la plus récente (Pléistocène supérieur ancien, OIS.5). L'étude des divers morphotypes dentaires des ours en fonction de la localisation dans les tronçons conforte ce schéma évolutif.

Abstract

The Azé Caves : from speleology to paleontology, through the bears. The touristic cave of Azé (Saône-et-Loire) is located in southern Burgundy, northwest of Mâcon. The upper cave Azé 1 contains a prehistoric site, the oldest in Burgundy, and numerous accumulations of cave bear fossils up to 300 m from the entrance. Originally, in 1963, the known cave was no more than 60 m. Thanks to Maurice Bonnefoy and various teams, after a gigantic work of desobstruction for more than 57 years, this cavity now reaches 400 m of galleries. The various studies show a partition into three sections closed successively by important stalagmite formations. The U/Th dating of these blockages proves that the more ancient cave bears penetrated down to the bottom of the cavity, the bears of the Lata Middle Pleistocene (OIS 6) could only penetrate as far as section 2, median. The closure at 60 m reduced the use of the anterior part of the cavity and of the Galerie des Aiglons to bears of the more recent period (Early Upper Pleistocene, OIS.5). The study of the various dental morphotypes of bears according to their location in the sections confirms this evolutionary pattern.

1. Introduction

Les grottes touristiques d'Azé, Grottes de Rizerolles (ou Grottes de la Balme de Rochebin), à 15 km au nord-ouest de Mâcon, s'ouvrent à l'altitude de 275 m dans le vallon de la Mouge, au nord du village d'Azé (Saône-et-Loire) (Fig.1). Elles se développent dans les calcaires du Bajocien supérieur et du Bathonien inférieur.

En 1958 se constitue la Société Spéléologique de la Haute Mouge qui explore puis aménagera le réseau karstique en vue de son exploitation touristique. Seule la grotte supérieure Azé 1 (ou grotte « préhistorique »), abrite des vestiges du Paléolithique ancien, le plus vieux gisement préhistorique de Bourgogne, et de nombreux fossiles d'ours des cavernes. Les différents aménagements n'ont pas été sans conséquences pour l'intégrité de la grotte mais un certain nombre de fouilles scientifiques ont pu être menées à bien, rendant les Grottes d'Azé bien étudiées et célèbres internationalement.

2. La grotte supérieure, Azé 1

La Grotte d'Azé 1 fonctionne essentiellement pendant le Pléistocène moyen médian et récent, peut être même un peu plus tardivement jusqu'au début du Pléistocène supérieur, avant son colmatage presque total par l'argile et des concrétionnements importants qui obturent complètement la galerie touristique en plusieurs points. Le blocage de l'entrée par des dépôts de pente extérieurs existait encore pour l'entrée de la galerie des Aiglons (Fouilles R. Villeneuve) avant sa désobstruction. Cette deuxième galerie (12 m de large x 3 m de hauteur), parallèle à la galerie touristique, mais très proche (5 m à l'est et 5 m en contrebas) permet d'expliquer le passage des ours aux périodes les plus récentes par la sortie de cette dernière. Elle

est reliée au niveau supérieur par une galerie de jonction, Azé 1-6, large d'un mètre (Fig.2).

La cavité Azé 1, à l'origine, n'est pénétrable que sur les 60 premiers mètres. Ce sont les progrès de l'exploration spéléologique à partir de 1963 et des efforts gigantesques de désobstruction (des milliers de wagonnets) qui ont permis des avancées progressives dans la connaissance de la grotte, rythmées par le franchissement des blocages stalagmitiques successifs.

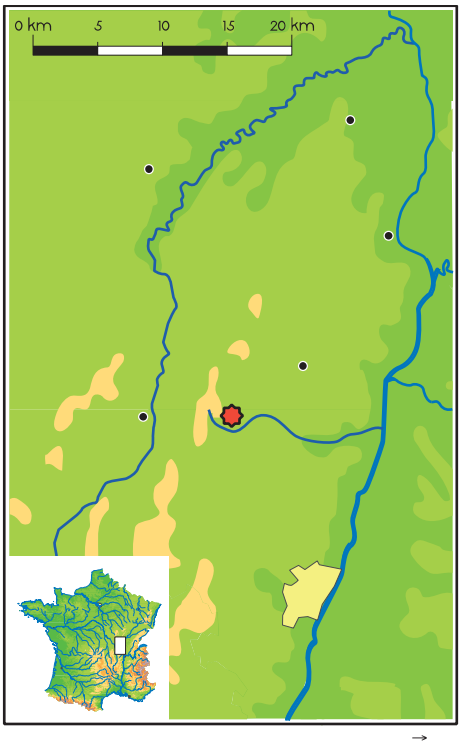

Figure 1 : Localisation des Grottes d'Azé.

Finalement dans l'évolution de la cavité d'Azé 1 on peut distinguer trois phases, chronologiquement datées par les blocages, modulant au cours du temps les possibilités d'accès aux ours venant hiverner dans la grotte (Fig.2) :

- la phase 1 : toute la cavité est parfaitement accessible aux ours depuis l'entrée (Azé 1-1, Fouilles J. Combier) jusqu'au fond après la baïonnette (220 m) avec Azé 1-4 (spéléos). Dans la salle du fond (salle des ours) se trouve le gisement d'Azé 1-3 (Fouilles A. et J. Argant).
- la phase 2 : vers 190 000 ans la grosse stalagmite de la salle du 14 juillet et la formation de brèche bloquent progressivement le passage bas fermant la salle des ours. Le gisement d'Azé 1-2 (Fouilles A. et J. Argant) se trouve à 90-100 m de l'entrée. Les ours ne peuvent aller que jusqu'à la Salle du 14 juillet.
- la phase 3 : le puissant blocage stalagmitique des 60 m se met en place progressivement. Les ours ne peuvent aller au-delà. De plus, l'entrée d'Azé 1 est obturée par les dépôts de pente. Un lac (permanent ou temporaire ?) occupe la salle d'entrée actuelle où se trouvent le gisement d'Azé 1-1 datant du Paléolithique inférieur (industrie très frustre) et de la faune (ours et lion des cavernes). Le passage se fait par la galerie de jonction (Azé 1-6) où se rencontrent plusieurs squelettes complets d'ours des cavernes, bloqués en travers comme l'ours N°2. C'est la fouille d'Azé 1-6 par R. Villeneuve qui a permis de trouver de nombreux vestiges paléontologiques et de découvrir la sortie de la Galerie des Aiglons à l'extérieur (Fouilles R. Villeneuve, Fouilles L. et J. Barriquand).

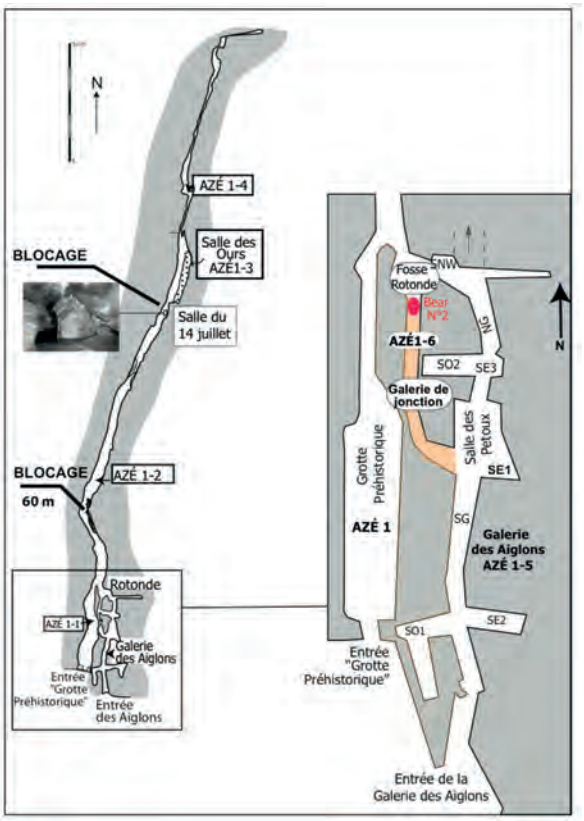

Figure 2 : Plan d'Azé 1 et détail de la galerie des Aiglons Azé 1-5 et de la galerie de jonction Azé 1-6. Position de l'ours N°2.

3. Les ours d'Azé 1

Les ours que l'on rencontre à Azé 1 sont tous trop anciens pour pouvoir être datés par le ^{14}C dont la limite actuelle de la méthode se situe vers 50000 ans. L'émail des dents d'ours, de lions, de hyènes n'est pas assez épais pour les datations ESR. Seule la méthode U/Th qui permet de dater les stalagmites, stalactites, concrétions diverses, peut nous indiquer les périodes de mise en place des grands systèmes stalagmitiques (Y. QUINIF *in* BARRIQUAND *et al.*, 2006) rendant certaines parties de la cavité impénétrables pour les ours (Fig.2).

M2 gauche		*U. etruscus*	*U. deningeri*	*U. spelaeus deningeroides*	*U. spelaeus ladinicus*
Vue occlusale		 A	 B	 C	 D
Réf. photo		Saint-Vallier 20 161 739	AZÉ 1-3 J15-41	AZÉ 1-2 111	AZÉ 1-6 Ours n°2
Dim. (mm)	MD	30,40	42,90	46,44	48,54
	VL	17,43	21,56	24,87	23,95
	HC	-	10,35	11,31	11,16
Description		- peu longue - très large à l'avant - talon court - forme triangulaire - faible rebord à l'arrière du talon	- assez longue - assez large à l'avant - talon net, court avec rétrécissement - bords plutôt parallèles avant le talon - fort rebord à l'arrière	- plus longue - très large à l'avant - talon large, continu - triangulaire - rebord net à l'arrière mais faible	- très longue - étroite - talon très allongé - à bords ± parallèles - faible rebord à l'arrière
Présence à Azé		Absent	Présent dans toute la grotte (phase 1)	Phase 2	Phase 3 et Aiglons

Figure 3 : Différents morphotypes de M2 d'Azé. Comparaison avec Saint Vallier (Drôme, France). Le premier, A, correspond à la forme ancestrale Ursus etruscus nettement plus ancienne que les ours d'Azé 1 pour montrer qu'on ne la rencontre pas dans la grotte, cavité donc plus récente que 1,1 Ma. Les trois morphotypes B, C, D correspondent aux ours d'Azé 1 selon leur degré d'évolution, du plus ancien au plus récent) :
(*Ursus etruscus*) ----> *Ursus deningeri* ----> *Ursus deningeroides* (= *U. spelaeus deningeroides*) ----> *Ursus spelaeus ladinicus.*

Les seuls éléments, les plus nombreux dont on peut disposer pour essayer de comparer entre eux les ours d'Azé 1, restent donc les dents. La deuxième molaire supérieure (M2), dernière de la rangée jugale supérieure, enregistre bien l'évolution de par sa position terminale. Le stade évolutif, au sens large, correspond au bilan global de la dynamique des populations au hasard des rencontres entre mâles et femelles, donc de la génétique mais également à l'adaptation de ces populations aux changements climatiques par le biais de l'évolution des écosystèmes et des ressources alimentaires alors disponibles. À Azé, les études ont permis de constater des différences morphologiques sur les nombreuses M2 disponibles et donc l'existence de morphotypes différents en fonction de la position dans la cavité. La figure 3 présente les principaux morphotypes de M2 :

- A - morphotype « *Ursus etruscus* » (ours étrusque), forme ancestrale des ours des cavernes. Ne se rencontre pas à Azé, gisement nettement plus récent que ceux du Villafranchien au Plio-Pléistocène (jusqu'à 1,1 Ma).
- B - morphotype « *Ursus deningeri* » (ours de Deninger), forme la plus ancienne du Pléistocène moyen médian, les ours les plus anciens d'Azé 1.
- C - morphotype « *Ursus deningeroides* », forme plus récente du Pléistocène moyen récent.
- D - morphotype « *Ursus spelaeus ladinicus* », la forme la plus récente, OIS.5 ou 4, mais d'âge supérieur à la limite des datations ^{14}C.

Tout au fond de la grotte, Azé 1-4 livre *Ursus deningeri*, de même qu'Azé 1-3. La salle d'entrée Azé 1-1 (fouilles J. Combier) renferme également des vestiges d'*Ursus deningeri* ainsi qu'une industrie très frustre du Paléolithique inférieur, prouvant le passage de l'homme préhistorique.

Azé 1-2 livre tout un ensemble de vestiges d'ours plus récents qu'Azé 1-3 d'après l'étude dentaire (ARGANT, 1991), ce que confirme l'existence d'un morphotype différent pour la M2, celui d'*Ursus spelaeus deningeroïdes*, tout à fait semblable à la photo d'une M2 de Repolüsthöhle (Autriche), site éponyme (RABEDER *et al.*, 2016, fig.4-1). Cet ensemble d'Azé 1-2 se rattache au Pléistocène moyen récent par la présence dans la microfaune d'*Arvicola* (campagnol) dont la m1 possède les caractéristiques dentaires des formes de la fin du Pléistocène moyen (JEANNET, 1980). La présence de *Paleoperdrix* (forme ancestrale de perdrix) confirme cette période (MOURER-CHAUVIRÉ, 1975).

L'ours N°2, retrouvé complet dans la galerie de liaison Azé 1-6 (Fouilles R. Villeneuve, sauvetage Thierry Argant ; ARGANT *et al*., 2019) ne correspond ni à *Ursus deningeri*, ni à *Ursus spelaeus deningeroïdes*. Il s'agit d'un ours de grande taille, au tibia plus long et moins massif. La M2 correspond bien à celle de la photographie d'un crâne d'*Ursus spelaeus ladinicus* du type des Conturines (Italie) (RABEDER et KAVCIK, 2014). Dans la Galerie des Aiglons (Azé 1-5) ont été recueillis deux crânes complets d'ours. Le plus au sud, renversé, montrait une série dentaire tout à fait conforme morphologiquement à ce que l'on peut observer sur l'ours N°2. Cet ours N°2, Galerie de jonction (Azé 1-6), se situe chronologiquement entre la fin du stade OIS 6 et au plus tard au stade OIS 4, en tout cas avant la limite de 50 000 ans de la méthode de datation ^{14}C-AMS. La palynologie indique une période tempérée assez chaude attribuable au stade OIS.5. On peut avancer un âge compris entre 130 000 et 57 000 ans.

4. Conclusion

En conclusion, la grotte d'Azé 1, à la suite d'un enchaînement de circonstances favorables : (1) dimensions modestes mais suffisamment importantes pour offrir des facilités à une époque pour l'hibernation des ours, (2) remplissage presque total à la fin du Pléistocène moyen récent (OIS 5 ou début de l'OIS 4) lui permettant d'être épargnée par les érosions intenses des périodes froides de la dernière glaciation, (3) situation lui offrant un avenir touristique motivant l'Association d'Azé, sous la direction de Maurice Bonnefoy, pour son aménagement et la réalisation de travaux considérables, (4) des équipes scientifiques très motivées et compétentes ayant pu intervenir, tout cela a permis une connaissance irremplaçable de ce système karstique, les ours fossiles contribuant grandement à la datation et à la connaissance des étapes de l'évolution de la cavité grâce à la paléontologie.

Remerciements

Cet article n'aurait pu être réalisé sans le concours d'un grand nombre de bénévoles : spéléologues, responsables de l'Association des Grottes et du site d'Azé, acteurs de l'aménagement, scientifiques, animateurs et commentateurs "grand public"… et bien d'autres, qui ont fait, par leur engagement et leur enthousiasme, les Grottes d'Azé d'aujourd'hui. Qu'ils soient tous ici reconnus et remerciés.

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Bear claw marks in clay: differential conservation in caves harboring bat colonies. Mas d'Azil, Sirach and Lare caves, France

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Abstract

Numerous traces of bear visits have been found in caves. They generally correspond to claw marks on walls or to cave bear wallows. Sometimes, these clues are not always well preserved and do not allow the confident identification of the presence of bears. The differential preservation of clue on limestone walls can hamper speleologists and paleontologists in their diagnoses. One must not interpret the absence of claw marks on the rock walls of a cave as an absence of bears. In addition to condensation-corrosion, biocorrosion, due in particular to the pervasive presence of bats in a cave, should be considered as a significant process responsible for the removal of traces on limestone walls. After briefly presenting the speleogenetic processes caused by bats, we present the French caves of Mas d'Azil (Ariège), Sirach (Pyrénées-Orientales) and Lare (Alpes-de-Haute-Provence), which have been frequented by bears, to demonstrate these processes. Here, only the claw marks in the clay are preserved, while their extensions on the limestone walls have completely disappeared. These observations confirm that the clues of bear frequentation are preserved in a different way, depending on the history of the cave, but also on the nature of support, rocky or clayey, on which they were produced.

Résumé

La conservation différentielle des griffades d'ours dans l'argile dans les grottes abritant des colonies de chauves-souris : grottes de Mas d'Azil, de Sirach et de la Lare. Des nombreux indices de fréquentation par des ours ont été relevés dans les grottes ; le plus souvent il s'agit de griffades ou de bauges. Parfois, ces indices ne sont pas toujours conservés et ne permettent pas d'identifier l'ours. La conservation variable des traces sur les parois calcaires peut gêner les spéléologues et paléontologues dans leur diagnostic. Il n'est pas possible d'interpréter l'absence de griffades sur les parois rocheuses d'une cavité comme une absence des ours. En effet, la condensation-corrosion, mais surtout la biocorrosion due notamment à la présence massive de chiroptères dans une grotte, peuvent être responsables de la disparition des traces sur les parois calcaires. Après avoir rappelé sommairement les processus de spéléogenèse générés par les chauves-souris, trois cavités françaises fréquentées par les ours permettront d'illustrer le propos. Il s'agit des grottes du Mas d'Azil (Ariège), de Sirach (Pyrénées-Orientales) et de la Lare (Alpes-de-Haute-Provence). Ici, seules les griffades dans l'argile sont préservées, alors que leurs prolongements sur les parois calcaires ont complètement disparu. Ces observations confirment que ces indices de fréquentation animale sont préservés de manière différentielle selon l'histoire de la cavité, mais aussi selon la nature du support, rocheux ou argileux, sur lequel elles ont été réalisées.

1. Introduction

Cave bear wallows and claw marks are present in some caves, however, in other caves only bear wallows are present, claw marks on the rock walls are absent.

Examination of caves frequented by bears and recent evidence of biocorrosion generated by bats (AUDRA *et al.*, 2018) can explain this apparent anomaly. The presence of bear claw marks mainly results on the various conservation situations. The question of the absence of bear claws must be considered as well as the question of the absence of art on the walls of prehistoric caves (BRUXELLES *et al.*, 2018). "Hidden art" has no more foundation than the hidden claw marks of bears, and their absence neither support the conclusion bear absence in the cave, nor the postulate of specific species that did to scratched walls.

The studies in different caves with differential conservation of cave bear claw marks can help to understand and discuss this essential question.

2. The effects of biocorrosion on cave walls

The corrosion of cave walls generated or induced by the occupation of caves by wildlife, in particular by the presence of large bat colonies, is called biocorrosion. These processes concern the different types of rocks as sandstone or even migmatites (GUTHERZ & BRUXELLES, 2016). However, the limestone walls of karst caves provide the best examples. The role of bats in the biocorrosion of cave walls may be direct, by their respiration inducing a local rise in temperature, humidity, and CO_2 concentration, and indirect, by the mineralization of guano generating corrosive percolations and release of acidic gases.

While bats are responsible for most of the biocorrosion in caves, condensation-corrosion is also a very active phenomenon in caves to the surface. This phenomenon, mainly maintained by bats, can potentially be supported by other hosts that find refuge in caves.

The massive presence of bats in caves is responsible for a powerful condensation-corrosion which is exerted on the walls and ceilings of the galleries. The volumes of the galleries evolve by expansion of the voids, which causes a significant retreat of the walls with rates of at least 5 to 15 mm / ka (LUNDBERG & MCFARLANE, 2009, 2012, 2015; AUDRA *et al.*, 2018).

Condensation-corrosion processes caused by the prolonged stay of bats lead to a considerable expansion of karst conduits which can reaching several meters.

However, it is difficult to appreciate the importance of the retreat of the walls that have disappeared, except when speleothems, display growth laminae. The biocorrosion indifferently cuts the limestone walls and calcite (Fig. 1).

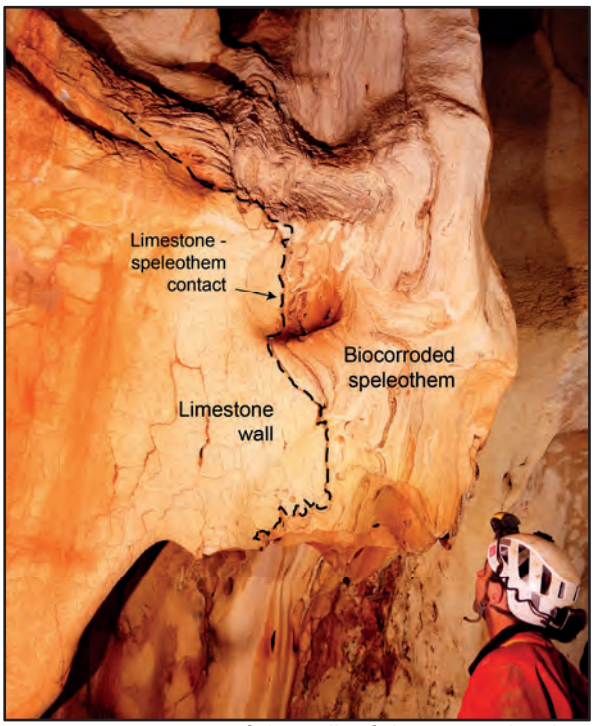

Figure 1: Biocorrosion of the walls of the Guano Chamber, Fairies Cave (Tharaux, Gard, France). To the right, a speleothem showing growth laminae indicates retreat of material. Without the presence of these laminated calcite, it would have been difficult to appreciate the importance of biocorrosion on the rock face (to the left).

3. Some examples of differential conservation of claw marks

The Mas d'Azil cave (Ariège) is a prehistoric cave internationally known for its Magdalenian and especially Azilian occupations. The eponymous site of Mas d'Azil is at the origin of the name of this culture from the end of the Paleolithic. It is also an underground bypass of the Arize River. The volumes of the through-cave are large enough to harbor an underground road following the route of the river. A maze of perched galleries develops above and laterally to the underground river. They were formerly directly opened to the surface (north slope). Indeed, the Bats Chamber corresponds to an extreme point, very close to the surface, however collapsed blocks are now closing the access. Formerly, the Bats Chamber was only accessible by narrow conduits to for both animals and men.

From 1956, an artificial tunnel dug in the sediments of the Mandement Chamber (LE GUILLOU, 2013).

In 2017, we discovered bear claw marks on a clay surface in the Bats Chamber (Fig. 3). It was a very astonishing discovery, since no other traces of bear were known in this chamber.

The bear that entered in the Bats Chamber through the passages currently plugged (north slope) probably marked all the rock faces, but only those in the clay veneer where biocorrosion is not effective could have been preserved.

The least communication with the surface, whether natural or artificial, allows bats to take up new spaces; and the claw marks left by bears on rocky supports quickly disappeared after biocorrosion effects.

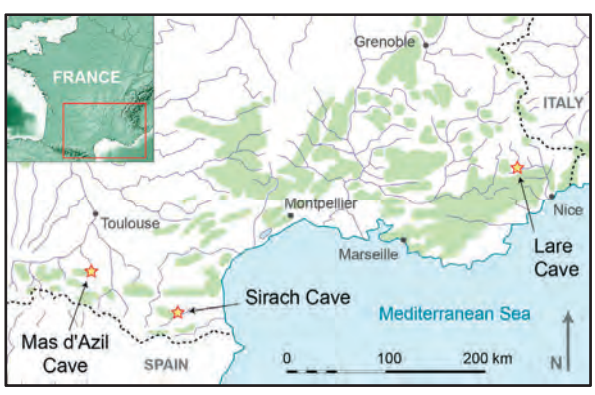

Figure 2: Location map of the three studied bear caves.

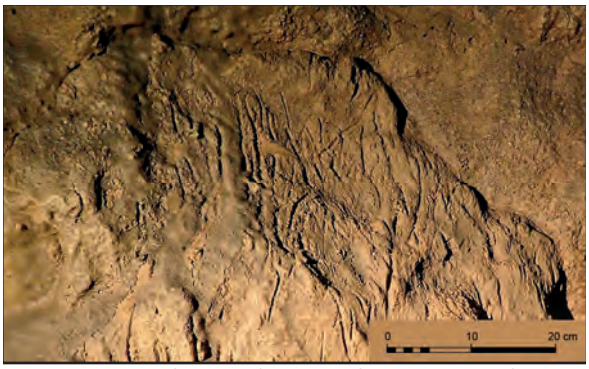

Figure 3: Bear claw marks on a clay veneer in the Bats Chamber, Mas d'Azil Cave (Ariège).

• The Sirach Cave (Pyrénées-Orientales) is a cave known in the past and which opens along a path. It is cited in the work of Abbé LUCANTE (1880). In his speleological inventory, Henri SALVAYRE (1977) mentions the presence of bats, but not the presence of the bear. The cave corresponds to a former functional emergence during the first phases of karstification of the massif (HEZ, 2015).
It is dug in a limestone breccia and has walls on which we can see rounded blocks of all sizes.

Access to this cave is very easy and we also know that the cave was very frequented by bats. Indeed, the porch of the cave has always been widely open to the outside. At the bottom of the cave, there are bear wallows, partly concreted by cave pools. However, there is no claw marks on the rock walls of the cave.

In 2015, we understood the origin of this apparent anomaly. Indeed, many blocks fallen from the vault rest on the ground without being able to identify their imprints on the ceiling. On the ground, the blocks are more or less encrusted with gypsum, indicating the presence of sulphates. In this context, these sulphates coming from guano bats which have now disappeared. Elsewhere, dark borders visible in cross sections of soil fill, along with gypsum blooms, also indicate the presence of old guano piles.

The cave has obviously been frequented for a very long time by colonies of bats favoring a biocorrosion of all the limestone walls several centimeters thick. In the Sirach Cave, the marks of collapses in the vault are entirely erased. On this basis, and due to the presence of bear wallows, we looked for claw marks on non-calcareous supports, less sensitive to biocorrosion.

It is in a niche containing a little clay that we were able to find the only claw marks preserved in this area (Fig. 4).
These claw marks are only visible on the clay support and are not visible above in the limestone blocks of the breccia.
The claw marks disappeared in the limestones but were well preserved in the clay.

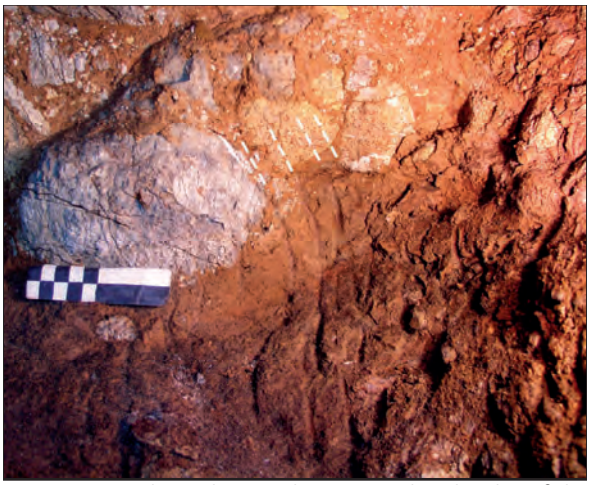

Figure 4: Rare bear claw marks preserved in the clay of the Sirach Cave (Pyrénées-Orientales). There is no longer any trace on the limestone blocks of the breccia. The dotted lines show the extension of the claw marks that completely disappeared on the limestone surfaces.

• The galleries of the Lare Cave (Saint-Benoît, Alpes-de-Haute-Provence) form a maze of tiers of an ancient emergence, which currently pours out at the foot of a nummulitic limestone cliff along the Coulomp valley. Although the cave is somehow difficult in access, it has been continuously opened and visited since at least the Neolithic. Colonies of bats gathering thousands of individuals (mainly Schreiber's bent-winged bat and Greater Mouse-eared bat) occupy the cave especially for swarming. It is mainly a site of transit and reproduction. The cave shows deeply corroded speleothems and in many places limestone walls are entirely bare. The cave has been known for ages for about 300 m. In the inner confined area, which is partly preserved from biocorrosion, old signatures (from 1574) attest continuous visits during the last 6 centuries, the oldest signature (NOBÉCOURT, 2020).
Explorations have pushed the length of the cave to more than 2 km (AUDRA & BIGOT, 2009).
During our numerous visits in the cave, no evidence of the bear presence has been found.

In 2014, a new passage was discovered, showing an impressive pile of guano. Some recent guano deposits are present in the formerly known part, however, similar large pile may have been present, but have disappeared under the footsteps of visitors or after collection as fertilizer.

In 2015, we discovered bear claw marks on a clay bench, which was unfortunately severely degraded by the overcrowding of the cave. This clay bench, located about 200 m from the entrance, is the single place in the cave attesting to the presence of the bear. It is evident that claw marks previously covered any rock walls, but they completely disappeared under the effect of biocorrosion generated by bats swarming.

5. Conclusion

The caves of Mas d'Azil, Sirach and Lare harbor bear claw marks, but these are rare and strictly restricted to some patches of clay deposits. Yet is evident that they previously also extended along any limestone walls. Even if rare, they testify the presence of bears. Their partial disappearance can be explained by the condensation corrosion processes boosted by the biocorrosion of limestone walls caused by bats.
Thus, evidences of retreat of the rocky walls by biocorrosion processes should lead us not to conclude too quickly to the absence of bear in a cave.
The clues or traces may have been partially or totally erased; bears indiscriminately scratch the walls, whether they are rocky or clayey.

Consequently, bear claws marks must be carefully searched on different substrates and in particular on clay, which is insensitive to biocorrosion and therefore more likely to preserve claw marks than limestone walls.
The presence of biocorrosion features is a clue to take into account before any hasty conclusion about cave bear absence.

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Le site archéo-paléontologique du Mas des Caves à Lunel-Viel (Hérault) : Historique des recherches et nouveaux travaux

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En Mémoire d'E. Bonifay

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Résumé

Découvertes et prospectées dès le début du 19ème siècle, les grottes du Mas des Caves (Lunel-Viel, Hérault) firent l'objet de fouilles intensives à partir des années 1960 par E. Bonifay avec de nombreux travaux scientifiques. La grotte I (LV I) livre un matériel paléontologique et archéologique abondant, daté de la fin du Pléistocène moyen. La reprise des travaux depuis 2019 se justifie par de récentes avancées méthodologiques et numériques, et a pour objectif de mieux dater et caractériser les dépôts et les ensembles fossiles, lithique et faune. Un bref historique et un résumé des résultats sont proposés, complétés par les nouveaux acquis de ce site emblématique d'Europe de l'Ouest.

Abstract

The archaeo-paleontological site of Mas des Caves at Lunel-Viel (Hérault): History of research and new works. Discovered and prospected at the beginning of the 19th century, the caves of Mas des Caves (Lunel-Viel) were the subject of intensive excavations from the 1960s by E. Bonifay with many scientific studies. The cave I (LV I) yields abundant paleontological and archaeological material dating to the end of the Middle Pleistocene. The revival of work since 2019 is justified by recent methodological and numerical advances, and aims to better date and characterize the deposits and the lithic and fauna assemblages. A brief history and a summary of the results are given, supplemented by the new achievements of this emblematic site of Western Europe.

1. Introduction

Les grottes du Mas des Caves à Lunel-Viel, entre Montpellier et Nîmes, se développent au sein d'une mollasse carbonatée Miocène, contrairement aux nombreuses cavités de la région creusées dans des calcaires secondaires (Jurassique, Crétacé). Localisées dans les plaines du Bas-Languedoc, paysage de coteaux et de petites collines arrondies à leur sommet recouvert d'alluvions (galets quartzeux et calcaires – paléoRhône), elles se trouvent à basse altitude (environ 50 m a.s.l.) et à environ 9 km du littoral Méditerranéen, bordé d'étangs saumâtres.

2. Historique

C'est lors de l'exploitation d'une carrière pour la mollasse qu'une petite ouverture révèle la première grotte (appelée ici LVI), galerie relativement rectiligne de 150 m de long, 10-12 m de largeur et de près de 6 m de hauteur (variable suivant les secteurs de la cavité), orientée NE-SO. D'autres galeries plus étroites (LVII et LVIII) sont parallèles à LVI. Cette découverte du début du 19ème siècle, fera l'objet de premières fouilles par Marcel de Serres, professeur à l'Université de Montpellier, de 1824 à 1827, publiées dans des monographies (DE SERRES *et al.* 1828, 1839). Le site tombe complètement dans l'oubli jusqu'en 1962 lorsque Eugène Bonifay (CNRS) reprend des recherches dans la galerie (jusqu'au début des années 1980), ce qui lui permit en 1971 de découvrir la doline (LV V) et la grotte n°4 (LV IV). Cette dernière est une galerie (longue d'environ 90 m) dans le prolongement de LVI, riche en spéléothèmes (ce qui n'est pas le cas dans LVI), non fouillée (mais avec un ramassage de faune en surface) et rebouchée en 1974, et à ce jour non accessible et intacte. Il s'agit du même réseau et l'effondrement de la voûte ('doline', 50 m de long sur 20 m de largeur) constitue l'entrée originelle de LVI et IV (BONIFAY 1968 et 1976 ; BONIFAY M.F. et E. 1965 ; BONIFAY et COMBIER 1984).

3. Bilan des travaux : 19ème siècle

La grotte LVI a fait l'objet des principaux travaux menés dans ces dépôts très fossilifères. Le remplissage est formé à la base d'argiles rouges finement varvées (épaisseur d'environ 6 m) sur lesquelles se développent les dépôts de cailloutis

de galets enrobés dans une matrice de sables et limons argileux. Ces dépôts sont issus des formations superficielles surplombant la mollasse, lessivées dans la cavité. Leur épaisseur est variable de 2 m en aval jusqu'à près de 5 m vers la doline (avec un gradient granulométrique), et 14 couches ont été distinguées. Elles livrent un riche matériel archéologique associé à des vestiges paléontologiques (faunes, flores) très abondants. Ceux-ci ont fait l'objet de très nombreuses études, notamment dans le cadre de travaux universitaires. Un essai de bilan est donné ci-dessous.

Les grands mammifères sont bien représentés, souvent par des crânes et mandibules entières, ainsi que par de très nombreux ossements souvent complets du squelette appendiculaire (BONIFAY M.F. 1971, 1973, 1980 et 1991 ; BRUGAL 1985 ; EISENMANN *et al.* 1985 ; NOURY 1997). Près de 14 espèces de carnivores sont présentes : *Cuon priscus*, *Canis lupus lunellensis*, *Vulpes vulpes*, *Lynx* cf. *pardina*, *Lynx spelaea*, *Panthera* (*Leo*) *spelaea*, *Panthera pardus lunellensis*, *Crocuta spelaea intermedia, Hyaena prisca*, *Ursus deningeri*, *Mustela palerminea*, *Lutra* sp., *Meles thorali spelaeus*, Pinnipèdes. Les herbivores représentent huit taxons : *Bos primigenius trochoceros*, *Cervus elaphus*, *Euctenoceros mediterraneus*, *Capreolus* cf. *sussenbornensis*, *Sus scrofa*, *Dicerorhinus etruscus*, *Equus mosbachensis palustris*, *Equus hydruntinus minor*. Plusieurs formes évolutives (ssp.) ont été décrites pour la première fois dans ce gisement, importantes pour le cadre biochronologique des associations animales en Europe de l'Ouest. Le loup et l'hyène (et grande abondance de coprolithes *album graecum*), les équidés, bovinés et cervidés sont les taxons les plus fréquents, permettant de définir un paléoenvironnement plutôt tempéré (type interglaciaire) et de rapporter l'ensemble du dépôt à la seconde moitié du Pléistocène moyen (interglaciaire « Mindel-Riss', selon E. BONIFAY).

Méso- et micro-faunes sont également abondants : Insectivores (*Talpa*, *Sorex*), Lagomorphes (*Oryctolagus cuniculus lunellensis,* DONARD 1982), Chiroptères, Rongeurs [*Microtus brecciensis*, *Apodemus sylvaticus*, *Eliomys quercinus*, *Pliomys lenki*, *Pitymys duodecimcostatus*, *Microtus agrestis* (JEANNET 1976)], Oiseaux (près de 33 espèces, MOURER-CHAUVIRE 1975), Reptiles (*Testudo* sp.), Amphibiens (*Rana*), Poissons, Gastéropodes. Les flores sont renseignées par la présence de graines de micocoulier (*Celtis australis*) et des charbons de bois (*Cercis siliquastrum*, *Quercus* sp. à feuillage caduc, détermination J.L. VERNET).

Les équilles osseuses sont également nombreuses, et leurs études intégrées aux autres vestiges fauniques a permis de suggérer la possible utilisation de ces os par les hommes (BONIFAY 1976 et 1986), mais aussi de démontrer de l'utilisation de la cavité par des carnivores, servant de repaires, en particulier pour l'hyène des cavernes (DIEZ 1986 ; FOSSE 1992, 1995 et 1996).

Les prédateurs humains ont aussi fréquenté le site, comme l'atteste la présence d'artefacts lithiques (en silex, quartzite ou quartz) ainsi que l'existence de structures, en particulier de combustion (BONIFAY 1981 et 1989 ; LEGRAND 1987 et 1994). L'outillage est caractérisé par des outils lourds (type galets aménagés) mais aussi par des lames et racloirs, et le débitage Levallois est présent. Cette industrie a été rapproché d'un faciès de l'Acheuléen méditerranéen.

Figure 1 : Vue générale 3D du Secteur 5 (Photogrammétrie/orthomosaïque L. Pascal) © 2020.

4. Travaux 21ème siècle et en cours

Plusieurs travaux ont été poursuivis et initiés, en prévision de la reprise des fouilles, précisant certains points taxinomiques. Deux nouveaux genres ont été créés, notamment à partir du matériel de Lunel-Viel : le cervidé *Haploidoceros* (qui remplace *Euctenoceros*, CROITOR et *al.* 2008) et la tortue *Eurotestudo* (LAPPARENT DE BROIN *et al.* 2006). Les riches séries fossiles ont permis de mieux établir les dynamiques évolutives du loup et des léporidés

(BOUDADI-MALIGNE 2010 ; PELLETIER 2018), et de préciser le statut taxinomique des lynx (FOSSE et *al*. 2021). Les restes de rhinocéros ont été réattribués à *Stephanorhinus hemitoechus* et un élément (astragale) appartient à *Stephanorhinus kirchbergensis* (UZUNIDIS 2017). L'analyse des méso- et micro-sures dentaires (*Equus*, *Bos*) (UZUNIDIS 2020) apporte de nouvelles données sur les biotopes et la paléo-alimentation des ongulés.

Les recherches actuelles mobilisent une importante équipe de spécialistes en géologie, sédimentologie (dont archéomagnétisme), géochronologie (OSL, ESR/U/Th, Be/Al, racémisation, zircon), paléontologie animale et végétale, paléoécologie, écométrie, taphonomie, archéologues, tracéologie, paléogénéticiens, biochimistes… appuyée par des relevés photo- ou laser-grammétriques systématisés (fig. 1). Les résultats sont encore préliminaires mais on peut signaler : 1) dépôt attribué soit au MIS 9 (e.330-300 ky) soit au MIS 7 (e.240-186 ky), 2) découverte de nouveau taxon : Mégacéros et Proboscidiens, 3) pas de traces de chauffe dans une structure auparavant attribuée à un 'foyer', 4) précision sur les ensembles osseux, taxinomique (fig. 2) et taphonomique (ex. os ingérés, taphozonation), 5) outillage rattaché à un Paléolithique moyen ancien, 6) trace de poli sur un fragment de lame en silex, résultant d'activités anthropiques (boucherie)… De nombreuses perspectives et axes de recherches sont attendus à l'avenir dans ce site exceptionnel et emblématique dans l'espace ouest-européen (Brugal *et al.* sous-presse)..

Figure 2 : Modélisation 3D d'une mandibule d'hyène des cavernes du Mas des Caves

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The Cave bear (*Ursus spelaeus*) scratches in Chauvet cave (Ardèche, France): identification, 3D mapping and paleoethological consideration from wall marking activities

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Abstract

The Chauvet Cave in south-eastern France (Ardèche) is world famous for its exceptionally well-preserved rock art (paintings, engravings), dating exclusively from the early Late Paleolithic (32-36,000 years). This cavity also contains evidence of occupation by cave bears (*Ursus spelaeus*), on the floors (bones, beds, footprints) and walls (scratches, bärenschliffen). Based on both 3D scans and photogrammetric datasets of floors, walls and vaults in several galleries, a morphometric analysis is currently carried out and proposes a new methodological approach for these paleobiological records (size and shape of scratches, individual measurements of scratches, inter-scratches measurements, density of scratches/m^2, height of ursid marks on the walls, variability, spatialization). First results suggest a high density of scratches in deeper galleries of the cavity (between 80 and 160 meters from the Paleolithic entrance). Scratch sizes reveal intense wall marking activities by cave bear cubs and adult females and in a much less proportion by adult/large males.

Résumé

Les griffades d'ours des cavernes dans la grotte Chauvet (Ardèche) : identification, cartographie 3D des activités marquées sur les parois et considérations paléoéthologiques. La grotte Chauvet Pont d'Arc dans le sud-est de la France (Ardèche) est mondialement célèbre en raison de l'exceptionnelle préservation des représentations artistiques (peintures, gravures), datées exclusivement du Paléolithique supérieur ancien (32-36.000 ans). Cette grotte renferme également des indices de fréquentation par les ours des cavernes (*Ursus spelaeus*), sur les sols (ossements, bauges, empreintes) et les parois (griffades, polis de parois). Reposant à la fois sur un scannage 3D des sols, parois et voûtes ainsi que sur des relevés photogrammétriques, une analyse morphométrique des griffades a été engagée pour différentes galeries et propose une nouvelle méthode d'étude pour ces enregistrements paléobiologiques (forme et taille des griffades, mesures de griffades isolées, mesures inter-griffades, densité de griffades/m^2, hauteur des marques ursines sur les parois, variabilité et répartition spatiale). Les premiers résultats suggèrent une forte densité de griffades dans les galeries les plus profondes de la cavité (entre 80 et 160 mètres de l'entrée paléolithique). La taille des griffades traduit un marquage intense des parois par les oursons et les adultes femelles et dans une mesure bien moindre par les ours des cavernes mâles.

1. Introduction

The caves occupied by cave bears (*Ursus spelaeus*) are very common in Europe (Figure 1). While the abundance of bone remains is the main criterion for characterizing a cave bear denning site, many (unexcavated) cavities contain evidence of long-time occupation by the species, based on footprints, beds/nests, scratches and polished walls. All these "traces of life" or bioglyphs (VIEHMANN, 1973, 1987) are particularly important in the extra-Alpine regions, especially in France and Spain. Identified from the beginning in Paleolithic rock art researches (BREUIL, 1908; CARTAILHAC, 1908), these paleobiological records constitute an original support in studies on the behavior of cave bears but also on the interactions with human/predator occupation of deep caves during the Late Paleolithic, many decorated caves yielding this pattern of painted/scratched walls. The Chauvet Pont d'Arc cave, which contains the oldest directly dated Palaeolithic paintings in Europe (QUILES *et al.,* 2016), is also one of the most important cave bear sites due to the abundance and excellent preservation of ursid bioglyphs in all the accessible galleries. This article reminds the evolution of research and techniques on this topic as well as observations concerning the main bioglyphs (i.e., scratches).

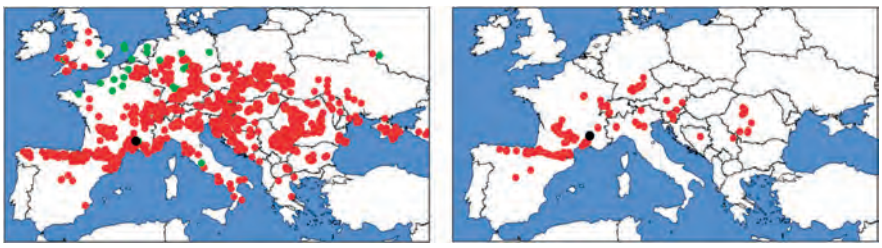

Figure 1: Geographical distribution of European cave bear sites (left) and sites yielding cave bear scratches and/or beds (right). Red circles = caves; green circles = fluviatile sites; black circle = Chauvet Pont d'Arc cave.

2. Material and method

The conservation of floors and walls leading the current research in the cavity, all analyses are based on pictures, photogrammetry and high-resolution 3D scanning of areas/galleries yielding these kinds of paleobiological records. Descriptions of the scratches are based on previous works in Palaeolithic rock art (BREUIL, 1908; CARTAILHAC, 1908; VIALOU, 1979; LORBLANCHET, 1981; LADIER *et al.,* 2003a,b) and on a methodological work made by caving research (MOURET, 1988). Based on these data, a protocol for analysis/measurements of scratches is carried out, taking into consideration the body size of extant carnivores, the morphometry of cave bear scratches and also their topographical context.

3. Results

The Chauvet Pont d'Arc cave contains 3703 cave bear bones (including 190 skulls = MNI; FOSSE & PHILIPPE, 2005), more than 300 beds/nests and numerous scratched walls (Figures 2-4). This major site for Paleolithic rock art is also an excellent observatory for the study of cave bear behavior. Modern or Pleistocene carnivores using caves are fossorial animals (mustelids) or species occupying the galleries as dens (canids, felids, hyenids, ursids). Their biological marks on floors result from digging (burrows, nests) and displacement (footprints) and from rubbing along walls (displacement into the darkness) and from wall marking activities (scratches as behavioural or "technical" marks). Available measurements on extant carnivores suggest a correlation between their body length, shoulder height and weight (Table 1) and, consequently, provide indications for specific identification of bioglyphs visible in cavities (i.e., height of wall rubbing, height of wall marking); markings (tree trunks) by extant ursids (brown bear, *Ursus arctos;* american black bear, *Ursus americanus*) standing upright on their rear legs correspond to x~1.5 of their body length. In Chauvet Pont d'Arc cave, a very clear dichotomy of wall surface state appears between the floor up to 120-130 cm height with the upper parts including both Paleolithic paintings and cave bear scratches (Figure 2).

	body length (cm)		weight (kg)		shoulder height (cm)	
	F	M	F	M	F	M
M. marmota	47-60		2-4	3-8		
H. cristata			2-4		20-25	
M. martes	40-45	48-53	0,48-0,85	0,67-1,05	15	
G. gulo	62-67		9-30		40-45	
M. meles			8-11	8-13	30	
A. lagopus	50-65	55-75	4-6		30	
V. vulpes	58-80		3,5-8	5,5-10	35-40	
C. alpinus			10-13	15-20		
C. lupus	87-117	100-130	18-62	20-80	65-80	
L. lynx	80-130		18-25		60-75	
P. pardus	110-140	130-190	35-50	45-85	45-60	50-70
P. leo	158-192	172-250	120-180	180-240	107	123
C. crocuta	95-150		40-85		70-92	
U. arctos			60-200	100-680	90-110	
U. maritimus	170-250	190-290	150-500	300-800	120-150	
U. spelaeus			180-230 **(225)** 142-986 **(244)**	354-634 **(418)** 224-1316 **(319)**		

Table 1: Main measurements of extant carnivores (and large rodents). Bodymass estimation for cave bear. F = female; M = male.

The lower part of the walls is cleaned (no clay), and « polished » by the cave bear furs whereas in the upper parts, scratches appear, either isolated or on large surfaces mixed or not with engravings/paintings.

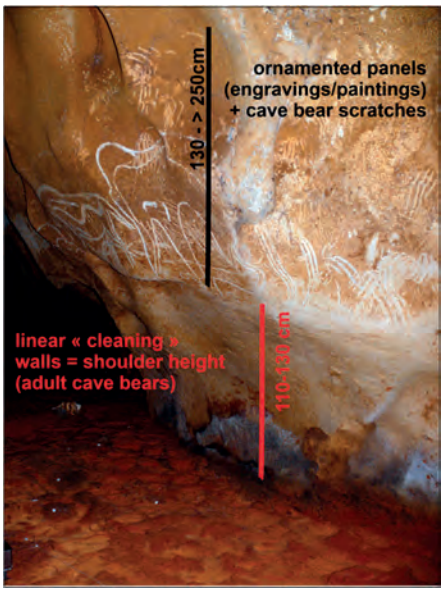

Figure 2: Example of wall modification resulting from human and cave bear activities in the Chauvet Pont d'Arc cave (Cheval gravé, Salle Hillaire). Picture: Ph. Fosse.

Overall, the paintings/engravings or ornamented panels are adjacent to the scratched areas (concentration of human and animal activities on the same walls). The superimposition of human and animal marks is documented in the cave in an exceptional way and frequency and is at the origin of the systematic work on the characterization of cave bear scratches. By considering several variables from the contextual and ichnometric data (Table 2), several observations were made:

1. topographical context	
1.1	distance from the entrance
1.2.1	scratches n°(1-x)
1.2.2	scratched zone (Length x width)
1.3	height from the floor (min/max)
1.4	presence of polished walls (Bärenschliffen)
1.5	archaeological (rock art) context and position (under/over paintings)
2. scratches	
2.1	number of digits (1-5)
2.2	morphology of digits (parallel, oblique, horizontal ...)
2.3	upper extremity of digit : with/without circular depression (claw)
2.4	length max
2.5	width max
2.6	width inter-scratches
2.7	width digit (1-5)
2.8	morphology and section of digit (deep, flat, sharpen)

Table 2: Variables retained in the study of cave bear scratches in Chauvet Pont d'Arc cave.

1) although a few scratches were found near the paleolithic entrance area (~30 m) lit by daylight, the first isolated and small scratches (< 10 cm wide) appear beyond 60 meters (galerie du Cactus, end of the Salle des Bauges); then, scratches areas become much more common and are very abundant up to the deepest galleries (galerie des Croisillons, Le Belvédère, La Sacristie), more than 150/200 meters from the Paleolithic entrance;
2) The scratches generally consist of 4 or frequently 5 sub-parallel digits (distinction with scratches led by digitigrad carnivores), oblique and vertical on flat walls, sinuous on the reliefs, in response to the force produced by the front legs scratching the limestone (Figure 3).

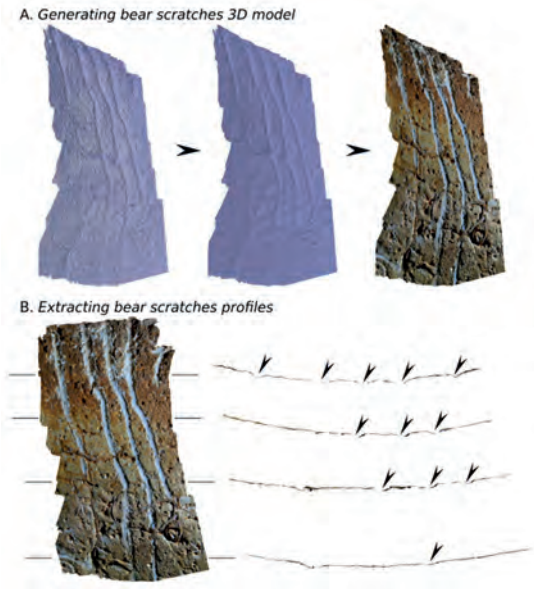

Figure 3: Example of photogrammetry and cross-section of cave bear wall marking scratches from Chauvet Pont d'Arc cave. Pictures : Ph. Fosse & J.B. Fourvel.

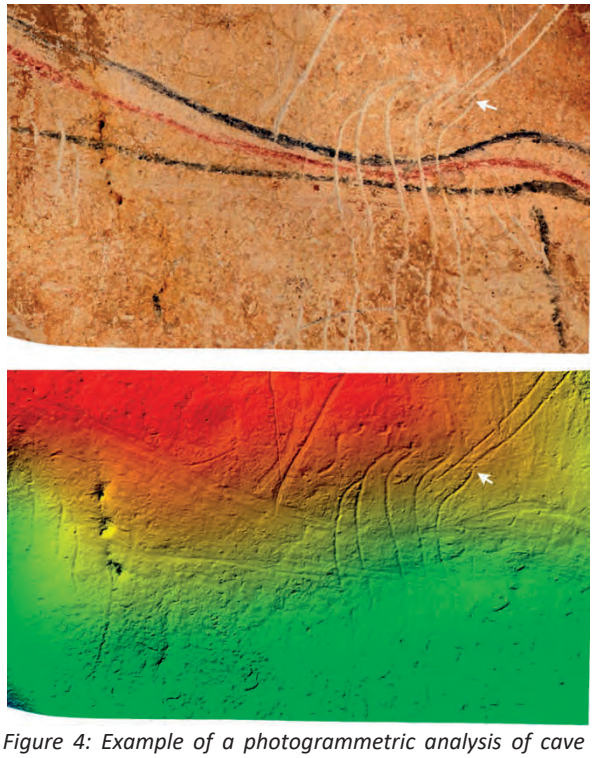

Figure 4: Example of a photogrammetric analysis of cave bear scratches covering a cave lion dorsal painted line from Chauvet Pont d'Arc cave (Salle du Fond). Pictures & scans : F. Baleux, C. Fritz, A.Laurent, T. Sagory, G. Tosello.

These traces, more dynamic (zigzagging), produce wall marking modifications that are comparatively wider than scratches made on vertical walls. The measurements recorded in several galleries (Salle Hillaire, Galerie des Croisillons, Le Belvédère) show two main scratch size

classes: one grouping scratches of small size (width = 7-10 cm for 5 digits) positioned between 140 and 170 cm from the floor: the other much wider scratches (12-15 cm width) found at these same heights (1.70 m) and up to 2.50 meters from the floor. These two categories are sometimes associated on the same flat walls or scratched panels, but often dissociated (gallery entrances, deep and narrow walls in the niches, low vaults for the former, large regular surfaces on high flat walls for the latter) correspond on the one hand to cave bear cubs and on the other hand to adult females. This sexing is based on the general growing pattern noticed on modern brown bears (BLANCHARD, 1987); very rare isolated scratches (Salle Hillaire, Salle du Crâne, Salle du Fond) have been identified at a height of nearly/over 4 metres on the highest walls and attest to the presence of males;

3) The 3D scans suggest that scratches have a shallow U-section (see Figure 3);

4) the photogrammetric analysis of scratches appears to be a useful tool to precise the chronology of wall marking traces, both by Humans and cave bear and reveal unique examples of mixed decorated panels resulting from wall sub-diachronic modification by Aurignacians and cave bear (see Figure 4).

4. Conclusions/perspectives

Cave bear scratches are still poorly studied. However, many decorated caves contain paintings/engravings and these bioglyphs (Aldène, Altamira, Bara Bahau, Baume Latrone, Chauvet, Coliboaia, Cougnac, Cussac, Ekain, Escabasses, Font de Gaume, Gargas, Isturitz, Letzetxiki, Le Portel, Marsoulas, Massat, Pech Merle, Rouffignac, Les Trois Frères, Tuc d'Audoubert...). Studying cave bear scratches is important from a chronological point of view (succession of ursid occupations, alternation Humans/cave bear wall marking), paleobiological (ethological significance of such and specific intense wall marking) and taphonomic (identification/evolution of biotic and abiotic traces on walls). Digitized cave bear scratches from Chauvet Pont d'Arc cave will allow to propose an ichno-morphometric corpus on these bioglyphs (variability, size and shape, topography) and criteria for distinguishing those ursid wall marking traces from human-origin ones and from other extinct and extant carnivore species as well.

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Nouveau regard sur l'éthologie de l'hyène des cavernes et sa fréquentation de l'endokarst profond. L'exemple de l'Aldène (Hérault)

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Résumé

L'Aldène constitue un très vaste réseau karstique situé dans le Sud de la France. Il s'ouvre au sein des gorges de la Cesse qui incisent le Causse du Minervois sur la frange méridionale de la Montagne Noire. Cette cavité conserve un très riche patrimoine archéologique, du Paléolithique ancien à l'époque moderne et industrielle, dont de nombreux témoignages d'une fréquentation humaine du réseau profond au début du Paléolithique supérieur et au Mésolithique. L'Aldène constitue aussi un extraordinaire gisement paléontologique où la présence de l'hyène des cavernes (*Crocuta crocuta spelaea*) est remarquable. Cette espèce a laissé de nombreux vestiges très bien conservés, et notamment des bioglyphes (empreintes, coprolithes, etc.), dans des secteurs profonds du réseau. Alors que l'hyène des cavernes est souvent considérée comme un taxon trogloxène, fréquentant épisodiquement l'endokarst peu profond pour des raisons de prédation ou de reproduction, les vestiges de l'Aldène, mal documentés ou encore inédits, induisent de nouvelles problématiques sur l'éthologie de ce carnivore, en lien avec une troglophilie probablement plus importante. L'étude ichnologique qui est entreprise ici doit également permettre d'apporter un cadre de connaissances pour l'observation et la conservation des sols dans la pratique de la spéléologie.

Abstract

A new look at the ethology of the cave hyena in deep karst, from the study of cave de l'Aldène (Hérault). Aldène is an important karstic system located in Southern France. This karstic cavity preserves an important an rich archaeological and cultural heritage covering a wide time span from the Early Palaeolithic up to modern times and industrial era. Aldène is also known for its Late Paleolithic-Mesolithic human occupation up to the deepest part of the cavity. This cave is also an important paleontological site, where the presence of the cave hyena (*Crocuta crocuta spelaea*) is remarkable. This species inhabited the cavity providing us numerous remains including bones and bioglyphes (footprints, coprolites, etc.) as well which are located up to the deepest part of the karstic system. While the cave hyena is generally considered as a trogloxene species, using only shallow endokarst as breeding or living lair, the bioglyphes from Aldène highlight new information and questions about the palaeoethology in cave hyena (such as a more important trogophile behavior than expected). Here we present the preliminary analysis of the ichnological records at Aldène. This research should provide clues to recognize and preserve these particular non-osseous remains.

1. Aldène, une grotte qui laisse des traces…

L'Aldène constitue un réseau spéléologique, de presque 10 km de développement, réparti sur quatre niveaux hydrogéologiques. Seuls les deux premiers d'entre eux, qui sont fossiles, contiennent des vestiges paléontologiques. Le premier étage, connu de tout temps, est réputé pour ses vestiges osseux de faune depuis le début du 19ème siècle, principalement par les travaux pionniers de Marcel de Serres.

Malheureusement une exploitation de phosphate détruira entre 1890 et 1950 la quasi-totalité des remplissages et donc des vestiges… Le deuxième étage a été découvert en 1948 par l'abbé Cathala. Cette exploration va révéler, entre autres, des vestiges paléontologiques rares, portant à la fois sur des restes osseux mais surtout et dans une densité unique des bioglyphes de faune sous la forme de bauges, polis, empreintes de pattes et griffades d'ours, mais également et de façon plus rare pour l'ichnologie de l'hyène des cavernes (*Crocuta crocuta spelaea*), de nombreuses traces relativement très éloignées de l'entrée primitive du réseau entre 500 m et 1 000 m et sur plus 1 500 m de développement.

En plus de leur répartition, la nature même de ces vestiges non osseux interroge sur le comportement de l'hyène en milieu karstique profond.

2. Étudier le comportement de l'hyène

Cette analyse se fonde sur l'enregistrement systématique des bioglyphes observés à Aldène. Il s'agit de repérer dans l'espace de la cavité les témoignages du passage de l'hyène. Nous avons qualifié trois types de bioglyphes : les coprolithes, les empreintes et les bauges pour lesquels nous pouvons suspecter une origine non-ursine. Toute la difficulté réside dans l'acquisition des données primaires, notamment pour ce qui concerne les empreintes. L'approche photogrammétrique (modélisation 3D) est le meilleur recours pour acquérir un lot de données tout en travaillant dans une perspective conservatoire de ces vestiges bien particuliers. À cela nous ajoutons l'enregistrement des vestiges paléontologiques attribuables à l'hyène qui apportent nombre d'informations quant à l'éthologie du prédateur. Notre étude s'intéresse au seul secteur de la cavité (le Réseau Secondaire) présentant encore conservés les sols archéo-paléontologiques et les reliefs ichnologiques.

3. Les indices de fréquentations dus à l'hyène

Les indices de fréquentations dus à l'hyène sont répartis tout au long du réseau secondaire, depuis la galerie Paul Ambert jusqu'au Toboggan des Fauves (Fig. 1). Nous dressons ci-après un inventaire de ces éléments, de leurs caractéristiques, avant d'aborder leur apport paléoéthologique.

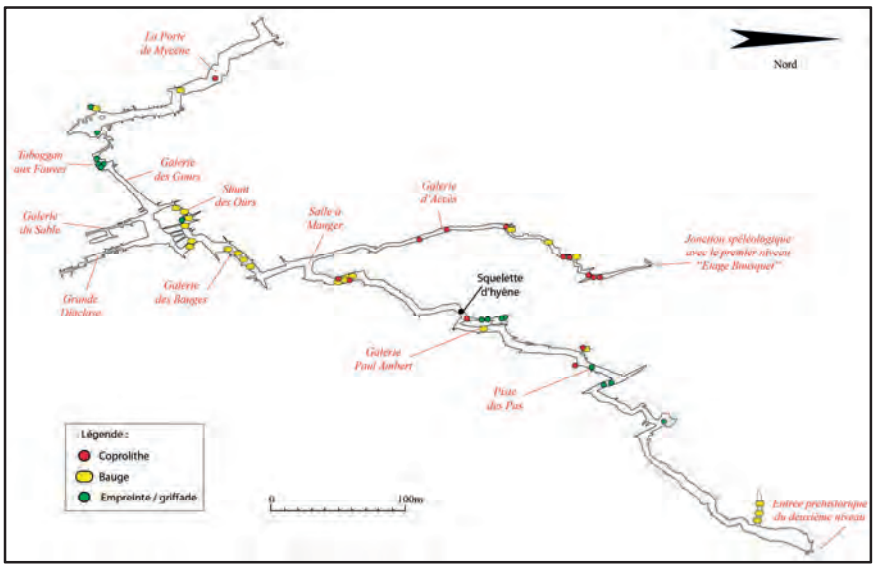

Figure 1 : Localisation des différents bioglyphes et vestiges paléontologiques enregistrés dans le réseau secondaire de l'Aldène.

Paléontologie – Les restes osseux d'hyène sont présents en plusieurs points du réseau, jusque dans les zones les plus éloignées de l'entrée préhistorique. Nos observations attestent de l'absence d'individu juvénile. Au contraire, les restes dentaires qualifient des animaux adultes, voire âgés. Il n'est pas rare de trouver, dans le cas de site d'hivernation, une surreprésentation des adultes et des séniles, généralement morts au cours de l'hivernation (ceci est bien décrit chez l'ours des cavernes). Les spécimens paléontologiques de l'Aldène devront faire l'objet d'un décompte précis afin de déterminer le nombre minimum d'animaux morts au sein même de la cavité.

Coprolithes – L'ostéophagie chez l'hyène se traduit par la production de laissées qui ont la propriété de se préserver au cours du temps. Ces coprolithes signent le passage du prédateur et souvent la circulation d'un animal au comportement paisible, explorant et marquant le milieu au sein duquel il évolue. À l'Aldène, ces indices sont nombreux. On les retrouve tout au long du secteur prospecté. Il s'agit systématiquement d'ensemble de coprolithes comprenant jusqu'à une dizaine de boulettes (Fig. 2). Si la conformation de ces amas est assez semblable à ce que l'on trouve dans le registre moderne, il est tout aussi probable qu'une partie de ces accumulations puissent être des restitutions artificielles postérieures à la découverte de la cavité. Une étude plus fine devra préciser ce point.

Figure 2. Coprolithes d'hyène de l'Aldène.

Bauges – Les bauges, bioglyphes récurrents dans les cavités fréquentées par les ours, se caractérisent par leur morphologie sub-circulaire et leur diamètre variant de 0,6 à 3,4 m pour l'ours brun (*Ursus arctos*) et de 0,7 à 1,9 m. pour l'ours des cavernes (*Ursus spelaeus*), leur profondeur n'excédant pas les 0,6 m. (minimum estimé à 0,2 m) (FOSSE *et al.*, 2004). À l'Aldène, nous retrouvons toute une série de bauges de très petites tailles (dépassant rarement les 0,5 cm de diamètre), se distinguant d'une bauge de très grande taille dépassant 1,8 m. de diamètre. Outre la taille, la forme de ces petites bauges est globalement ovalaire ce qui les distinguent des grandes bauges produites par les ours qui sont généralement sub-circulaires (Fig. 3). Certaines de ces bauges ovalaires sont même associées des griffades distinctes de celles produites par les ours. Si nous émettons ici l'hypothèse d'une origine autre que l'ours, une étude morphométrique de l'ensemble des bauges et des griffades devra être entreprise pour affiner cette idée.

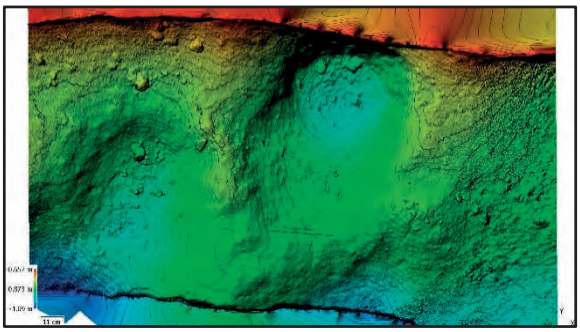

Figure 3 : Carte de profondeurs de deux bauges de l'Aldène.

Empreintes – Les empreintes constituent le meilleur indice d'un comportement troglophile. La première empreinte d'hyène clairement identifiée provient de la piste des pas humains à 300 m de l'entrée préhistorique. Cependant les empreintes les plus importantes, tant par leur qualité de préservation que leur abondance, proviennent du Toboggan des Fauves à près d'un kilomètre de l'entrée préhistorique. Les premiers relevés photogrammétriques soulignent la richesse de ce secteur et offrent la possibilité de décrire ces empreintes sous un jour nouveau (Fig. 4). Elles se distinguent bien des canidés, entre autres par la dissymétrie de la pelote palmaire, et des félidés, par la présence systématique des griffes. On dénombre plusieurs centaines d'empreintes (partielles et complètes) faisant du Toboggan des Fauves un cas tout à fait unique. Ne s'agissant ici que d'une présentation préliminaire, il conviendra par la suite de produire une étude plus fine visant à identifier des pistes individuelles et préciser les modalités comportementales qui ont eu lieu dans ce secteur.

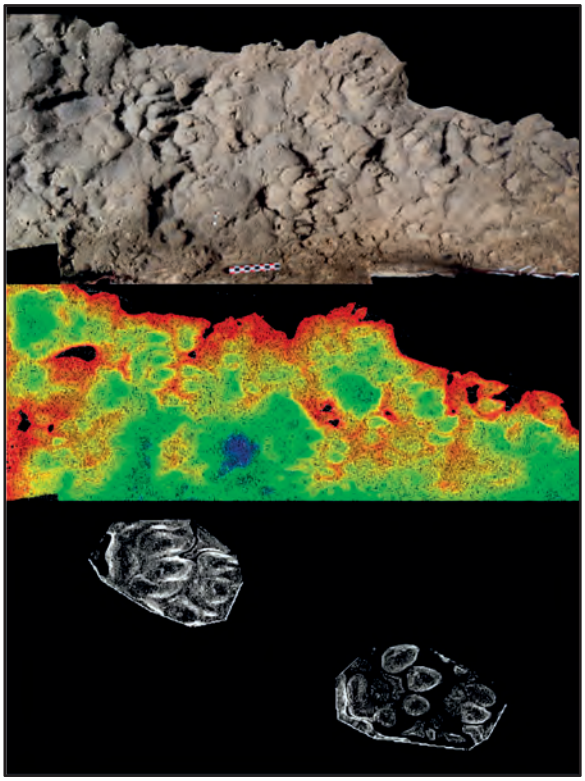

Figure 4 : Modélisation photogrammétrique d'un secteur du Toboggan des Fauves et extraction des cartes de profondeurs et contours.

4. L'hyène, un occupant des milieux profonds ?

Les différents éléments mis au jour à Aldène permettent d'aborder le comportement de l'hyène sous un nouvel angle. Et si finalement le comportement de l'hyène ne se résumait pas simplement à une ostéophagie prononcée et une occupation du milieu souterrain peu profond en vue de l'élevage des hyénons ? Ces aspects (traces de dents et restes de juvéniles) sont les arguments généralement avancés pour décrire une tanière fossile (FOSSE 1994 ; FOURVEL 2012). Le cas de l'Aldène en diffère par plusieurs points. Aucun juvénile n'est attesté tant d'un point de vue ostéologique qu'ichnologique. En outre, si quelques traces de dents affectent les restes d'ours (en particulier), nous n'atteignons jamais l'intensité observée dans les sites à hyènes typiques (FOURVEL 2012). L'Aldène se distingue de ce modèle par la situation des bioglyphes (les empreintes en particulier) attestant du passage de l'hyène dans les secteurs les plus profonds de la cavité (Toboggan des Fauves). Les bauges adoptent des proportions et une morphologie qui semblent se distinguer de ce que l'on connaît chez l'ours des cavernes (FOSSE *et al.* 2004). Les éléments en présence semblent traduire une troglophilie prononcée de l'hyène, avec une apparente aisance dans le karst profond. De fait, pouvons-nous envisager un comportement d'hivernation chez l'hyène des cavernes ?
Considérons brièvement quelques exemples d'explorations profondes chez l'hyène des cavernes. À Chauvet (Ardèche), si aucune empreinte n'a été identifiée, un crâne d'hyène a été reconnu dans le secteur du Belvédère à près de 200 m de l'entrée (PHILIPPE & FOSSE 2003). Dans le réseau Salomé, réseau secondaire dépendant de la grotte du Déroc (Ardèche), une occupation mêlant ours et hyène atteste de l'occupation du milieu souterrain à une centaine de mètres de l'entrée (FOURVEL *et al.* 2017). Il s'agit ici d'un exemple de site à ours où l'hyène passe secondairement charogner

les individus morts naturellement. Dans la même situation, mentionnons enfin le cas du réseau Ursus (Ardèche), dépendant du trou du Renard, où, à plus de 60 m de l'entrée, dans une galerie basse et difficile d'accès nous retrouvons des restes d'hyènes une fois encore associés à une importante population d'ours (FOURVEL & LATEUR 2018). Ces quelques exemples montrent toute la complexité du comportement du carnivore et sa capacité à explorer les milieux profonds. À l'inverse, la majorité des tanières fossiles correspond finalement à des cavités peu profondes (généralement moins de 50 m de développement (FOSSE 1994 et 1997 ; FOURVEL 2012). Dans le registre moderne, les hyènes tachetées et brunes n'occupent pas de tanière profonde. Il s'agit pour l'essentiel de petits terriers ou cavités de faibles dimensions excédant rarement les 10 à 15 m. de profondeur (KRUUK 1972 ; SKINNER 1976). Seule l'hyène rayée, dans certains secteurs du Moyen-Orient, est capable de produire des accumulations osseuses à plusieurs centaines de mètres de l'entrée (KEMPE *et al.* 2006). Il s'agit ici essentiellement de l'incidence de la position écologique du prédateur. Si l'hyène tachetée est dans les rangs les plus hauts de la chaîne trophique, il ne lui est pas nécessaire n'y d'occuper des réseaux profonds ni d'accumuler quantité d'ossements. L'hyène rayée, en tant que charognard strict, réagit à l'inverse afin de répondre à la pression de compétition avec les autres grands prédateurs.

5. Conclusions

L'Aldène, par ses vestiges ichnologiques particulièrement bien conservés, ouvre de nouveaux champs de recherches quant à l'éthologie d'espèces éteintes comme l'hyène des cavernes, prédateurs pour lesquels nous considérions jusqu'alors avoir une vision fine de la variabilité comportementale. L'Aldène est l'exemple le plus éloquent posant la question de l'occupation du milieu profond et de la possible hivernation de l'hyène lors des phases froides du Pléistocène supérieur.
D'autres exemples (Chauvet, réseau Ursus, réseau Salomé) suggèrent une occupation des cavités en sympatrie avec les populations ursines. Nous pouvons distinguer ce comportement de l'occupation de tanières (dans des cavités moins profondes ou réduites aux secteurs d'entrée) caractérisée par des traits paléobiologiques et taphonomiques propres. À l'heure actuelle, aucun modèle moderne ne semble applicable à ce comportement chez l'espèce fossile (ce faisant, l'actualisme montre ici l'une de ces limites).

Le cas de l'Aldène, outre les questionnements inhérents à la conservation de ces vestiges non-osseux, ouvre la voie à la recherche de ces nouveaux indices comportementaux, probablement sans égal dans le registre moderne. La caractérisation de ces indices de fréquentation (empreintes, coprolithes), à la lumière des contextes topographique et archéo-paléontologique, doit faire l'objet d'un soin particulier au sens où ceux-ci, bien que rares, constituent vraisemblablement les meilleurs éléments pour décrire le plus finement possible le comportement de l'espèce.

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Symposium 08 - special session

Natural Traps

Natural Traps

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English

The mission of this session is to review our knowledge of natural traps that provide abundant faunal remains from the accidental entrapment of the surrounding fauna, mostly represented by whole vertebrate skeletons, and that are subject to methodical paleontological excavations. The trapped faunal assemblages they reveal complement the information obtained from the analysis of faunas hunted by man, which are represented in archaeological sites by incomplete, highly fragmented bone elements and by species selected for their food and sometimes cultural interest. These natural accumulations are often exceptionally well preserved and constitute a privileged tool for understanding the evolutionary processes affecting species under the influence of environmental factors. These are important references not only for paleontology but also for taphonomy. In the latter case, the analysis of bone surfaces and fractures offers the possibility of establishing, for comparative purposes, the characteristics of abiotic and post-depositional phenomena with the impacts of anthropic actions. These caves are also a window on the formation of the endokarst, the dynamics of the fillings, the post-depositional processes, the influence of the karst morphologies for the host avifauna of the epikarst, which can also be responsible for the presence of microfauna from the regurgitation pellets (raptors), as well as the diversification of the faunal spectra.

Français

Cette session a pour mission de faire le point sur nos connaissances des avens-pièges naturels qui fournissent d'abondants restes fauniques provenant du piégeage accidentel de la faune environnante, majoritairement représentée par des squelettes entiers de vertébrés, et qui font l'objet de fouilles paléontologiques méthodiques. Les assemblages fauniques piégés qu'ils révèlent complémentent les informations obtenues à partir de l'analyse des faunes chassées par l'homme qui sont figurées dans les sites archéologiques par des éléments osseux incomplets, très fragmentés et par des espèces sélectionnées pour leur intérêt alimentaire et parfois culturel. D'une conservation le plus souvent exceptionnelle, ces accumulations naturelles constituent un outil privilégié pour la compréhension des processus évolutifs affectant les espèces sous l'influence des facteurs environnementaux. Ce sont des référentiels importants non seulement pour la paléontologie mais aussi pour la taphonomie. Sur ce dernier volet, l'analyse des surfaces osseuses et des fracturations offre la possibilité d'établir à des fins comparatives les caractéristiques relevant des phénomènes abiotiques et post-dépositionnels avec les impacts relevant des actions anthropiques. Ces avens sont aussi une fenêtre ouverte sur la formation de l'endokarst, la dynamique des remplissages, les processus post-dépositionnels, l'influence des morphologies karstiques pour l'avifaune hôte de l'épikarst pouvant par ailleurs être responsable de la présence de la microfaune issue des pelotes de régurgitation (rapaces), ainsi que la diversification des spectres fauniques.

Horse skeleton (Equus ferus gallicus) from Coulet de Roches (Monieux, Vaucluse, France) dated to 22 190 +/- 90 cal BP, found in state of anatomical connection. Photo : Evelyne Crégut-Bonnoure.

Squelette d'un des chevaux, Equus ferus gallicus, du Coulet des Roches (Monieux, Vaucluse, France) datant de 22 190 +/- 90 cal BP, trouvé en connexion anatomique. Photo : Evelyne Crégut-Bonnoure.

Deux avens-pièges remarquables du Sud-Est de la France : Le Coulet des Roches et l'aven des Planes (Monieux, Vaucluse)

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Résumé

Le Coulet des Roches et l'aven des Planes sont deux avens-pièges vauclusiens. Le premier a fourni des informations inédites sur la faune et le paléoenvironnement de la fin du Pléistocène supérieur et du début de l'Holocène, de 36 060 ± 620 Cal BP à 3 610 ± 40 cal BP. Les dépôts sédimentaires du Dernier Maximum Glaciaire et du Dernier Glaciaire sont majoritaires, livrant une faune froide, jusque-là inconnue en Provence, constituée de squelettes complets de grands et petits mammifères, et d'oiseaux. Un niveau argileux daté de 26 700–26 250 cal BP, résultant d'un lessivage de sédiments absents aujourd'hui à proximité immédiate de l'aven, fournit des fossiles d'invertébrés et de vertébrés marins du Cénozoïque et du Mésozoïque. L'aven des Planes fournit des compléments d'informations sur le Dernier Glaciaire. C'est à ce jour le seul site de Provence à avoir livré les squelettes complets de deux rennes.

Abstract

Two remarkable natural traps in South-East France: Le Coulet des Roches and l'aven des Planes (Monieux, Vaucluse). Coulet des Roches and Aven des Planes are two Vauclusian pitfalls. The first provided new information on the fauna and the palaeoenvironment dating from the end of the Late Pleistocene and the beginning of the Holocene, from 36,060 ± 620 Cal BP à 3,610 ± 40 ± 40 Cal BP. The sedimentary deposits from the Last Maximum Glacial and the Last Glacial are the most dominant, providing a cold fauna, not yet discovered in Provence, consisting of complete skeletons of large and small mammals, and birds. A clay layer dated to 26,700–26,250 cal BP, resulting of an intense groundwater leaching of residual geological soils absent today in the immediate vicinity of the aven, provided invertebrate and marine vertebrate fossils from Cenozoic and Mesozoic. Aven des Planes provides additional information on the Last Glacial. It delivered the skeleton of two reindeer, the only ones known in Provence.

Introduction

Dans les années 1960 et 1970, deux clubs du Comité Départemental de Spéléologie de Vaucluse (CDS 84), le Groupe spéléologiques de Carpentras (GSC) et la Société spéléologique d'Avignon (SSA) ont sillonné les hauts plateaux vauclusiens à la recherche d'avens inviolés et de la Sorgues souterraine. Leurs travaux de désobstruction ont révélé plusieurs gisements paléontologiques dans la partie sud du Ventoux. Deux ont fourni une riche faune du Pléniglaciaire et du Tardiglaciaire, totalement inédite pour la région provençale : le Coulet des Roches et l'aven des Planes.

Le Coulet des Roches

L'aven est situé dans la partie nord-ouest des Monts de Vaucluse, en bordure ouest du plateau d'Albion. L'orifice d'entrée est un ellipsoïde d'environ 4 m de long par 2 m de large donnant accès à un puits vertical qui s'élargit très rapidement jusqu'à la cote actuelle de -14 m à l'aplomb de l'ouverture. Il donne accès à une grande salle d'environ 10 m de long sur 3 à 4 m de large (Fig. 1). Dans l'angle sud-ouest se trouve une diaclase, élargie par les spéléologues, dont le point bas est à -16,50 m. Les sédiments conservés occupent une surface évaluée à 25 m^2.

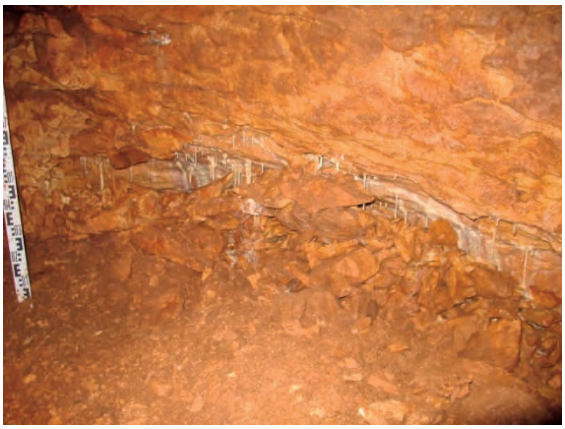

Figure 1 : Vue générale du Coulet des Roches (à gauche). Cliché Ch. Bérard (GSC ; 2016) et concrétionnement sur la paroi ouest (à droite). Cliché É. Crégut-Bonnoure.

Figure 2 : Vue éloignée de deux des chevaux du Coulet. Clichés É. Crégut-Bonnoure

Les parois portent la trace de plusieurs épisodes de concrétionnement datées par Uranium/Thorium (Pléistocène moyen, Greenlandien, phase Atlantique et âge du Fer ; sept datations) (Fig. 1). Cinq unités stratigraphiques (US) ont été reconnues et la faune a été datée par radiocarbone (31 datations) (CRÉGUT-BONNOURE et *al*. 2014, 2018). Les travaux de désobstruction ont détruit en presque totalité l'US1 et l'US2 et ont entamé l'US3.

Un total de 47 759 vestiges a été identifié et répertorié en 13 années de fouilles (de 2007 à 2019). Toutefois, le nombre d'objets est supérieur à ce chiffre car de nombreux « lots » d'esquilles et de petits os ont été dotés d'un numéro de référence global et le nombre de spécimen n'est pas précisé. La concentration des squelettes dans l'angle sud-est du site est en relation avec la présence d'un névé de fond d'aven.

La composition faunique varie au sein du remplissage. Grâce aux déblais, nous disposons d'informations sur les parties détruites par les travaux de désobstruction (CRÉGUT-BONNOURE et *al*. 2014). La faune se compose de restes de grands mammifères, de micromammifères et de quelques restes de chauves-souris contemporains de l'Holocène. Il faut ajouter 5 964 ossements de reptiles et d'amphibiens. Les oiseaux ont fourni 885 restes identifiant 23 espèces (rapaces diurnes et nocturnes, corvidés, passereaux).

L'US2 a fourni des éléments d'une faune tempérée attribuable à l'Holocène. Dans cette unité l'analyse des charbons de bois et des pollens dévoile un paysage de forêt ouverte avec pin (*Pinus*), alisier (*Sorbus)*, orme (*Ulmus*), tilleul (*Tilia*), frêne (*Fraxinus*), genévrier (*Juniperus*), noisetier (*Corylus*).

Les analyses polliniques des US du Tardiglaciaire et du Pléniglaciaire montrent la domination des taxons herbacés communément rencontrés en milieu steppique (Caryophyllaceae, Cichorioideae). Le nombre de mammifères et d'oiseaux de ces mêmes ensembles est élevé avec cinq carnivores, cinq herbivores, deux lagomorphes, cinq insectivores, 13 rongeurs, 18 oiseaux (CRÉGUT-BONNOURE et *al*. 2018 ; CRÉGUT-BONNOURE 2019). Les micromammifères sont majoritaires avec 652 individus (nouveau décompte) (22 genres et/ou espèces appartenant aux insectivores et rongeurs) (PELLETIER et *al*. 2020). Viennent ensuite le lièvre variable (*Lepus timidus*), la belette pygmée (*Mustela nivalis minuta*) et l'hermine (*Mustela erminea*), avec respectivement 114, 48 et 20

individus (CRÉGUT-BONNOURE et *al*. 2018 ; PELLETIER et *al*. 2020 ; et nouveaux décomptes / inédit). Chez les grands mammifères, le cheval (*Equus ferus gallicus*) est représenté par 15 individus et le bouquetin alpin (*Capra ibex*) par 14 individus. Les oiseaux ont fourni 7 591 restes.

Certains taxons sont typiques d'un environnement froid et ont une présence exceptionnelle, voire inédite, en Provence. Ils caractérisent les épisodes les plus froids du Dernier Maximum Glaciaire et du Dernier Glaciaire : renne (*Rangifer tarandus* : trois phalanges), renard polaire (*Vulpes lagopus*), belette pygmée, hermine d'Europe centrale, lièvre variable, lemming à collier (*Dicrostonyx torquatus*), campagnol nordique (*Microtus oeconomus*), campagnol des hauteurs (*Lasiopodomys gregalis*), harfang des neiges (105 restes), chocard à bec jaune (*Pyrrhocorax graculus*), crave à bec rouge (*P. pyrrhocorax*). Chez les oiseaux, le chocard à bec jaune est dominant (3 396 restes), ce qui est conforme à l'éthologie de l'espèce qui a l'habitude de nicher dans les anfractuosités naturelles. Quatre des chevaux sont contemporains de l'épisode tempéré humide du GI 3 ainsi qu'un isard (*Rupicapra pyrenaica* ssp.), trois chiroptères thermophiles (Sérotine bicolore, *Vespertilio murinus* ; vespertillon de Bechstein, *Myotis bechsteini* ; grand murin/petit murin *Myotis* ex gr *myotis/blythii*), un serpent (Coronelle, *Coronella* sp.), auxquels s'ajoutent de la musaraigne pygmée (*Sorex minutus*), du mulot sylvestre (*Apodemus sylvaticus*) et des campagnols (des champs, *Microtus arvalis* ; des neiges, *Chionomys nivalis* ; amphibie, *Arvicola amphibius*), et de la caille des blés (*Coturnix coturnix*). Cet épisode tempéré-humide n'avait pas encore été identifié en Provence.

Les squelettes sont pour la majorité en connexion et en parfait état de conservation. Le cheval est l'espèce qui a livré le plus de squelettes entiers (n=12) (Fig. 2) et une jument gravide est présente. Il possède un museau court et large et des extrémités de membres graciles, ce qui est conforme à une adaptation en milieu froid et sec (BOULBES & VAN ASPEREN 2019). L'usure dentaire montre une alimentation riche en graminées. La robustesse de la diaphyse de métapodes est plus accentuée chez les individus contemporains de l'épisode tempéré-humide daté de 26 700–26 250 cal BP.

L'existence d'un isard est inattendue, l'espèce présente à l'est du Rhône depuis le Pléistocène moyen étant le chamois, *R. rupicapra*. Trois hypothèses sont envisagées : soit l'individu du Coulet est un *R. pyrenaica pyrenaica* issu du stock pyrénéen, soit un *R. pyrenaica ornata* venu d'Italie, soit un hybride entre *R. pyrenaica* ssp. et *R. rupicapra*.

La collection de Lagomorphes du Coulet des Roches représente potentiellement l'une des dernières populations pléistocènes de Provence avant l'arrivée du lièvre européen (*Lepus europaeus*). Elle se caractérise par une grande taille (PELLETIER et *al*. 2020). L'accumulation des micromammifères correspond à une coprocœnose de rapace nocturne, le harfang des neiges correspondant au profil recherché. Un autre prédateur (carnivore) est à même d'être également intervenu, comme l'attestent les traces de digestion plus importantes sur le matériel osseux. La présence de communautés micromammaliennes dites « non-analogues » dans le remplissage permet de suggérer qu'au cours de l'OIS 2, deux types de refuges contigus coexistaient dans la région : les zones alpines qui abritaient des espèces liées à un climat rigoureux durant les épisodes interstadiaires (« refuge méridional cryptique »), et les zones de plaine, situées notamment le long du Rhône, qui constituaient un corridor et un abri pour les espèces thermophiles au cours des épisodes glaciaires (refuge méridional). À ce jour, le matériel du Coulet constitue la plus grande accumulation de restes d'oiseaux de la fin du Pléistocène supérieur de la Provence et nous livre des informations inédites sur cette période.

Le niveau argileux daté de 26 700–26 250 cal BP, a fourni des restes d'invertébrés et de vertébrés marins, absents dans la roche encaissante (Urgonien) qui révèlent un apport ultérieur à la formation de la cavité. Leur présence résulte d'un lessivage de sédiments des étages géologiques qui ne sont plus trouvés aujourd'hui à proximité immédiate de l'aven.

L'aven des Planes

L'aven se trouve dans la même zone que le Coulet des Roches. Il se présente sous la forme d'un puits cylindrique, dont l'ouverture est de 2,70 m sur 1 m. La profondeur actuelle est de –14 m. Vers – 10 m de profondeur, le puits s'élargit en deux branches. Il a été désobstrué en 1970 puis sondé en 2005 et 2006. Il est en cours de fouilles depuis 2017.

La partie supérieure du remplissage a livré des sépultures de l'âge du fer et une faune mêlant espèces domestiques et sauvages (carnivores, cervidés, insectivores, rongeurs, oiseaux, reptiles, batraciens) (CRÉGUT-BONNOURE et *al*. 2014 ; CRÉGUT-BONNOURE 2019). C'est vers 11 m de profondeur qu'une faune froide de la fin du Pléistocène a été découverte. Les espèces dominantes sont le lièvre variable (70 individus), le lapin (*Oryctolagus cuniculus* ; 30 individus) et le cheval (10 individus). L'existence de deux squelettes complets de renne est unique pour la Provence. Il faut ajouter le squelette d'un jeune bouquetin alpin. Les rongeurs et les oiseaux sont plus rares qu'au Coulet des Roches du fait de l'étroitesse du puits : marmotte (*Marmota marmota primigenia*), campagnol (des neiges, de Fatio (*M.* (*T.*) *multiplex*), des champs), mulot sylvestre, busard Saint-Martin (*Circus cyaneus*), faucon pèlerin (*Falco peregrinus*), lagopède cf. des Alpes (*Lagopus cf. mutus*), chocard à bec jaune, cassenoix moucheté (*Nucifraga caryocactates*), caille des blés. Les amphibiens sont représentés par le crapaud calamite (*Epidalea calamita*).

Quelques restes incomplets de deux chevaux présentant des traces de l'action de carnivores et celles du *weathering* suggère leur position secondaire au fond de l'aven. Ils pourraient représenter des individus morts à proximité immédiate du site suite à une prédation par des carnivores. Cette faune froide est datée du Dernier Glaciaire (CRÉGUT-BONNOURE 2007). Les niveaux contemporains du Coulet des Roches ayant été partiellement détruits, elle fournit donc des informations complémentaires sur la faune de cette période.

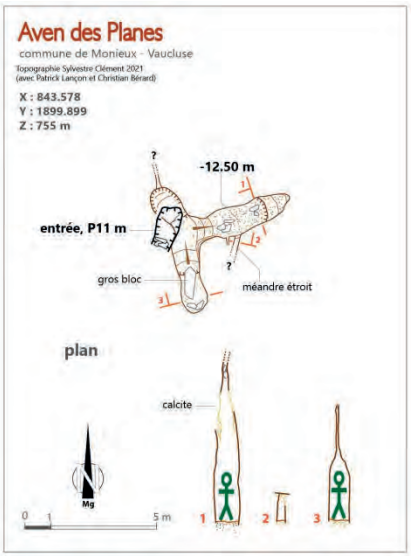

Figure 3 : Colonne de gauche, plan du fond de l'aven des Planes (Topographie S. Clément). Colonne de droite, métatarsiens de renne (haut) et crâne de marmotte (bas) (échelle 1 cm.). Clichés C. Triat.

Conclusion

Le Coulet des Roches et l'aven des Planes sont deux sites paléontologiques majeurs de la fin du Pléistocène supérieur et du début de l'Holocène en Provence. Le large spectre faunique qu'ils offrent est totalement inédit. Grâce à l'état de conservation exceptionnel du matériel, à la présence de squelettes complets et aux nombreuses datations radiométriques, il est possible de cerner l'évolution des biocénoses au cours du temps et d'appréhender les réponses adaptatives des espèces et de leurs associations en fonction des fluctuations climatiques de la fin du Pléistocène.

Les vestiges exhumés constituent aussi un référentiel pour les études taphonomiques et pour les approches en paléogénétique (TEACHER et *al*. 2011 ; RODRIGUEZ VARELA et *al*. 2015 ; UREÑA et *al*. 2017 ; BACA et *al*. 2019).

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A natural trap for *Capra ibex* in Provence (SE France): the Oustau dei Gàrri-grèu hole (Var, France).

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Abstract

The Oustau dei Gàrri-grèu, located near Toulon and recently discovered by cavers, is a new natural trap for Alpine ibex, *Capra ibex*, in Provence. A paleontological survey conducted in 2020 made possible to identify seven individuals within a large scree cone. The original access is unknown, but it should be in ceiling. The chronology of this accumulation is imprecise, but the Late Last Glacial Maximum is excluded.

Résumé

Un piège naturel pour *Capra ibex* en Provence : l'Oustau dei Gàrri-grèu (Var). L'Oustau dei Gàrri-grèu, situé à proximité de Toulon et récemment découvert par les spéléologues, est un nouveau piège naturel provençal pour le bouquetin alpin, *Capra ibex*. Une opération de sondage en 2020 a permis d'identifier sept individus au sein d'un important éboulis. L'accès originel n'est pas connu mais doit se situer en plafond. La chronologie est imprécise mais une contemporanéité avec l'extrême fin du Pléniglaciaire est exclue.

1. Introduction

In the South-East of France, the Siou-Blanc karst is located in the southernmost part of the limestone Provence. In its southern part, a fault separates it from the rocky bar of Tourris that houses the Oustau dei Gàrri-grèu, discovered in 2019 (MAUREL & MAUREL 2019). This karstic system seems to have been formed thanks to a break. Numerous bones belonging to seven alpine ibexes, *Capra ibex*, were discovered in this locality, located near Toulon, within a large scree cone, in distinct loci.

2. The Oustau dei Gàrri-grèu hole

The hole opens 700 m to the east of the Aven de la Ripelle which is an important karstic cavity that could be the ancient outlet of the karst spring of Ragas de Dardennes before it disconnected from the network by a geological accident. An archaeological survey reports some rock shelters in this area (BARGE 1978).

The site begins by a small opening leading to a descending gallery followed by a severe narrowing that gives access to a small concretized chamber and an inter-stratum giving access to a small hole and a gallery (Fig. 1). On the north-west side, there is a chamber of about twenty meters in diameter. Its surface is covered by large scree reaching to the depth of -31 m. A network of galleries is accessible from the top of the scree cone.

On the eastern side a hole of about ten meters in depth allows access to a heavily concretioned room at the depth of -36 m. Screes and speleothems are numerous.

Remains of *Capra ibex* were collected in the first chamber and in a lateral extension (Fig. 1). The original access is unknown, but the morphology of the cave system does not allow the incursion and the trapping of ibexes through it: trapping of the animals in the cave must have occurred by openings in the ceiling, now obstructed.

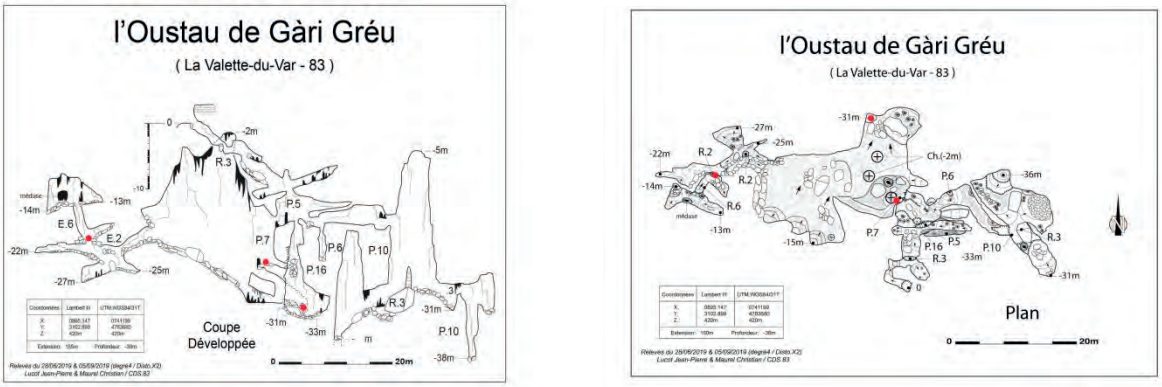

Figure 1: Topographical settings according to Jean-Pierre Lucot and Philippe Maurel. Cross section and plane. Red circle: location of the ibex remains.

3. Distribution of the alpine ibex

C. ibex has been present on the alpine arch and its slopes since the late Middle Pleistocene (MIS 7, MIS 6): Petralona in Greece (*C. ibex macedonica* Sickenberg, 1971), the breccia of the Prince cave in Italy, Camburg in Germany (*C. camburgensis* Toepfer, 1934) and in France at Le Lazaret (Nice; Alpes-Maritimes) and Rigabe (Artigues; Var) (CRÉGUT-BONNOURE 2020).

This ibex is relatively common in the Alps and in the Provence area during the Late Pleistocene, becoming rare during the early Holocene (COUTURIER 1962; CRÉGUT-BONNOURE 2020; CRÉGUT-BONNOURE *et al*. 2018; GRIGGO *et al*. 2012). In the east and south of the Provence, it has been recognized in 20 caves/holes. Remains have been discovered in the Var department at Rainaudes I (Le Muy; MIS 2) and Les Cèdres (Le Plan d'Aups; Holocene). The species is documented in the Alpes-Maritimes department at Baume Périgaud (Tourrette-Levens; MIS 3) and Les Gras (Escragnolles; MIS 2). It is observed in the Bouches-du-Rhône department at Le Tonneau (La Bouilladisse; MIS 5), L'Adaouste (Jouques, upper levels; MIS 2), Baumo Voutado (Saint-Antonin-sur-Bayon; MIS 2), La Montagne (Sénas; MIS 2), and in the Vaucluse department at Grand abri aux Puces and La Masque (Entrechaux; MIS 5e), Les Auzières II (Méthamis; MIS 5e, MIS 4), Valescure/Vallescure (Saumanes; MIS 4), Baume-des-Peyrards (Buoux; MIS 4), Chinchon I (Saumanes; MIS 2), Roquefure (Bonnieux; MIS 2), Unang (Malemort-du-Comtat; MIS 2), Soubeyras (Ménerbes; MIS 2), Aven Christian (Bedoin; MIS 2), Coulet des Roches (Monieux MIS 2), Gramari (Méthamis; Holocene).

3. The alpine ibex from Oustau dei Gàrri-grèu

The skeletons are disarticulated and the majority of the bones are isolated, broken and trapped between the stone blocks of the scree. This material is altered by current water circulation and some of bones are concretioned. The paleontological survey conducted in 2020 allows us to extract some bone and dental remains which could be destroy due to their position on the surface of the scree cone. Seven individuals were identified: three juveniles, two sub-adults males, an adult female and an adult male.

The morphology of the cranium, the horn cores, the third upper molar (M3), the third lower premolar (p3) and the metapodials are the best criteria for identification and for taxonomy in Caprinae, especially to distinguish the Pleistocene Caprini *Hemitragus* and *Capra* that are the two cliff-dwelling species which evolve and coexist in Provence during the Pleistocene times (CRÉGUT-BONNOURE 2006, 2020). The main morphological characteristics of the remains from Oustau dei Gàrri-grèu permit to identify the ibex.

The third upper molars are efficient elements to discriminate Ibex's species and sub-species (CRÉGUT-BONNOURE 2006, 2020). In the alpine ibex lineage the interstylar surfaces are asymmetrical especially at the base, the posterior being the longest, and the metastylar wing is well developed at the base of the crown. One of the two M3 from Oustau dei Gàrri-grèu belongs to an old individual and its interstylar surfaces are slightly asymmetrical (mésial length: 6.7 mm; distal length: 7.7 mm). The second one belongs to the sud-adult male whose cranium is unfortunately fragmented and whose skeleton is concretioned (Fig. 2d). This M3 is still included in the left maxillary fragment but the lingual side is visible (Fig. 3a). The metastylar wing is well developed at its base. The interstylar asymmetry is not very important (mésial length: 6.6 mm; distal length: 7.6 mm). These two teeth are quite similar. They differ from M3 dating from MIS 2 (Last Glacial Maximum and Last Glacial) which are characterized by significant asymmetry.

There are three p3s. Two of them belongs to the previous old individual and are present on the two mandibles that were crushed on each other during fossilization (Fig. 2a). Due to their heavy wear stage, we could not appreciate their morphology. The p3 belonging to the previous sub-adult is slightly worn (Fig. 3b). The metaconid dilates from the top

to the base of the crown but does not constitute a column at its top. The dilation of the metaconid is observed in Provence from MIS 3 to MIS 2 (CRÉGUT-BONNOURE 1992 and 2020; CRÉGUT-BONNOURE *et al*. 2014 and 2018). It is restricted to the top of the crown, constituting a small column (Fig. 3e, f). The dilation of the p3 from Oustau dei Gàrri-grèu is distinct. Some similarities exist with a female specimen from Coulet des Roches dating from 22,250-21,870 Cal BP (MIS 2) (CRÉGUT-BONNOURE *et al.* 2014, 2018) (Fig. 3d). There are too similarities with the ibexes from Valescure/Vallescure cave dating from MIS 4 (Fig. 3c).

Figure 2: Capra ibex remains in situ. Photos H. Tainton (b, c), E. Crégut-Bonnoure (a, d).

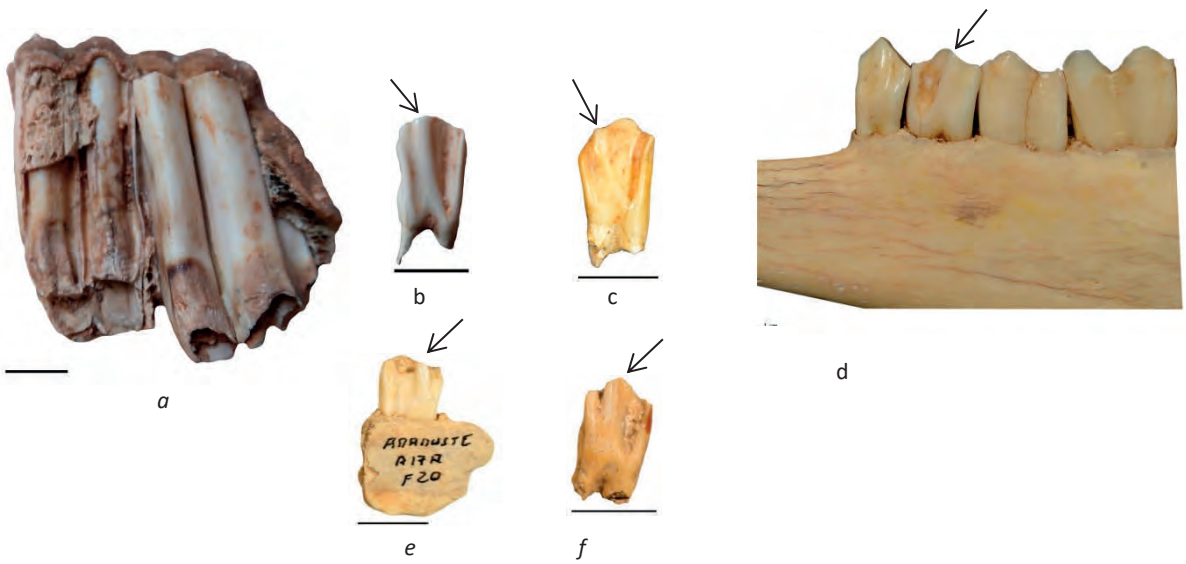

Figure 3: Capra ibex. M2, M3 (a) and p3 (b) from Oustau dei Gàrri-grèu (sub-adult male). c: p3 from Valescure/Vallescure, p3 (MIS 4). d: Coulet des Roches, mandible of the female dating from 22,250-21,870 Cal BP (MIS 2). e: p3 from Adaouste (MIS 2). f: p3 from Roquefure (MIS 2). Arrow: metaconid. Lingual views. Scale: 1 cm. Photos E. Crégut-Bonnoure (a, b), C. Triat (c, d).

5. Conclusion

The Oustau dei Gàrri-grèu brings new data on the geographical distribution of the Alpine ibex in Provence area. The contemporaneity of the seven individuals is not proven, the fall in this trap cave having been staggered over time. The teeth morphology permits to exclude the late Last Glacial Maximum. Despite analogies with MIS 4 populations, the limited number of M3 and p3 cannot produce robust data. Radiocarbon dating is now required to specify the chronology of this accumulation as well as geomorphological analysis to specify the origin of the trapping.

Acknowledgments

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A new natural trap for Ursus arctos in Provence (SE France): the Zorus hole (Var, France).

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Abstract

The Zorus hole was formed in Jurassic dolomitic limestone. A small opening provides access to a small 6 m deep pit. At the bottom, a small chamber leads to a pitch about 27 m deep. Bones remains identified as brown bear*, Ursus arctos*, belonging to at least five individuals were discovered. One of them is positioned inside a gour, on a lateral projection of the pit. An incomplete cranium associated with some bones is buried in sandy sediment at a depth of - 32m. Close to it, scratches are visible on a clay level on the wall. Another individual is present in a depression. At depths between 37 m and 38 m, two other brown bears are identified. Among the remains, two m1s are present. Their morphology is similar to the populations from the late Middle Pleistocene and of the early Late Pleistocene from South-East France.

Résumé

Un nouveau piège naturel pour Ursus arctos en Provence (SE France) : le trou de Zorus (Var, France). L'aven de Zorus est creusé dans du calcaire jurassique. Une ouverture étroite donne accès à un petit puits de 6 m aboutissant dans une petite salle qui se poursuit par un puits vertical de 27 m. Plusieurs ossements d'*Ursus arctos* ont été découverts qui identifient cinq individus. L'un se trouve dans un gour en bordure du puits principal. Un crâne incomplet et plusieurs ossements sont enfouis dans un sédiment sableux à – 32 m. À proximité des griffades sont conservées sur une paroi argileuse. Un autre individu est présent dans une dépression. Aux profondeurs de – 37 m et – 38 m, deux autres ours bruns sont identifiables. Parmi les restes se trouvent deux m1. Leur morphologie est identique celle des populations de la fin du Pléistocène moyen et du début du Pléistocène supérieur du Sud-Est de la France.

1. Introduction

The southern part of the Provence region (Alpes-de-Haute Provence, Alpes-Maritimes, Bouches-du-Rhône, Var, Vaucluse departments), in the Southeastern of France, is a karstic area riddle with abundant caves and natural pits in which archaeological and paleontological remains dating as far as 1 Ma old are known. The Pleistocene fauna is rich, with a wide variability of species. Among carnivores, ursids are present from Early Pleistocene to Holocene, and four species are identified: Deninger bear (*U. deningeri*), cave bear (*U. spelaeus*), Asiatic black bear (*Ursus thibetanus*) and brown bear (*U. arctos*). Their chronological range is not exactly the same and *U. arctos* is the more abundant. This species has been recorded in the new locality of Zorus.

2. Distribution of the Ursidae in Provence

In the north-western Alps, cave bears and brown bears are common in karstic sites (caves, pits) (42 sites from Ain, Doubs, Isère, Savoie and Haute-Savoie departments; ARGANT *et al.* 2018). Both as well as Deninger and Asiatic black bears are also present in the east and south of this area (51 sites) (Fig. 1).

U. deningeri has been recognised in three caves whose chronological range covers the Early Pleistocene to the late Middle Pleistocene (QUILÈS & CRÉGUT-BONNOURE 2006): Le Vallonnet (Roquebrune-Cap-Martin, Alpes-Maritimes; MIS 23, L'Escale (Saint-Estève-Janson, Bouches-du-Rhône; MIS 12), Les Cèdres (Le Plan d'Aups, Var; MIS 6). *U. spelaeus*, identified in seven localities, appears in the late Middle Pleistocene and disappears in the Late Pleistocene (QUILÈS & CRÉGUT-BONNOURE 2006; SLIMAK *et al.* 2010). This species is documented in the Alpes-Maritimes department at Lazaret Cave (Nice; MIS 6;$), Baume Obscure (Tourrettes-sur-Loup; MIS 5 ?), Pié Lombard (Tourettes-sur-Loup ; MIS 4), Albaréa cave (Sospel; MIS 4), Merle cave (Tourrette-Levens ; MIS 4). In Vaucluse department it is reported from the Grand Abri aux Puces (Entrechaux; MIS 5e) and Valescure/Vallescure (Saumanes; MIS 4).

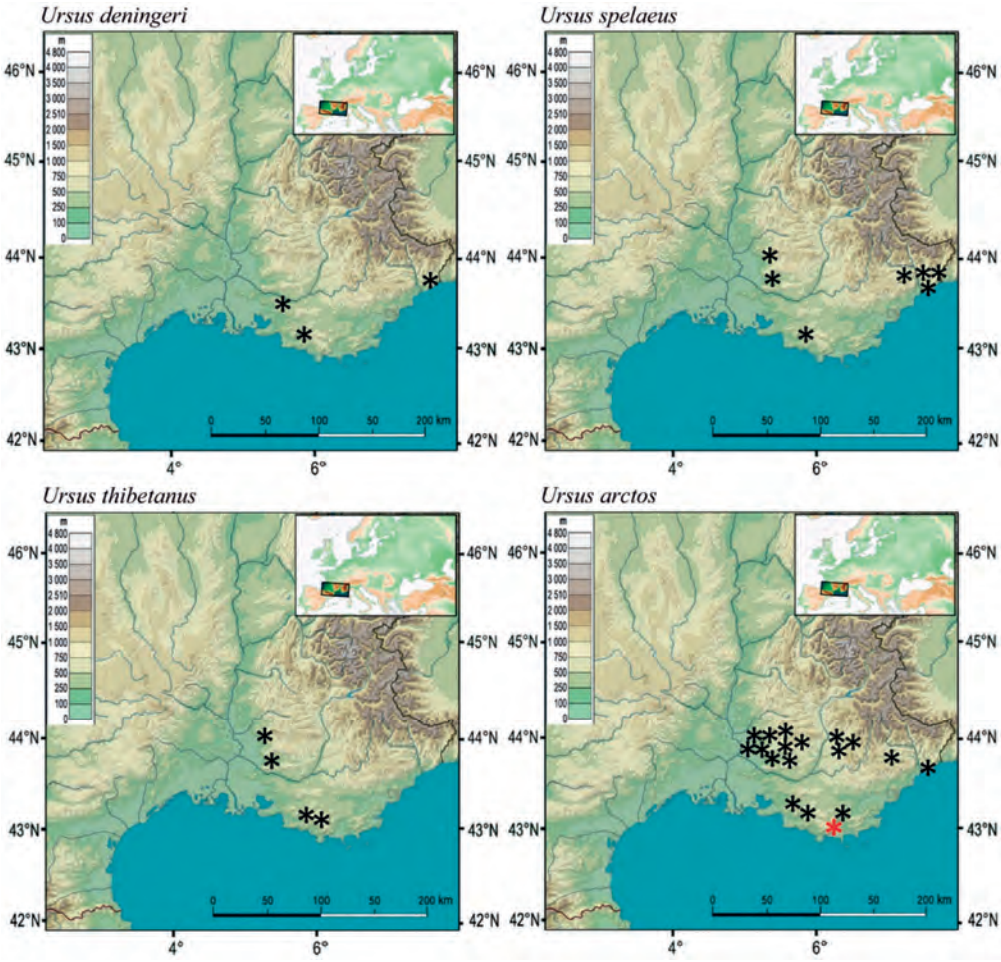

Figure 1: Geographical distribution of Ursids in southern part of Provence. Red star: Zorus hole. Graphic design E. Desclaux.

U. thibetanus is scarce and occurs only in four sites dated from the late Middle Pleistocene and the early Late Pleistocene (QUILÈS & CRÉGUT-BONNOURE 2006; CRÉGUT-BONNOURE 2015): in the Var at Cimay (Saint-Anne-d'Evenos; MIS 7) and Les Cèdres (MIS 6), in Vaucluse at Bérigoule n° 5 (Murs; MIS 6) and Grand Abri aux Puces (MIS 5e).

U. arctos is recognized in 37 localities from the late Middle Pleistocene to the Holocene (QUILÈS & CRÉGUT-BONNOURE 2006; CRÉGUT-BONNOURE *et al.* 2011; CRÉGUT-BONNOURE 2008, 2020; FOURVEL & FREREBEAU 2019). In the Alpes-de-Haute-Provence department it is observed at Murée Cave (Montpezat; Holocene), Aven de Vauclare (Esparron-de-Verdon; Holocene), La Fare (Holocene). In the Alpes-Maritimes department the brown bear is documented at Lazaret (MIS 6), Les Gras (Escragnolles; MIS 3) and Baume Périgaud (Tourrette-Levens; MIS 3). In the Bouches-du-Rhône department it is present in Adaouste (Jouques; MIS 5d, lower levels) and in the Var department at Les Cèdres (MIS 6), Grotte aux Puces (Cabasse; MIS 4) and Espiguières (Aups; MIS indet.)). It is abundant in Vaucluse department: Bau de l'Aubesier (Monieux ; MIS 7, MIS 6, MIS 4), Bérigoule n°5 (MIS 6), Grand Abri aux Puces (MIS 5e), La Masque (MIS 5e), Les Auzières (Méthamis ; MIS 5e), Baume des Peyrards (Buoux ; MIS 4), Valescure/Vallescure (MIS 4), Baume Troucade (Murs ; MIS 4 ?), Aven du Contadoux (Sault ;

Holocene), Luberon Sud (MIS indet.), Luberon nord (MIS 5-4), La Clairière (La Roque-sur-Pernes ; MIS 1), Mont Ventoux (Brantes ; Holocene, 13 traps), La Balance (Avignon; Holocene), Réseau du Pas du Loup (MIS indet.; Saint-Léger du Ventoux).

We have to add the vauclusian Bérigoule n° 5 locality with *U. deningeri-spelaeus* group.

Compared with other regions of France, *U. thibetanus* and *U. arctos* are relatively abundant while *U. deningeri* and *U. spelaeus* are poorly represented. It is probably due to the ecology of these species. *U. deningeri* and *U. spelaeus* are present in important karstic galleries located in the north-western Alps and the western side of the Rhône valley. Such galleries are missing in the karts located on the western side of the Provence area where vertical holes are predominant. On the contrary, *U. arctos* and *U. thibetanus* occupy small galleries.

3. Zorus hole

The cavity has been discovered in 2010 by cavers from Speleological Club of Sanary. It is located in the area of Siou-Blanc karst managed by National Office of Forest. It is developed into Jurassic dolomitic limestone along to a N130° oriented fault. The original access is currently sealed with stalagmitic floor. A small opening provides access to a small hole to the current depth of 6 m. At the bottom there is a small 8 m long chamber which averages 2 m in width, leading to vertical pit about 27 m deep (Fig. 2).

Numerous bones belonging to *Ursus arctos* were discovered in four locations. Some of them are covered by stalagmitic deposits. First investigations suggest a complete sedimentary infill drained away before bear frequentation,with at least three morphological changes. One of them could date from the end of the Pleistocene, another one is older and the third one could date from the Holocene.

Five brown bears are identified in the vicinity of the vertical pit. One of them is positioned inside an old gour, on a lateral projection of the pit, at depth of 27 m. It belongs to an old individual. The skeleton is complete but partially covered by stalagmitic deposit. The visible bones are the left mandible, the maxillary, the right humerus associated with the ulna and the radius, the left humerus, the tibia, the innominate bone, and several vertebrae. At a depth of 32 m, an incomplete skull, belonging to a powerful male, associated with some bones is buried in sandy sediment (Fig. 2). The skull is positioned on a femur and, close to it, a broken humerus is visible and scratches can be seen on a clay level on the wall (Fig. 2). Quite at the same place, in a depression, other bones identify another individual. Two other brown bear have been found at a depth of 37 and 38m respectively.

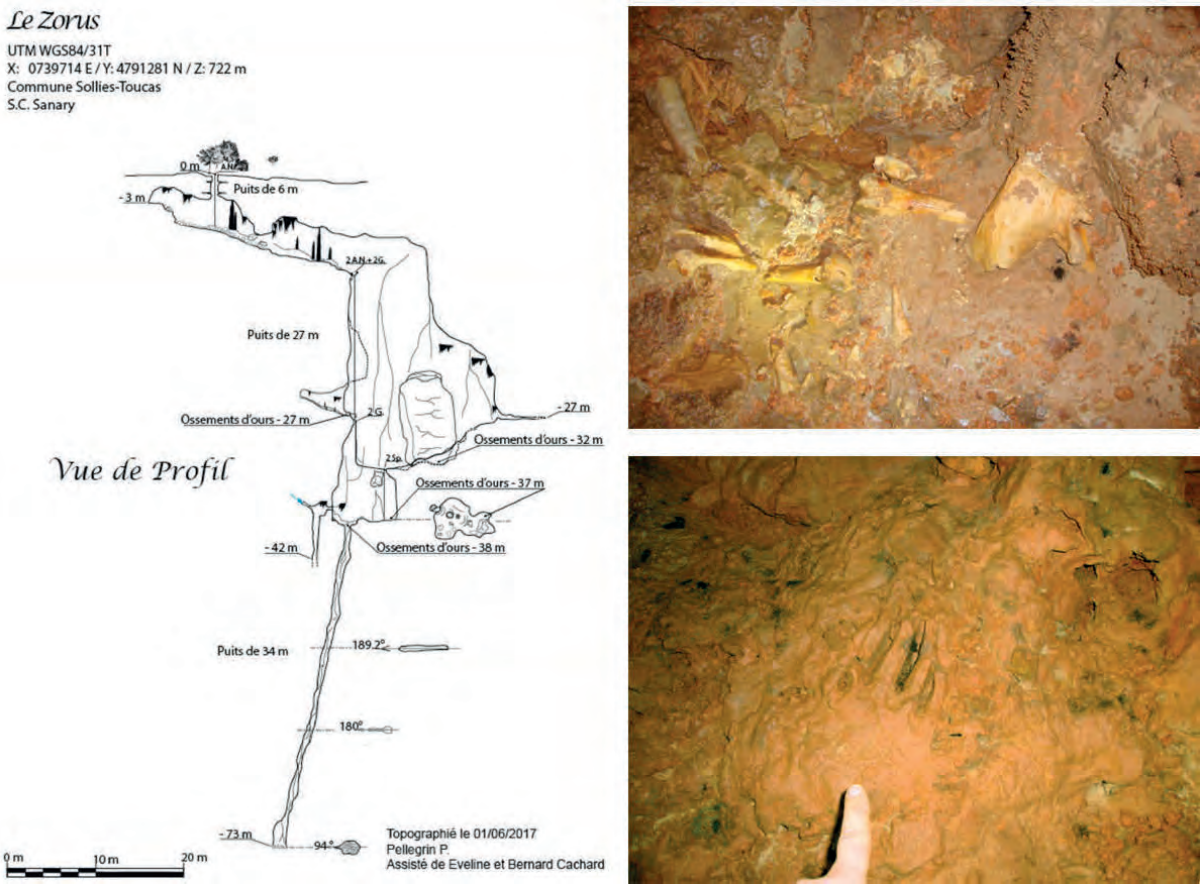

Figure 2: Zorus. Topographical settings according to P. Pellegrin, E. and B. Cachard and general view of the second individual (- 32 m depth) and the scratches. Photo E. Crégut-Bonnoure.

4. Evolutionary stage

The morphology of premolars and molars varies during Pleistocene, and chronological morphotypes are identified (CRÉGUT-BONNOURE *et al.* 2011). The m1 is one of the teeth which enable to evaluate the chronological position of the individuals. Two of them, belonging to two individuals, where collected at – 37 m. The metaconid is preceded by two smaller denticles with a decreasing height and an entoconid with a small denticle on its mesial side (Fig. 3).

This morphology is similar to the *U. arctos* populations dating back to the late Middle Pleistocene (MIS 6/ MIS 7) (Les Cèdres; Bau de l'Aubesier: levels H, I) and to the early Late Pleistocene (MIS 5e) (Grand Abri aux Puces and Masque cave) (CREGUT-BONNOURE *et al.* 2011). The scatter diagram plotting the length and the breath ratio of the trigonid indicates the proximity of these molars with the Grand Abri aux Puces brown bear.

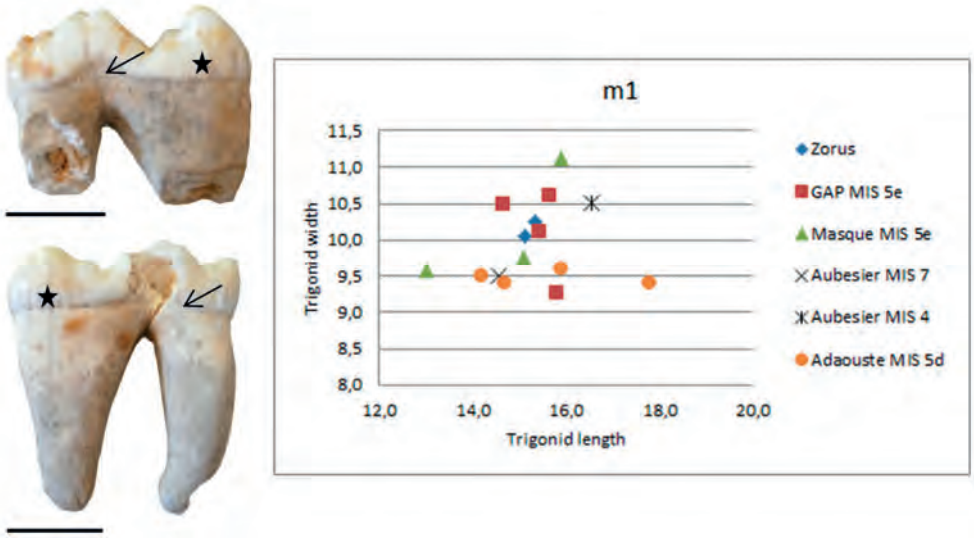

Figure 3: Lower m1, right and left specimens, lingual views (Photo E. Crégut-Bonnoure) and scattered diagram of the length and the width of the trigonid. Arrow: metaconid. Star: entoconid. Abbreviation: GAP: Grand Abri aux Puces.

5. Conclusion

More investigations are needed, especially for dating the sediment infill and the five individuals. The excavation of the site is planned. It is the third reported occurrence of *Ursus arctos* in the Var department. This discovery shows the importance of natural traps regarding research on large mammals rarely hunted by man as is the case for brown bear.

Acknowledgments

We wish to thank Fabrice Mallet, from National Office of Forest, for its authorization to prospect this hole, and Emmanuel Desclaux, from Lazaret laboratory, for the graphic design.

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Les aven-pièges : apport à la connaissance des paléoenvironnements pléistocènes et implications archéologiques. L'exemple du Quercy

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Résumé

La région des causses du Quercy est formée de plateaux calcaires du Jurassique dans lesquels des milliers de cavités ont été recensées. Les gouffres - ou avens - en constituent une particularité forte montrant un potentiel informatif exceptionnel grâce aux faunes d'âge quaternaire qu'ils renferment. Dans les années 2000, le développement de nouveaux outils méthodologiques (datations, taphonomie, écométrie, etc.) a permis de renouveler les études pluridisciplinaires sur ces sites. Plus d'une centaine de cavités ont livré des assemblages fauniques et quelques-unes ont pu être fouillées autorisant la reconstitution des paléocommunautés de vertébrés dans une chronologie bien maîtrisée. Leur étude permet de développer les nombreuses implications sur les paléocommunautés (taxinomique, éco-éthologique, paléobiodiversité), les paléoenvironnements climatiques, mais aussi sur les comportements humains paléolithiques.

Abstract

The pits-falls: contribution to the knowledge of Pleistocene paleoenvironments and archaeological implications. The example of the Quercy region (Southwest of France). The Quercy region is made of Jurassic limestone plateaus in which thousands of cavities have been recorded. Vertical cavities (avens) are important component showing an exceptional informative potential thanks to the Quaternary faunas they contain. In the 2000s, the development of new methodological tools (dating, taphonomy, ecometry, etc.) made it possible to renew multidisciplinary studies on these sites. More than a hundred cavities have yielded faunal assemblages and some have been excavated, allowing the reconstitution of climatic paleoenvironments in a well-controlled chronology. Their study implies numerous implications on vertebrate paleocommunities (taxonomic, eco-ethological, paleobiodiversity as well as for paleolithic human behavior.

1. Introduction

La région des causses du Quercy est formée de plateaux calcaires du Jurassique dans lesquels, sur près de 5 500 km^2, des milliers de cavités ont été recensées. Celles dont l'entrée est horizontale ont souvent été occupées ou fréquentées par les animaux (ex. carnivores) et les hommes, que ce soit pour leurs habitats ou des réalisations pariétales. À côté de ces sites, les cavités dont l'accès est vertical - gouffres, avens, igues - constituent une particularité forte de cette région car elles livrent souvent des faunes piégées d'âge quaternaire (BRUGAL *et al*. 2006). Ces sites ont précocement intéressé les paléontologues (CUVIER 1834) mais leurs études sont restées rares.

Dans les années 1960-70, des travaux paléontologiques sont effectués sur des faunes fossiles de quelques avens contemporains de la fin du Pléistocène sur le causse corrézien (La Fage, Jaurens, Siréjols) et plus au sud, dans le cadre du projet Padirac (e.g., GUÉRIN & PHILIPPE 1971 ; PHILIPPE *et al.* 1980 ; PHILIPPE 1994). C'est dans les années 1990-2000 que plusieurs programmes de recherche ont vu le jour avec notamment la création d'un thème spécifique au sein des services de la sous-direction de l'Archéologie, Dir. du Patrimoine : « *Les accumulations naturelles avec indice de fréquentation humaine* » (BRUGAL & JAUBERT 1991, 1997 ; BRUGAL 2012). Dans ce cadre, les sites quercynois font figure de leaders avec un premier Programme Collectif de Recherche et un regain de fouilles et d'études (COUMONT 2006 ; COUMONT *et al.* 2013).

2. Karsts du Quercy : un fort potentiel

Dans les années 1980, une trentaine d'accumulations naturelles étaient connues des paléontologues. Depuis, nous avons œuvré auprès des différents clubs spéléologiques de la région afin de les sensibiliser à l'importance de ces gisements. Lorsque cela est possible, des visites de sites par des paléontologues sont organisées pour approfondir les diagnostics. Elles permettent d'évaluer l'importance des gisements, leur richesse taxonomique, leur potentielle étendue chronologique (datations) et si besoin d'entreprendre des sondages ou des fouilles. Depuis 2018 une nouvelle phase de nos projets vise à recenser et étudier tous les sites ayant livré des restes fossiles du Pléistocène et de l'Holocène. Désormais plus d'une centaine de sites est référencée pour le département du Lot ce qui porte à environ 130 sites pour l'ensemble du Quercy (Fig. 1).

La chronologie des remplissages fossilifères, en particulier supportée par des jeux de dates carbone 14 et sur des bases biochronologiques (degré d'évolution des espèces) permettent de renseigner les peuplements mammaliens depuis le Pléistocène moyen (soit au moins les derniers 200 000 ans). L'évolution significative des méthodes de datation, avec notamment la généralisation de la méthode AMS, a permis d'établir des séquences qui montrent l'évolution précise de la composition faunique dans un territoire cohérent - le Quercy - au cours de 40 derniers millénaires. L'exemple de l'igue du Gral est en cela illustratif, avec plus de 60 datations réalisées (CASTEL *et al.* 2008, en préparation).

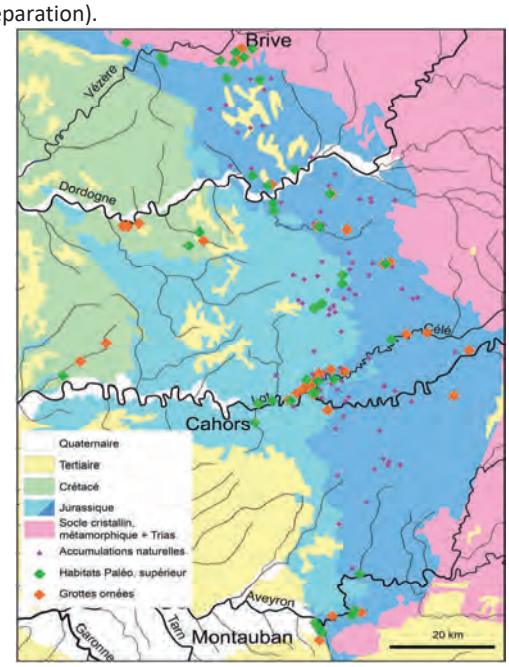

Figure 1 : Distribution spatiale des accumulations naturelles (toutes périodes confondues), des habitats du Paléolithique supérieur et des grottes ornées du Quercy.

2.1. Apports paléontologique, taphonomique, paléoécologique et paléoenvironnemental

Les cavités en aven constituent des pièges naturels dans lesquels des animaux sont tombés. Il s'agit principalement d'herbivores vivant en troupeaux, mais aussi de léporidés et petits vertébrés. Les carnivores peuvent être également tombés mais lorsque les dénivelés sont faibles ou des entrées latérales existent, leur présence peut résulter de leur attirance pour les ressources que constituent les carcasses des autres vertébrés. Ces avens peuvent livrer un grand nombre d'individus (parfois plusieurs dizaines pour certains ongulés comme le renne, le cheval ou le bison), mais aussi avoir piégé des espèces moins fréquentes (ex. mégacéros, antilope saïga). Les squelettes sont complets mais rarement en connexion, et la plupart du matériel osseux et dentaire est très bien conservé, avec beaucoup d'éléments entiers. Enfin, ces séries ont des structures paléobiologiques (âge, sexe) souvent bien renseignées. Les grottes-repaires de carnivores constituent d'autres sources d'informations complémentaires. Cet ensemble de données constitue un atout majeur dans les études pluridisciplinaires, sur les espèces et les communautés animales (paléobiodiversité) au cours du temps (BRUGAL *et al.* 2013).

De tels corpus sont étudiés paléontologiquement par des analyses morphométriques qui précisent les degrés évolutifs ou adaptatifs des taxons. Ces données, replacées dans le temps, apportent une vision dynamique des changements en relation avec des contextes paléoclimatiques. Des études spécifiques peuvent être conduites : e.g., méso- et micro-usure dentaire pour préciser les régimes alimentaires (UZUNIDIS & BRUGAL 2018), isotopiques pour reconstituer les réseaux trophiques, paléogénétique pour documenter la diversité de ces populations, etc. Couplé au travail mené sur les associations mammaliennes il est possible de caractériser les paramètres éthologiques et écologiques, et *in fine* d'apporter des informations essentielles sur les paléoenvironnements climatiques. Les reconstitutions paléoenvironnementales s'appuient sur la diversité et la fréquence relative des espèces identifiées et leur correspondance avec les milieux et climats actuels.

Les modalités d'accumulations en milieu karstique sont généralement difficiles à interpréter en relation avec la dynamique souterraine, souvent très active. L'examen des dépôts karstiques et de l'état de conservation des vestiges osseux met en évidence des processus sédimentaires souvent complexes et permet de mieux expliciter l'homogénéité des assemblages fauniques (COSTAMAGNO 1999, COUMONT *et al.* 2013). Les carnivores ont pu jouer un rôle plus ou moins important dans l'accumulation, la modification et la distribution spatiale des vestiges. Enfin, il est apparu que les différentes espèces présentes dans un environnement donné n'avaient pas toutes les mêmes aptitudes à éviter les avens. La fréquence avec laquelle les os d'une espèce sont conservés et leur mode de fragmentation, leur altération ou les indices de marques sur les surfaces osseuses sont autant de données qui peuvent être confrontées aux données archéologiques et par conséquent permettent de rediscuter dans les sites archéologiques, des modalités de transport et d'exploitation alimentaire et technique des carcasses par les groupes humains.

2.2. Avens et archéologie

Jusqu'à la fin du XXe siècle, la connaissance de l'environnement animal des hommes préhistoriques a été essentiellement basée sur la faune identifiée dans les sites archéologiques. D'autres disciplines comme la géologie des formations quaternaires ou encore la palynologie étaient mises à profit pour valider ces résultats. Parallèlement, la datation directe ou indirecte de peintures de certaines grottes ornées mettait en évidence l'existence de fortes distorsions entre bestiaires et faunes des sites d'habitats. Le développement des recherches sur les accumulations naturelles couplé à une systématisation des datations AMS, a rendu possible l'individualisation de phases d'accumulations beaucoup plus fines en avens. De telles données ont permis de confronter plus précisément les ensembles fauniques dits « naturels » avec les données archéologiques (CASTEL *et al.* 2008). Ainsi, à partir de la longue séquence datée de l'igue du Gral (Sauliac-sur-Célé, Lot), il a été possible de rediscuter des stratégies de chasse des occupations humaines du Paléolithique supérieur et des thématiques pariétales (CASTEL *et al.* 2014).

Même si certaines phases de la fin du Pléistocène demeurent encore mal documentées, les données des accumulations naturelles couplées à celles des occupations humaines dont les spectres de chasses ont été datés, permettent d'esquisser plusieurs réalités. Dans le centre du Quercy on constate une biomasse d'ongulés importante notamment autour du Dernier maximum glaciaire (DMG : il y a 22 000 ans environ). Les avens fournissent en abondance rennes, chevaux et bisons alors que dans les habitats on trouve essentiellement du renne, du bouquetin et marginalement du chamois et du cheval. Plusieurs constats peuvent être faits. Un des plus importants est que les populations du Solutréen supérieur, du Badegoulien et des phases initiales du Magdalénien ont délibérément chassé de petites proies alors que des gibiers plus gros étaient disponibles (CASTEL & CHAUVIÈRE 2014). Cette stratégie de subsistance est le résultat du mode d'organisation des groupes humains. En première hypothèse, on peut proposer que, conformément à certains modèles ethnographiques, les chasseurs qui fréquentaient le Quercy étaient structurés en petits groupes avec des besoins alimentaires limités. De telles réévaluations des choix alimentaires ont des implications beaucoup plus larges à tous les niveaux de l'économie et des modalités de subsistance. Finalement, la surabondance du renne dans les sites d'habitats n'est pas uniquement le reflet de la biomasse disponible et l'Âge du renne n'est en fait que l'expression de choix économiques.

À une échelle plus large, ces modalités de choix du gibier contrastent avec ce que l'on peut observer dans le nord de l'Aquitaine où les proies de la taille du cheval et du bison sont beaucoup plus fréquemment chassées (CASTEL *et al.* 2005, 2014).

Ces données, des avens et des spectres de chasse, ont pu être confrontées aux bestiaires des grottes ornées contemporaines. En Quercy, ces dernières sont difficilement datables du fait de l'utilisation du manganèse et non du charbon de bois. Néanmoins, dès lors que l'on désigne un cadre géographique et chronologique suffisamment précis il devient possible de mieux cerner les différents choix réalisés par les populations de la fin du Paléolithique. Les résultats obtenus ne concernent pour l'instant que le Quercy central et l'une des phases de l'art pariétal quercinois (Fig. 2).

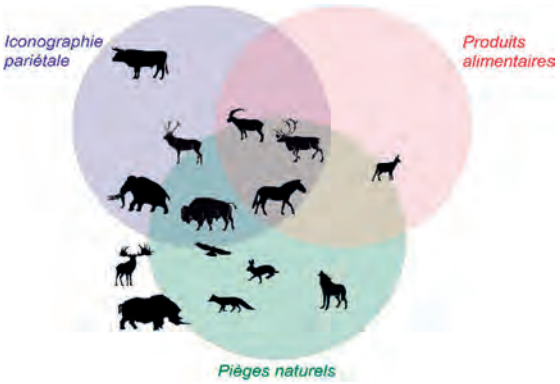

Figure 2 : Confrontation entre les corpus naturels, les archéofaunes (faune chassée par les préhistoriques) et les représentations pariétales animalières (Groupe de Sainte-Eulalie) dans la basse vallée du Célé autour du DMG (LORBLANCHET 2018 ; CASTEL & BOUDADI-MALIGNE 2017 ; silhouettes animales © MALLYE).

Le développement des recherches sur les accumulations naturelles permet ainsi l'élaboration d'un nouveau cadre paléoenvironnemental qui peut être mis en relation avec les modèles climatiques récemment développés. Grâce à cette multiplicité des sources d'informations sur les environnements du Passé, on pourra mieux comprendre la variété des comportements humains, évaluer la diversité des solutions que ces populations ont mises en œuvre pour répondre aux contraintes imposées par les milieux et finalement, mieux envisager les choix figuratifs réalisés dans les grottes ornées. Dans cette perspective, le rôle pivot joué par le Quercy apparaît incontournable.

3. Perspectives

Les séquences paléontologiques suffisamment fines et précisément datées sont encore rares (voir néanmoins CASTEL & BOUDADI-MALIGNE dir., à paraître). Afin d'étendre les comparaisons entre les données des accumulations naturelles et les données archéologiques, il est nécessaire de fouiller et dater de nouveaux corpus issus d'avens ou d'accumulations naturelles en général. De tels gisements, favorables à ces recherches, existent sur toute la bordure orientale du Bassin d'Aquitaine. En Quercy, plusieurs sites scientifiquement exploitables ont récemment été investigués.

Ces résultats devront être complétés par une meilleure caractérisation des processus saisonniers pour lesquels une plus grande finesse chronologique est requise ; ainsi les possibles migrations du renne en Aquitaine échappent toujours en partie à notre compréhension (KUNTZ 2011).

Enfin, le matériel exceptionnel provenant des accumulations naturelles ouvre de nouvelles perspectives d'analyses génétiques permettant notamment de rechercher les réponses démographiques et adaptatives des populations de vertébrés de la fin du Pléistocène et du début de l'Holocène aux changements climatiques.

4. Remerciements

Nous tenons à remercier tous les spéléologues qui nous ont guidés sous terre ainsi que les bénévoles qui nous ont accompagnés dans ces terrains souvent difficiles et ont participé à la restauration du matériel paléontologique. Les financements ont été obtenus auprès des institutions de rattachement des chercheurs ainsi qu'auprès du ministère de la Culture, du conseil départemental du Lot et du Fond National Suisse pour la recherche scientifique.

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L'igue de la Cave-aux-Endives II (Loubressac, Lot) : une accumulation remarquable de mammifères du Pléistocène supérieur dominée par le bison

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Résumé

Les fouilles paléontologiques réalisées dans l'igue (aven) de la Cave aux Endives II en 2019-2020 permettent de présenter une étude de cas dans tout son historique, depuis sa découverte purement spéléologique en 2004 jusqu'aux études scientifiques variées récemment initiées. Cette présentation permet en outre de mettre en lumière la complexité des opérations archéo-paléontologiques lorsqu'elles sont menées dans ce type de cavité, expliquant de fait leur faible exploitation scientifique. Les fouilles menées dans cette grotte, riche en vestiges fauniques, permettent d'identifier 4 unités stratigraphiques, la principale (US4) contenant des restes de bisons, de chevaux et de rennes et, plus marginalement, des restes de cerfs, de loups et de léporidés. La datation directe indique que ces espèces ont été piégées pendant l'OIS 3 et peut-être avant, certains échantillons dépassant la limite du ^{14}C n'ayant pas pu être datés.

Abstract

The Cave-aux-Endives II (Loubressac, Lot): a remarkable accumulation of Upper Pleistocene mammals dominated by bison. The paleontological excavations carried out in the pitfall of "La Cave aux Endives II" in 2019-2020 allows to present a case study in all its story board, since its purely speleological discovery in 2004 until the various scientific studies recently initiated. This presentation also highlights the complexity of archaeo-paleontological fieldworks when they are carried out in this type of cavity, explaining why they are still uncommon for the scientific exploitation. Excavations conducted in this cave, rich in faunal remains, allow us to identifiy 4 stratigraphic units, the main one (US4) containing mainly remains of bison, horse and reindeer and, more marginally, remains of deer, wolf and leporids. Direct dating indicates that these species were trapped during OIS 3 and maybe earlier: some samples over the 14C limit could not be dated.

1. Contexte général et cadre de l'intervention

L'igue de la Cave aux Endives II se situe à proximité immédiate du gouffre de Padirac, dans le nord du département du Lot (Fig. 1). L'accès naturel au réseau se fait par la Cave aux Endives I sur la commune de Padirac. Un puits de 19 m permet d'accéder à la partie active d'un réseau souterrain. À partir de 2003, le Spéléoclub de Saint-Céré a entrepris l'exploration de la cavité et c'est en septembre 2004, après 200 m d'une succession de siphons qui pour l'occasion ont été pompés, qu'une grande salle est découverte. Celle-ci semble être une diaclase élargie qui remonte pratiquement jusqu'à la surface. Elle est partiellement comblée par deux cônes d'éboulis. Le plus important est constitué d'une petite castine relativement instable, descendant du point supérieur à quelques mètres sous la surface jusqu'au réseau souterrain actif. Dans son tiers inférieur, il se mêle aux produits de démantèlement d'une coupe dans laquelle de nombreux ossements sont observés. En progressant vers l'aval du réseau souterrain principal, d'autres fossiles sont éparpillés sur une grande longueur notamment après les siphons de la partie aval du réseau. Afin de faciliter l'exploration du réseau souterrain en aval de cette salle, un accès artificiel est créé en novembre 2005 à environ 25 m au-dessus du gisement.

Nous sommes contactés par les découvreurs en 2008 et une première visite est organisée à la fin de l'année. De 2008 à 2017, nous effectuons plusieurs interventions qui permettent de récolter un matériel abondant provenant d'effondrements de la coupe (cf. *supra*). Nous avons ainsi reconnu la présence d'une demi-douzaine d'espèces, dont le bison, le cheval, le renne, le cerf, le loup et le lièvre. Dans le ruisseau aval nous repérons également la présence du mammouth et du lion des cavernes sans garantie qu'ils

proviennent de la même zone. À la suite de plusieurs effondrements, le gisement actuel n'occupe plus qu'une petite partie de sa surface initiale. Il s'effondre une nouvelle fois pendant l'hiver 2012-2013.

L'accès au gisement, s'il est facilité par l'entrée artificielle, requiert toutefois une bonne pratique de la spéléologie : plusieurs fractionnements derrière deux étroitures n'ont rien de complexe pour un spéléologue mais, combinées à l'instabilité des terrains, elles deviennent rédhibitoires pour conduire une fouille dans de bonnes conditions selon des procédures classiques avec une équipe de bénévoles.

À partir de 2017, constatant que le gisement se réduit rapidement, la décision est prise d'entreprendre une meilleure caractérisation de celui-ci dans son contexte karstique, notamment en constituant une équipe de spécialistes polyvalents à la fois archéologues, paléontologues et spéléologues. Une lecture stratigraphique de la coupe est réalisée et plusieurs échantillons sont sélectionnés pour des datations au radiocarbone.

Les résultats des datations permettent de suspecter un gisement dense en vestiges, stratifié, daté entre 30 000 ans et au-delà des limites de la méthode du ^{14}C (soit du stade isotopique 3 *a minima*) (Fig. 2). En 2018, lors du prélèvement d'un os pour datation, un fragment de crâne de bison est découvert. Pour réaliser son dégagement, nous décidons d'organiser une véritable fouille. Grâce à la mobilisation du Spéléoclub de Saint-Céré, les fractionnements sont rendus plus pratiques, une petite plateforme est fixée dans la pente facilitant la tenue d'une fouille et un éclairage puissant est installé. Un carroyage est mis en place tant bien que mal sur les rares repères fixes.

Les vestiges osseux sont exceptionnels par leur conservation, bien que fortement fissurés et fracturés sur place. L'équipe de terrain doit donc unir des compétences spéléologiques à la capacité d'identifier des os entiers mais brisés et couverts d'une boue plus ou moins liquide et de les extraire sans en perdre des fragments.

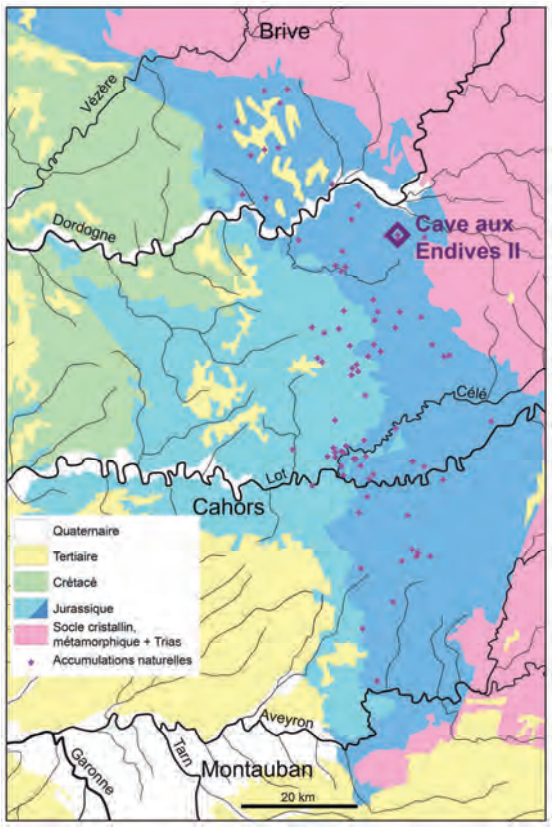

Figure 1 : Cadre géographique et géologique de l'igue de la Cave aux Endives II et des accumulations naturelles de faune en Quercy.

Entre les campagnes de 2019 et de 2020, le gisement s'effondre une nouvelle fois conduisant à la destruction irrémédiable de la couche supérieure mais affectant peu les ensembles inférieurs. Après la réalisation de nouveaux amarrages contre la paroi au-dessus de l'accumulation fossilifère afin de se protéger d'un nouvel éboulement, le début de la campagne 2020 consiste à remettre le site en état et recréer un carroyage.

Projet / financement	Taxon	Labo.	Références	Age brut (BP)	Age calibré (calBP 95,4% IntCal 20)
ACR-M.-P. Coumont	Bison	CDRC-Lyon	Lyon-6948(SacA19417)	26460+/-320	31132-30121
CD46/Archéologies /J.-C. Castel Prosp.-Inv.	Cheval	Poznan	Poz-100151	28560+/-340	33814-31824
CD46/Archéologies /J.-C. Castel Prosp.-Inv.	Cerf	Poznan	Poz-119321	43800 ± 1800 BP	52358-43735 (94,9%) et 43699-43410 (0,6%)
CD46/Archéologies /J.-C. Castel Prosp.-Inv.	Renne	Poznan	Poz-119369	35900 ± 800 BP	42125-39640
GDR-Ph. Fosse	Lion	CDRC-Lyon	Lyon-11696(SacA41916)	> 40 000 BP	
CD46/Archéologies /J.-C. Castel Prosp.-Inv.	Cerf	BETA	17826	> 43500 BP	

Figure 2 : Résultats des datations. L'os de bison a été prélevé avant le relevé de la stratigraphie, position mal déterminée ; H.S. hors stratigraphie, réseau aval.

2. Premiers résultats

D'un point de vue sédimentaire, quatre unités stratigraphiques (US) peuvent être identifiées (Fig. 3). Si les trois premières sont assez pauvres en restes osseux, l'US4 de couleur brun-sombre est nettement plus riche en fossiles, surtout dans sa partie inférieure. Des distinctions entre les couches peuvent également être faites sur la base des associations fauniques.

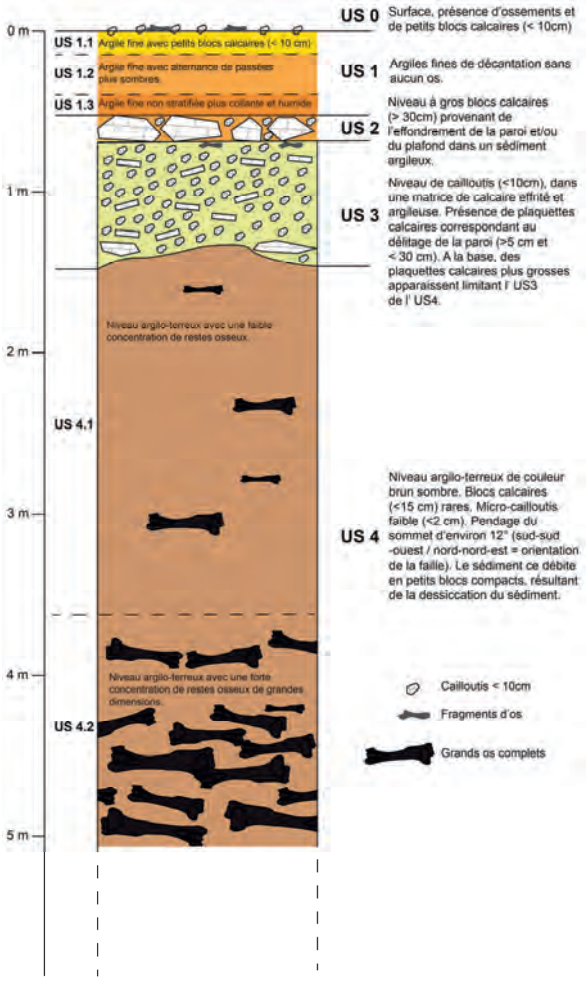

Figure 3 : Stratigraphie simplifiée du gisement.

Les couches supérieures sont dominées par le trio bison-cheval-renne qu'accompagnent le cerf, le loup et les léporidés (Fig. 4). Ces niveaux d'extension limitée sont datés entre 26 000 et 44 000 ans BP ; ils pourront être mis en correspondance avec d'autres corpus locaux, paléontologiques, archéologiques, mais aussi avec les bestiaires représentés dans les grottes ornées (cf. communication de CASTEL *et al.*, même session).

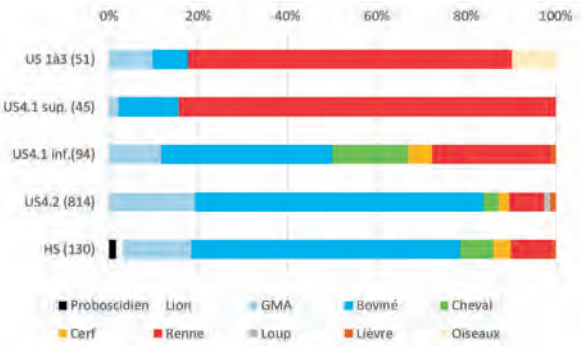

Figure 4 : Spectres fauniques des quatre ensembles stratigraphiques principaux. Entre parenthèses : nombre de restes ; H.S. : hors stratigraphie ; GMA : grand mammifère indéterminé / détermination en cours.

Les recherches conduites dans ce nouveau site quercynois apportent de nouvelles informations sur les paléoenvironnements biologiques et climatiques contemporains des occupations humaines de la première moitié du Paléolithique supérieur. Elles viennent compléter celles d'autres accumulations naturelles fouillées récemment selon des standards habituellement réservés aux habitats paléolithiques et bien datées telles que l'igue du Gral (CASTEL & BOUDADI-MALIGNE 2017 ; CASTEL *et al.* 2014, 2018 ; COUMONT *et al.* 2013) ou le Pras de Marrou (CASTEL *et al.* 2013). Si la présence du bison, du renne et du cheval est classique en Quercy tout au long des stades isotopiques 2 et 3 (BRUGAL *et al.* 2013), celle du cerf est beaucoup plus discontinue et le matériel de la Cave aux Endives contribuera à préciser les limites chronologiques de ses incursions.

La couche inférieure (US 4.2), dont la base n'est pas connue, est dominée à plus de 90 % par le bison qui est représenté par tous les éléments du squelette, bien conservés avec des os entiers. Elle n'est pas datable par le ^{14}C mais semble proche chronologiquement des formations sus-jacentes. Difficile à fouiller et nécessitant parfois une restauration importante du matériel, elle offre cependant la possibilité d'études paléobiologiques variées sur une population de bisons remarquable, autorisant une comparaison avec d'autres séries fossiles du Sud-Ouest de la France (BRUGAL *et al.* 1998, 2013).

Malgré une surface de fouille réduite (2 m^2), un nombre important de grands os de bisons ont pu être récoltés (Fig. 5). La plupart du matériel est suffisamment complet pour effectuer une étude morphométrique, et un premier décompte permet d'estimer un nombre minimum d'individus de 12, dont un jeune adulte et un juvénile.

Figure 5 : Fémurs de bisons les plus complets. L'exemplaire de couleur noire a été collecté dans le ruisseau souterrain aval. Échelle 30 cm.

Les dimensions des ossements semblent indiquer une majorité de femelles (les grands bovidés ont un fort dimorphisme sexuel), et permettent de proposer une attribution au bison des steppes *Bison priscus*. Une partie d'une harde composée de bisonnes et leurs petits a dû chuter dans ce puits servant de piège, dans un contexte certainement saisonnier. Ces différentes données permettront de préciser la dynamique évolutive et morphologique de cette espèce lors du dernier glaciaire ainsi que les facteurs taphonomiques explicitant la nature, saison et origine de l'accumulation fossile.

3. Perspectives

Cette étude de cas soulève la complexité des opérations de terrain à caractère archéo-paléontologique dans des cavités nécessitant la collaboration avec des équipes de spéléologues. Cette synergie est essentielle pour mener des actions scientifiques de qualité qui à terme fournissent des informations majeures sur les associations fauniques du Pléistocène supérieur et les milieux dans lesquels les hommes préhistoriques ont vécu. Pour des raisons sanitaires connues, les études paléontologiques ont été repoussées au printemps 2021. Elles détermineront les besoins supplémentaires en matière de datations et de fouilles.

Remerciements

Les opérations de terrain ont pu être réalisées grâce au dévouement de nos bénévoles spéléologues ou archéologues. Nous tenons à remercier tout particulièrement Michel et Catherine Espéret qui ont beaucoup fait pour en assurer la réussite. Les financements ont été assurés par le Service de l'Archéologie d'Occitanie (ministère de la Culture) et le Muséum de Genève. Les restaurations du matériel ont été dirigées en grande partie par Jean-Marie Zumstein (MHNG).

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The recent history of the Spanish ibex (*Capra pyrenaica*) in the French Pyrenees: a contribution of speleology to palaeontology

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Abstract

Over the last 40 years, research on (sub)fossil Spanish ibex (*Capra pyrenaica*) in the French Pyrenees is mainly based on discoveries made by cavers. In the western Pyrenees, more than 25 natural sites yielding Spanish ibex remains are known allowing palaeoecological research. Based on topographical settings (maps, bone location), paleontological records (osteometry, sexual dimorphism) and taphonomic analysis (skeletal discarding, biotic/abiotic traces), this paper provides information on the formation processes for some unpublished caprid sites. The deposits are mainly located in high mountains, in (deep) vertical holes or descending galleries having trapped one or two adult Spanish ibex or exceptionally several (non-) adult individuals. Osteometrical dataset suggests that males are more often trapped than females. Bone surfaces do not bear any important predator nor scavenger activities (large and/or small carnivores). The sites correspond to natural incursions of Spanish ibex into dark galleries, which are diachronic and/or independent of wintering occupations by brown bears (*Ursus arctos*).

Résumé

L'histoire récente du bouquetin d'Espagne (Capra pyrenaica) dans les Pyrénées françaises : une contribution de la spéléologie à la paléontologie. Au cours des 40 dernières années, les recherches sur les bouquetins des Pyrénées (*Capra pyrenaica*) reposent principalement sur des découvertes spéléologiques. Dans les Pyrénées occidentales, plus de 25 sites naturels renfermant des restes de bouquetins sont actuellement connus, autorisant des recherches paléoécologiques. A partir des données topographiques, paléontologiques et taphonomiques, cet article propose de caractériser les processus de formation des sites à caprinés. Les ossements sont principalement situés en haute montagne, au fond de puits (profonds), ou dans des grottes à galeries descendantes (ressauts), ayant piégé un à deux individus et exceptionnellement plusieurs animaux (non-) adultes. Les données ostéologiques (mesures) suggèrent que les bouquetins mâles sont plus fréquemment piégés que les femelles. Les surfaces osseuses ne présentent pas d'importantes traces de prédation ou de charognage (grands/petits carnivores). Ces sites correspondent à des incursions naturelles de bouquetins dans les galeries sombres qui sont indépendantes/diachroniques des occupations hivernales par les ours bruns (*Ursus arctos*).

1. Introduction

Caprini and *Rupicaprini* are typical cliff-dwelling bovids from mountainous regions. In the French Pyrenees, the Spanish ibex (*Capra pyrenaica* Schinz, 1838) is the main cliff-dwelling species identified along historical and Palaeolithic times (FOSSE *et al.* 2021). Steep areas in a limestone context and abundant grasslands favoured its survival until the end of the 20th century (CRAMPE 2020). This region (including Pyrénées Atlantiques and Hautes Pyrénées) constitutes a unique reservoir for caving (numerous sites known to date, explored by various clubs: ARSIP, GSO, SSPPO ...). Important discoveries and research both in archaeology and palaeontology come from these active caving clubs (CAZENAVE *et al.* 1994). This paper is a short survey on several unpublished sites yielding Spanish ibex remains, their topographical features, as well as their paleontological and taphonomic contents dealing with Spanish ibex cranial/postcranial skeletal parts.

2. Materials and methods

The western part of the Pyrenees (French and Spanish) is composed of large valleys rising to the summits above more than 2000 meters (a.s.l.) mainly in a limestone context. More than 25 karstic sites (caves, holes) yield identifiable bone remains belonging to the brown bear and the Spanish ibex (CLOT 1982; CRAMPE 2020; FOSSE *et al.* 2021).

Recently, similar deposits have been discovered on the southern slope of the Pyrenees (GARCIA-GONZALEZ 2012; SAUQUE *et al.* 2015, 2018), allowing to consider this transboundary region as a homogenous geographical, mammalogical and karstological setting (Fig 1). Data on Spanish ibex remains were collected both by cavers (topography, location) and palaeontologists (osteometry and taphonomy from private collections and museums (Arudy, Lourdes)). Comparative data come from CLOT (1982) for the French Pyrenees, ALTUNA (1978), ALTUNA & MARIEZKURRENA (1985) and CASTAÑOS (1986) for the Spanish deposits and from RODRIGUEZ & QUIRALTE (2016) for modern samples. Those works allow sexing most of bones (skulls, metapodials) presented below.

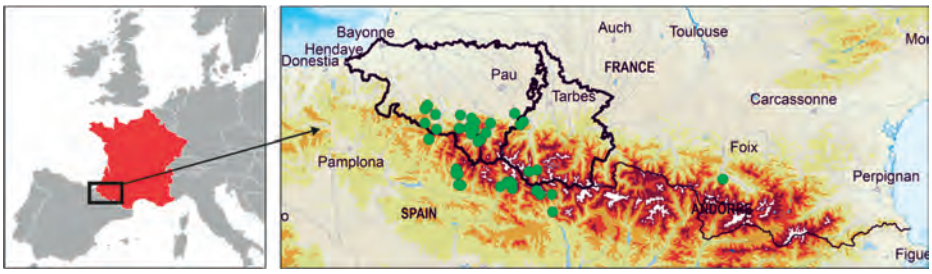

Figure 1: Location of karstic sites (green circles) yielding spanish ibex (Capra pyrenaica) remains discovered by cavers.

3. Results

The survival of the Spanish ibex in the western Pyrenees is attested by historiographical and speleological discoveries (CLOT 1982; CAZENAVE *et al.* 1994; CRAMPE 2020; FOSSE *et al.* 2021). A geographical area spanning the Basque country to the Aspe and Ossau valleys provided almost all the skulls/(sub)complete skeletons of the Spanish ibex from the French Pyrenees (Erbinia (930 m a.s.l.; Minimum Number of Individuals =3), TH1 (988 m; MNI=1), Zazpigagn (1 465 m; MNI=3), Uthurri (1 610 m; MNI=2), grotte sans nom (1 skeleton), PT 10 (1 190 m; MNI=2), Maquisards (1 250 m; MNI=1), Tuta de Lurtas (1 200 m; 2 skeletons), BSE 21 (1 270 m; MNI=1), gouffre des Bouquetins (1 850 m; MNI=2), Clot deth Pedaing de la Baigt (1 995 m; MNI=1), Permayou inf. (2 240 m; MNI=2)). Chourrugue Ouest cave (1 805 m, Hautes-Pyrénées) yields the most important sample (7 skeletons) from the French Pyrenees. In addition to these deposits, some other caves have delivered isolated skeletal elements: gouffre CB41 (600 m), Harzabaleta (800 m), Har Mahagn (855 m), Lénézobi 9 (~850 m), Etxekortia 2 (1 065 m) in the Basque country; Osque du Pont d'Escot (560 m), PT 4 (1 130 m), Arriutort (1 535 m), Hors (2 120 m) in the Béarn; Barbat (2 640 m) in the department 65 (isolated skull found in a firn patch close to the peaks). All these deposits allow to draw the geographical range for the species on the northern slope of the Pyrenees. Sites are considered as Holocene according to the state of preservation of bones (articulated skeletons, unbedded and/or discarded skeletal elements sometimes covered by a thin layer of concretion) and from radiocarbon dates (Zazpigagn: 6 851 ± 156 cal BP and 580 ± 110 uncal BP; PT10: 6 044 ± 139 cal BP; gouffre des Bouquetins: 1 443 ± 118 cal BP). Only one AMS radiocarbon date has been obtained, recently (Chourrugue Ouest, 3 645 ± 65 cal BP). Although new dating is necessary, those data already allow the reconstruction of a diachrony of site frequentation by Spanish ibexes (Zazpigagn) and a homogeneously broad pattern in their chronological distribution (before AD). The topography of the deposits reveals the systematic trapping of ibexes that fell into vertical holes directly open to the surface (type A sites *in* FOSSE *et al.* 2021; Fig 2), or individuals died in descending galleries (type B1 sites; Fig 3) or in those leading to deep holes (type B2 sites; Fig 4).

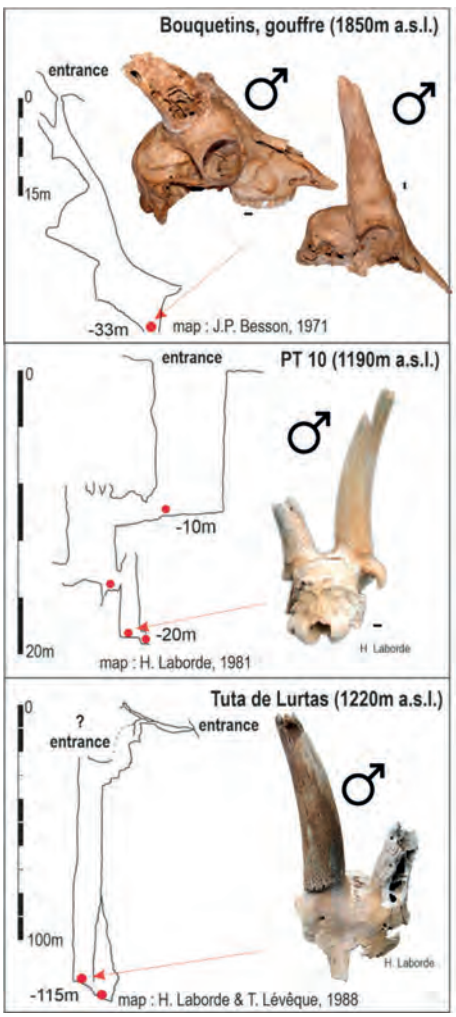

Figure 2: Topographical settings and location of the Spanish ibex remains (red circles) in French pyrenean natural traps (type A). Bar scale =1 cm.

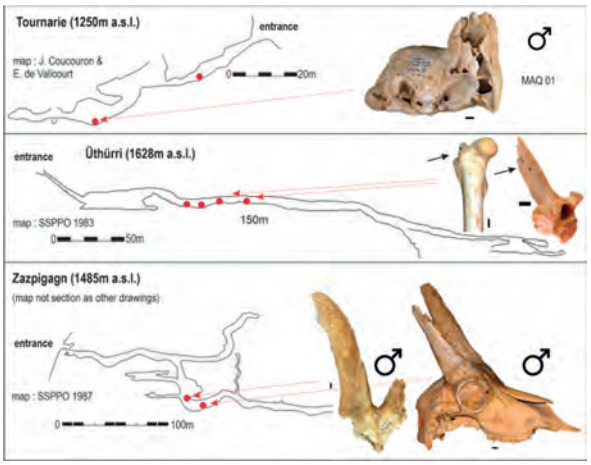

Figure 3: Topographical settings and location of the Holocene Spanish ibex remains (red circles) in French pyrenean caves (type B1). Bar scale = 1 cm. Pictures : Ph. Fosse.

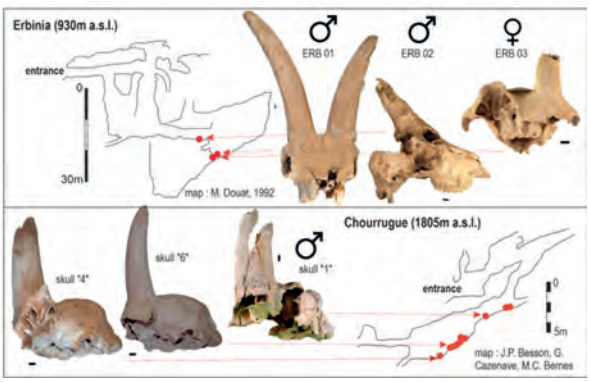

Figure 4: Topographical settings and location of the Holocene Spanish ibex remains (red circles) in French pyrenean caves (type B2). Bar scale = 1 cm. Pictures : Ph. Fosse.

All of those sites correspond to a (summer?) frequentation of cave entrances. Although quantified data are still scarce, first observations based on horn cores and on metacarpals (Figures 5, 6) highlight a high frequency of adult males over females (gouffre des Bouquetins: 2 males; Erbinia: 2 males and 1 female; PT 10: 1 male and 1 female; Tuta de Lurtas, Barbat: 1 male). The intra-sexual variation is important (metapodials). Only Chourrugue Ouest yielded more females (n=6) than males (n=4), but some small skulls could belong to subadult male individuals as well. To date, this site would be the only known sample yielding adult female and juvenile remains, in accordance with (seasonal) ethological data. All these natural traps are characterized by the absence of very young ibexes (< 1 year) but in Chourrugue Ouest and Erbinia caves, unfused long bones belonging to juvenile/subadult individuals are quite common. The use of limestone porches and/or the first galleries of deep caves seems to be a behavioural feature of subadult/adult individuals. Taphonomic data are rare but seem to correspond more to diachronic deaths (C14 dates, spatial distribution of skeletons into the galleries) than to episodes of collective accidents (Chourrugue Ouest?). Karstic sites are characterized by the presence of sub-complete skeletons, dislocated *in situ* at the bottom of holes (grotte sans nom, Permayou inf., PT 10, Tuta de Lurtas), disarticulation of naturally dead animals (Zazpigagn) or carcasses transported by water streams.

Large predator activity (brown bear) has not been observed whereas scavenging by small ones (foxes?) appears quite common but with slightly modified bone surfaces or extremities (tooth-/gnawing marks on ibex bones in Arriutort, Chourrugue Ouest and Uthurri; Fig 3).

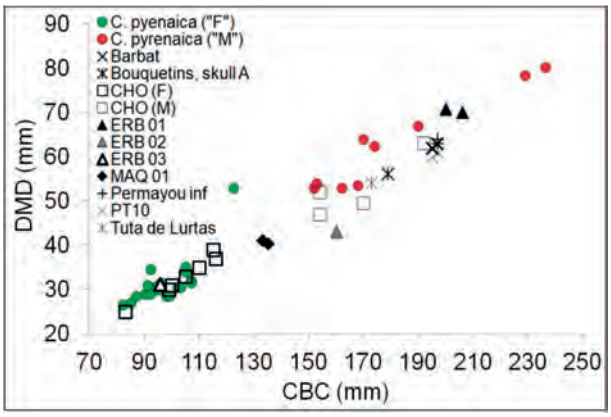

Figure 5: Sexing spanish ibex horn cores from French western Pyrenean sites. CBC = Circumference of horn core base, DMD = Antero-posterior diameter of horn core base, CHO = Chourrugue, ERB = Erbinia, MAQ = Maquisards.

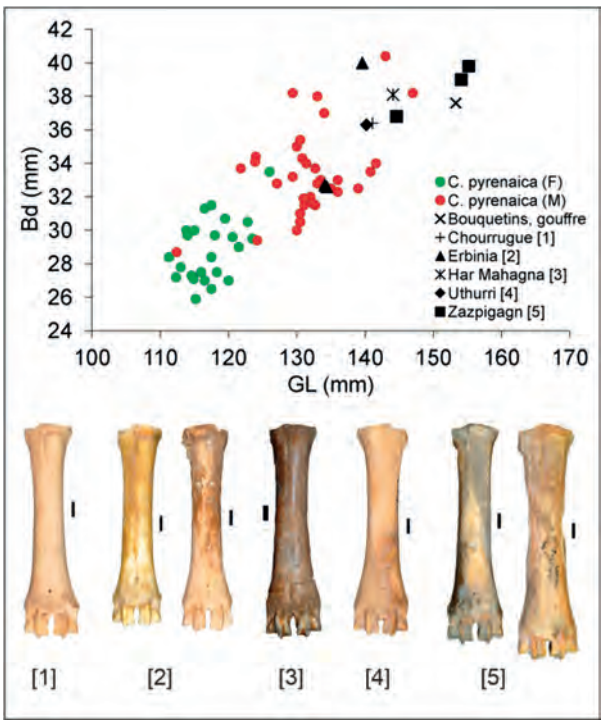

Figure 6: Sexing Spanish ibex metacarpals from French western Pyrenean sites. GL = great length, BD = distal width. Source as in Fig. 5. All bones are illustrated at the same scale (bar scale = 1 cm). Pictures: Ph. Fosse.

Rodent activity on dry bones, reflecting a long-term exposure, is sometimes observed (gnawing marks on skulls and innominate bones in Chourrugue Ouest). Spanish ibex remains are not found in the same places/galleries as brown bear bones, reflecting diachronic occupations (dates C14 to be analysed).

4. Conclusions/perspectives

Spanish ibex sites are abundant in the western Pyrenean karsts and contribute to our knowledge of its biogeography and ecology for Holocene and Middle/Late Pleistocene times. Discoveries by cavers provide interesting information on topographical, paleontological and taphonomic data and allow to discuss some of the Spanish ibex behavioural features (frequentation of karstic settings, ibex sex ratio, mortality profiles, scavenging activity) that can be used as guidelines for extant and extinct different ibex species or relative zoological groups (*Rupicapra, Hemitragus* ...). Speleology and palaeontology appear to be complementary on ibex research, from discoveries and expertise up to studies/methods. In the western Pyrenees, this research is particularly active and allows to study human-animal relationships on conservation, environments and history of human societies. Typology of French Pyrenean sites is very similar to Spanish ones (Type A: AN-15, MS-2; type B1: CS-59; type B2: Barranco Jardin J-1, Bucardo: GARCIA-GONZALEZ 2012; SAUQUE *et al.* 2015). This systematic topographical configuration suggests that natural trapping of Spanish ibex in vertical karst settings is the main cause of site formation (for Holocene deposits). In the (sub)horizontal and deep caves, the natural frequentation by the ibexes of galleries far from the entrances (Üthürri, Zazpigagn, Barranco Jardin J-5?) caused diachronic *in situ* natural deaths and also seems to be a common taphonomic feature. Predation or scavenging by large carnivores has not been identified yet in regional sites. In most Pyrenean deposits, the predominance of Spanish ibex males over females is noteworthy (AN-015, Barranco Jardin J-1, Barranco Jardin J-5, MS-2). This characteristic is also found in the Late Pleistocene deposits (Malarnaud (GRIGGO 1991) and Soulabé in Ariège, Los Batanes (SAUQUE *et al.* 2018) and Erralla IV (ALTUNA & MARIEZKURRENA 1985) in the Spanish Pyrenees). The characterization of ibex sites is based on new discoveries and multidisciplinary collective studies carried out by cavers and palaeontologists; this collaboration is essential for a better understanding of site formation processes and the (paleo)ecology of extant and extinct mammals dying (i.e., ungulates), kept (livestock) or living (i.e., large carnivores) in caves.

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L'aven de la Rouvière (Rogues, Gard) : approche géoarchéologique et paléospéléologique d'une grotte citerne néolithique

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Résumé

Lors de sa découverte par les spéléologues, l'aven de la Rouvière a révélé un ensemble de vestiges archéologiques parfaitement conservés depuis la fin du Néolithique. Si la première intervention archéologique réalisée au moment de la découverte avait pour objectif la sauvegarde du site et des mobiliers, elle a également permis de définir un programme de recherche. Il s'en est suivi une succession de campagnes de fouilles qui ont permis d'étudier la globalité de la cavité et surtout de mettre en évidence sa relation directe avec un établissement de plein-air situé juste à l'avant de l'entrée de l'aven. L'étude de ce gisement a, dès le départ, été orientée dans une démarche géoarchéologique permettant d'organiser la fouille archéologique en lien avec l'évolution du contexte sédimentaire lié à la spécificité du karst. Au terme de cette recherche, l'histoire du site peut être restituée assez précisément et démontre que les différentes phases d'aménagements identifiées dans la grotte étaient en lien avec le fonctionnement du karst.

Abstract

The Rouvière sinkhole (Rogues, Gard): geoarchaeological and paleospeleological approach of a Neolithic cistern cave. When it was discovered by speleologists, the cavity revealed a set of archaeological remains perfectly preserved since the end of the Neolithic period. If the first archaeological intervention carried out at the time of the discovery was aimed at safeguarding the site and the furniture, it also made it possible to define a research program. There followed a succession of excavation campaigns which made it possible to study the whole of the cavity and above all to highlight its direct relationship with an open-air establishment located just in front of the entrance to the cave. The study of this deposit was from the outset oriented towards a geoarchaeological approach making it possible to organize the archaeological excavation in real connection with the evolution of the sedimentary context linked to the specificity of the karst. At the end of this research, the history of the site can be reconstructed fairly precisely showing that the various development phases identified in the cave are linked to the functioning of the karst.

1. Une découverte exceptionnelle.

La cavité se trouve sur le Causse de Blandas (Gard), petit plateau karstique satellite du Larzac dans la région des Grands Causses, au sud du Massif central. Dès sa découverte en 1989, à seulement quelques mètres de son entrée, cet aven a révélé son passé préhistorique : plusieurs panneaux de vases cassés en place jonchaient le sol de la première salle, desquels émergeaient deux vases intacts (Fig. 1) ; surprenant, 5000 ans après leur dépôt ! Prenant de grandes précautions, l'équipe spéléologique a poursuivi son exploration jusqu'au terme de l'aven identifiant ainsi la quasi-totalité des vestiges liés à l'utilisation préhistorique. Prévenus dès la découverte, les archéologues de la Direction Régionale des Affaires Culturelles ont pu réaliser avec les spéléologues une première expertise du gisement, mettant en évidence une grotte citerne de la fin du Néolithique (GALANT 2003) ; l'intérêt majeur du site résidait dans l'obstruction de son entrée pendant ou très peu de temps après sa dernière utilisation, constituant un milieu clos dans un état de conservation exceptionnel. Outre l'aspect patrimonial majeur, il y avait là un potentiel d'étude archéologique tout à fait formidable et unique.

Une intervention archéologique a été réalisée suite à la découverte. Elle a permis le prélèvement raisonné de tous les éléments mobiliers accessibles sans fouille ; afin, bien sûr, d'éviter tout pillage et ne pas compromettre le potentiel scientifique. Il a également été réalisé un relevé de toutes les constructions de pierre sèche, et des aménagements de la cavité, autres particularités rares de ce site. Ceci a permis une évaluation très complète du potentiel archéologique et la définition d'un programme de recherche mis en œuvre de 1992 à 2004 (GALANT et *al*. 2000). Ces travaux ont permis la fouille exhaustive de l'aven afin d'établir son mode de

fonctionnement en lien avec l'économie de l'eau sur les Grands Causses à la fin du Néolithique.
Dès la définition de la problématique de cette recherche, il est apparu que le contexte morphologique de cette cavité qui présente une géométrie verticale, entraînait une diffusion sédimentaire gravitaire depuis l'extérieur, amplifiée par les infiltrations directes des ruissellements de surface issus du thalweg en bordure duquel se trouve l'entrée. Grâce aux conseils du géomorphologue Paul Ambert, il a été décidé de conduire cette recherche non pas dans la seule optique de l'archéologie, mais d'adapter les travaux à la nature des comblements en lien avec la dynamique du karst. Ceci revenait à essayer d'identifier et de comprendre la mise en place des masses sédimentaires et, dans un deuxième temps, les relations induites avec les données archéologiques. Cette approche totalement novatrice en ce début des années 1990 avait reçu un accueil très favorable chez les karstologues mais a été beaucoup plus difficile à imposer chez les archéologues… et pourtant !

2. Une démarche collaborative

La démarche choisie impliquait d'entreprendre le dégagement total de la surface des sols afin d'identifier leurs composantes et leur géométrie. Cette approche a demandé une mise en œuvre technique complexe (planchers hors sol démontables et évolutifs, méthodes d'enregistrement adaptées, etc.) ainsi que des prouesses de contorsionniste exceptionnelles pour les fouilleurs qui se sont succédé sur le site au cours de ce programme de 15 années de recherches…

Plusieurs décapages successifs ont ainsi été réalisés, en s'adaptant aux contraintes topographiques de la cavité. Les différents secteurs d'étude étant eux contraints par la morphologie de la cavité. La présence du mobilier archéologique au sein des assemblages sédimentaires a permis d'observer des interventions successives d'origines anthropiques, se plaçant après des périodes de dynamiques sédimentaires naturelles. Parallèlement à l'étude des remplissages en place, tous les indices liés à l'évolution géomorphologique de la cavité, comme les traces de remplissages disparus, mais aussi la répartition et l'état des spéléothèmes, ont été relevés ; ainsi plusieurs faits ont pu être identifiés et mis en lien direct avec les données archéologiques. Cette approche très contraignante, car sortant de la démarche unique de la fouille archéologique habituelle, a nécessité une très bonne communication entre l'archéologue et le géomorphologue ; mais devant les enjeux notés des mobilisations sédimentaires, c'est ce dernier qui pouvait dicter les orientations de la fouille. La seule fouille archéologique de ce site, tout aussi spectaculaire qu'il était, n'aurait conclu qu'à des faits déjà observés dans les rares sites de ce type étudiés depuis la fin du 19ème siècle sur ce territoire. Seul l'enregistrement des données permet d'identifier au mieux certains faits de détail, comme par exemple l'origine de la fragmentation des vases après l'abandon du site, ou d'aborder de façon plus contemporaine les aspects chronologiques détaillés. Mais le croisement des données archéologiques avec celles de l'étude géomorphologique a permis de mieux comprendre l'interaction entre les faits naturels et les faits anthropiques. On peut dès lors proposer un autre schéma sur l'utilisation du site, situation qui dans un deuxième temps permet également de mieux comprendre certains faits archéologiques.

Figure 1 : La première salle de l'aven lors de sa découverte (cliché Albert Colomer).

3. Des résultats plus que surprenants…

La fouille des salles en continuité de l'entrée a dégagé un plancher stalagmitique où des micro-gours s'étaient développés sur sa surface. Ceci ne peut se réaliser qu'en espace ouvert. Or, les sédiments accumulés sur ce plancher contiennent des éléments archéologiques dès le niveau de contact et jusqu'à leur sommet (soit plus de 0,7 m). Cette situation indique qu'avant l'utilisation préhistorique, il n'y avait pas de sédimentation et que donc l'entrée de la cavité était fermée sans relation sur l'extérieur.

Au bas du couloir d'entrée, une draperie stalagmitique vient barrer la galerie. En ce point et en voûte, on identifie des concrétions cassées très localisées ; l'espace ainsi aménagé permet le passage d'une personne. Sur les parois du couloir

d'entrée, les traces de remplissages disparus marquent un niveau qui vient contre la draperie de base. Celle-ci montre un découpage associé à des impacts de pics, qui indiquent un aménagement préhistorique. De ces observations, on peut déduire que les Néolithiques sont à l'origine de l'ouverture artificielle de l'entrée et qu'ils se sont ensuite engagés dans le couloir partiellement comblé. À son extrémité, ils ont aménagé un passage dans les concrétions en voûte ; puis, ils ont exploré la suite du réseau et constaté que la galerie se terminait une quinzaine de mètres plus loin sur un bassin naturel de plusieurs mètres cubes d'eau : une richesse sur les causses, à peine 10 m sous la surface. C'est ce fait qui a dû induire l'utilisation de l'aven. Le premier aménagement réalisé par les préhistoriques a consisté à vider le remplissage du couloir d'entrée et ainsi dégager la draperie qui l'obstruait. C'est dans cette draperie qu'un passage a été aménagé en la découpant, mettant ainsi en relation directe, par une sorte de porte, les salles et le couloir d'entrée. Dans ce dernier, l'enlèvement du remplissage a généré une pente importante que les Hommes ont compensée par la construction d'escaliers en pierre retrouvés lors de la fouille.

L'étude des remplissages des deux premières salles a permis d'observer que les assises de base des murs d'épierrement se situaient à des niveaux différents. De même, au sein de la puissance sédimentaire un dallage du sol, fait de dalles calcaires exogènes à la cavité, marquait un niveau de fonctionnement. Quant à eux, les éléments archéologiques montraient une mise à plat sur leur plus grande face, liée à un épandage des comblements ; or, celui-ci est réalisé dans une géométrie perpendiculaire à celle des colluvionnements depuis l'entrée de l'aven. Ces observations permettent de conclure que l'ouverture de l'accès a entraîné l'introduction gravitaire de sédiments extérieurs, accentuée par les passages répétés, formant ainsi un talus dans la première salle à la base du couloir d'entrée. Lorsque ce talus devenait gênant dans la gestion de l'espace domestique, destiné au stockage de l'eau, il était épandu pour redonner une horizontalité fonctionnelle. Progressivement avec l'usage, les sédiments se sont accumulés. La communication entre les deux salles se réalisait via un passage étroit (0,4 m) et assez haut (1,8 m). Avec l'accumulation sédimentaire qui se formait au fur et à mesure de l'utilisation de la première salle, ce passage s'est réduit en hauteur (1,10 m) ce qui le rendait mal aisé. Il a alors été condamné et, à environ 2 m de là, un nouveau passage a été ouvert, moins haut mais beaucoup plus large. Cette succession d'éléments montre bien la progressivité de l'aménagement de la cavité dans un but de la garder fonctionnelle au cours de son utilisation. Le bassin naturel terminal formait le réceptacle final de ce transit sédimentaire entretenu depuis les salles situées en amont. L'origine du bassin s'explique par le contexte dolomitique, propice à la formation de bouchons sableux qui favorisent la mise en place d'une citerne suspendue au-dessus d'un colmatage stabilisé. Les témoins sédimentaires relevés sur les parois de la galerie nous indiquent un débourrage du fond de cette citerne avec une évacuation, sans doute brutale, des sédiments vers l'aval du réseau (Fig. 2).

Celui-ci était constitué par une diaclase qui a été partiellement comblée. On retrouve dans ces sédiments la même composition que celle des sols des deux salles. Un tel phénomène de débourrage est dû à une inondation du réseau depuis le thalweg extérieur. Il est certain que cet évènement a dû perturber les utilisateurs du site et on imagine leur désarroi lors de la découverte du passage béant en lieu et place de leur réserve d'eau… pourtant, ils ont prolongé l'exploration de la cavité, puisqu'on a retrouvé au point bas de l'aven une zone de collecte d'eau matérialisée par des vases placés sous un égouttoir. Pour y accéder, deux ressauts de quelques mètres constituent des obstacles, surtout lorsqu'on est chargé d'un récipient rempli d'eau. On constate sur les parois au sommet de ces deux ressauts, des traces de prélèvement de boulettes d'argile. L'expérience montre que lors de phases d'attente les spéléologues jouent avec l'argile ; on peut alors imaginer des personnes placées en attente pour aider au transport de l'eau qui se prêtent à des jets de boulettes d'argile. Outre l'aspect ludique, ceci indique une organisation de corvées d'eau depuis la zone de collecte, jusqu'à celle de stockage située dans la première salle. Ces circonstances, de disparition de la citerne naturelle, de mise en place d'un nouveau point de collecte et de l'important travail induit par la remontée de l'eau, ont sûrement pu favoriser l'abandon du site. Les conditions externes et le fonctionnement du vallon en surface sont à prendre en considération.

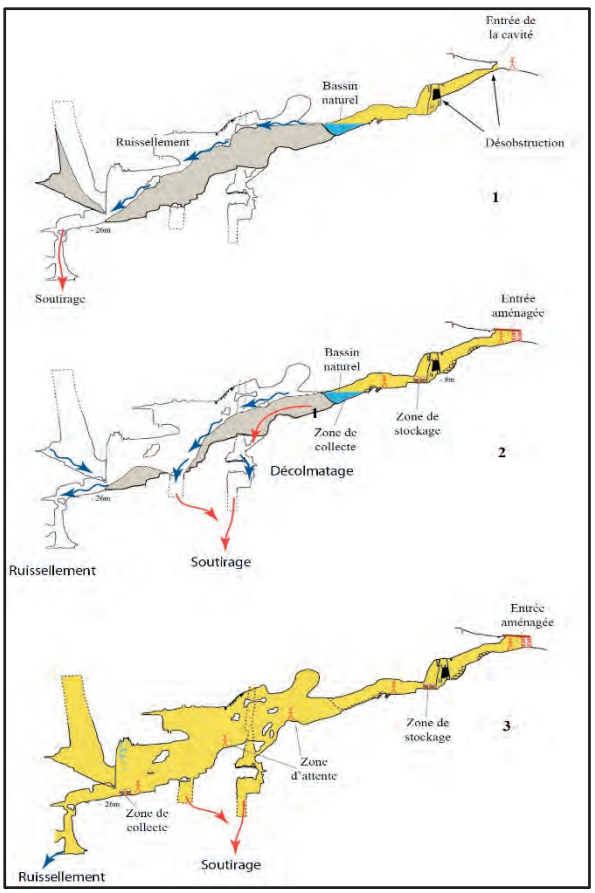

Figure 2 : Les principales évolutions géomorphologiques du site en lien avec son occupation préhistorique.

4. Découverte d'un habitat extérieur

La composition des comblements du couloir d'entrée, mis en place lors de l'utilisation du site, indique de nombreux indices d'anthropisation. Suite à ce constat, la prospection du champ situé à l'avant de l'aven ayant été négative, une série de sondages y a été réalisée. Ils ont révélé la présence d'un niveau archéologique structuré ainsi que d'éléments d'architecture en pierre sèche, sous environ 1 m de remplissage. Le dégagement du recouvrement sur 400 m^2 a révélé un ensemble architectural très bien conservé, constitué de cabanes accolées édifiées sur une plateforme aménagée en rive droite du thalweg. La coupe géomorphologique complète de celui-ci a permis d'établir que l'autre rive avait été laissée libre afin de favoriser l'écoulement naturel. La cabane principale était en relation directe avec l'aven, via un couloir et un aménagement de l'entrée de la cavité destiné à contrôler son accès.

La fouille de cet ensemble, contemporain de l'utilisation de la cavité, a montré que ces constructions avaient été partiellement détruites par une crue, puis reconstruites avec la mise en place d'un mur palissadé destiné à détourner les écoulements du versant vers le thalweg. Cette crue destructrice est probablement à mettre en relation avec celle qui a entraîné le débourrage interne de l'aven. Cette occupation extérieure en lien avec l'aven citerne a également impacté l'environnement du site, notamment par l'ouverture des versants. L'enregistrement sédimentaire indique que cette situation a favorisé les écoulements en direction du site : les hommes ont généré leur propre inondation ! Les traces de désordres hydrologiques récurrentes désignent ainsi le facteur le plus probable d'abandon du site.

Figure 3 : la cabane extérieure au fond de laquelle est aménagé le passage qui contrôle l'accès à l'aven citerne.

5. Nécessité de l'approche croisée.

Cette étude montre l'intérêt de l'approche croisée entre la géomorphologie et l'archéologie pour appréhender un gisement en contexte karstique (BRUXELLES et *al*. 2010). Ainsi, le dégagement des sols est guidé par les observations géomorphologiques ce qui permet de s'interroger sur les faits sédimentaires et surtout leur interprétation à la vue des impacts anthropiques. Plus de trente ans après la découverte de l'aven de la Rouvière, l'approche géoarchéologique se généralise sur les fouilles archéologiques induisant de nombreux résultats inédits. Dans le karst profond, l'observation des faits anthropiques est fréquente permettant ainsi de percevoir la volonté que les groupes humains ont eue tout au long de l'histoire de découvrir le monde souterrain des grottes et des avens. L'exemple développé ici indique la nette différence de perception des traces entre ce qui est observé en surface et les conclusions que l'on peut en tirer après une approche croisée entre la géomorphologie et l'archéologie. Il paraît inconcevable aujourd'hui de ne pas conduire une telle recherche en associant les deux disciplines.

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Des avens-pièges à Artiodactyles dans le massif des Bauges : Trois exemples sur le plateau du Revard (Savoie).

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Résumé

Le massif des Bauges est situé dans les Préalpes françaises septentrionales. Il renferme des réseaux karstiques très étendus, principalement développés dans les calcaires urgoniens. Certaines cavités des Bauges ont fonctionné comme des pièges naturels, et ont permis une excellente conservation des ossements des animaux qui y sont tombés, notamment durant l'Holocène. À titre d'exemple, sont présentées trois cavités situées sur le plateau du Revard, ayant la particularité d'avoir piégé des Artiodactyles : le creux de Élaphes (Les Déserts), qui a livré les squelettes quasi complets de trois aurochs et de deux cerfs ; le gouffre de la Chèvre (La Féclaz), qui a permis de recueillir un bucrâne d'aurochs mâle ; et le trou des Artios (Saint-François-de-Sales), qui renferme encore les squelettes d'un aurochs, de sept cerfs et d'un chevreuil. L'étude paléontologique de ces sites et les datations ^{14}C renseignent la chronologie des fréquentations des troupeaux d'Artiodactyles – surtout d'aurochs – dans le massif. Les observations sur la répartition spatiale des ossements et leur état de conservation permettent de mieux comprendre les processus de formation de ces sites, et alimenteront notre référentiel taphonomique sur les altérations climato-édaphiques et biologiques dans les karsts d'altitude.

Abstract

Natural trap for Artiodactyls, three examples on Revard plateau (Savoy, France). The Bauges mountains are located in the northern French Pre-Alps. They contain very extensive karstic systems, mainly developed in the Urgonian limestones. Some cavities of the Bauges have functioned as natural traps and have allowed an excellent preservation of the bones of the animals that fell there, especially during the Holocene. For example, three cavities located on the Revard plateau are presented, having the particularity of having trapped Artiodactyls: the creux de Élaphes (Le Deserts), which delivered the almost complete skeletons of three aurochs and two deer; the gouffre de la Chèvre (La Féclaz), where we collected a male aurochs bucranium; and the trou des Artios (Saint-François-de-Sales), which still contains the skeletons of one aurochs, seven deer and one roe deer. The paleontological study of these sites and the ^{14}C dates give the chronology of the frequentation of the herds of Artiodactyls - especially aurochs - in the massif. Observations on the spatial distribution of the bones and their state of preservation allow a better understanding of the processes of formation of these sites and will complete our taphonomic reference on the climatic and biological alterations in the high-altitude karsts.

1. Introduction

Le plateau du Revard est situé dans la partie occidentale de la Savoie, au pied du mont Revard (1563 m), dans le Parc Naturel Régional du Massif des Bauges. Excepté sur son flanc occidental qui présente une barre rocheuse, l'accès à ce plateau se fait par des pentes douces qui empruntent la vallée de la Leysse au sud, la vallée du Serrioz au nord-ouest ou celle du ruisseau de Saint-François à l'est. C'est un plateau karstique mamelonné, constitué de calcaires barrémiens à faciès urgonien, dont l'altitude moyenne est de 1360 m. Ce plateau est parsemé de gouffres et de dolines. C'est donc un lieu de prédilection pour les spéléologues qui ont entrepris, depuis plusieurs années, le recensement de toutes les cavités. À ce jour plus de 330 cavités pour plus de 73 km de galeries ont été inventoriées. Certaines de ces cavités communiquent avec le plateau par des puits d'effondrement plus ou moins verticaux qui ont pu fonctionner comme des pièges naturels pour la faune holocène. C'est notamment le cas pour les trois sites que nous présentons dans cet article : le creux des Élaphes, le gouffre de la chèvre et le trou des Artios où sont tombés des cerfs, mais aussi des aurochs. La présence de ces derniers dans des avens-pièges est tout à fait remarquable.

2. Le creux des Élaphes

Le creux des Élaphes est situé sur la commune des Déserts, au nord-ouest du plateau du Revard, à 1375 m d'altitude (Fig. 1). Il s'ouvre par deux entrées qui portent les numéros n° 174 et n° 174 bis dans l'inventaire spéléologique du Spéléo-Club de Savoie. Elles permettent d'accéder à une petite galerie de 200 m de long.

Figure 1 : Plan de localisation des sites présentés dans cet article.

Cette cavité a été découverte en mai 1994 par S. Guibot, après une petite désobstruction. Dans le courant de la même année, la topographie précise de la cavité a été réalisée, et la présence de nombreux ossements attribués à du cerf a également été notée. M. Philippe, après avoir été informé de cette découverte, a organisé et dirigé une fouille de sauvetage en octobre 1996 (PHILIPPE *et al.*, 2001).

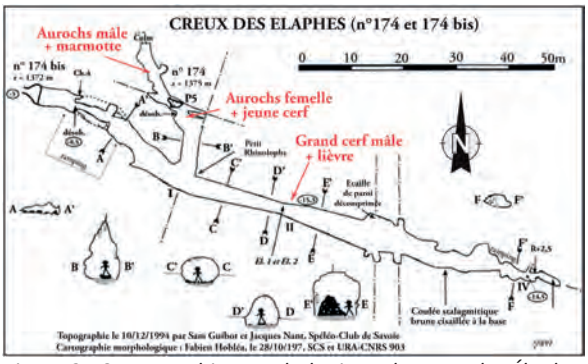

Figure 2 : Cartographie morphologique du creux des Élaphes (in : Philippe *et al.*, 2001- *modifié C. Griggo) avec localisation des ossements.*

Cette fouille a permis de recueillir, entre les blocs du grand éboulis formé depuis la base du puits d'entrée n°174 jusqu'à sa confluence avec la galerie principale, les squelettes presque complets d'un jeune cerf mâle et d'une femelle d'aurochs (Fig. 3), ainsi que quelques os d'un très jeune veau. Dans la galerie principale a été prélevé le squelette pratiquement complet d'un cerf mâle adulte. Les ossements étaient étalés, sans connexion anatomique, sur une surface de 5 à 6 m^2, et recouverts d'une mince couche de calcite. À proximité se trouvaient également le crâne et quelques os d'un lièvre variable. Dans la petite galerie nord-ouest, mêlés aux blocs calcaires, de nombreux ossements d'un aurochs mâle sub-adulte ainsi qu'un crâne de marmotte ont été prélevés (PHILIPPE *et al.*, 2001).

Figure 3 : Creux des Élaphes – crâne de la femelle d'aurochs.

Ces différents animaux sont a priori tombés dans la grotte en passant par le puits n° 174, qui a donc fonctionné comme un aven-piège. La chute n'a pas toujours été mortelle et certains d'entre eux : le grand cerf et le lièvre variable dans la galerie principale, le jeune aurochs dans la petite galerie nord-ouest, ont donc erré dans les galeries avant de mourir. Les études morphologiques et biométriques effectuées sur ces différents animaux ont montré que les cerfs étaient des animaux robustes, de stature comparable à celle des cerfs de la fin du Pléistocène (PHILIPPE *et al.*, 2001). En ce qui concerne les aurochs, bien que plus grands que les bœufs néolithiques, leur taille était relativement petite comparée aux aurochs holocènes du référentiel de L. Chaix (2001) (Fig. 4 – étoile bleue).

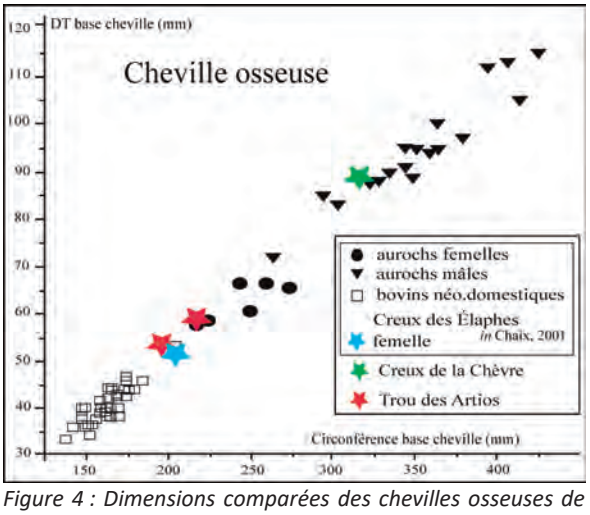

Figure 4 : Dimensions comparées des chevilles osseuses de corne d'aurochs. Les dimensions sont prises à la base.

Quatre datations ^{14}C ont été réalisées :
- Cerf de la galerie principale : 6 980 ± 50 BP (LY-8055) soit entre 5 982 et 5 741 cal BC.
- Aurochs mâle de la petite galerie nord-ouest : 7 340 ± 45 BP (OXA-10015 ; LY-1292) soit entre 6 361 et 6 073 cal BC.
- Aurochs femelle du grand éboulis : 7 352 ± 34 BP (KIA-7476) soit entre 6 356 et 6 079 cal BC.
- Ossements provenant du grand éboulis : 7 190 ± 50 BP (LY-8054) soit entre 6 219 et 5 926 cal BC.

Elles se situent toutes dans une tranche de temps bref, correspondant au milieu de l'Holocène et plus précisément à l'Atlantique ancien.

3. Le creux de la Chèvre

Le creux de la Chèvre, qui porte aussi les noms de Perte Teppes de Lachat, ou trou de la GS, se trouve sur la commune de La Féclaz, au sud du plateau du Revard, à 1340 m d'altitude (Fig. 1). Cette petite cavité de 50 m de développement qui porte le n° 167 dans l'inventaire spéléologique du Spéléo-Club de Savoie, a été découverte en 1987, puis redécouverte en 1991. Après plusieurs désobstructions en 1991 et 1993 pour passer trois trémies, la topographie de cette petite galerie a pu être levée (Fig.5).

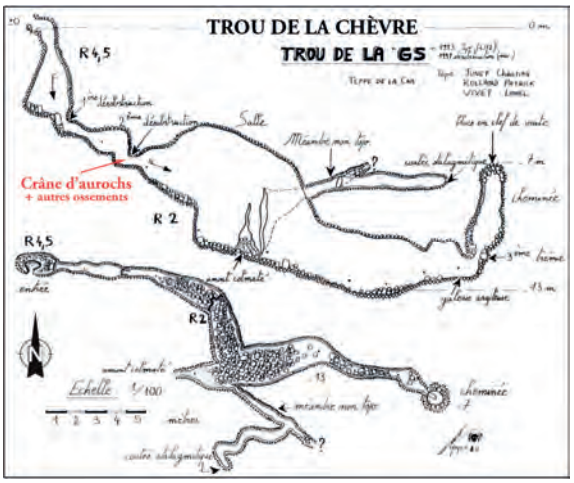

Figure 5 : Relevé topographique du Creux de la Chèvre (C. Junet, P. Rolland et L. Vivet - modifié C. Griggo) avec localisation des ossements.

En décembre 2019, L. Couard, accompagné de C. Hermen, C. Da Costa et D. Jaromin, en évacuant les blocs calcaires pour élargir une étroiture avec un bon courant d'air au niveau du deuxième ressaut, ont découvert deux fragments d'un crâne d'aurochs, ainsi qu'un pelvis de Boviné et un métatarsien de cerf. Le travail de désobstruction a immédiatement été stoppé et, quelques jours plus tard, les ossements ont été confiés à C. Griggo. Les deux fragments crâniens remontent entre eux et ils correspondent à la région postérieure (os frontaux et occipital) sur laquelle sont encore présentes les bases des chevilles osseuses de corne (Fig. 6). Les fortes dimensions de ce crâne, notamment celles de la base des chevilles osseuses, permettent de l'attribuer à un mâle d'aurochs (Fig. 4 – étoile verte).

Figure 6 : Creux de la Chèvre – arrière-crâne *d'un aurochs mâle, après recollage – vue supérieure.*

Une datation ^{14}C obtenue sur ce crâne a donné un âge de 7 770 ± 45 (Lyon-17913(GrM)), soit entre 6 656 et 6 476 cal BC. Cette date, légèrement plus ancienne que pour le creux des Élaphes, correspondent au Boréal récent.

4. Le trou des Artios

Le trou des Artios est situé au nord-est du plateau du Revard sur la commune de Saint-François-de-Sales (Fig. 1). Cette cavité correspond à un aven constitué de deux puits qui débouchent dans une large cavité.

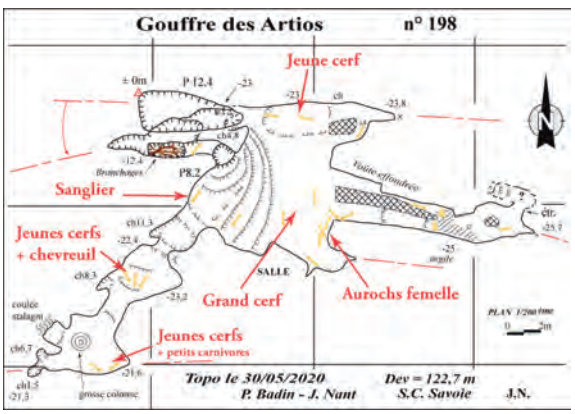

Figure 7 : Relevé topographique du trou des Artios (P. Badin, et J. Nant - modifié C. Griggo) avec localisation des ossements.

Le puits d'entrée, profond de 12,4 m, présente une large ouverture. À sa base, un petit couloir permet d'accéder au second puits, profond de 8,2 m, qui débouche dans une salle assez large, au sommet d'un cône d'éboulis (Fig. 7).

Cette cavité, qui porte le n° 198 dans l'inventaire spéléologique du massif des Bauges, a été découverte en février 1984 par B. Cabrol (S.C.S). Il signale alors la présence d'ossements de cerf et de vache. En mai 2020, J. Nant et P. Badin, accompagnés de L. Badin sont retournés dans la grotte pour en faire le relevé topographique précis (Fig. 7). Ils sont alors intrigués par les fortes dimensions du crâne de Boviné qu'ils attribuent à de l'aurochs (Fig. 8), ils en informent M. Philippe et C. Griggo.

Figure 8 : Trou des Élaphes – Crâne d'une femelle d'aurochs.

Une nouvelle visite en juillet 2020, a permis de confirmer que le Boviné était bien un aurochs. Un inventaire effectué dans l'ensemble de la cavité a révélé la présence, à la base du grand cône d'éboulis de la salle principale et dans les deux coupoles amonts, de squelettes plus ou moins complets de sept cerfs (trois adultes, quatre jeunes), ainsi que de quelques ossements se rapportant à un sanglier, un

grand ongulé indéterminé, un blaireau, un canidé indéterminé, un oiseau de grande taille. Il s'agit d'animaux vraisemblablement tombés dans le piège naturel que constitue la large ouverture au sommet du puits d'entrée.
Tous ces ossements, de couleur brun-orangé, présentent un bon état de conservation. Dans la salle principale, ils sont mêlés aux blocs calcaires et certains montrent de petits encroûtements de calcite. Dans les coupoles amont, les os sont pris dans une fine coulée de calcite. Tout cela plaide en faveur d'une certaine ancienneté. Cependant cet aven-piège est toujours actif, comme l'atteste le squelette complet d'un chevreuil, trouvé dans la coupole amont n°1, en connexion anatomique quasi parfaite. Ses os, de couleur très claire, sans encroûtement de calcite, ainsi que la présence de matière organique sur le sol qui matérialise la silhouette de l'animal laissent penser qu'il est très probablement tombé dans la grotte tout au plus il y a quelques dizaines d'années. Par ailleurs, sa présence n'a pas été signalée lors de la découverte.
À ce jour, seul le crâne de l'aurochs a été sorti de la grotte. Des analyses morphologiques et biométriques permettent de préciser qu'il s'agit d'une femelle d'aurochs, de stature plutôt petite (Fig. 4 – étoiles rouges). Des échantillons seront prélevés pour datations ^{14}C, et un dossier de demande de fouilles a été déposé auprès du SRA Auvergne Rhône-Alpes.

5. Conclusion : des aurochs fossiles sur le plateau du Revard

En France, l'aurochs est relativement rare dans les sites du Pléistocène. Il devient plus fréquent dès le début de l'Holocène, où il est, avec le cerf, l'un des principaux gibiers des chasseurs mésolithiques. À partir de la période gauloise, ses effectifs diminuent considérablement. Quelques populations reliques semblent encore présentes dans les Ardennes, le Massif Central et les Pyrénées jusqu'à la période antique. L'aurochs disparaît définitivement de France à la fin du 12ème siècle (VIGNE *et al*., 2003).
Les trois cavités du plateau du Revard présentées dans cet article ont fonctionné comme des avens-pièges, et se caractérisent par la présence de l'aurochs et du cerf. Si ce dernier est relativement fréquent en contexte karstique dans les Alpes nord-occidentales, en revanche, la présence de l'aurochs est tout à fait remarquable. En effet, à notre connaissance, ce Boviné n'a été signalé, en région Rhône-Alpes, que dans un autre aven-piège naturel : le gouffre de la Vuillette, situé en Chartreuse (altitude : 1 470 m). Il s'agit d'un aurochs mâle, daté de 4 290 ± 160(LY 1292), soit entre 3 365 et 2 476 cal BC (DROUIN et PHILIPPE, 1992). En contexte archéologique, la présence de l'aurochs n'est attestée que dans deux sites : l'abri sous-roche de la Fru, en Chartreuse (altitude : 570 m), dans un niveau azilien daté de 10 800 cal BC (PION *et al*., 1990), et dans le site néolithique des Baigneurs, sur les berges du lac de Paladru (altitude : 492 m), occupé entre 2 668 et 2592 av. J.C. (BOCQUET, 2012).
Les datations des aurochs du creux des Élaphes et de celui du creux de la Chèvre placent ces animaux au milieu de l'Holocène, contemporains des cultures mésolithiques. Ces Bovinés étaient donc présents, en Rhône-Alpes, depuis au moins la fin du Tardiglaciaire (site de La Fru) et jusqu'au Néolithique récent (site des Baigneurs).
Par ailleurs, la présence d'aurochs dans trois avens du plateau du Revard est très certainement liée à la configuration particulière de ce plateau et à celle de son réseau karstique. En effet, ce plateau, facilement accessible depuis les vallées environnantes, constitue un vaste replat qui a dû être recouvert d'une forêt mixte, entrecoupée de nombreuses clairières dès le début de l'Holocène, constituant ainsi un environnement favorable pour des hardes de cerfs et d'aurochs. Son réseau karstique, quant à lui, se développe sur plus de 73 km de galeries explorées, et compte plus de 330 cavités inventoriées. Plusieurs d'entre elles communiquent avec la surface par des avens, qui résultent de l'effondrement d'une voûte de cheminée d'équilibre du paléo-réseau. Ces avens ont pu constituer autant de pièges naturels pour la faune holocène.
Pour conclure, il convient de souligner les bonnes relations entretenues, depuis plusieurs années, entre le milieu spéléologique et le milieu scientifique. Des découvertes qui auraient pu passer inaperçues contribuent aujourd'hui à une meilleure connaissance des zoocénoses quaternaires dans les Alpes nord-occidentales.

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Caractérisation du gisement fossilifère de l'aven du Devès de Reynaud (Saint-Remèze, Ardèche, France) Histoire et apport de l'étude des paléofaunes

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Résumé

Les avens-pièges constituent de véritables sources d'informations sur les paléofaunes et les paléoenvironnements locaux en minimisant les biais induits par la sélection anthropique ou celle des carnivores. Cette présentation s'attache à caractériser le gisement fossilifère de l'aven du Devès de Reynaud à travers l'examen paléontologique et taphonomique des séries osseuses provenant des collectes anciennes et des travaux récents dans la cavité. L'assemblage paléontologique historique est issu de l'exploitation des phosphates pour l'agriculture au cours des années 1880. Dans les années 1970, un spéléologue signale des niveaux de retombées volcaniques au sein de séquences sédimentaires encore en place. Une étude sédimentologique et des datations entreprises en 2019 (projet TéphrArd) permettent de replacer chronologiquement l'accumulation du Pléistocène moyen (350 ka) à la fin du Pléistocène supérieur (12 ka). L'étude de la faune, au-delà de la caractérisation du site en aven-piège, confirme et affine cette chronologie, et apporte des informations complémentaires sur les dynamiques d'accumulation. Des comparaisons avec d'autres sites pléistocènes de l'Ardèche méridionale permettront de préciser les paléoenvironnements ainsi que les périodes d'accumulation. Le cas de l'aven du Devès de Reynaud illustre bien ici l'apport des études pluridisciplinaires intégrées incluant la spéléologie pour l'étude du milieu karstique et des environnements passés.

Abstract

Characterisation of the fossiliferous deposit of the Devès de Reynaud pitfall (Ardèche, France). History and contribution of the study of paleofauna. Pitfalls can be good sources of information on paleofauna and local paleoenvironments by minimizing the biases induced by anthropogenic or carnivore selection. This presentation aims at characterizing the fossiliferous deposit of the aven du Devès de Reynaud through the paleontological and taphonomical examination of the bone series coming from ancient collections and recent investigations in the cavity. The historical paleontological assemblage comes from the exploitation of phosphates for agriculture during the 1880s. In the 1970s, a speleologist reported levels of volcanic fallout within sedimentary sequences still in place. A sedimentological study and dating undertaken in 2019 (TéphrArd project) allows us to chronologically place the accumulation from the Middle Pleistocene (350 ky) to the end of the Late Pleistocene (12 ky). The study of the fauna, beyond the characterization of the site as a pitfall, confirms and refines this chronology, and provides additional information on the dynamics of accumulation. Comparisons with other Pleistocene sites in southern Ardèche will allow us to specify the paleoenvironments as well as the periods of accumulation. The case of the aven du Devès de Reynaud is a good illustration of the contribution of integrated multidisciplinary studies including speleology for the study of karstic and past environments.

1. Introduction

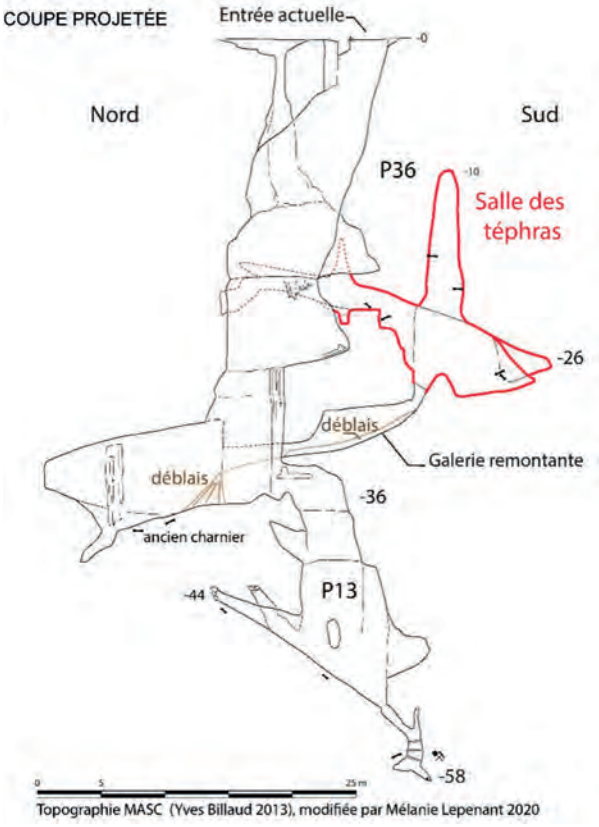

Figure 1 : Coupe projetée de l'aven du Devès de Reynaud

L'aven du Devès de Reynaud est une cavité s'ouvrant sur le plateau de Saint-Remèze, en Ardèche, dans le sud-est de la France. Son accès est constitué d'un puits volumineux de 36 m de hauteur tandis que la cavité se développe sur une centaine de mètres au total (Fig. 1).
Des indices d'aménagement (ancrage de plateformes) et des traces d'extraction sédimentaire (coups de piochons sur les parois, déblais) y sont visibles. Ils seraient contemporains de l'extraction du gisement fossilifère au cours de la seconde moitié du 19ème siècle. Celui-ci, situé dans une salle adjacente au puits principal (« salle des téphras »), a aujourd'hui presque entièrement disparu. La ressource en phosphates de chaux qu'il constituait est évoquée dans les archives (CHANTRE, 1901), comme la principale raison de son exploitation. Cette ressource, une fois broyée, était alors utilisée comme adjuvant pour l'agriculture. Edouard-Alfred Martel est le premier à faire mention de « l'Abîme du Devès de Reynaud » (MARTEL 1894) et relate les découvertes paléontologiques (Fig. 2) faites dans le cadre de ces extractions par Jules Ollier de Marichard, préhistorien ardéchois de l'époque.

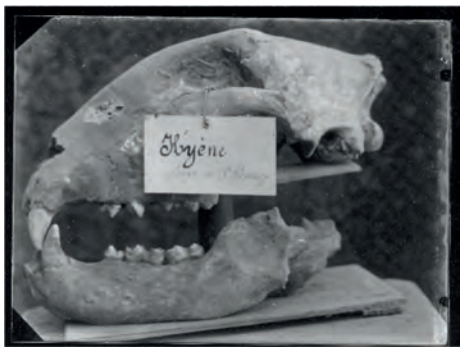

Figure 2 : Plaque photographique tirée par Léopold Chiron à la fin du 19ème siècle. Fossiles provenant de « l'Aven de St-Remèze ». Malgré l'étiquette, l'ensemble semble composite. La mandibule porte des dents d'ours tandis que la morphologie du crâne ainsi que la denture semblent indiquer un crâne de lion plutôt que d'hyène. Celui-ci présente d'importants indices de restauration. Fonds Chiron-Goury, archives départementales du Gard

Le gisement est ensuite tombé dans l'oubli au cours du 20ème siècle et seuls les spéléologues continuèrent l'exploration du gouffre. Dans les années 1970, des niveaux de cendres volcaniques sont repérés dans le secteur du gisement fossilifère par l'un d'eux (DEBARD & PASTRE 2008). L'étude de ces téphras constitue l'objectif du projet TéphrArd, porté par Simon Puaud (UMR7194, HNHP) (PUAUD *et al.* 2020 *; à paraître*). Ce projet a donné lieu à une mission sur le terrain en 2019 au cours de laquelle de nouveaux restes paléontologiques ont été découverts, à l'origine du travail de Master 2 présenté ici. L'objectif de ce dernier était la caractérisation du gisement paléontologique à travers l'étude de ses modalités de dépôt et de la paléofaune qui le compose. Le travail de recherche documentaire qui lui a été adjoint avait pour objectif de retrouver des collections anciennes, de mieux comprendre les modalités d'extraction des fossiles au 19ème siècle et d'ainsi mieux appréhender l'histoire du gisement dans toute sa complexité.

2. Matériels et méthodes

Deux collections provenant de la salle des téphras étaient déjà en notre possession. Elles correspondent au matériel prélevé lors de la mission TéphrArd en 2019 (NR = 293) et à du matériel prélevé par Yves Billaud en 1974 (NR = 43).
Suite à des recherches préliminaires, deux collections sont venues s'y ajouter. La plus importante correspond à du matériel paléontologique déposé entre 1889 et 1897 au Musée de Lyon, aujourd'hui Musée des Confluences (CCEC ; NR = 117). Quelques restes ont également été retrouvés au centre de conservation de paléontologie de l'Université Claude Bernard à Lyon (fonds UCBL-FSL ; NR = 6).

À partir de ces collections, trois ensembles d'études ont été définis en fonction de leur emplacement stratigraphique dans la salle des téphras (zone supérieure, zone inférieure, zone indéfinie) afin de limiter les biais de quantification liés à des périodes d'accumulation différentes. Nous ne présentons ici que les résultats globaux.
L'étude des restes osseux combine des méthodes classiques de quantification et de détermination archéozoologiques avec une analyse taphonomique (états de surface et fragmentation des restes).

3. Résultats

Ce sont au total 69 individus qui ont été comptabilisés à partir de 282 restes déterminés (Fig. 3).

Taxa	Total NRDt	%NRDt	NMIc	%NMIc
Mammuthus sp.	24	8,5%	2	2,9%
Total PROBOSCIDEA	**24**	**8,5%**	**2**	**2,9%**
Bos primigenius	2	0,7%	1	1,4%
Bison cf. *priscus*	36	12,8%	8	11,6%
Bos/Bison	64	22,7%	9	13,0%
Rupicapra sp.	1	0,4%	1	1,4%
Sous-total Bovidae	**103**	**36,5%**	**19**	**27,5%**
Cervus elaphus	24	8,5%	5	7,2%
Rangifer tarandus	26	9,2%	9	13,0%
Capreolus capreolus	1	0,4%	1	1,4%
Cervidae indet.	11	3,9%	3	4,3%
Sous-total Cervidae	**62**	**22,0%**	**18**	**26,1%**
Total ARTIODACTYLA	**165**	**58,5%**	**37**	**53,6%**
Coelodonta antiquitatis	4	1,4%	2	2,9%
Equus sp.	49	17,4%	11	15,9%
Total PERRISSODACTYLA	**53**	**18,8%**	**13**	**18,8%**
Crocuta crocuta cf. *spelaea*	4	1,4%	1	1,4%
Ursus arctos	1	0,4%	1	1,4%
Canis familiaris	2	0,7%	1	1,4%
Cuon sp.	14	5,0%	1	1,4%
Vulpes vulpes	3	1,1%	3	4,3%
Vulpes sp.	4	1,4%	2	2,9%
Sous-total Canidae	**23**	**8,2%**	**7**	**10,1%**
Total CARNIVORA	**28**	**9,9%**	**9**	**13,0%**
Marmota marmota	1	0,4%	1	1,4%
Rodentia indet.	3	1,1%	2	2,9%
Total RODENTIA	**4**	**1,4%**	**3**	**4,3%**
Lepus sp.	7	2,5%	4	5,8%
Total LAGOMORPHA	**7**	**2,5%**	**4**	**5,8%**
Pyrrhocorax graculus	1	0,4%	1	1,4%
Total AVES	**1**	0,4%	**1**	1,4%
TOTAL	**282**	**100,0%**	**69**	**100,0%**
NRT	459			

Figure 3 : Spectre faunique de l'aven du Devès de Reynaud. NRDt : Nombre de restes déterminés totalement. NMIc : Nombre minimum d'individus par combinaison. NRT : Nombre de restes total.

Le spectre faunique est diversifié avec dix espèces d'herbivores et cinq de carnivores, dont une espèce domestique, représentant des niches écologiques variées. Les herbivores représentent les trois quarts de l'assemblage et sont dominés par les bovinés (*Bison priscus* et *Bos primigenius*), les équidés (*Equus* sp.), le renne (*Rangifer tarandus*) et le cerf (*Cervus elaphus*). Viennent ensuite le mammouth (*Mammuthus* sp.), le rhinocéros laineux (*Coelodonta antiquitatis*), le chamois (*Rupicapra* sp.) et le chevreuil (*Capreolus capreolus*). Les carnivores sont peu représentés en nombre de restes et sont dominés par le renard (*Vulpes vulpes* et *Vulpes* sp.). Des restes de dhole (*Cuon* sp.), d'hyène des cavernes (*Crocuta crocuta* cf. *spelaea)* et d'ours brun (*Ursus arctos*) sont présents. Une mandibule et un fragment de maxillaire de chien (*Canis familiaris*) ont également été découverts et feront l'objet d'une étude ultérieure pour déterminer s'il s'agit d'une intrusion récente ou non (localisation stratigraphique manquante). Le spectre est complété par quelques restes de lièvre, de marmotte, de petits rongeurs et d'oiseau.
La population qui constitue cette faune est composée pour un tiers d'individus juvéniles.

La majorité du matériel correspond à des os complets ou quasi-complets, dont certains de grandes dimensions (e.g : mandibule et fémur de mammouth). La fragmentation, lorsqu'elle est présente, est le plus souvent sub-récente et liée à l'extraction des restes au piochon au cours du 19ème siècle. Des indices de fragmentation plus ancienne, sur os sec, sont visibles sur près d'un tiers du matériel et s'expliqueraient par des remaniements post-dépositionnels liés à des phénomènes naturels. Par ailleurs, moins de 1 % des restes présentent une fragmentation sur os frais, c'est à dire sub-contemporaine de la mort de l'animal. Aucun indice de fracturation anthropique n'a été relevé.

L'analyse de l'état des surfaces osseuses révèle des modifications climato-édaphiques variables, souvent de faible intensité. La présence de stries d'abrasion naturelle, fines et en petite quantité, témoigne d'un déplacement limité et non répété du matériel osseux pouvant être attribué à du charriage sédimentaire ou à du piétinement. Il n'y a pas de polissage associé. L'ensemble de ces marques indiquent que les os sont restés en surface quelques temps avant enfouissement mais qu'ils ont été globalement bien préservés. Les marques de consommation de carnivores sont rares (<5 %) et peu prononcées. Aucune marque anthropique n'a été relevée sur le matériel étudié.

Enfin, les représentations anatomiques sont globalement équilibrées et les nombreux remontages suggèrent que certains éléments étaient en connexion anatomique au moment de leur dépôt.

4. Discussion et conclusion

Les espèces en présence sont cohérentes avec les datations du projet TéphrArd qui indiquent des dépôts allant du milieu du Pléistocène moyen (350 ka) à la toute fin du Pléistocène supérieur (12 ka) (PUAUD *et al.* 2020 ; *à paraître*). Considérant les résultats actuels de l'étude paléontologique et l'absence de localisation stratigraphique pour une majorité des restes, il n'est pas possible d'apporter plus de précisions sauf pour la partie supérieure de la salle des téphras. La faune de ce secteur présente des similitudes avec l'aven de l'Arquet (GAMBERI *et al.*, 2011) et le niveau 4 de la Baume Moula (DEFLEUR *et al*. 2001). Ceci permet d'estimer une période de dépôt comprise entre le MIS 2 et le MIS 4 pour cet ensemble. La poursuite des études paléontologiques et la comparaison avec d'autres avens-pièges locaux devra permettre de préciser ces périodes de dépôt.

Les données populationnelles (espèces herbivores et grégaires majoritaires ; fort taux d'individus juvéniles), l'étude taphonomique des restes osseux ainsi que les représentations squelettiques indiquent que cette accumulation serait liée à la chute d'animaux à travers un piège naturel, un aven-piège (COUMONT, 2006). Celui-ci, aujourd'hui colmaté en surface, devait être adjacent à l'entrée actuelle (Fig. 3) de la cavité. Cette interprétation serait notamment cohérente avec la morphologie de la salle des téphras qui présente un conduit vertical à sa partie supérieure formant vraisemblablement le reliquat de l'ancien puits d'entrée. D'autre part, il ne semble pas qu'une entrée secondaire, plus accessible pour les hommes ou les carnivores ait existé, ni que l'eau soit la cause principale de l'accumulation.

Les résultats sédimentologiques du projet TéphrArd, quant à eux, indiquent que les dépôts sédimentaires sont liés à un contexte fluviatile peu compétent. L'eau, provenant d'autres secteurs du karst, aurait donc eu un rôle important dans leur mise en place. La confrontation de ces résultats avec ceux de l'étude faunique apporte donc de nouvelles perspectives sur l'interprétation de la mise en place du gisement de l'aven du Devès de Reynaud. Son histoire pourrait ainsi être liée à un dépôt mixte, gravitaire et fluviatile, par phases successives ou de façon concomitante. L'extraction du gisement au 19ème siècle, à la base de ce qui pourrait être l'ancien puits d'entrée, nous prive aujourd'hui de certaines données qui pourraient aider à l'interprétation de ses dépôts.

Dans ce contexte, la poursuite de l'investigation historique devra permettre de retrouver de plus amples témoignages sur les travaux entrepris à l'aven du Devès de Reynaud et de mieux cerner les modalités d'exploitation des phosphates en cavité en Ardèche au cours du 19ème siècle.

Ainsi, les études menées sur les dépôts sédimentaires et fossiles de l'aven du Devès de Reynaud apportent des éléments sur l'histoire géologique de la cavité et viennent compléter les données existantes sur les paléo-environnements et les paléofaunes du Pléistocène sur le plateau de Saint-Remèze. Les témoignages récents laissés dans la cavité, combinés aux archives, permettent, quant à eux, de retracer l'histoire de son exploration et de son utilisation par l'Homme. L'aven du Devès de Reynaud constitue ainsi un exemple de cavité aux multiples facettes, conservatrice d'un patrimoine souterrain à la fois d'intérêt scientifique et historique, ici digne d'être mis en valeur.

Figure 4 : Entrée actuelle de l'aven du Devès de Reynaud

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Nous remercions chaleureusement tous les acteurs et collaborateurs du projet TéphrArd ainsi que toutes les personnes et les institutions qui ont donné de leur temps et aidé à rendre ce travail possible. Nous remercions également toute l'équipe du Symposium 8 de nous permettre de présenter ces travaux au Congrès 2021 de l'Union Internationale de Spéléologie.

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Volume V

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