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PROCEEDINGS

VOLUME IV

Session 09 : Exploration, Speleological Techniques, and Materials

09:1 : Cave Diving

09:2 : Exploration

09:3 : Topography, Mapping, 3D Scanning, and Documentation

Session 10 : Cave Rescue: Karst Geomorphology

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Proceedings of the 19th International Congress of Speleology

38° Congresso Brasileiro de Espeleologia

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FOREWORD

The proceedings of the 19th International Congress of Speleology, held in Belo Horizonte (Brazil) from July 20 to 27, 2025, comprise seven volumes that gather over 400 scientific papers (extended abstracts) distributed across sixteen thematic sessions. These works were evaluated by an extensive group of reviewers, each guided by a Brazilian and a foreign coordinator, aiming to ensure their collective relevance, proper presentation, and compliance with the UIS Code of Ethics. The layout of the articles was prepared by the authors themselves and is their sole responsibility; however, the editorial team made an extra effort to maintain a minimum standard in their presentation.

These proceedings represent the work of more than a hundred individuals—scientists, technicians, and explorers who voluntarily dedicated thousands of hours to their production. To all of them, our heartfelt thanks. We hope you enjoy it and that the science compiled herein broadens the technical and academic horizons of karst and cave science.

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Session 09

EXPLORATION, SPELEOLOGICAL TECHNIQUES, AND MATERIALS

09:1: Cave Diving

Underwater Explorations on Almonda Cave, Portugal – new achievements

Rui Luís (1,2), Pedro Arriegas (2,1), Paulo Rodrigues (3), Armando Ribeiro (2), Tiago Grosso (2) & Nuno Sousa (2,1)

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Abstract

The Almonda's Spring Cave (or Olho do Moinho da Fonte) is located on the south-east edge of Serra de Aire's anticline (Torres Novas), being a consequence of, among others, the contact between Maciço Calcário Estremenho and the less permeable and non carsifiable terrains of Low Tejo's basin.

This cave and its spring constitute the rising of the subterranean hydrologic network of the most extensive karst system in Portugal. Almonda spring cave has a horizontal development of roughly 17 km and a 285 m depth, including a 197,5 m deep underwater tunnel. It is the biggest and deepest cave in Portugal (2024). With an extensive system of underground passages, fossils or actives and, due to its complexity and dimension, its exploration and recording are still to be finished (started in 1937). It is also the site of the major archaeological cave study in Portugal, with an occupation from Neanderthal times (400 thousand years) until roman age (year 400).

This paper aims to describe the project (2011-2024), the exploration history, the current state of the underwater explorations, the methods and techniques used, the goals achieved and the areas still to be explored.

Résumé

La grotte d'Almonda (ou Olho do Moinho da Fonte) est située sur le bord sud-est de l'anticlinal de Serra de Aire (Torres Novas), conséquence, entre autres, du contact entre le Massif Calcaire Estremenho et les sols moins perméables du bassin du Tage.

Cette grotte et cette source constituent la remontée du réseau hydrologique souterrain du système karstique le plus étendu du Portugal. La grotte d'Almonda a un développement horizontal de 17 km et vertical de 285 m, y compris un tunnel sous-marin de 197,5 m de profondeur. La grotte est la plus grande et la plus profonde du Portugal (2024). Avec un vaste système de galeries souterraines, fossiles ou actives et, en raison de sa complexité et de sa dimension, son exploration et son enregistrement sont encore à terminer (commencé en 1937). C'est également le site de la plus important étude archéologique de grotte au Portugal avec une occupation de l'époque néandertalienne (400 mille ans) à l'époque romaine (an 400).

Cette article vise à décrire le projet (2011-2024), l'historique de l'exploration, l'état actuel des explorations subaquatiques, les méthodes et techniques utilisées, les objectifs atteints et les zones restant à explorer.

1. Introduction

Located in Torres Novas municipality, Zibreira parish, local of Casais Martanes, 393017,6N 83654,85W - WGS84, altitude 83 meters, military map 319.

The most extensive karst cave in Portugal, known so far, presents a 285m depth including a 197,5 m deep underwater gallery and a total length of 17 013 metres.

2. Brief History

Around 80 years ago, more properly in 1937, its entrance was rediscovered, a fossil spring. The archaeologists Vaultier and Bensaúde, with the help of Reverend Eugenio Jallay, the engineer Melo Nogueira and professor G. Zbyszewski, explored 50 m of dry gallery until an underground lake and detected archaeological findings dating the Bronze age.

In 1955, with SPE – Sociedade Portuguesa de Espeleologia aiming to evaluate the spring's hydrologic potential, and upon Renova's tissue factory request, Pereira de Sousa and F.J.R. de Abreu crossed the first lake in a canoe but without going much further than their predecessors.

In 1961, K. Lindberg with J. de Almeida Fernandes organised the first biospeleology expedition in Almonda's Cave.

Still in 1961, Álvaro Vilar Moreira, José Carlos Belchior and Vasco

Fernandes, teachers at São João de Brito College in Lisbon, reach a small room in a labyrinth after discovering a narrow access.

The same Álvaro Vilar Moreira, after several explorations, in 1962, managed to discover an access which allows him to overcome the siphon constituting the first lake. He discovers then the main part of the labyrinth and the North gallery (Zilhão, J.).

Since then, and as a result of stone tools' discovery in 1987 by STEA – Sociedade Torrejana de Espeleologia e Arqueologia, several archaeological sites (from Lower Palaeolithic to the Roman period) have been discovered in this cave, and are being studied ever since.

In archaeological terms, and according to the archaeologist João Zilhão, we are facing a system of deposits with few parallels worldwide, and with representation of all the pre-historic stages.

During the 60's and 70's the topography work continued, but it is in the 80's and in the following years that speleologists João Neves (SAGA – Sociedade Amigos das Grutas e Algares) and Christian Thomas (SCX – Speleo Club de I´X), using diving techniques, in several explorations and with the help of several associations (CEAE – Centro de Estudos Arqueológicos e Espeleológicos, NEL – Núcleo de Espeleologia de Leiria, GIDC – Grupo de Investigação e Divulgação Científica, GEZ – Grupo de Espeleologia da Zibreira and NEUA – Núcleo de Espeleologia da Universidade de Aveiro), largely expand the knowledge on the system.

In 1993 the Cave was classified as a Public Interest Site – Decree-Law n^0 45/93, DR, I Series-B, n^0 280, of 30-11-1993.

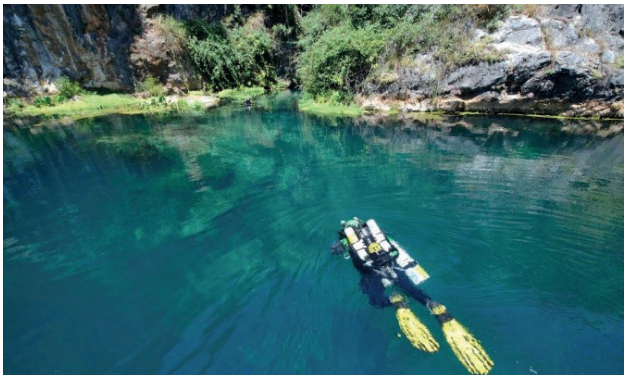

Figura 1: Cave's entrance – Renova's factory dam – dry season.

3. Geological Context

The cave is located in Estremenho Karst Massif (MCE) aquifer system, which belongs to the largest hydrogeological unit of Western Mesocenozoic Basin.

The MCE corresponds to a morphostructural unit in the Portuguese territory that is detached from surrounding regions by its geological and geomorphological peculiarities.

It is constituted by materials constituted by Jurassic carbonated rocks which includes mostly limestones but also, dolomite limestones, clayey limestones, marls and marly limestones. The Massif is limited at South, West and East, by faults, along which MCE was elevate. The faults make the contact between MCE and the surrounding Cretaceous and Tertiary non karst or less carsifiable terrains.

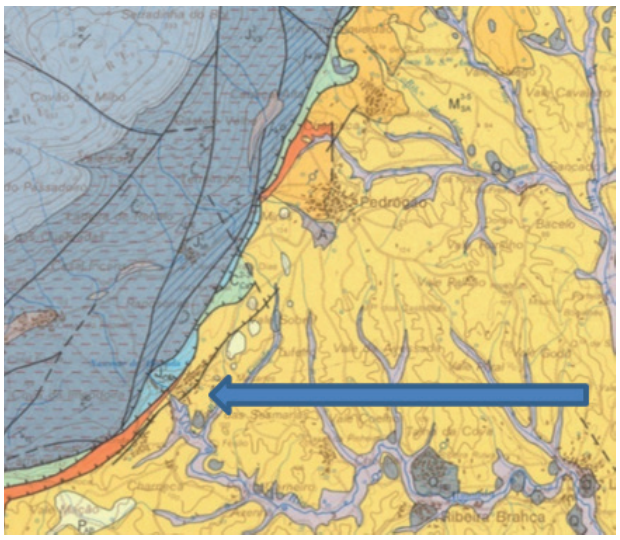

Figure 2: Extract from Chart 27A – Torres Novas, Portugal Geological Map, scale 1:50 000 (picture without scalea.

4. Hydrogeology

The aquifer system is quite complex, presenting a typical karst aquifer behaviour, characterized by the existence of few perennial springs and several temporary springs with high water flows, but with highly pronounced variations over time. It is constituted by several subsystems whose limits coincide approximately with large morphostructural units that divide the MCE. Each of those subsystems is related to a perennial karst spring and, occasionally, with several temporary springs which discharge only on peak periods. The delimitation of recharge areas of each spring presents substantial difficulties due to the highly complex pattern of drainage in karst environment. The safest procedure of delimitation is through tracing operations, which is, introducing a substance (tracer) whose presence is later on detected in the discharge location. (Almeida et al. 2000). The five main springs are located at the massif limits, in the contact area with rock less permeable from the Jurassic, Cretaceous or Tertiary. Two of them are located in the West limit (Liz and Chiqueda) and the other three in the South and East limits (Almonda, Alviela and Alcobertas).

The Olhos de Água do Alviela spring is the most significant in the whole massif, presenting a discharge higher than 1 hm3/day while in the dry season it registers values of 30 000 m3/day. The average annual discharge is 120 hm3/year. In Almonda and Liz springs the estimated discharge values are between 80 and 100 hm3/year and between 60 and 70 hm3/year, respectively, in comparison with the discharge values from Alviela's spring (Almeida et al. 2000b).

The spring in the present research, Almonda's cave spring, or Olho do Moinho da Fonte (the costumary name), has the second largest discharge of this aquifer system and it's located on the far east of the triangle Alviela, Almonda and Polje de Minde.

5. Groundwater Flow

Dye tracing carried out in 1986, (Crispim, 1995) with uranine injected in one of Minde's polje's sinkhole (Pousia do Parramal, with fluocaptors placed in three monitored springs, Olhos de Água do Alviela, Olho da Maria Paula (Vila Moreira) and Olho do Moinho da Fonte (Almonda's spring) showed fluorescein transition only in the first two.

In 1989 (flooding period – December) and in 1990 (at the end of the flooding period – March) Crispim confirmed with dye tracing the connection between one of the sinkholes from Minde's polge (Algar do Zé Lenha) south-east sector and the Almonda's spring. The speeds obtained are around 241 m/h and 191 m/h, respectively in relation to the flooding period and the end of the flooding period.

In March of 1991, during the flooding period, the tracing was repeated in both polje's sectors, south-west and south-east, with differentiated tracers in order to detect the possible circulations. In this multitracing it was confirmed once again the non-connection between Algar do Parramau (south-west) and the Almonda's spring and the connection of Algar do Zé Lenha (south-east) with the mentioned spring. The average speed was around 238 m/h.

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Figure 3: Circulation lines traced. (Crispim). Dashed line - not confirmed. Continuous line - confirmed.

10-Algar do Zé Lenha (sinkhole), 11-Pousia do Parramal (sinkhole), 12-Alviela's Spring, 13-Vila Moreira's Spring, 14-Almonda's spring

Two possible areas of origin to Almonda's spring water are from Serra d´Aire anticline, and from Moitas Venda/ Polje de Minde.

6. The Underwater Exploration past

In the 80's occurred a considerable impulse on submerged areas studies, with explorations being led by Neves e Thomas. Back then, the access to the submerged zone was through a dry upper entrance, with a large part of the system having been explored and photographed under these difficult circumstances, where the heavy equipment had to be carried through narrow passages until the flooded zone.

In 1991 STEA unblocked the current submerged entrance located in the spring, but the recurrent movement of large stone blocks would involve the regular clearance of the entrance during the following years. During a substantial part of the year the strong flow resulting from two subterranean streams, designated by West and North, prevents the system to be dived in, but from this date on, and even with this constraint, the submerged zone becomes accessible underwater, with the dives starting at Renova's factory dam.

From that period resulted the most important publications: Thomas, C., (1985, Neves, J. (1985 and 1986), Zilhão, C. et al. (1991), Thomas, C. (1988, 1989, 1991 and 1997).

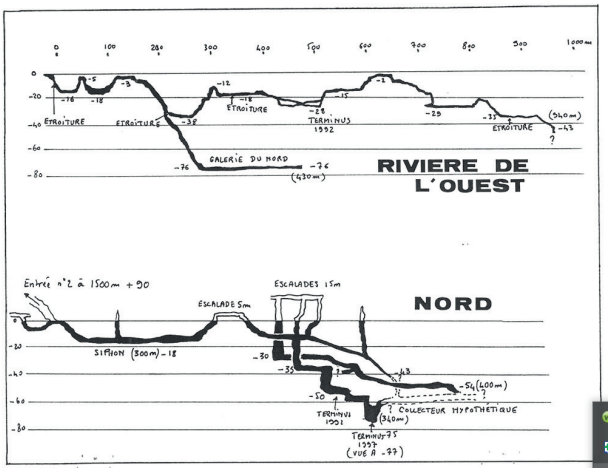

Figure 4: Thomas, C. (1997) – Expeditions report Portugal. Underwater profile from the entrance (top) and the underwater northern extreme - Almonda Novo (bottom).

7. The Project (2007-2011-2024)

In 2007 members from XploraSub, NEUA and SAGA associations Aproceed to a new clearance of the entrance, which has been stable since then. The cave's submerged area rigging and the underwater topography are then restarted, in a more systematic way.

Diving into the system, through a very narrow access, we come across a subterranean labyrinth, where several levels of galleries overlap themselves, presenting multiple permutations. This is a hostile environment, only accessible to certified cave-divers. After this labyrinth and the lake mentioned above, known as the Cistern, the galleries become more defined, with wider dimensions and a greater depth.

Between 2008 and 2010 members of XploraSub and NEUA proceed to a regular work, first around the labyrinth zone and after around other submerged areas. The cave was refitted with lifeline and navigation signals, the galleries' systematic tagging was initiated and the topographical information improved. Errors were rectified, secondary galleries were mapped and with the addition of new details the draw was enhanced.

These works constituted the embryo of PROJECTO ALMONDA [Almonda's Project], which has its beginning in 2011, when it was decided to structure the underwater exploration under a XploraSub/NEUA partnership, but counting on with other participants as well, both as individuals or from other associations.

Still in 2011 and 2012 it is organised a cave-diving campaign, which counts with Renova's and CPAS Filling Station (managed by J. Forte--Faria) support, launching the regular exploration bases of underwater areas. The deepest and most remote zone of North's Gallery, with -78m of depth, was reached. In that year no unexplored areas significant to the system development were found, but several branches from main galleries, presumably never visited before, were explored.

After this campaign, it was foreseen the need to map certain secondary deep areas, located in the furthermost part of North Gallery and it became indispensable to adopt more streamlined gear riggings, to negotiate restrictions within the West Gallery. Then it was also expected that, in due course, this task would be extended to dry cave areas.

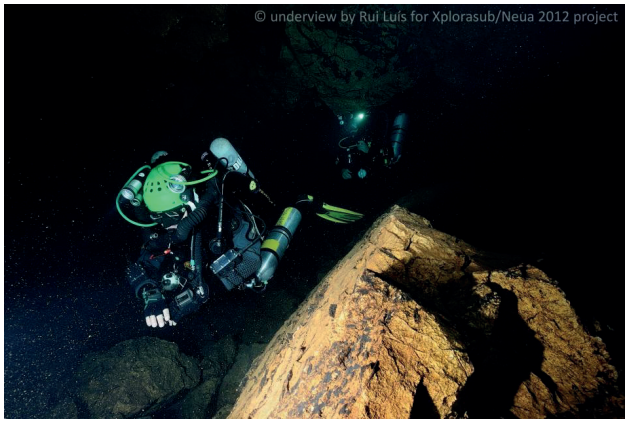

Figure 5: *North Gallery - downward.*

In 2013, the Almonda's Project started being developed under a partnership between XploraSub and AESDA. During that year, 28 explorations dives were undertaken, with an average duration of more than two hours and an average maximum depth of -41m. Great progress was achieved on topography of several galleries and others passages were marked for future checking. There was also an upgrade on all cave navigational markers, in order to make them more resistant to the abrasion due to the water flow during winter, raising consequently the security level. In Gallery A (North) a steel cable was laid until -66m, which implied the remake of the topography of some sections.

Already in 2014, and besides early rains, 18 dives were performed, with an average duration of almost two and a half hours and an average maximum depth of -30m. In the course of that year, the work in the dry area began, allowing to tune the underwater topography and the progress on a global understanding of the system. Several submerged passages to the dry area were marked, being then achieved its connection to the dry topography meanwhile initiated. The cave's submerged entrance was also geographically referred. The cave navigational markers kept being maintained and improved, with the replacement of damaged lifeline and unreadable labels.

Figure 6: *Almonda River in flood season - spring.*

With the connection between dry and underwater topographies it was possible to confirm the true position of the cave, both underwater and dry areas, and to establish comparisons with earlier literature.

With the overlapping between earlier topography (Thomas, 1991) and the one produced by Almonda's Project it was possible to detected a scale error on the underwater plan map from Thomas.

The work in 2015 had an early start and besides some rain in October it was possible to extend it almost until the end of the year, with 22 dives, with an average duration of almost two hours and an average maximum depth around -38m.

Work in dry areas kept progressing, not only in order to assess underwater topography and referencing it to the outside, but also to enhance the global knowledge of the system.

In 2015 there was maintenance, revision and correction on the navigational markers (line, mooring and labels) in several galleries, revising the steel wire in Gallery A; topometry was checked, revised (in sections where the cave equipment was modified) or performed on Gallery A; the exit to a dry area designated as Almondinha II was marked, the topography connection between several stations was redone and the map topography of a significant section of Gallery A was produced in a scale of 1/100. Furthermore, underwater images (photography) from the galleries were captured, namely from Gallery A (North).

On dry exploration, the two siphons in West Gallery were overcome and the exploration on those galleries proceeded.

In 2015 it was registered an underwater development of 916 m, with an unevenness of 78 m (0 to -78m) - 277 stations, with a 4.52% error. Dry and underwater after revision with 3.68% error. Over the topometry the galleries were drawn in a scale of 1/100. The lifeline was also repaired in Galleries A (North) and W (West). Several film shootings were also taken during a number of dives.

As in 2015, in 2016 due to a late rainy season it was possible to access to the system in December, which allowed to dive for 22 times, with an average of 135 minutes and a maximum average depth of more than -43m, while achieving a huge progress in the submerged galleries work.

In 2017 some dry and underwater activities were carried out to finalise the underwater survey from the entrance and to start the polygonal of the dry northern section of the cave – usually known as Almonda Novo.

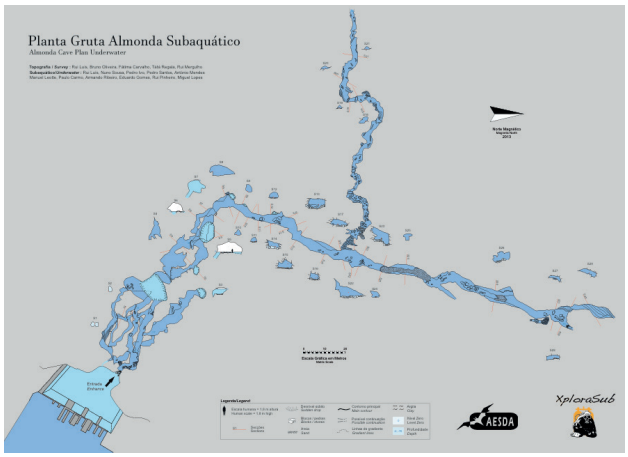

Figure 7: *Underwater survey plan published in Trogle n.7 – AESDA.*

Between 2018 and 2020 only maintenance and training dives were performed. In later 2021 a first dry activity was carried out to prepare the exploration of Almonda Novo underwater galleries.

From 2022 onwards, the Almonda Project became an AESDA-XploraSub-GEM joint venture in order to explore the northern section of the cave (Almonda Novo) and its underwater galleries which were dived in late 1997. During 2022, 20 activities took place to raise our acquaintance with the dry and underwater galleries. The furthest point of the lifeline at north was reached, by Cape Canaveral syphon, and the line was extended for more 120 meters of new tunnel -76 meters deep by Armando Ribeiro and Tiago Grosso.

During 2023, 7 activities were carried out and the lifeline was extended on the cave for more 145 meters underwater and to a maximum depth of -165 meters. Push dives were performed by Armando Ribeiro and Tiago Grosso.

Then, in 2024 it was possible to carry out another 14 activities to push further the limits of the cave. A depth of -197.5 meters was reached, with a development of more 135 meters. The push dive was performed by Armando Ribeiro, with the support of Tiago Grosso and Hugo Ballester.

Between 2022 and 2024, the push divers were supported by the divers Rui Luís, Luís Gonçalves, Nuno Sousa and Hugo Ballester. All the divers were also supported by a huge human effort of speleologists that reach an average of 20 cavers in each activity, with a total of 100 cavers from the 3 associations involved.

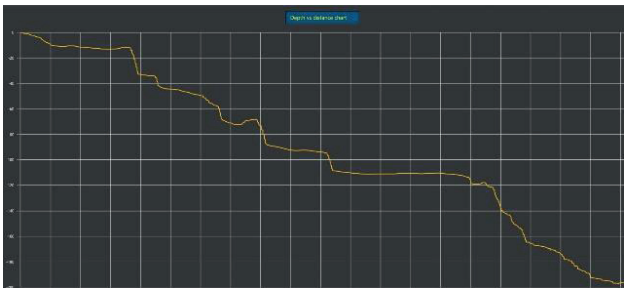

Figure 8: *Profile from the last dive.*

To perform this type of dives in quite harsh conditions divers used dual rebreathers, scooters, heating systems and carbon cylinders. To reach the final siphon it was needed to carry all the dive and support equipment through a dry section of the cave with 600 meters length and an unevenness of 87.5 meters. After that herculean effort it was necessary to dive a first shallow siphon of -30 meters depth and 250 meters length. Between this first siphon and the one to be dived, a dry section was necessary to be overtaken by the cave divers alone, carrying all their gear. With an extension of 50 meters and an 5 meters unevenness, 2 hours more had to be added to the journey inside the cave. To return, after a 3 hours dive, the same was mandatory. In total, to perform the dives from the start in the first siphon and to return to the surface it took 10 hours long.

Figure 9: *Survey map of the cave.*

8. Conclusion

The cave, with this long and fruitful endeavour from the joint-venture, has now a known extension of 17 013 metres and a -285 meters depth. This depth turns Almonda cave to be the deepest one in Portugal.

This work was only possible thanks to the strong collaboration between three institutions with a high degree of commitment and professionalism. This cave showed once again that knowledge is always temporary and possible to overcome. This cave will continue to reveal itself to science as cavers continue to work there, while collaborating and disseminating their results.

Acknowledgments

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Explorations of phreatic caves in Nobres, Brazil, and the first insights about the karst aquifer

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Abstract

This paper combines findings from underwater cave explorations with geoscientific data to enhance the understanding of the karst aquifer. Underwater explorations in Nobres -MT produced maps of diving lines in Pai João (PJ) and João Terêncio (JT) caves. The diving and safety procedures adopted to explore the caves with depths of over 100 meters ensured incident-free dives, facilitating the exploration and survey. The maps reveal that JT spring is a vauclusian cave while PJ, located at the bottom of an ephemeral sinkhole functions like a lake but also exhibits the structure of a vauclusian cave. The integration of geological and geomorphological data with the cave maps reveals that the vauclusian structure of the caves is related to their location in a lithological contact zone with siliciclastic rocks. These rocks form a hydraulic barrier for the karst groundwater promoting upward flows and developing conduits in subvertical strata. Topographic data were used to verify the altitude difference between the cave entrances. However, the results were inconclusive, opening the possibility to infer whether the caves are components of a single hydrological system or represent two independent systems. This question leads to exploring possible evolutionary aspects of the caves.

1. Introduction

This paper presents the preliminary findings from the exploration of phreatic caves in Nobres, Mato Grosso, Brazil and how integrating the cave maps with geological and geomorphological information improves the understanding about karst aquifers.

The Nobres region (Fig.1) presents a tropical climate, humid in the summer, dry in the winter with transitional seasons in autumn and spring. The average annual temperature is 25°C and the total annual rainfall is 1920 mm. These conditions support the development of vegetation with features of both: the Cerrado and the Amazon rainforest.

The landscape developed in folded lithologies exhibits karst surfaces that are lower in relation to the surrounding relief formed by siliciclastic rocks. The karst formed in Neoproterozoic dolomites from the Nobres Formation occupies an eroded anticline structure with more than 50 km in length and variable width between 2 and 5.5 km. The anticline flanks expose Neoproterozoic rocks from the Raizama Formation, consisting of sandstone and arkose with conglomerate layers and intercalations of siltstone and claystone; these rocks support ridges and plateaus adjacent to the karst.

The study focuses on the karst sector related to the Serra das Furnas ridge, drained by the basin of the Quebozinho River and the João Terêncio and Lúcio Feio exsurgences; the regional base level is the Cuiabá River. Most of the area is withing the Gruta Azul state park, a natural reserve managed by the state of Mato Grosso.

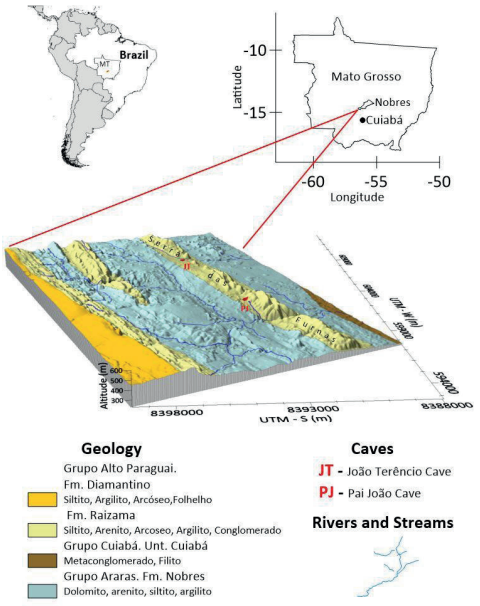

Figure 1: *Location of caves, geology (CPRM, 2004) and geomorphology of the Serra das Furnas region.*

Based on reports from divers, we decided to explore two locations, Pai João and João Terêncio caves. The entrance to

Pai João Cave is at the base of a steep sinkhole on the ridge slope (Fig. 4 A and B). This ephemeral sinkhole collects water from a small drainage basin. According to reports from the local community, during the rainy season, the water level inside the sinkhole can rise more than ten meters

compared to the level observed during dives. From the parking area, it is necessary to walk a trail of 1.8 kilometers to reach the entrance of the sinkhole. From there, a descent of approximately 50 meters on rough terrain leads to the water's surface. Although it is not a long distance, transporting the various cylinders used in the dives (along with various support materials) is very labor-intensive, requiring the support of the local volunteers. Very little information was available about previous dives in this area, but it was brought to our attention that in the past 20 years or so dives were conducted there, although no signs of previous surveys were observed.

The second target, João Terêncio Cave is a spring located in the thalweg of the Mutum Creek, near the section where the drainage crosses the lithologies of the Serra das Furnas ridge; in this sector, the ridge relief is less pronounced. The cave is within private property, which uses its water for agricultural activities. Tubes connected to the resurgence also supply properties downstream. In this area, the logistics for diving are straightforward because vehicles park next to the cave (Fig. 5 A and B). The site has been explored on multiple occasions, and we discovered lines left by previous explorers. However, no published maps of the cave were found.

Two expeditions were conducted in the area, the following sections outline the procedures adopted and the results obtained.

2. Materials and methods

2.1. Dive Planningo

During the first expedition, in May 2023, it became clear that, given the extreme depths of the systems, special protocols would have to be used to assure the safety of the exploration team. All dives were conducted in closed circuit rebreathes (JJ CCR, Sweeden). The gas chosen as diluent consisted in a mix of 10% oxygen, 70% helium and 20% nitrogen and the rebreathers were set to keep the oxygen pressure at 121 kPa (1.2 ATA – total pressure equal to gauge plus 0.93 atm of surface pressure) throughout the dive, raising the oxygen pressure to 141 kPa (1.4 ATA) at 162 kPa (6 msw – meters of sea water). The mix chosen keeps the density of the breathing gas lower than 5 g L-1, reducing substantially the risk of hypercapnia. Additional cylinders, containing enough gas for each one of the exploration divers to complete the dive safely out of the closed-circuit units were placed in the cave. The mixes chosen for such "bail out" gases were: (i) 10% oxygen, 70% helium and 20% nitrogen; (ii) 15% oxygen, 55% helium and 30% nitrogen; (iii) 21% oxygen, 35% helium and 44% nitrogen; (iv) 50% oxygen, 25% helium and 25% nitrogen; and (v) pure oxygen.

All decompression schedules were defined using ZHL-16C algorithm. Compartments half-times for nitrogen and helium were set to the original values published by Bühlmann (1984). Maximum supersaturation pressures for each compartment at the end of the dives were adjusted so that the intercept a of the linear equations used to limit the compartment j supersaturation for a given ambient pressure P_{amb}, in the format $P_j = \frac{P_{amb}}{bj} + a_j$ were multiplied by 0.75, while factor b_j were adjusted tocalculate stops 0.45 of the original pressure limits given by Bühlmann's values. Compartment on-gassing and off-gassing were calculated through the application of the following differential equation:

$$\frac{dP_j}{dt} = k_j \bullet \left(P_A - P_j\right) \qquad \text{(eq 1)}$$

Where P_j is the pressure of inert gas in compartment j, PA is the alveolar (inspired) pressure of inert gas, and k_j is the inverse of the half-time of the compartment multiplied by the natural logarithm of 2 (kj=ln2 · t12j-1). Solving (eq 1) we obtain:

$$P_j(t) = P_{0,j} \bullet e^{-k_j \bullet t} + P_A \bullet \left(1 - e^{-k_j \bullet t}\right)$$
(eq 2)

Where $P_{0,j}$ is the initial pressure of inert gas in compartment *j* at the time of a change in the inspired gas and/or hydrostatic pressure.

2.1.1. Safety concerns

Given the extreme depth of the system, which caused the divers to spend long periods of time at depths of over 100 meters (resulting in an average of 300 minutes), and given the remoteness of the location, during the second expedition in 8/2004, a multi-place hyperbaric chamber was taken to the site and stationed at the parking area. The purpose of this chamber was to recompress and treat any diver suffering from decompression sickness. A group of trained rescuers from the military firefighters (Corpo de Bombeiros do Estado do Mato Grosso), provided logistical support, guaranteeing that an eventual victim could be removed from the cave and taken to the hyperbaric chamber safely.

2.2. Cave Mapping and Determination of Flow Direction

Lines were placed aligned with the direction of the conduits and tied in specific survey stations. These lines have the primary goal of providing orientation to the divers, always assuring that can be followed all the way to open water, in accordance with the prevailing cave diving protocol. In addition, the lines are used as a survey tool (lines of sight) in a protocol where its azimuth, inclination, and distance between stations are used to produce a map. In this exploration, distances between walls and floor to ceiling (WFC) were not recorded. To assure the precision of the survey process, a device capable of recording the position of the line was used (Mnemo, Ariane's Line, 2023). All data obtained by the device were treated using Ariane, a 3D cave mapping software, both from the same enterprise (Ariane's Line, 2023).

To verify by visual inspection the water flow and its general direction in Pai João Cave, a bottle with 5 grams of fluorescein dye dissolved in 500 ml of water was released into a conduit during one of the dives.

2.3. Integration of Cave Maps with Surficial Data

Using SIS software (Ferrari, 1998), cave topography parameters exported from Ariane software were adjusted for magnetic declination and georeferenced with GPS coordinates. The data were then exported to the Autodesk DXF file format. The DXF files imported into Global Mapper software (Blue Marble, 2023) and Surfer software (Golden Software 2024) enabled the creation of maps and 3D visualizations of cave lines, integrating various surface data such as geology, digital terrain models, satellite imagery, and cartographic information. The combined visual inspection of cave maps with the other information provides preliminary insights about the genesis and structure of the karst aquifer.

3. Results

Approximately 900 meters of passages, mainly in Pai João Cave, where explored. Although access to the cave entrance requires a much more elaborate logistical plan, the conduits are larger and water clearer.

The Pai João Cave develops in a vertical tunnel of approximately 20 meters of diameter down to a depth of 50 meters, where it splits into two different tunnels (bifurcation sector) that reconnect at a depth of approximately 80 meters. At this point the cave forms a very large tunnel, whose dimensions were not yet determined, heading E and after with inflections to NE and S. On the SW wall of the entrance vertical tunnel, there is another conduit at a depth of approximately 40 meters. This passage leads to a well-defined tunnel, heading initially to SW/W and after with inflections to NW and NE. Depth goes up to approximately 30 meters, before starting to descend at a constant slope down to a depth of 100 meters. The survey line follows the right wall and, as the cave reaches a depth of 100 meters; both the left wall and the floor become too distant to be seen, even in the extremely clear water found in the cave. At this point exploration continued NW, following the ceiling of the tunnel for approximately 200 meters (Fig. 2).

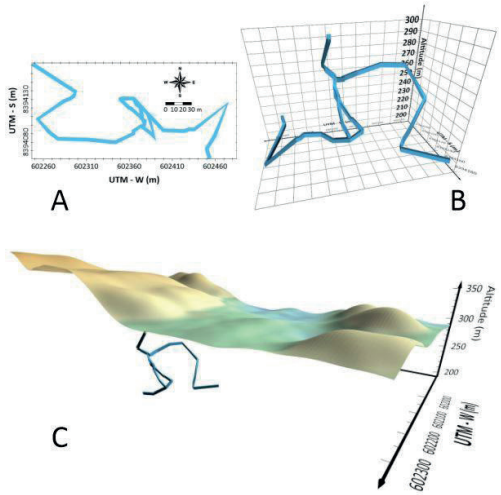

Figure 2: *Pai João Cave lines: Plan view (A), simple 3D model (B) and 3D with the surface topography. The rectangular passages model consider 2-meter WFC distances to improve the visualization.*

The fluorescein dye released at Pai João, at a depth of approximately 40 meters (Fig.4D), initially appeared static, but after some minutes, the plume followed slowly down by the SW conduit of the bifurcation sector.

The conditions at João Terêncio spring cave are very different. The cave entrance is located at a depth of 6 meters and descends into a constant slope down to a depth of approximately 90 meters. The descending tunnel is relatively small, not allowing two divers to swim side by side in most of the passages, and visibility is reduced due to accumulation of silt. At a depth of approximately 90 meters the cave develops into a much larger tunnel heading initially to W and after with inflections to NW and NE (Fig. 3).

The maximum depths reached in the Pai João and João Terencio caves were 101 meters and 109 meters, respectively. The images bellow (Fig.4 and 5) show the areas explored and aspects of the dives.

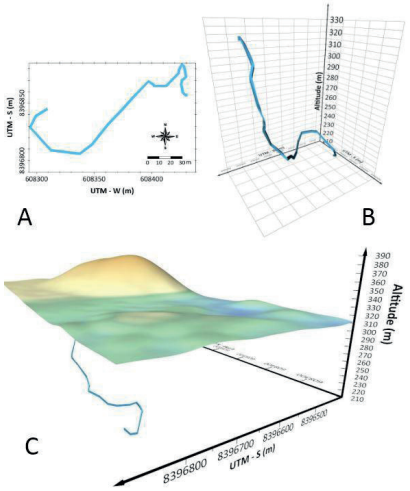

Figure 3: *Plan view (A), simple 3D model (B) and 3D with the topography of the lines of sight of João Terêncio Cave. The rectangular passages model consider 1-meter WFC distances to improve the visualization.*

The mapped lines show that João Terêncio Cave presents structure of an artesian spring, also known as vauclusian spring. Due to pressure, water rises to the surface from a depth of more than 109 meters through a nearly vertical conduit. Pai João Cave is not a spring; it works as a lake connected to ascending conduits; the tracer released indicate flow in the passages. Although the maps do not show the true contours of the passages, divers in both caves perceive relatively small ascending conduits connected to larger ones at the basal portions of the caves.

Based on GPS coordinates, the distance between the cave entrances is 6.591 km; the topographic profile obtained with Copernicus digital elevation model, with 30 m resolution (ESA, 2024), shows that João Terêncio Cave is approximately 18 meters higher than Pai João Cave. The geological map (CPRM, 2004) shows caves positioned on the southeastern flank of the anticline, along the contact zone between the dolomites and the siliciclastic rocks of the Raizama Formation (Fig. 1) and an alignment between the general development direction of both caves with the contact zone and geological lineaments (Fig 6. A and B).

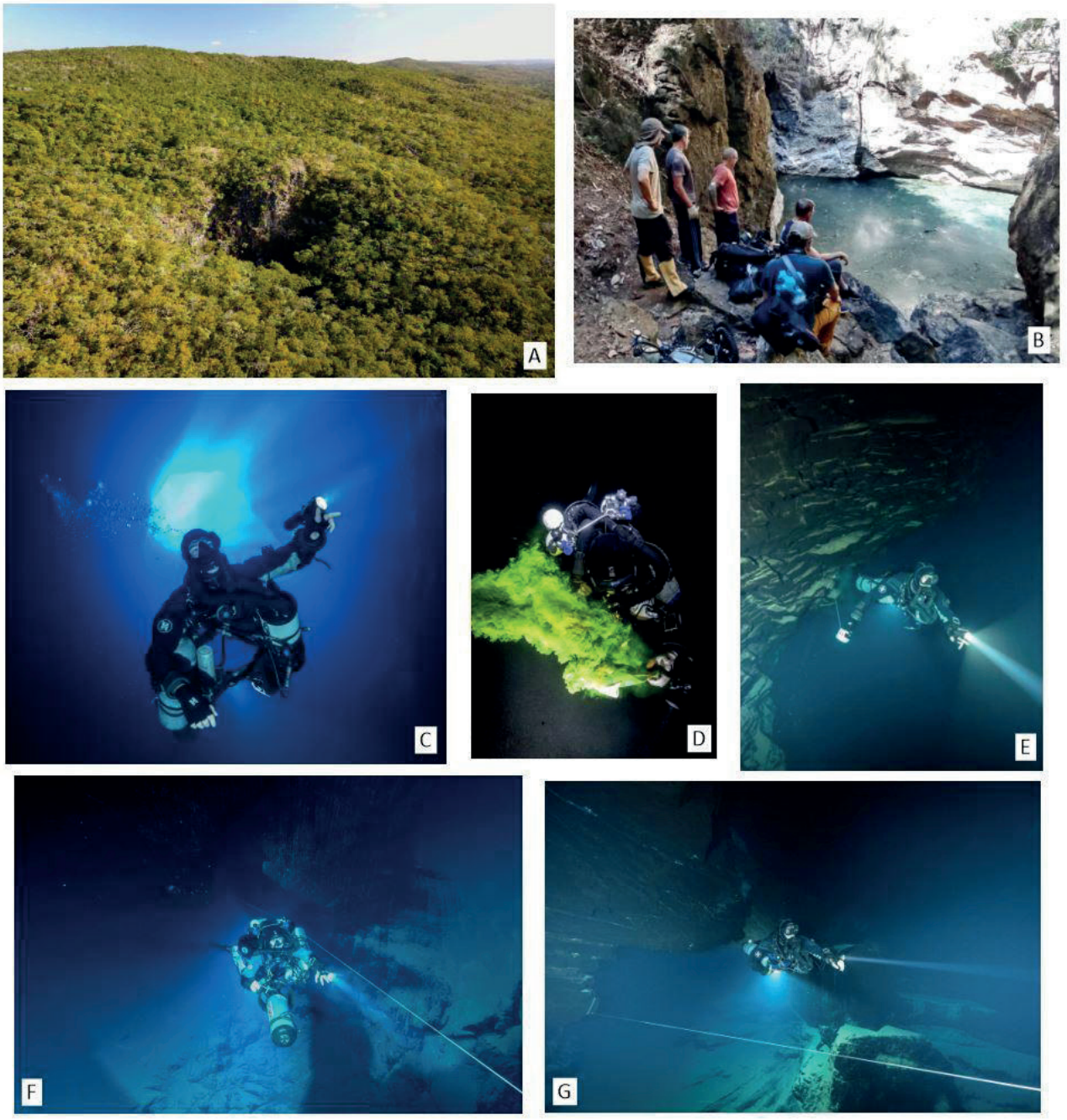

Figure 4: *Images of Pai João Cave: A- Aerial view of the doline at Serra das Furnas; B- Cave entrance; C-Diver with cave entrance in background; D-Releasing fluoresceine dye E, F an G- Mapping and exploration at different points in the cave. Subaquatic images by Kirill Egorov.*

4. Discussion

4.1. About the dives

The dive plan and the safety measures implemented ensured incident-free dives, facilitating the exploration and survey. Lucky the hyperbaric chamber infrastructure was never used.

The depths of the system and the extreme exposures, in terms of ambient pressure and times, cause the dives to become excessively long, due to the long decompression required before the divers can safely return to the surface. To illustrate the burden of this time of exposure, it suffices to say that probabilistic decompression models calculate the incidence of decompression sickness in this type of profile in the range between 7% and 11%. That, in itself, justifies the infrastructure brought to the site to treat divers in the event of a diving related injury.

The utilization of closed-circuit rebreathers in combination with ample open-circuit bail-out gas is a mandatory safety procedure, to ensure that divers will be able to exit the cave, even in the case of a failure in the breathing apparatus. For future explorations in the area, however, the team will opt for the addition of spares closed-circuit rebreathers as bail-out equipment, which will add even for safety for divers to deal with unforeseen situations.

4.2. What the caves reveal about the aquifer

The proximity and alignment of the caves with the siliciclastic rocks at the syncline flank (Fig. 6 A and B), combined with the ascending patterns of the cave conduits, indicate that the Raizama Formation acts as a barrier for the karst groundwater that flows towards the regional base level, the Cuiabá River. This conformation may concentrate and promote upward flows along the lithological contact zone, developing conduits in subvertical strata (Fig 6 C). Based on divers' perceptions, the caves developed in this context have large conduits in the basal sector and relatively small ones rising towards the surface. This cave forming process lasted for thousands of years and relates to the evolution of the plateau that divides the Amazon and Paraná hydrographic basins.

Figure 5: *A and B- Aerial views of João Terêncio Spring; C- Aspects of the spring; D, E and F- Start diving procedures at cave entrance.*

The topographic data shows that João Terêncio Cave is 18 meters higher than Pai João (Fig. 6 D). This elevation difference suggests that a hydrological connection between them is improbable: a lake in the system cannot be lower than the system's spring. However, considering the 30 m resolution of the topographic model used in the analysis and potential imprecision in the GPS coordinates, the difference cannot be categorically confirmed.

From these considerations, two hypotheses arise: A) the caves are part of the same system; B) the caves are independent systems. Under hypothesis A, a tracer test can confirm the connection between the caves. However, although Pai João Cave is at the bottom of an ephemeral sinkhole, it displays characteristics of a vauclusian cave, raising another possibility: during geological evolution, both caves were part of a distributary vauclusian system. At some point, the drainage became more effective at João Terêncio spring and Pai João Cave functioned as an estavelle, before ceasing its spring function. Under hypothesis B, the challenge is to discover the output(s) of the Pai João system; nevertheless, the hypothesis of a vauclusian spring that lost its original hydrological function is also valid.

5. Conclusion

The Serra das Furnas exploration project, in special Pai João sinkhole e João Terêncio spring represents an incredible logistical challenge. Due to the extreme depths encountered, each diver needs more than 100 kg of equipment, which must be taken and retrieved from the cave frequently. In the case of Pai João, this transportation is even more challenging, given the distance between the road and the actual cave entrance.

The integration of geological and geomorphological information with the knowledge obtained during the dives led to an understanding of the karst aquifer and the formulation of conceptual models about the genesis and evolution of the caves.

The inferences presented are just the first step for the future researches with the caves of Serra das Furnas. Certainly, understanding the karst in the region will require hydrological monitoring and experiments with natural and artificial tracers, besides of course, the maintenance of underwater explorations.

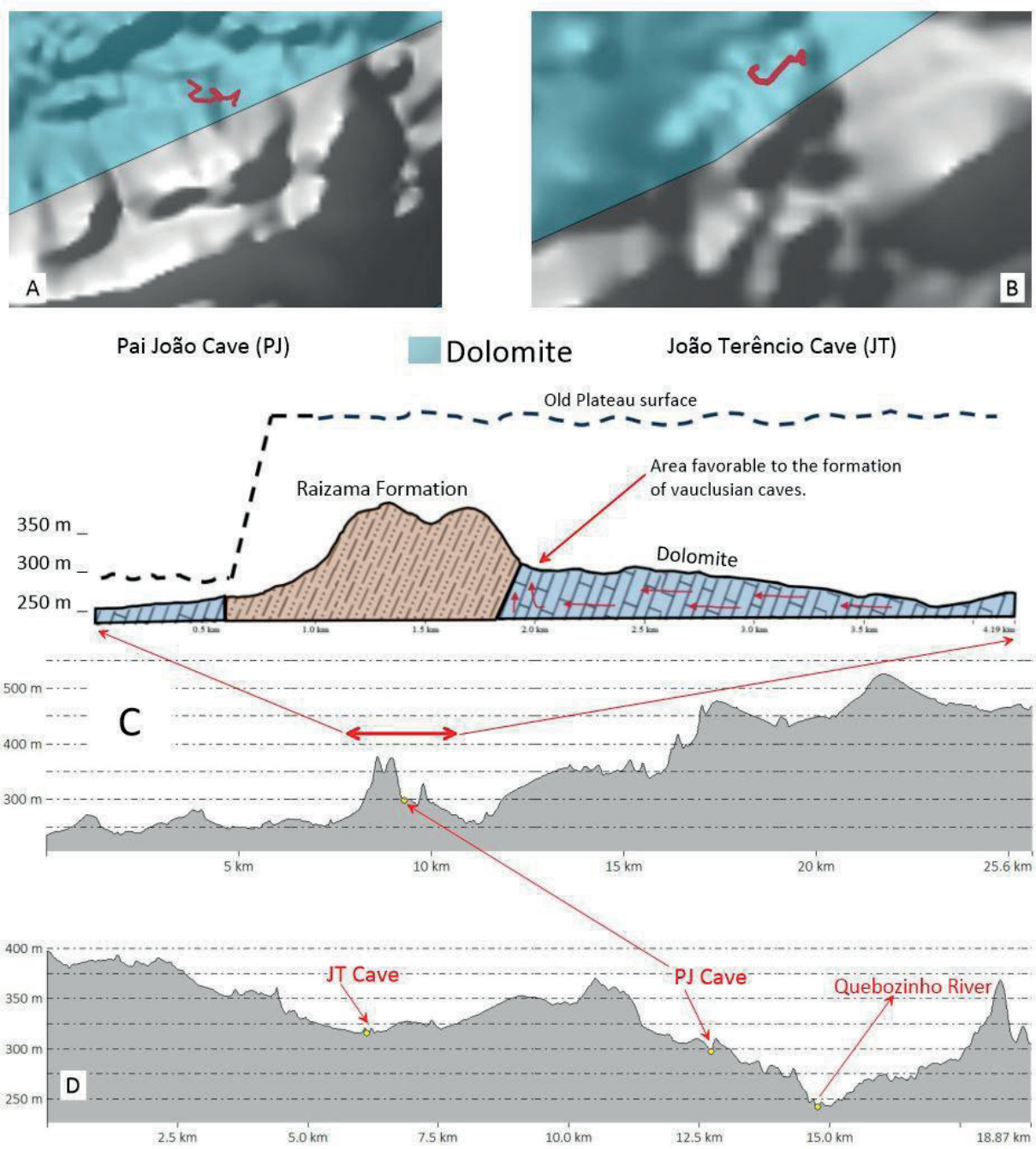

Figure 6: *A and B - Alignment of the caves with geological lineaments and the contact zone between the dolomite and rocks of Raizama Formation. C - Geologic profile near Pai João Cave and its approximate location in the regional topographic profile. D – Topographic profile showing the location of both caves.*

Acknowledgments

Special thanks to Carla Rocha and Pousada Casa de Pedra for the logistical support, to Corpo de Bombeiros do Estado do Mato Grosso, to the Government of the State of Mato Grosso, and of course to Anny Oliveira and all the volunteers that supported the logistical requirements of this project.

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Remote dives in the west of Hirlatzhöhle, Upper Austria

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Abstract

Hirlatzhöhle is Austria's 3rd longest cave with a total length of over 118 km. The focus of exploration is at the far west and the far east of the cave, both of which require the logistics of multi-day expeditions with several camps. Diving in Hirlatzhöhle has been of interest since the beginning of the systematic exploration of the cave – diving through various sumps in the cave lead to discovery of long, previously unknown dry passages.

Since 2019 the authors have been diving in Hirlatzhöhle, mostly in the western parts of the cave. One of the main goals is to explore the sump at the end of Megalodontencanyon which is believed to drain into Waldbachursprung, a karst-spring approx. 1500 m north and 140 m lower in elevation than the current end of exploration.

During one of the expeditions the team found a somewhat nondescript sump called "Kleiner Schritt zur Seite" ("little sidestep") in the same area. Surprisingly this siphon was longer than anybody expected and lead to the discovery of several subsequent sumps, yielding a total of more than 300 m of new passage. Even after several trips there is still a lot of potential in this area with yet more sumps to be dived.

Résumé

Hirlatzhöhle est la troisième plus longue grotte en Autriche avec une longueur totale de plus de 118 km. L'exploration se concentre à l'extrême ouest et à l'extrême est de la grotte, qui nécessite la logistique d'expéditions de plusieurs jours avec plusieurs camps. La plongée à Hirlatzhöhle présente un intérêt depuis le début de l'exploration systématique de la grotte: les plongées des siphons ont conduit à la découverte de longs passages secs jusqu'alors inconnus.

Depuis 2019, les auteurs plongent à Hirlatzhöhle, principalement dans la partie ouest de la grotte. L'un des principaux objectifs est d'explorer le siphon situé à l'extrémité du Megalodontencanyon, qui s'écoule dans Waldbachursprung, une source karstique située environ 140 m plus bas en altitude que la fin actuelle de l'exploration de la grotte.

Dans la même zone, l'équipe a trouvé un siphon appelé « Kleiner Schritt zur Seite » (« petit pas de coté ») Étonnamment, ce siphon était plus long que prévu et a conduit à la découverte de plusieurs siphons, produisant un total de plus de 300 m de nouveau passage. Même après plusieurs expéditions, il reste encore beaucoup de potentiel dans cette zone avec encore plus de siphons à plonger.

1. Introduction

Hirlatzhöhle is located in Dachstein-Mountains, a 580 km² wide karstified area in the central part of the Northern Calcareous Alps. It's characterized by voluminous phreatic passages that are episodically flooded and extend over large horizontal distances (BEHM et al., 2016).

Hirlatzhöhle is Austria's 3rd longest cave with a total length of over 118 km and Austria's second deepest cave (depht: 1559 m). The current focus of exploration is at the far west, the far east and the highest parts of the cave. All those areas are only reachable by long camping trips lasting several days. Diving in Hirlatzhöhle has been of interest for a long time – there are several sumps to be found in the cave, and diving through them lead to discovery of long passages. As Hirlatzhöhle is one of Austria's most prominent caves it has been attracting cavers from all over Europe for a long time.

One sump that was not passed until February 2022 is the siphon at the end of Megalodontencanyon in the west of the cave. The first attempt to dive that sump by Peter Hübner and Barbara Wielander in February 2019 was aborted when both divers reached their gas-turnaround point before being able to resurface. However, it was noticed that the spacious underwater passage continued to be as big as before. It is believed that the water in this sump drains into Waldbachursprung, a karst-spring located approx. 140 m below Megalodontencanyon (fig.1).

The spring's catchment area includes glacial outflows from the Hallstätter Glacier, extends to the foot of the Dachstein south walls and also receives an inflow from the lake "Hinterer Gosausee". From the entrance of the karst-spring it's possible to descend approx. 40 m deep to the horizon of the constantly flowing spring outlets during times of low water (BENISCHKE, 2016).

In 2005 Peter Hübner and Anke Oertl tried diving in Waldbachursprung-Spring after clearing an obstruction in the dry passage before the siphon. They reached a rather spacious, water-filled passage but had to turn around after diving only a short distance, although the passage seemed to continue.

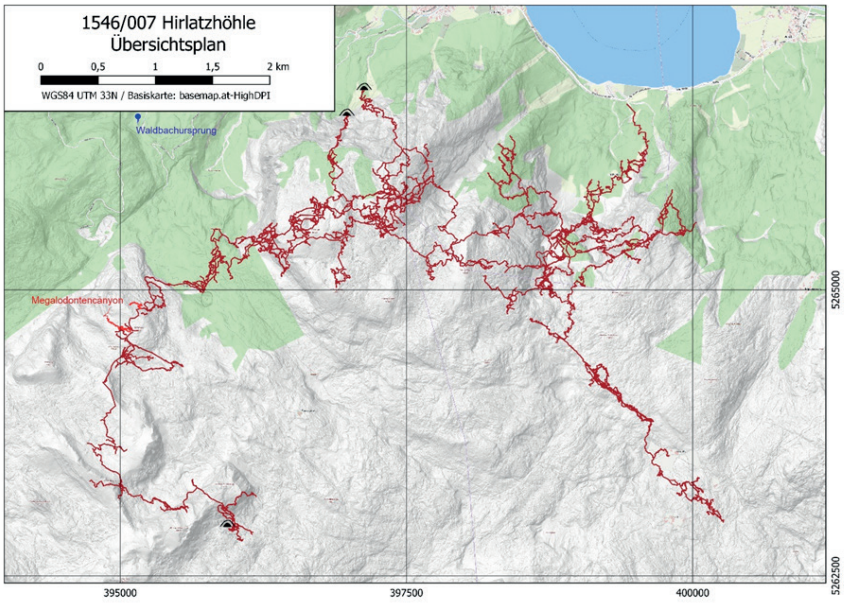

Figure 1: *Map of Hirlatzhöhle, showing a plan-view of the cave, Megalodontencanyon, the cave-entrances and the spring Waldbachursprung. Map: Axel Hack.*

Diving in Waldbachursprung-Spring is only possible during cold winter months, when the water level is extremely low. This is why attempts are currently being made to search for a connection between the spring and Hirlatzhöhle (which has been proven by tracing-experiments) from the direction of Hirlatzhöhle - even though this project requires complex planning and is very time consuming.

In Hirlatzhöhle the according sump is located at the end of Megalodontencanyon in the area of “Wilder Westen” (“wild west”), approx. 10 hours from the cave-entrance. To reach the sump, divers and supporters have to set up their camp at Grünkogelbiwak approx. 8 hours from the cave entrance. The way to this camp leads through mostly large passages and pits equipped with ladders. From there another 1-2 hours are needed to pass Megalodontencanyon. In this narrow canyon, several obstacles like pitches and traverses need to be passed. At the end of the canyon a spacious sump is situated. Diving is carried out downstream. Although the current is not noticeable during periods of low water, diving can only be done in winter (otherwise there is too much water in the lower parts of the cave).

In the immediate vicinity of the camp in Grünkogelhalle another, somewhat inconspicuous siphon was found: the siphon in “Kleiner Schritt zur Seite” (“little sidestep”). Since it could not be ruled out that this siphon also has a connection to the drainage system of Waldbachursprung-Spring, it was decided to try diving there as well (fig. 2).

2. Materials and conditions

A characteristic of the siphons we explored is that they are generally comfortable to dive. The siphons are dimensioned in such a way that you can easily pass through them without removing any equipment and even diving with backmount-configuration would be possible. Nevertheless, we decided to do most of our dives with sidemount-configuration. Steel and carbon diving-tanks of 4-9 l in size were used (pressure: 250-300 bar of air). The carbon-tanks were packed in plastic tubes or covered with rubber for protection.

In the siphons of “Kleiner Schrit”, Rafael Wagner used an OMG rebreather.

The maximum depth was usually less than 10-15 m. The siphons were not particularly long, the longest sump was the first siphon in “Kleiner Schritt” with a length of almost 100 m. Due to the cold water temperature of 4° C, we were mostly in drysuits, which, however, required increased caution when negotiating narrow spaces both underwater and behind the siphon - a tear in the drysuit led to the premature abortion of a dive in “Kleiner Schritt” in February 2024. The visibility was usually quite good - due to the light current, there is hardly any sediment in these siphons to be found.

3. Results

Figure 2: *Siphon in "Kleiner Schritt zur Seite". Photo: Barbara Wielander.*

Figure 3: *Stefan and a bed of megalodonts in Megalodontencanyon. Photo: Barbara Wielander.*

From 2019 till 2024 six international diving-expeditions to the west of the cave were organized by the authors (table 1), starting with two trips to Megalodontencanyon.

Megalodontencanyon in the western parts of the cave has been known since the early 1990s. A low crawlway is soon followed by a larger hall, from the ceiling of which a sometimes breathtaking waterfall falls several meters into the depths. The sometimes quite narrow canyon with the eponymous megalodont beds (fig. 3) then meanders for around 700 m towards the northwest until it ends at a beautiful, crystal-clear siphon.

During the first diving attempt by Peter Hübner and Barbara Wielander, 50 m could be dived, without the end of the submerged section being visible. After a forced break due to Corona and several lockdowns, it was decided to resume diving there at the beginning of 2022. The international expedition was supported by FSE and Korda's (ESP 2022-01).

The siphon consists of two parts: The first part of the siphon continues north, the same direction as the canyon before. After 5 meters (depth approx. 3 m), a small air-filled chamber is reached. In 2019, when this chamber was discovered, it was noticed that there the water level is 1 m below the water level of the entrance-pool to the siphon, suggesting that occasionally the water-level in the whole siphon is lower and the chamber is sufficiently airtight to keep air trapped against the rising water-table at least for a while.

The continuation from this chamber is a water-filled pit, approx. 15 m deep. After descending this pit, the water-filled passage (approx. 1,5 m wide and 3 m high) continues to the west. After approx. 45 m the siphon ends at a shallow pool. Just after the pool the water disappears into a narrow canyon (maybe penetrable), leading eastwards. The main continuation is a spacious gallery heading upwards to the north-east. The gallery was surveyed to a length of 103 m, before a pit of approx. 10 m depth was reached. The pit seems climbable but given the remote location, it will need the help of a handline to descend it. At the bottom the passage seems to continue as before. The main feature of the passage are large pools filled with water. Hence the passage was named "Trivialer Riesenkolkzufluss" ("trivial inlet with large potholes") – fig. 4 (WIELANDER, 2022).

Four dives were carried out in "Kleiner Schritt zur Seite" ("little sidestep"), which is close to the camp in Grünkogel and much easier accessible than Megalodontencanyon. A steep but climbable fissure can be followed to a depth of approximately 80 m below the camp in Grünkogel. There a horizontal gallery is met. To the east the main passage can be followed for several meters before arriving at a sump. This part of the cave has been mapped in the 1990ies, but then no further attention was paid to it. When re-surveying it in autumn 2021, it was noticed that the siphon at the eastern end is – while being smaller than the impressive sump in Megalodontencanyon - spacious enough to attempt a dive.

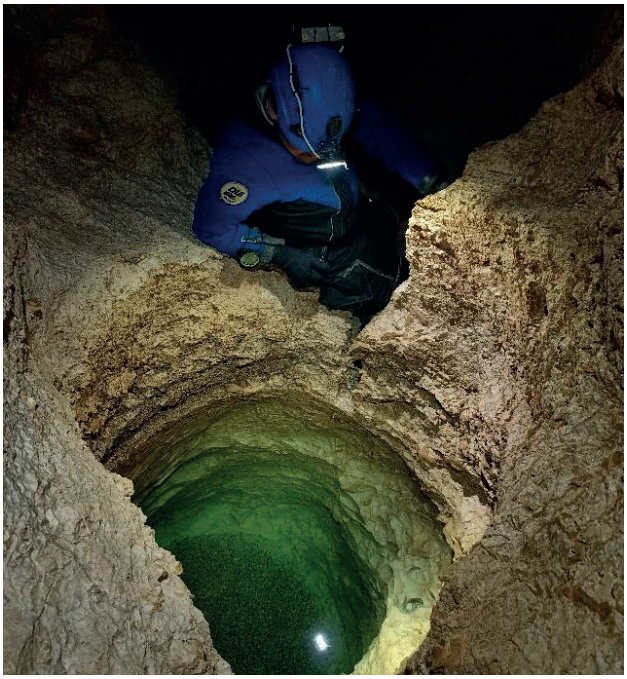

Figure 4: *Stefan looking at one of the pools in the new gallery. Photo: Barbara Wielander.*

So far, 4 siphons with dry sections in between them have been dived in "Kleiner Schritt" (total length 303 m, diving distance 170 m). The first siphon, about 100 m long, has an active water-inflow. Its depth can fluctuate by more than one meter within a couple of hours, depending on weather conditions on Dachstein-Mountain (rainfall, snowmelt, …). The drain of this siphon is a low crevice that we didn't manage to pass.

The subsequent siphons were stagnant at the time of the dives and are only likely to have an inflow of water during flood events. The current end of exploration is a siphon located at the end of "Südsee" ("Southern Sea"), in the southeast of the mapped galleries, and it is likely to be of similar dimensions to the previous siphons.

Date	Sump	Divers	Helpers
7.-10.2.2019	Megalodontencanyon	Peter Hübner (DE), Barbara Wielander (AT)	Tanino Albanese (IT), Jakub Cib (CZ), Corin Donne (GB), Tobias Fellinger (AT), Paul Karoshi (AT), Alexej Kopchinskiy (UA), Rebecca Lawson (GB), Camille Leveque (FR), Leo Pichler (AT), Felix Rosebrock (AT), Ralf Sattra (AT), Amelie Schönenwald (DE), Johannes Wallner (AT), Alexander Wendel (AT)
5.-8.2.2022	Megalodontencanyon	Stefan Gaar (DE), Barbara Wielander (AT)	Erik Birkhoff (NL), Lisette de Graauw (NL), Zsolt Németh (HU), Ferenc Kovács (HU), Lajos Sass (HU), Attila Szórádi (HU)
29.10.-1.11.2022	Kleiner Schritt zur Seite	Rafael Wagner (AT), Barbara Wielander (AT)	Erik Birkhoff (NL), Tobias Fellinger (AT), Lisette de Graauw (NL), Helmut Hubalek (AT), Rebecca Lawson (GB), Artur Papp (AT), Daniel Wondrak (AT)
5.-8.1.2023	Kleiner Schritt zur Seite	Stefan Gaar (DE), Barbara Wielander (AT)	Damir Androic (HR), Gogo Berov (BG), Jurica Jagetic (HR), Efi Hristova (BG), Paul Karoshi (AT), Valentina Kras (HR), Alicia Roslaniec (PL), Josip Tezak (HR)
9.-12.2.2023	Kleiner Schritt zur Seite	Rafael Wagner A(T), Barbara Wielander (AT)	Yordanka Donkova (HR), Georgi Georgiev (BG), Anastasiia Gorbenkova (RU), Axel Hack (DE), Kalin Hristov (BG), Efi Hristova (BG), Luka Ivancic (HR), Paul Karoshi (AT), Andrey Minogin (RU), Gorana Peric (HR), Alicia Roslaniec (PL)
8.-11.2.2024	Kleiner Schritt zur Seite	Stefan Gaar (DE), Barbara Wielander (AT)	Barbara Funk (AT), Anastasiia Gorbenkova (RU), Zsofi Kalotai (HU), Andrey Kozhenkov (RU), Ferenc Kovács (HU), Andrey Minogin (RU), Uwe Röschlaub (DE), Claudia Teissl (AT), Philipp Wallner (AT)

Table 1: *Overview of dives in Megalodontencanyon and "Kleiner Schritt zur Seite", 2019-2024.*

4. Outlook

There are still two open question marks in Megalodontencanyon - another dive is planned for February 2025. The hindrance is that the water-active Megalodontencanyon can only be dived in dry, cold winter weather. The main goal here is still to connect Hirlatzhöhle to Waldbachursprung-Spring.

The siphon at the eastern end of "Kleiner Schritt", which continues to the southeast, still waits to be explored- it remains exciting to see how it will continue under and possibly above water. A dive there is planned for autumn 2025.

In "Nordsiphon" ("northern siphon") in the east of the cave diving will continue in the next few years after a diving attempt in autumn 2024. The aim there will be to find a possible connection between two sumps: "Nordsiphon" and "Linzersiphon".

Ulrich Meyer successfully dived in "Unterfeld" ("lower field") in the Far East of Hirlatzhöhle in 2005; at the time, it was the furthest dive from the surface ever carried out in a cave wordlwide. Andreas Klocker would like to resume diving there – a trip to explore the surroundings of the siphon is planned for spring 2025.

5. Acknowledgments

We gratefully thank all participants and helpers who made diving in Hirlatzhöhle possible! Thanks to Axel Hack for providing us with maps and survey data! Thanks also to FSE and Kordas for supporting this project! And last but not least thanks to Peter Hübner for introducing us to the wonders of cave-diving in Hirlatzhöhle!

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Session 09

EXPLORATION, SPELEOLOGICAL TECHNIQUES, AND MATERIALS

09:2: Exploration

Bulha d'Água, as descobertas em 20 anos de explorações e o futuro da região

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Abstract

Bulha d' Água, located in Brazil, São Paulo State, in the north intersection of the PETAR and Intervales State Park, has been the object of a speleological systematic exploration since 2004. More than 80 caves were discovered or mapped during this period, but the full potential of the region is still unrevealed. Big caves like Buenos IV and Los Tres Amigos Abyss were presented to the speleological community and kilometers of new tracks were opened in the rain forest giving access to new regions to grant the continuity of the fieldwork. New species of anomuran crustaceans Aegla sp were found and records of the megafauna and other animals are available for researchers willing to accept the challenges of this region. Bulha d' Água is the latest unexplored caving region in São Paulo State and for next years and the possibility of new discoveries is a certainty.

1. Introducão

O Núcleo Bulha d'Água, situado nos limites entre o Parque Estadual de Intervales(PEI) com o Parque Estadual Turístico do Alto Ribeira (PETAR), vem sendo objeto de um trabalho sistemático de prospecção e mapeamento espeleológico nos últimos 20 anos. A região havia sido visitada esparsamente durante as décadas de 70, 80 e 90 por alguns pesquisadores de universidades paulistas para estudo da fauna local e da biologia subterrânea nas poucas cavernas até então conhecidas, e também por alguns grupos de espeleólogos para exploração e prospecção, mas não existia um trabalho sistemático de exploração de todo o potencial da região.

A partir de janeiro de 2004, no local que compreende o núcleo de Bulha D'Água, vales dos rios Buenos e Ribeirãozinho, Fundão, núcleo Caboclos e entornos, esse trabalho passou a ser realizado, sendo a atividade de prospecção, exploração e mapeamento liderada pelo grupo Bambuí de Pesquisas Espeleológicas, e se desenvolvendo com a colaboração de diversos espeleólogos e grupos de espeleologia.

O local é de grande potencial espeleológico, já evidenciado pelas descobertas de cavernas significativas como o abismo Los Três Amigos, Buenos IV e Velhos Caverneiros, tendo ainda várias regiões que foram pouco exploradas, sem contar as regiões que ainda não foram acessadas para avaliação de potencial.

Os resultados de exploração, prospecção e mapeamento vêm sendo apresentados regularmente aos orgãos responsáveis, a fim de garantir que o conhecimento adquirido seja compartilhado com os principais interessados, através de relatórios e apresentação dos mapas desenvolvidos.

Atuamos sempre com base em duas premissas básicas estabelecidas no início dos trabalhos na região, que são procurar esgotar o máximo possível o potencial de novas cavernas de cada região e somente explorar novas cavidades através da realização da topografia.

2. Materiais e métodos

As atividades de prospecção e exploração basearam-se primeiramente no georreferenciamento das trilhas de acesso às cavidades já conhecidas e definição das localidades com potencial para descobertas de novas cavernas, seguido da abertura de trilhas nestas regiões.

As atividades de exploração subterrânea consistem em percorrer o interior de cavidades efetuando o reconhecimento de suas morfologias, fazendo a avaliação da dificuldade técnica de acesso, verificando a importância da cavidade no contexto do sistema cárstico abordado e o seu potencial espeleométrico.

Para a etapa de documentação foram considerados os preceitos técnicos de levantamento segundo a BCRA (British Cave Research Association). As metodologias foram divididas em quatro principais abordagens:

a. Mapeamento subterrâneo: levantamento e execução das topografias das cavidades encontradas na região explorada;

b. Mapeamento de superfície: refere-se a mapeamento de trilhas, dolinas, drenagens, feições relevantes e identificação das coordenadas de cavidades;

c. Documentação fotográfica: refere-se ao registro fotográfico do carste estudado e das atividades realizadas;

d. Documentação escrita: refere-se ao registro escrito e publicado das atividades e apresentação dos resultados, por ocasião da conclusão dos trabalhos, aos representantes dos Parques.

As saídas de campo e sua consequente documentação são sempre coordenadas por espeleólogos do Grupo Bambuí de Pesquisas Espeleológicas (GBPE) e abertas a colaboradores e espeleólogos membros de outros grupos espeleológicos;

A metodologia de prospecção engloba o reconhecimento das feições geográficas, acessos e localização de cavidades naturais ou feições geográficas. Este reconhecimento é realizado através do estudo de cartas geográficas da região, uso do software Google Earth, fotos aéreas e aplicativos de geolocalização. Após o estudo preliminar destes dados são realizadas as saídas a campo para a verificação in loco dos perfis de relevo significativos ao tema do Projeto. Os softwares utilizados são o Google Earth, Garmin BaseCamp e o aplicativo Gaia GPS.

A metodologia de localização das entradas das cavidades naturais, bem como de outras feições geográficas relevantes foi realizada com a utilização do equipamento GPS (Global Positioning System – Sistema de Posicionamento Global). Adotou-se como referência no princípio dos trabalhos o datum WSG84 com a aquisição de coordenadas UTM (Universal Transversa de Mercator).

Estabeleceram-se procedimentos operacionais para qualificar a topografia, no mínimo, com o grau 4C BCRA (British Cave Research Association).

Os dados do mapeamento são tratados matematicamente por meio da utilização do software On station e Survex e o desenho final do mapa é realizado com o uso do software Adobe Illustrator ou softwares de ilustração similares.

A documentação cartográfica das cavidades é caracterizada por planta projetada (projeção ortogonal), perfil retificado e cortes de seção latitudinal em relação ao eixo principal do conduto, quando necessário, predominantemente na escala 1:250.

Os registros em mídia objetivaram a produção de material para ilustrar as publicações decorrentes dos trabalhos efetuados, bem como para evidenciar as ocorrências relevantes da biota cavernícola, fósseis, espeleotemas e outras referências relevantes que podem servir como material de consulta para trabalhos técnicos, científicos ou publicações relacionadas à área. A documentação oriunda das atividades de prospecção, exploração e georefenciamento se traduziu em material cartográfico, registros escritos e publicados das atividades e consolidação dos resultados nos relatórios que foram enviados aos Parques conforme definido na proposta de trabalho apresentada e protocolizada junto a Fundação Florestal (Camargo, 2013).

Figura 1 : *Gruta dos Velhos Caverneiros.*

Figura 2: *Gruta Buenos IV, entrada principal.*

3. Resultados

Até o momento, há 82 cavernas registradas na região, sendo 70 delas novas descobertas, e nas 12 cavernas já conhecidas foi realizado novo mapeamento e o acréscimo de novos desenvolvimentos identificados, em um total de 134 saídas a campo.

Foram elaborados 69 mapas, com um total de 13.500 metros de projeção horizontal, sendo que ainda há 13 cavernas em processo de exploração e/ou mapeamento (tabela 1).

Das cavidades descobertas na região, algumas são muito signifi-

cativas seja pela sua singularidade, desenvolvimento e beleza cênica, destacando-se o Abismo Los Três Amigos com seus 200 metros de desnível, galerias de mais de 50 metros de altura e um espeleotema do tipo cortina com mais de 30 metros de altura e comprimento de mais de 1,5 metros. Ainda existem áreas a serem exploradas nos níveis superiores.

Também não podem deixar de ser citadas a gruta Ribeirãozinho III, com sua entrada de beleza cênica, a Gruta Buenos IV, com seu imenso salão de entrada (Figura 2), a Gruta dos Velhos Caverneiros, com sua ressurgência no meio do paredão do cânion do rio Pilões, e a Gruta Buenos I, a maior da região, com 2.690 metros de desenvolvimento.

Entre outras particularidades, temos a Gruta do Megatério e o Abismo do Fóssil, com diversos registros paleontológicos que ainda não foram objeto de estudo. Em termos estudos paleontológicos, pode-se citar os trabalhos realizados pela Dra. Aline Marcele Guilardi, professora do Departamento de Geologia da UFRN, na datação de dentes de *Toxodon* encontrados no Abismo Los Três Amigos (~6.5 ka.) e identificação de exemplares da megafauna do Quaternário tardio com destaque para o registro fóssil de Equidae, sendo o primeiro registro formal para o Quaternário do Estado de São Paulo (Guilardi, 2011).

Outro ponto de destaque são os mais de 53 km de trilhas abertas na região de Mata Atlântica, que impõe altos níveis de dificuldades ainda mais considerando os desníveis existentes (Figura 3).

Em termos da fauna endêmica, vale ressaltar que até o momento temos duas novas espécies de Aegla descobertas nas grutas Ribeirãozinho III (*Aegla atropos*), Lago Subterrâneo (*Aegla charon*) e Velhos Caverneiros (espécime em estudo).

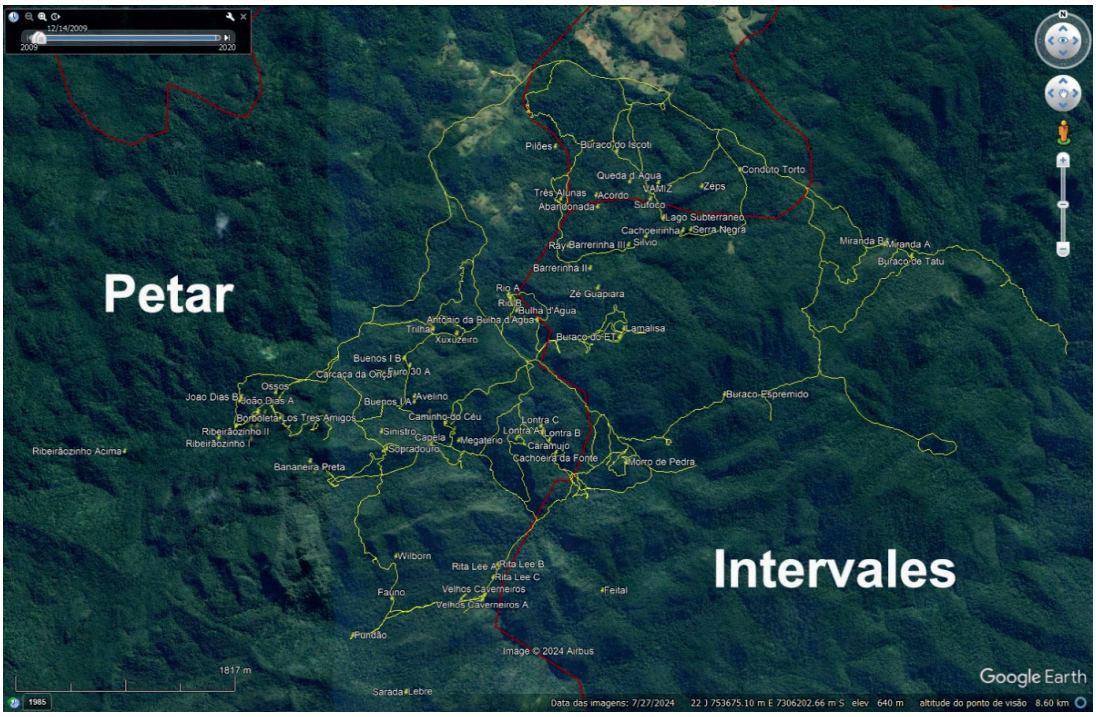

Figura 3: *Mapa da região de Bulha d' Água mostrando o relevo com trilhas e cavernas.*

Cavidade	Projeção Horizontal (metros)	Cadastro	Ano	Situação	Cavidade	Projeção Horizontal (metros)	Cadastro	Ano	Situação
Abandonada	29	SP-928	2019	Mapeada	Jerivazal	137	SP-065	2010	Mapeada
Achatada	19	SP-934	2018	Mapeada	João Dias	476	SP-164	2007	Mapeada
Acordo	40	SP-933	2019	Mapeada	Lago Subterrâneo	200	SP-786	2010	Mapeada
Antonio da Bulha d'Água	85	SP-568	2004	Mapeada	Lamalisa	62	SP-939	2013	Mapeada
Avelino	165	SP-932	2019	Mapeada	Lebre	68	SP-462	2006	Mapeada
Bananeira Preta	8	SP-787	2008	Mapeada	Lontra	104	SP-552	2004	Mapeada
Barrerinha I	50	SP-555	2005	Mapeada	Los três amigos	2400	SP-543	2007	Mapeada
Barrerinha II	21	SP-571	2005	Mapeada	Louco de Alegre	181	SP-547	2005	Mapeada
Barrerinha III	15	SP-557	2005	Mapeada	Maravilha	62	SP-156	2005	Mapeada
Borboleta	50	SP-151	2014	Mapeada	Megatério	50	SP-714	2008	Mapeada
Buenos I	2690	SP-068	2004	Mapeada	Miranda	62	SP-798	2009	Mapeada
Buenos II	228	SP-069	2005	Mapeada	Mole	34	SP-937	2023	Em exploração e/ou mapeamento
Buenos III	29	SP-567	2005	Mapeada	Morro de Pedra	*	*	2011	Em exploração e/ou mapeamento
Buenos IV	740	SP-857	2008	Mapeada	Ossos	191	SP-560	2007	Mapeada
Bulha d'Água	63	SP-556	2004	Mapeada	Pilões	201	SP-143	2004	Mapeada
Buraco de Tatu	*	*	2010	Em exploração e/ou mapeamento	Queda d'Água	33	SP-799	2005	Mapeada
Buraco do ET	*	*	2013	Em exploração e/ou mapeamento	Ray	4	SP-564	2005	Mapeada
Buraco do Iscoti	12	SP-546	2006	Mapeada	Ribeirãozinho Acima	21	SP-572	2006	Mapeada
Buraco Esprimido	*	*	2010	Em exploração e/ou mapeamento	Ribeirãozinho I	56	SP-152	2004	Mapeada
Buraco Pequeno	12	SP-569	2005	Mapeada	Ribeirãozinho II	66	SP-153	2006	Mapeada
Buraco do Sufoco	12	SP-943	2018	Mapeada	Ribeirãozinho III	1990	SP-138	2006	Mapeada
Cachoeira da Fonte	21	SP-550	2004	Mapeada	Rio	53	SP-936	2012	Mapeada
Cachoeirinha	34	SP-306	2005	Mapeada	Rita Lee	116	SP-940	2017	Mapeada
Caminho do Céu	87	SP-791	2009	Mapeada	Sapo	2	SP-942	2018	Mapeada
Capela	106	SP-166	2005	Mapeada	Sarada	*	*	2006	Em exploração e/ou mapeamento
Capinzal	255	SP-208	2004	Mapeada	Serra Negra	37	SP-563	2005	Mapeada
Caramujo	56	SP-570	2004	Mapeada	Siltito	7	SP-800	2013	Mapeada
Carcaça da Onça	*	*	2013	Em exploração e/ou mapeamento	Silvio	80	SP-549	2005	Mapeada
Casinha da Carol	11	SP-931	2012	Mapeada	Silvio Acima	51	SP-561	2005	Mapeada
Conduto Torto	68	SP-558	2005	Mapeada	Sinistro	30	SP-801	2008	Mapeada
Contra-vensão	36	SP-778	2005	Mapeada	Sopradouro	50	SP-941	2007	Em exploração e/ou mapeamento
Cornos Calcíticos	79	SP-790	2009	Mapeada	Travesseiro	11	SP-944	2019	Mapeada
Dolina Funda	27	SP-789	2008	Mapeada	Três Alunas	28	SP-946	2020	Mapeada
Duas Cobras	*	*	2013	Em exploração e/ou mapeamento	Trilha	*	*	2012	Em exploração e/ou mapeamento
Fauno	*	*	2017	Em exploração e/ou mapeamento	Trilha Los Três Amigos	13	SP-802	2008	Mapeada
Feital	35	SP-562	2006	Mapeada	VAMIZ	48	SP-935	2018	Mapeada
Fenda do Fábio	189	SP-930	2018	Mapeada	Velhos Caverneiros	224	SP-945	2017	Em exploração e/ou mapeamento
Fendão Fechado	31	SP-929	2019	Mapeada	Wilborn	50	*	2006	Em exploração e/ou mapeamento
Fendinha	27	SP-796	2012	Mapeada	Xuxuzeiro	24	SP-554	2004	Mapeada
Fundão	710	SP-105	2006	Mapeada	Zé Guapiara	30	SP-565	2006	Mapeada
Furo 30	277	SP-123	2004	Mapeada	Zéps	23	SP-803	2008	Mapeada

Tabela 1: *Cavernas trabalhadas na região.*

4. Discussão

O modelo atual de exploração, que se baseia de dois a quatro dias de estadia no loca, vai precisar ser alterado, pois esse tempo não é suficiente para que se possa alcançar as novas regiões e realizar um trabalho sistemático de exploração.

As novas áreas de exploração encontram-se cada vez mais distantes, o que implica na demanda de mais tempo para a execução dos trabalhos e um dos modelos a ser adotado será o de expedições de longa duração com vários dias de trabalho no local. Porém, a questão logística precisará ser estudada, visto que o local não dispõe de recursos básicos com acesso fácil como alimentação, combustível, suporte médico, energia e comunicação.

Outro aspecto que tem trazido dificuldades é a manutenção das trilhas, que frequentemente se fecham devido ao crescimento da mata e em determinadas épocas do ano, sobretudo aquelas em que os índices pluviométricos são elevados. A dificuldade de acesso é inevitável, quer seja pelos desafios impostos ao se percorrer as trilhas e atravessar as drenagens, quer seja pela inundação de alguns dos sistemas das cavernas

A precariedade da estrada de acesso à região também limita muito os tipos de veículos que podem chegar no local e é outro fator importante a ser considerado face a necessidade de transporte dos recursos até a sede de Bulha d'Água.

Em se tratando das áreas novas de exploração e com base no mapa da Figura 4, as regiões com possibilidades de descobertas de novas cavidades. São as regiões: 4. Vale do meio, 5. Trilha de Bulha d'Água, 6. Região do Sopradouro, 7. Região dos Los Três amigos, 9. Serra Negra, 10. Vale da Figueira, 13. Vale do Feital, 14. Cânion do Ribeirãozinho, 15. Vale do Fundão e 16. Região da João Dias.

Importante salientar que o potencial da exploração nesta parte do Estado de São Paulo não se limita a região de Bulha d'Água, pois existem extensas regiões nos entornos ainda inexploradas.

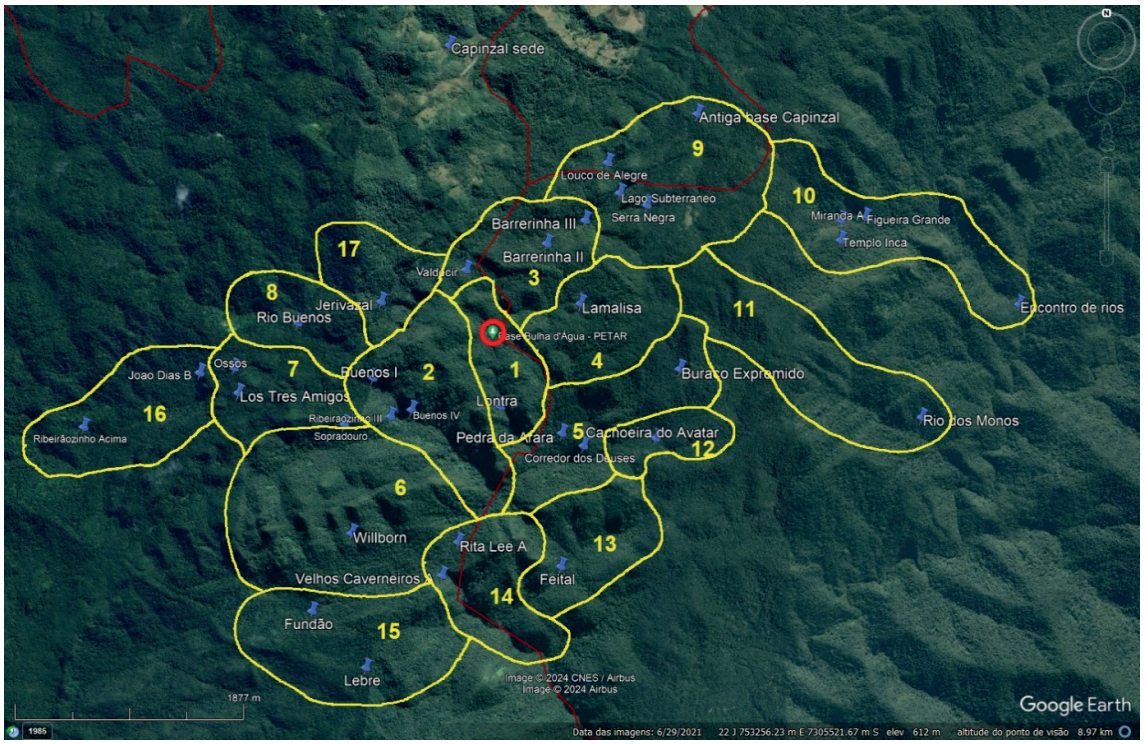

Figura 4: *Regiões de Bulha d'Água: 1 Base Bulha d´Água, 2 Trilha do Ribeirãozinho, 3 Região da Barreirinha, 4 Vale do meio, 5 Trilha de Bulha d'Água, 6 Região do Sopradouro, 7 Região dos Los Três amigos, 8 Vale dos Buenos, 9 Serra Negra, 10 Vale da Figueira, 11 Rio dos Monos, 12 Vale Avatar, 13 Vale do Feital, 14 Cânion do Ribeirãozinho, 15 Vale do Fundão, 16 Região da João Dias e 17 Vale do Jerivazal.*

5. Conclusões

Bulha d'Água tem um grande potencial de exploração e está demonstrado que os grandes desafios para as futuras atividades se encontram nas questões logística e no tempo que será dedicado para as explorações, pois as áreas com novas possibilidades de descobertas encontram-se de 3 a 5 horas de distância da base de pesquisa.

Com o trabalho destes 20 anos é possível saber o que é necessário para poder dar continuidade aos trabalhos e as possibilidades de novas descobertas.

Mesmo nas regiões já exploradas, não pode ser descartada a descoberta de novas cavidades. Cabe às futuras gerações de exploradores e pesquisadores garantir a continuidade deste trabalho para que a sociedade possa tomar conhecimento de tudo que a região pode oferecer.

Agradecimentos

Os agradecimentos vão às mais de uma centena de pessoas que já participaram deste projeto, seja indo uma vez ou seja estando estes 20 anos dedicando tempo e recursos para que esta região se torne mais conhecida. Um agradecimento especial para o Zé Guapiara (José Aparecido Ribeiro), mateiro, filho da região de Guapiara e um dos últimos grandes conhecedores dos segredos nativos da Mata Atlântica

local e toda sua família que sempre nos receberam com muito carinho e atenção. Também vão os agradecimentos à equipe do PETAR e seus gestores Rodrigo José Silva Aguiar e Juliana Conrado, a equipe do PEI e seu gestor Thiago Conforti, pelo suporte nos deslocamentos para a região, pelo uso da casa de pesquisa de Bulha d' Água e pelo suporte dado a fim de garantir a continuidade dos trabalhos.

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Prospecção e topografia de cavernas na porção norte da Serra de Baldim, Minas Gerais, Brasil

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Resumo Expandido

Há quatro anos o NAE – Núcleo de Atividades Espeleológicas, vêm prospectando e topografando cavernas na região norte da Serra de Baldim, abrangendo os municípios de Jequitibá, Santana do Pirapama e Baldim, Minas Gerais (Fig. 1), ao mesmo tempo em que reorganizava as atividades desenvolvidas pela entidade, com uma forte renovação de seu quadro de associados.

Em março de 2023, a Sociedade Brasileira de Espeleologia (SBE) publicou o edital 001/2023, que tinha por objetivo "apoiar projetos destinados à ampliação do conhecimento sobre o patrimônio espeleológico brasileiro". Esse edital preconizava o que atingimento desses objetivos poderia se dar pela validação das informações espeleológicas de cavernas já cadastradas e/ou pela prospecção espeleológica e espeleotopografia em áreas com potencial de ocorrências de cavernas, mas com poucos registros, caso da porção setentrional da Serra de Baldim.

Esse edital veio de encontro aos interesses do NAE, que buscou o apoio decisivo do Observatório Espeleológico (OE), para que juntos pudessem desenvolver e apresentar uma proposta de trabalho capaz de receber o patrocínio da SBE e, ainda, desse suporte ao desenvolvimento do NAE, fomentando a recepção e o treinamento de novos associados.

A Serra de Baldim constitui um conjunto de elevações com altitudes máximas de 1100 m, que formam um conjunto com cerca de 35 km de comprimento na direção aproximada N-S e 9 km na direção E-W. Esse alinhamento é subparalelo à Serra do Cipó, que integra a Serra do Espinhaço, dela distando 12 km.

A Serra de Baldim se interpõe, localmente, entre o rio das Velhas, sub-bacia do rio São Francisco, e o rio Cipó, afluente pela margem direita do rio das Velhas. A rede de drenagem da porção norte da Serra de Baldim é formada, em grande parte, por córregos de pequena vazão ou mesmo intermitentes, que descem perpendicularmente à crista da serra, ou seja, na direção E-W, formando vales encaixados com vertentes íngremes, chegando a formar cânions em alguns trechos próximos ao sopé da serra.

O substrato rochoso da Serra de Baldim é constituído por metapelitos e metacalcários, predominante da Fm. Lagoa do Jacaré e, secundariamente, por metapelitos da Fm. Serra de Santa Helena (Oliveira et al.), que integram o Gr. Bambuí. Essas unidades lito-estratigráficas se encontram em posição normal. O mapa geológico 1:100.00 (Fig. 2) indica que as camadas se encontram orientadas predominantemente na direção N-S, com mergulho entre 5° e 35°, sempre para leste. Com a mesma direção e caimento próximo ao acamamento, ocorre uma foliação conspícua, resultado do evento tectônico Brasiliano que afetou toda a região e que, localmente, gerou dobramentos e zonas de cisalhamento, também com direção N-S, aproximadamente.

No topo da serra, onde predominam rochas metapelíticas, os solos são rasos e pobres, se tornando mais espessos nos esporões que partem da crista. Nas vertentes dos vales que dissecam a serra, os solos também são rasos, podendo mesmo ser do tipo litólico. Nas bases da serra encontram-se solos espessos desenvolvidos sobre leques aluviais espessos, que possuem forte contribuição dos metacalcários que formam a base da serra. Essas áreas são utilizadas como áreas de plantio e de pastagem, constituindo parte do cinturão verde da região metropolitana.

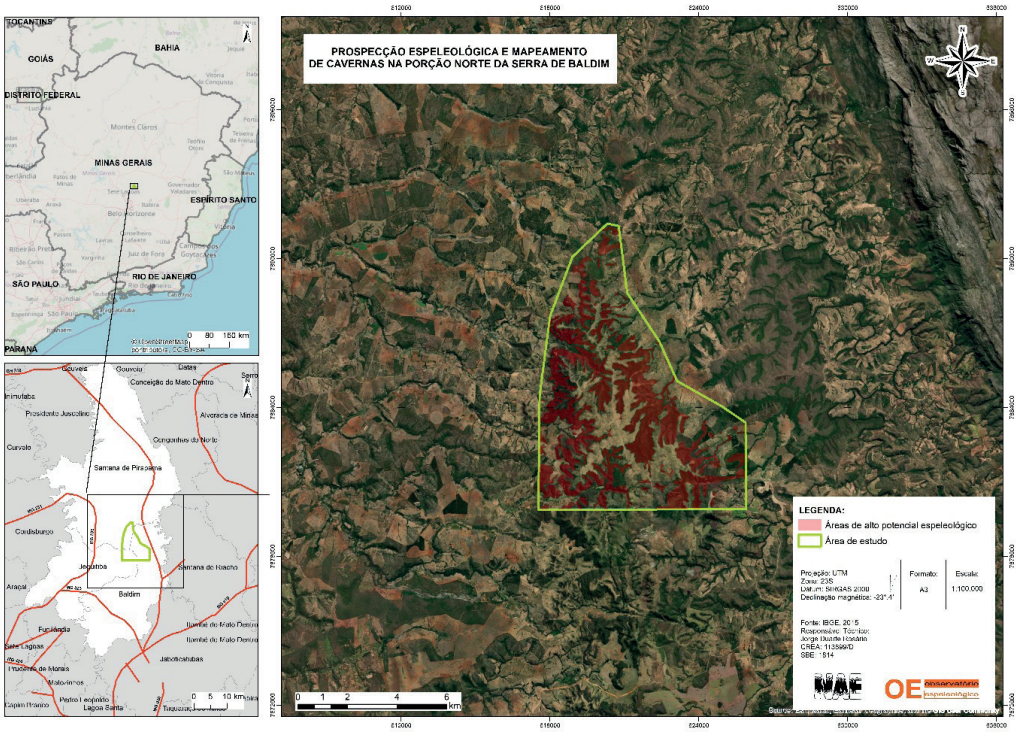

Figura 1: *Localização da área de estudo: porção norte da Serra de Baldim e mapa de potencial espeleológico.*

A Serra de Baldim, apesar da proximidade com a cidade de Belo Horizonte, capital de Minas Gerais e com a região cárstica der Lagoa Santa, carece de estudos espeleológicos sistemáticos, tendo sido contemplada por levantamentos esporádicos e pontuais por parte da comunidade espeleológica brasileira. Pode-se afirmar, também, que faltam estudos relacionados às ciências afins da espeleologia, tais como, geologia, geografia, biologia, arqueologia e paleontologia. A título de exemplo, o levantamento geológico de maior detalhe já apresentado, data de 2013, realizado na escala 1:100.000, contemplando uma pequena quantidade de dados estruturais e nenhuma seção geológica, ou seja, com nível de detalhamento pequeno.

Esses dados de escala regional serviram de base para a elaboração de uma carta de potencial espeleológico (Fig. 1), aliado ao conhecimento acumulado pela equipe do NAE nos últimos anos e a limitação de acesso a algumas áreas, impostas por seus proprietários, orientou os trabalhos de prospecção.

As atividades de campo, contemplaram atividades de prospecção, exploração e topografia, de acordo com a disponibilidade de equipes treinadas. Cabe destacar que um dos objetivos do projeto que deu origem a este artigo, foi preparar os novos associados a desempenharem as atividades de campo, inerentes aos levantamentos espeleológicos, sendo necessários dispender várias horas em treinamento. Além de 9 espeleólogos experimentados do NAE, que participaram em diversas etapas de campo, mais 10 novos associados, participaram dos trabalhos, sendo que 6 desses permanecem no NAE.

Os levantamentos realizados durante a vigência do projeto "Ampliando Rotas", confirmaram a potencialidade para ocorrência de cavernas na área, mas também apontaram para dois desafios, um deles inesperado.

Durante as análises das imagens de satélite se vislumbrou a baixa densidade de estradas na porção oriental da área do projeto, assim como seu mau estado de conservação. Esse fato tornou a prospecção dessa área bastante trabalhosa, exigindo longas caminhadas, por terrenos íngremes, até que se pudesse alcançar os vales onde estavam as áreas com maior potencial espeleológico.

O desafio inesperado, foi a recusa de diversos proprietários rurais em autorizar o acesso às suas propriedades, notadamente aqueles detentores das maiores glebas de terra. Assim, grande parte da área escolhida não pode ser prospectada, permanecendo com status de elevado potencial espeleológico ainda não investigado. Daí a concentração de cavernas em uma área mais restrita, onde os proprietários franquearam o acesso a seus terrenos, algumas vezes indicando locais onde poderíamos encontrar entradas de cavernas, como no caso da Gutas Minos, da Lapa do Suíte e da Lapa dos Morcegos (Fig. 4).

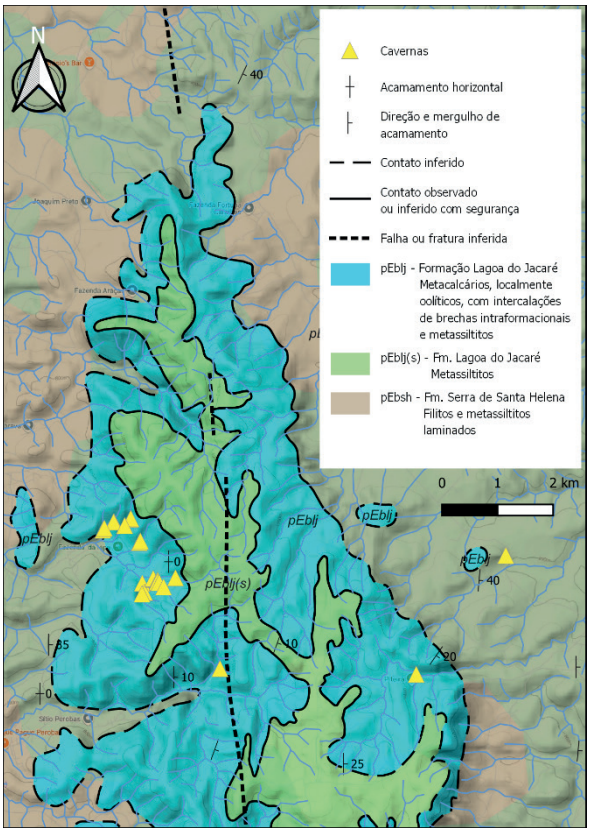

Figura 2: *Unidades litoestratigráficas (CODEMIG, 2012) e cavernas já registradas (CANIE, 2024 e NAE, 2025).*

Dentre as cavernas cadastradas, decidiu-se pela topografia imediata daquelas consideradas mais relevantes, quais sejam:

- Gruta da Ictiofauna
- Gruta Janela de Pedra
- Gruta Minos
- Gruta Ferradura
- Lapa do Fogão
- Gruta dos Morcegos
- Gruta Manduá
- Lapinha D'água da Moreninha (complemento)

A Lapinha D'água da Moreninha, já havia sido topografada em grande parte, entretanto, a descoberta de uma entrada superior e sua exploração, motivou a retomada da topografia. A Gruta Manduá, que vinha sendo utilizada para treinamento dos novos associados, teve sua topografia finalizada durante o projeto. A topografia da Gruta Minos se justificou pelo tamanho e beleza de seu pórtico de entrada. A Gruta da Ictiofauna foi topografada devido à presença de pinturas rupestres bem preservadas na sua entrada. As cavernas dessa área, assim como outras tantas, foram motivo de lavra, tanto para retirada extração de salitre, quanto de fósseis. Nesse quesito destacamos a Lapa das Perobas, topografada anteriormente pelo grupo Opilião Ogree, e as grutas Janela de Pedra e dos Morcegos. Vale destacar a Lapinha D'água da Moreninha, mesmo sendo a maior gruta da área, não foi lavrada devido à existência de um quase sifão, situado a poucos metros após sua entrada principal.

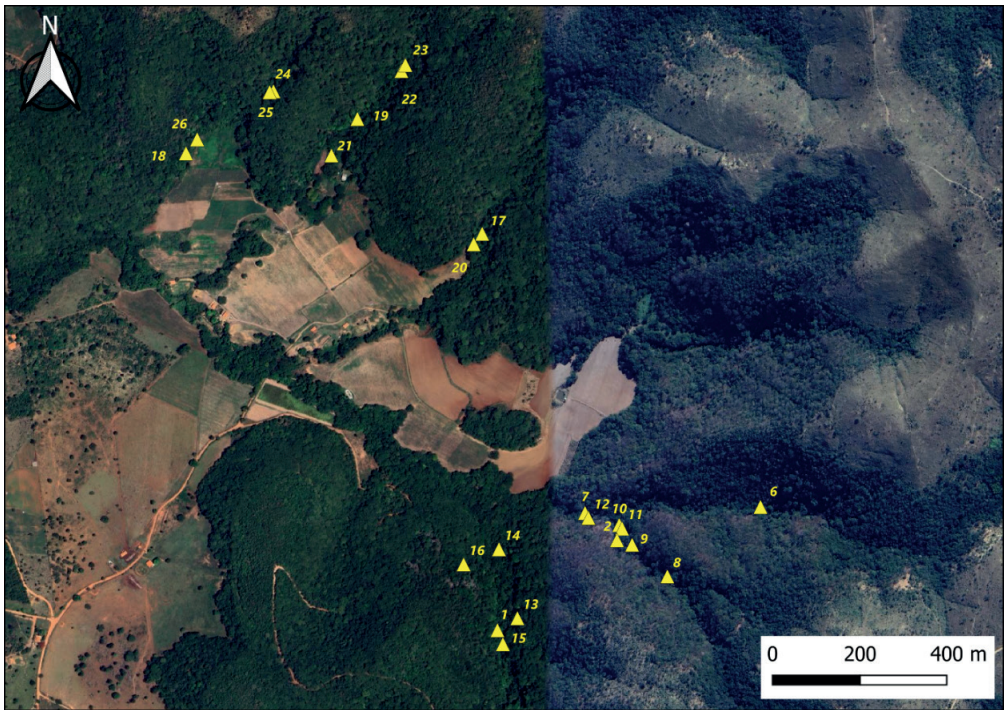

Figura 4: *Entrada principal das cavernas localizadas na área de maior densidade, na Fazenda da Lapa e vizinhança. Os nomes e cadastro no CECAV estão relacionados na Tabela 1.*

Num	Caverna	Município	CECAV
1	Gruta da Ictiofauna	Jequitibá	031250.09427.31.35704
2	Gruta Janela de Pedra	Jequitibá	031633.09565.31.35704
3	Gruta do Rato	Jequitibá	018790.05485.31.35704
4	Gruta do Oco do Pau Molhada	Jequitibá	027300.06044.31.35704
5	Gruta do Oco do Pau Seco	Jequitibá	027302.06045.31.35704
6	Gruta Minos	Jequitibá	031653.09567.31.35704
7	Gruta Beliche	Jequitibá	031626.09560.31.35704
8	Gruta da Bolha	Jequitibá	031632.09564.31.35704
9	Gruta Ferradura	Jequitibá	031634.09566.31.35704
10	Abrigo do Cisalhamento	Jequitibá	031660.09574.31.35704
11	Abrigo do Faísca	Jequitibá	031661.09575.31.35704
12	Gruta Sonim	Jequitibá	031662.09576.31.35704
13	Gruta do Ninho	Jequitibá	031663.09577.31.35704

Num	Caverna	Município	CECAV
14	Abrigo Sol Vermelho	Jequitibá	031631.09563.31.35704
15	Abrigo do Tubarão	Jequitibá	031625.09559.31.35704
16	Lapa do Fogão	Jequitibá	031627.09561.31.35704
17	Lapinha D'água da Moreninha	Santana do Pirapama	027130.06795.31.58508
18	Abrigo da Pedra Picada	Santana do Pirapama	027164.06796.31.58508
19	Lapa das Perobas	Santana do Pirapama	027165.06797.31.58508
20	Gruta Manduá	Santana do Pirapama	027301.06798.31.58508
21	Gruta dos Morcegos	Santana do Pirapama	031630.09562.31.58508
22	Lapinha do Suíte	Santana do Pirapama	031655.09569.31.58508
23	Gruta da Falsa Cobra	Santana do Pirapama	031656.09570.31.58508
24	Gruta Vizinha das Cortininhas	Santana do Pirapama	031658.09572.31.58508
25	Gruta das Cortininhas	Santana do Pirapama	031657.09571.31.58508
26	Sumidouro da Galharia	Santana do Pirapama	031659.09573.31.35704
27	Lapa da Forquilha	Baldim	014469.06781.31.05004
33	Gruta Duplex	Baldim	031654.09568.31.05004

Tabela 1: *Nome e registro no CECAV das cavernas exibidas na Figura 4.*

A maior parte das cavernas cadastradas encontra-se acima do nível do base local, sendo que seu desenvolvimento se dá predominantemente perpendicular aos vales em que estão inseridas. Suas entradas podem-se encontrar tanto na base das encostas desses vales, quanto a alguns metros acima delas. Os vales onde se encontram as bocas das cavernas possuem drenagem intermitente. Acima de 900 m de altitude, quando afloram apenas metassiltitos e filitos, algumas drenagens são perenes, mesmo após meses de estiagem, mas sempre com pequena vazão. Abaixo de 900 m predominam metacalcários como substrato rochoso, tanto no fundo quando nas encostas desses vales, e suas águas se infiltram no leito, em grande parte formado por blocos e matacões de metacalcários, metassiltito e, eventualmente, espeleotemas.

Esses vales se orientam na direção E-W, sendo que as cavernas ali alojadas têm seus condutos mais extensos orientados na direção N-S (direções aproximadas).

As descobertas realizadas nos trechos prospectados da porção setentrional da Serra de Baldim, confirmam o potencial espeleológico das partes que ainda não foram prospectadas, mas também apontam os desafios à vencer, dentro os quais destacamos: a baixa densidade e a má qualidade das estradas; a dificuldade técnica associada aos lances verticais; a resistência dos proprietários das grandes fazendas em consentir a entrada de espeleólogos para realizar os trabalhos de prospecção, exploração e topografia.

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NAE - Núcleo de Atividades Espeleológicas, OE – Observatório Espeleológico. RELATÓRIO FINAL - PROJETO "PROSPECÇÃO E TOPOGRAFIA DE CAVERNAS NA PORÇÃO NORTE DA SERRA DE BALDIM", 2024.

Recent exploration in Sistema Cheve, Oaxaca, Mexico

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Abstract

Sistema Cheve, located in northern Oaxaca, Mexico, is one of the world's deepest known karst systems, with a proven depth potential of more than 2,600 m. The cave was first discovered in 1986, but for many years progress was stopped by sumps and breakdown. In 2021, a major breakthrough occurred. This led to tens of kilometers of large tunnels that went beyond the second sump and substantially expanded the footprint of the cave. By the end of the expedition, seven camps had been established in the cave and over 20 km of new passages had been mapped. Fielding exploration teams at that distance from the entrance was a major logistical challenge. Recent efforts have focused on searching for new entrances near the terminus of the cave to provide a shorter route. In 2024, a new cave, All in a Day's Work Cave (Jornada de Trabajo), was connected into Cheve near Camp 7. Recent exploration has also focused Agua Pajarito (Palomora), a cave that lies between Cheve and Sistema J2, and has reached a depth of 758 m. A small expedition will be fielded in spring of 2025 to continue exploration of Agua Pajarito.

1. History of exploration

Cheve was first discovered in 1986, by Bill Farr and Carol Vesely (OLIPHANT & PISTOLE, 1994). During expeditions in 1987-1990 the cave was explored to a sump at -1,340 m. An initial dive in 1991 extended the depth by 22 meters but was unable to find a continuation. Many subsequent expeditions attempted to find the continuation of the cave, mostly working in extensive breakdown leads, with limited success. Ultimately, exploration shifted to other caves in the area, including Cueva Charco (-1,278 m). In 2003, a successful diving expedition passed the sump in Cheve and explored more than a kilometer of passages on the other side, before finding a second sump. The second sump was also successfully passed, but no way on could be found through the breakdown on the downstream side (STANTON, 2004).

Beginning in 2004, the project shifted effort to the lower elevation "Middle Karst," in hopes of finding another entrance into the continuation of Cheve beyond the sumps. This led to the discovery of Sistema J2 (-1,229 m), which occupied the project for nearly a decade. This cave also ended in a too-tight passage beyond two sumps.

Following the exploration in J2, the team returned to Cheve in 2017 with another diving effort planned. Another team camped beyond the sump and completed a series of climbs, but no major continuations were discovered. However, a new cave, Pena Negra, was discovered in a blind valley two kilomters from the main Cheve entrance. For the next few years, efforts focused on Pena Negra, extending it by many kilometers in extremely large tunnels and ultimately connecting it into Cheve. Efforts also continued in pushing breakdown leads near Camp 3 in Cheve.

In 2021, another major breakthrough occurred, after many years of pushing breakdown leads near Camp 3. This led to tens of kilometers of large tunnels that went beyond the second sump and substantially expanded the footprint of the cave in the direction toward the resurgence. By the end of the expedition, seven camps had been established in the cave and over 20 km of new passages had been mapped. At that point, the end of Cheve represented one of the most remote locations ever reached underground, at 12 km from the entrance. It takes a fast team that already knows the cave a full three days to reach Camp 7, and most teams require 4-5 days. The logistical pyramid to support cavers at this distance becomes immense, and many cavers are tasked simply with hauling food and supplies forward to the teams that are exploring.

Ultimately, the giant new passages ended in a small sump, and the way on was unclear (STONE & TOLES, 2022). The main Cheve stream is not seen in the new extension of the cave, and, in fact, is last seen only halfway to the current end of exploration.

2. Recent exploration

Following the major breakthrough in 2021, the extreme logistical difficulties in pushing the end of the cave led to a shift in strategy. In 2022, it was agreed that no teams would return to the end of the cave. Instead, cavers explored leads in the Pena Negra portion of the system, looked for higher entrances, and revisited the Middle Karst near San Miguel Santa Flor. The terminus of Cheve is located only about 550 m below the town of San Miguel Santa Flor. The presence of a sizeable sinking stream that was matched with a substantial infeeder in the bottom part of Cheve, suggested that finding a new entrance might be possible. An entrance near the current end of the cave would dramatically reduce logistical difficulties of continued exploration.

In addition to searching for new caves, a previously known cave, Agua Pajarito (previously known as Cueva Palomora, before we learned the local name), was also pushed. This cave had been revisited in 2021. Previous exploration ended in a tight crawlway at 120 m depth. In plan view, the cave was located near the ends of both Cheve and J2, making it an intriguing possibility for extension. After extended digging efforts, the tight crawlway was passed, leading to more rapidly descending, if narrow, passages. Exploration ended in 2021 that year at -259 m. Difficult exploration continued in 2022, ending at a depth of 368 m. Several other caves were explored in the area, but no major discoveries were made.

In 2023, we returned with a dual strategy. Three small teams would

make fast-and-light “alpine” exploration pushes from the main entrance to the end of Cheve, with a focus of climbing upwards toward the surface. These teams were supported by dedicated “sherpa” teams whose only job was to carry equipment through the cave to support the effort. These exploration pushes discovered that the lower parts of Cheve contain an extensive labyrinth of fossil passages that extend to elevations of more that 400 meters above the bottom of the cave and reach within 100 meters of the surface. However, none of these passages led to an entrance. Intriguingly, some of these passages are scalloped and indicate upward phreatic flow from the lower parts of Cheve, lifting upward and to the east, leading into a passage that was named Palomora Scenario. These passages are headed east, in the direction of both Palomora (Agua Pajarito) and J2, and perpendicular to the main NNW trend of the cave systems in the region.

In addition to the alpine pushes, further effort was focused on finding new entrances near San Miguel Santa Flor, particularly in the region near where the stream sinks. A new cave was discovered that contained strong airflow and a stream, which likely represented most of the sinking water. This cave was optimistically named Cueva Atajo (Shortcut Cave), because it seemed almost certain to be the key to a connection. However, at a depth of 144 m, this cave ended in a large sediment plug, with no clear way on.

Another cave, Jornada de Trabajo (All in a Day’s Work, ADW), was also located near the sink point. This cave was discovered only after we spoke with locals to see if they knew of holes blowing air out of the ground. Sure enough, one farmer led us to a 10-cm diameter blowing hole in the hillside above the sinking stream. After a few hours of digging dirt out of a crack, it was large enough to enter. This cave went down a short drop and then turned and went upstream up a mostly dry passage. After several short climbs, exploration shifted from this cave to Atajo, as it seemed much more promising. We could also see that there was a sinkhole several hundred meters up the hillside from ADW that the cave was climbing towards. It seemed likely that the airflow was coming from an upper entrance in that sink.

Towards the end of the expedition, after progress ceased in Atajo, efforts shifted back to ADW. Soon, the ascending passage intercepted a pit that was heading downwards, with tremendous airflow coming up. ADW was explored to -264 m before running out of time in the expedition. Further effort was also made in Agua Pajarito in 2022, more than doubling the depth to 734 m.

The 2024 expedition was focused entirely in San Miguel Santa Flor, with a primary focus on ADW and an attempt to connect to Cheve. After a few weeks of work, a connection was made, and ADW entered Cheve a few hundred meters from Camp 7. Most of the rest of the effort was focused on pushing leads in lower Cheve, fielding teams out of Camp 7 and a newly established Camp 8, which was located near the beginning of the Palomora Scenario passage. Numerous climbs and digs were pushed throughout lower Cheve and in the fossil levels several hundred meters above the deep point. However, we did not discover any clear continuation.

Additional teams also worked in Agua Pajarito, extending it to 758 m depth. As usual, it currently ends with a wet and windy dig. However, it is approaching the elevation of the large base-level passages in J2 and Cheve, and its location in between these caves, and in the direction of paleo flow from the bottom of Cheve, makes it particularly intriguing. We will field a small expedition in the spring of 2025 to continue exploration of Agua Pajarito. The next major Cheve expedition is planned for 2026.

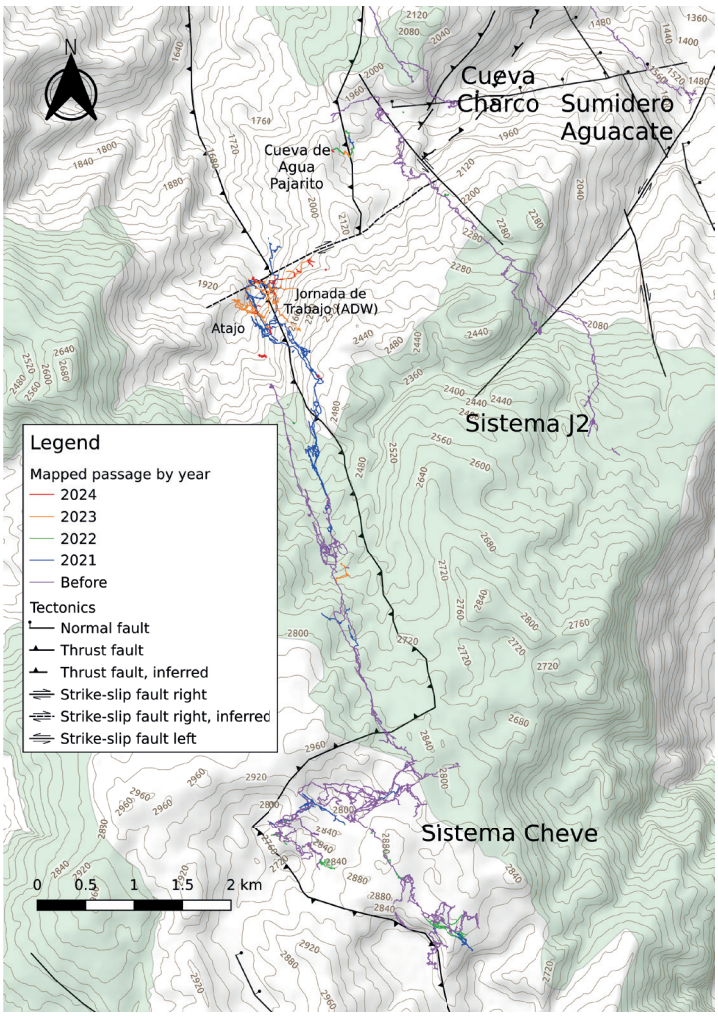

Figure 1: *Current line plot of Sistema Cheve and other nearby caves, colored by exploration year. Geological structures come from the recent geological map produced by the Geological Survey of Mexico (SGM, 2014).*

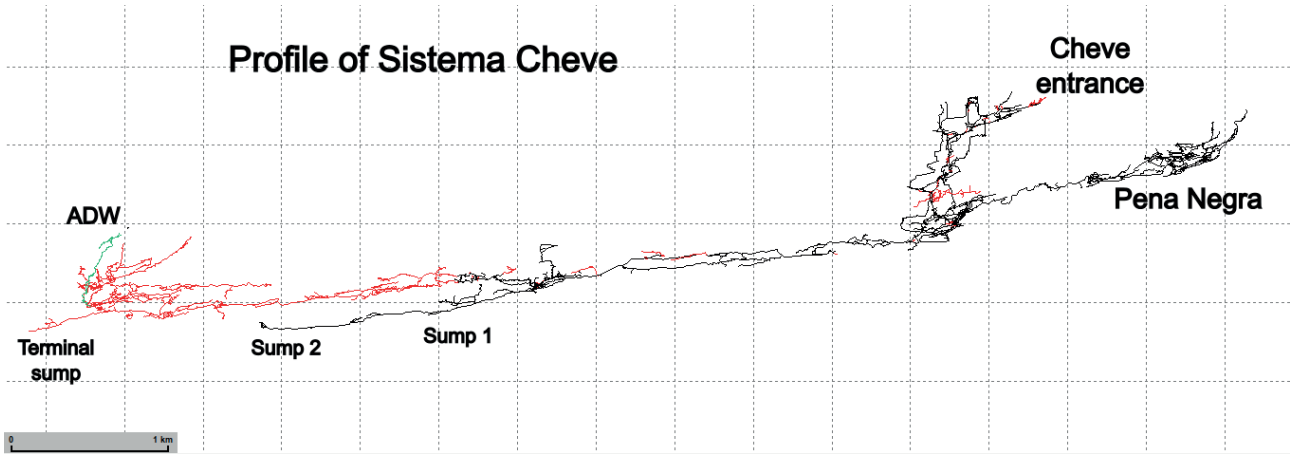

Figure 2: *Profile view of Sistema Cheve. Cave passages explored in 2021 or later are marked in red, except for Jornada de Trabajo (ADW), the new entrance to Cheve, which is shown in green. Note the extensive mazes of fossil levels above the terminal sump, which were the main focus of exploration in 2023 and 2024. The grid has a spacing of 500 m.*

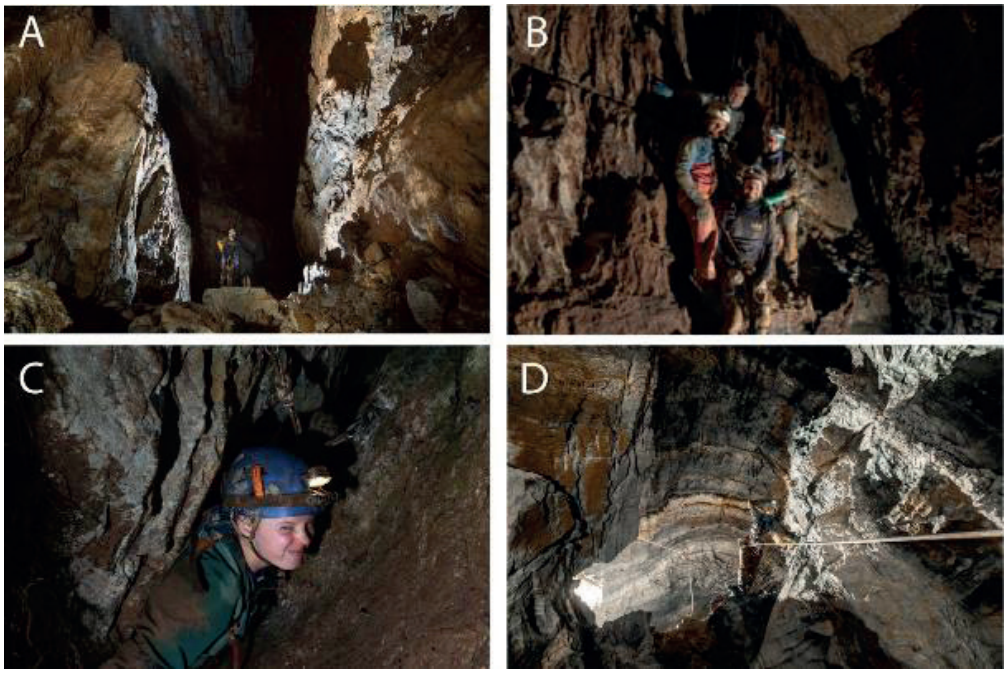

Figure 3: *Photos from the expedition. A) Large passage in Shining Path, in the lower part of Cheve. B) The connection team at the point where ADW entered Cheve. C) Tight drop in ADW. D) An open shaft in ADW.*

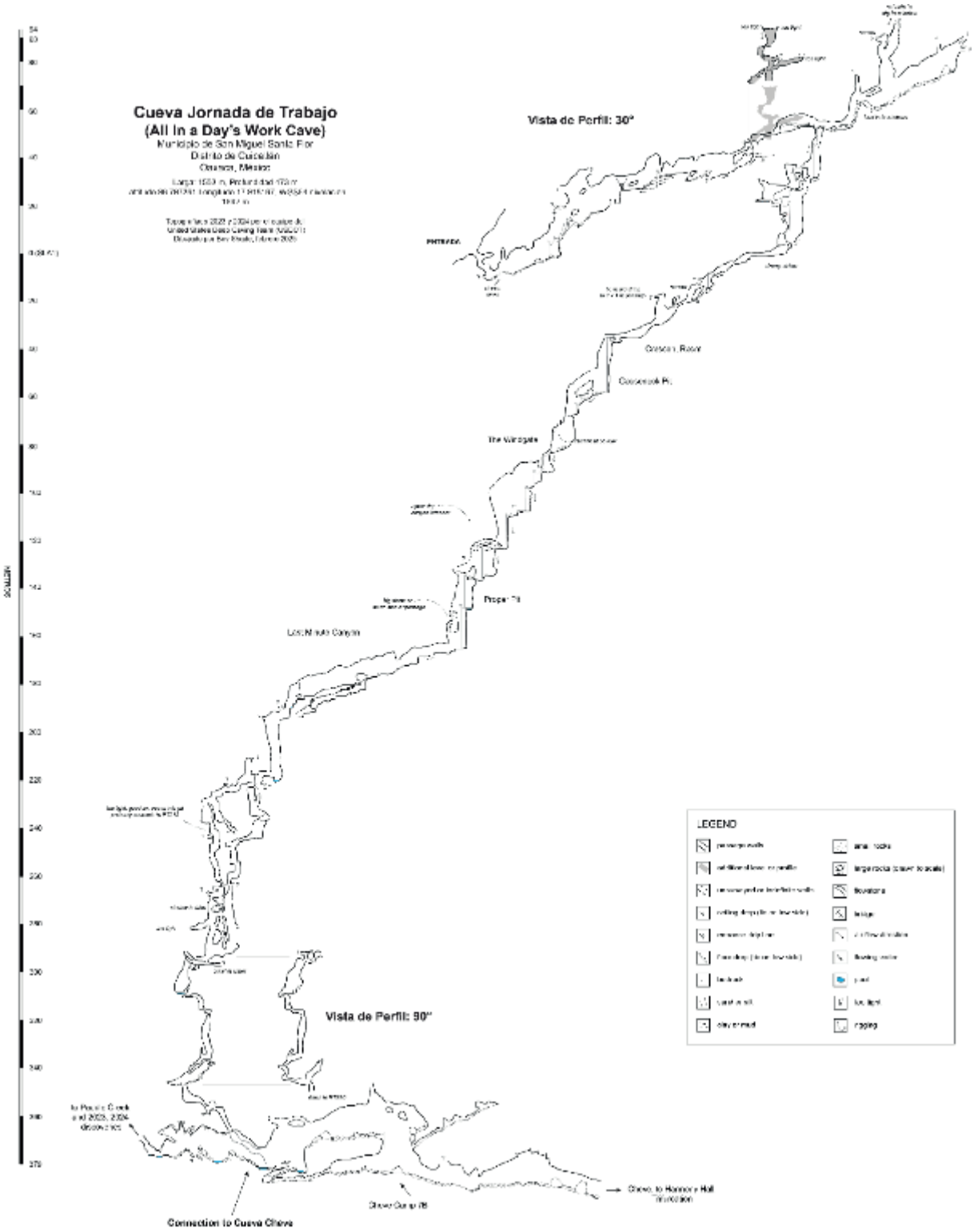

Figure 4: *Profile map of Jornada de Trabajo, or All in a Day's Work Cave (ADW).*

3. Conclusion

During initial exploration, the terminal passages in Sistema Cheve represented some of the most remote locations ever reached underground. These passages were 12 km and 3-5 days of travel from the Cheve entrance. With the discovery of a new entrance, Jornada de Trabajo, these passages are less than a day travel from the nearest entrance. This discovery greatly eases further exploration in the complex maze of passages near the current terminus, though the way on, for now, remains elusive. The cave system is currently 90.9 km long and 1,538 m deep. Agua Pajarito is also intriguing, since much of the paleo flow in Cheve seems to have gone in towards this cave. It could provide the key to downstream continuation of either Cheve or J2. From the current terminus of Cheve, it is an additional 12 km straight-line to the

resurgence cave, Cueva de la Mano with an approximately 1,200 m of additional elevation change. Linking this system to the resurgence, or even gaining most of the elevation change, would make Cheve by far the deepest known cave in the world.

Acknowledgments

Cavers from more than 20 countries have participated in the 39-year project to explore Sistema Cheve. We are grateful to the state authorities in Oaxaca City (in particular Civil Protection); to the village authorities on the mountain (particularly Concepcion Papalo, San Miguel Santa Flor, San Francisco Chapulapa, and Santa Ana Cuatemoc); and to our local friends and families on the mountain – many of whom we have known for several generations since the beginning of the project.

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Contributions to national speleological databases: caves of the middle Rio das Velhas watershed

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Abstract

The two primary Brazilian speleological databases (CNC and CANIE) are vital for the preservation and scientific understanding of Brazil's caves and their speleological heritage. To enhance and improve georeferenced cave data, as well as to produce maps and scientific content demonstrating the importance of these records, the Brazilian Speleological Society (SBE) launched the "Ampliando Rotas" call for proposals. This initiative aimed to encourage speleological groups across Brazil to explore, identify and map caves. In Minas Gerais, within the middle Rio das Velhas watershed, the Opilião - Speleological Study Group (OGrEE) identified and mapped ten caves, six of which were previously unregistered, totaling 2,871 meters of new passages in caves newly discovered or previously registered with inaccuracies. New caves in the Brazilian speleological databases are recorded and inaccurate information in their records is supplemented or corrected. The surveyed caves exhibited significant geological, biological, and cultural characteristics, including speleothems, endemic wildlife, and archaeological remains. Some caves displayed evidence of historical religious practices, while others contained active hydrological systems. The project underscored the importance of cave conservation and highlighted the potential of these sites for scientific research, education, and sustainable tourism.

Resumo

Os dois bancos de dados espeleológicos no Brasil (CNC e CANIE) são a chave para a preservação e conhecimento científico das cavidades nacionais e de seu patrimônio espeleológico. Visando o incremento e correção de dados georreferenciados das grutas, assim como produção de mapas e conteúdo científico que comprovem a relevância dos cadastros, o "Edital Ampliando Rotas" da Sociedade Brasileira de Espeleologia (SBE) teve como objetivo a exploração, identificação e mapeamento de cavernas em solo nacional por grupos de espeleologia brasileiros. Em Minas Gerais, na bacia do médio Rio das Velhas, o Opilião - Grupo de Estudos Espeleológicos (OGrEE) identificou e mapeou com sucesso dez cavernas, seis das quais eram desconhecidas anteriormente, totalizando 2.871 m de novos condutos de cavernas inéditas ou já cadastradas com imprecisões. Também efetuou registros, nos bancos de dados espeleológicos brasileiros, de novas cavernas e acrescentou ou corrigiu informações imprecisas nos seus registros. As cavernas exploradas exibiram características geológicas, biológicas e culturais significativas, incluindo espeleotemas, vida selvagem e vestígios arqueológicos. Algumas delas mostraram sinais de práticas religiosas passadas, enquanto outras apresentaram sistemas hidrológicos ativos. O projeto destacou a importância da conservação de cavernas e também enfatizou o potencial dessas cavernas para pesquisa científica, educação e turismo sustentável.

1. Introduction

The conservation of speleological heritage is essential for the advancement of scientific knowledge and the preservation of subterranean ecosystems and karst landscapes. Caves and karst systems are unique resources protected by the Brazilian Constitution (BRASIL, 1988). They harbor endemic biodiversity (ZAMPAULO; PROUS, 2022), paleoclimatic, historical, archaeological and cultural records (FERNANDES; FARIA, 2024), in addition to playing a critical role in aquifer recharge and hydrological regulation, due to the contact with groundwater (AUDRA; PALMER, 2015). However, the conservation of these systems faces significant challenges (FIGUEIREDO; RASTEIRO, 2010), underscoring the need for initiatives to promote their protection.

In this context, the *Sociedade Brasileira de Espeleologia* (SBE) launched the SBE 01/2023 call for proposals, titled "Ampliando Rotas" (SBE, 2023), which aims to foster speleological research and conservation. The initiative encourages speleological groups to develop projects focused on mapping, identifying and protecting caves in areas with high speleological potential. Opilião - Speleological Study Group (OGrEE) submitted a proposal to this call, which was approved, and in 2024, implemented the actions outlined in the project.

This project aimed to identify, map and register caves in the karst region of the middle Rio das Velhas watershed, located in the central region of the state of Minas Gerais, Brazil, which covers key municipalities to expand knowledge and to promote the conservation of the local speleological heritage. Additionally, it sought to address inconsistencies in existing speleological databases and enhance the training of OGrEE members to conduct fieldwork in the speleology domain. This entire area is of great importance in terms of traces of the first American populations and the recent scientific history of Minas Gerais, as it was the

birthplace of Brazilian paleontology and archaeology, with the Danish naturalist Peter W. Lund (1801–1880) being one of the first scientists to reveal to the world the natural heritage stored in the caves of the region (FERNANDES; FARIA, 2024).

This article aims to present the results achieved during the project, including the identification of new caves, corrections to existing records, and contributions to the national speleological databases. Furthermore, it discusses the relevance of the actions undertaken in strengthening speleological conservation in Brazil.

2. Material and Methods

To identify the speleological potential of the area under study, we collected information about caves previously recorded in Brazilian speleological databases (*Cadastro Nacional de Cavernas* - CNC managed by SBE and *Cadastro Nacional de Informações Espeleológicas* - CANIE managed by *Centro Nacional de Pesquisa e Conservação de Cavernas* - ICMBIO/CECAV of the Brazilian government), analyzed satellite imagery (Google Earth Pro and mobile applications such as Google Maps and AlpineQuest), and reviewed topographic and thematic maps, particularly from IBGE databases (IBGE, 2024), supplemented by the Avenza smartphone app.

During the fieldwork phase, we employed traditional speleological prospection and topographic survey methodologies (Figures 1 and 2).

Figure 1: *Speleological prospection in Curvelo (Minas Gerais, Brazil) surveys. Source: from the authors, 2024.*

In the study area, in addition to the electronic tools mentioned above, inquiries were made to residents to trace caves in the region. Speleological walks were conducted in areas with potential for the existence of caves. Once a cave was located, it was assigned a provisional code or name. When a newly discovered natural cavity was confirmed, an inventory was created following the CNC - SBE and CANIE - ICMBIO/CECAV registration protocols, using geographic coordinates of the cave entrance for verification.

Figure 2: *Topographic surveys in Água Santa II cave. Source: from the authors, 2024.*

The cave with the greatest speleological significance in a given region was then surveyed using rangefinders, clinometers and compasses. During this stage, we chose to use a paperless surveying technique facilitated by the TopoDroid application. Subsequently, the electronic sketches were digitized using software compatible with technical drawings.

The maps created complied with the same surveying standard defined by the BCRA and were classified in category 4C.

Finally, in the office phase, the newly discovered caves were registered in the CNC - SBE and CANIE - ICMBIO/CECAV databases, becoming part of the listed speleological records.

2.1. Study Area

The study area is located in the karst region of the Bambuí Geological Group (Figure 3) in the state of Minas Gerais, Brazil, covering the municipalities of Curvelo, Cordisburgo, Corinto, Monjolos, Presidente Juscelino, Santo Hipólito, Baldim, Jequitibá, Santana do Pirapama, and Jaboticatubas.

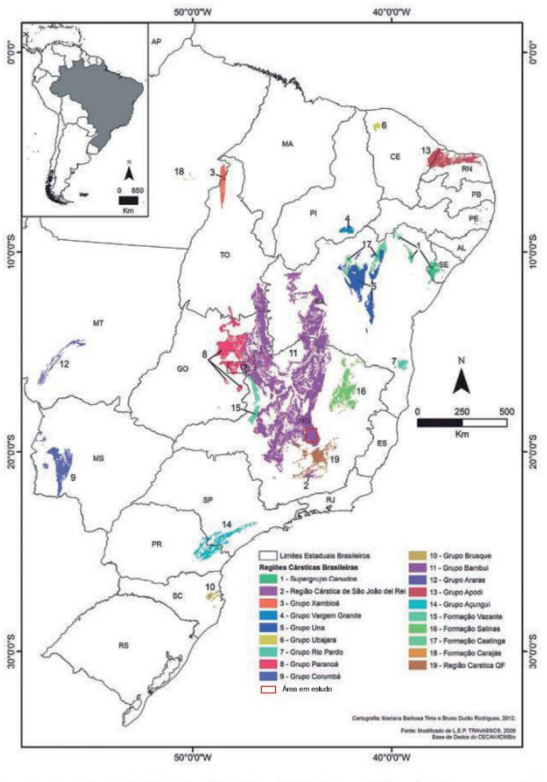

Figure 3: *Brazilian Karst Regions. Source: TRAVASSOS, L. E. P., 2019.*

According to Travassos (2010), the karst landscape encompassing Cordisburgo City and its surroundings is shaped by perennial and intermittent rivers, which are responsible for features such as lapiés, sinkholes, and valleys. Lima, Silva and Cassimiro (2024) point out that the region features outcrops of rocks belonging to the lower sequence of sedimentary rocks of the Bambuí Group, characterized from the base

to the top as follows:

i. **Sete Lagoas Formation**, located north of Belo Horizonte, composed of pelitic rocks with the Lagoa Santa facies, consisting of limestones and dolomites of diverse compositions;

i. **Serra de Santa Helena Formation**, composed of shales, silstones, marls and sparse lenses of black limestone;

i. **Lagoa do Jacaré Formation**, with sequences of siltstones, marls, black limestones, fetid limestones and oolitic and pisolitic limestones;

i. **Serra da Saudade Formation**, consisting of siltstones, green pelitic rocks, shales and claystones with sparse lenticular intercalations of limestone.

The area is part of the middle Rio das Velhas watershed, a tributary of the upper stretch São Francisco River, bordered to the right by the mountainous region of the Espinhaço Range. The vegetation covering the landscape consists predominantly of the phytophysiognomies of the Cerrado biome (Brazilian Savanna).

3. Results

Between January and September 2024, regions in the municipalities of Curvelo, Cordisburgo, Corinto, Monjolos, Presidente Juscelino, Santo Hipólito, Baldim, Jequitibá, Santana do Pirapama and Jaboticatubas (all in the state of Minas Gerais, Brazil) were visited and prospected (Figure 4).

These municipalities have a significant number of caves, most of which have already been registered in Brazilian databases; however, inconsistencies are observed when they are compared (Figure 5).

During the fieldwork phase, ten caves were identified and mapped (*Gruta da Água Santa, Toca do Geraldo, Lapa Velha Nova, Lapa da Lagoa do Rótulo, Gruta da Fazenda da Lapa, Gruta da Água Santa II, Gruta Peixe no Teto I, Peixe no Teto II, Peixe no Teto III* and *Gruta da Estiva I*). Of these, the last six caves were not listed in the databases of the referenced institutions and four caves had their records corrected based on contributions by the OGrEE. In total, 2,871 meters of new cave passages were surveyed in less than one year.

Municipalities	CNC - SBE	CANIE - CECAV
Baldim	12	8
Cordisburgo	47	76
Corinto	9	15
Curvelo	25	38
Jaboticatubas	4	31
Jequitibá	9	21
Monjolos	30	77
P. Juscelino	4	29
S. Hipólito	9	11
S. Pirapama	12	23
Total	**161**	**329**

Figure 5: *Number of caves in databases in Brazil.*

[1] Updated in: Dec/2024.

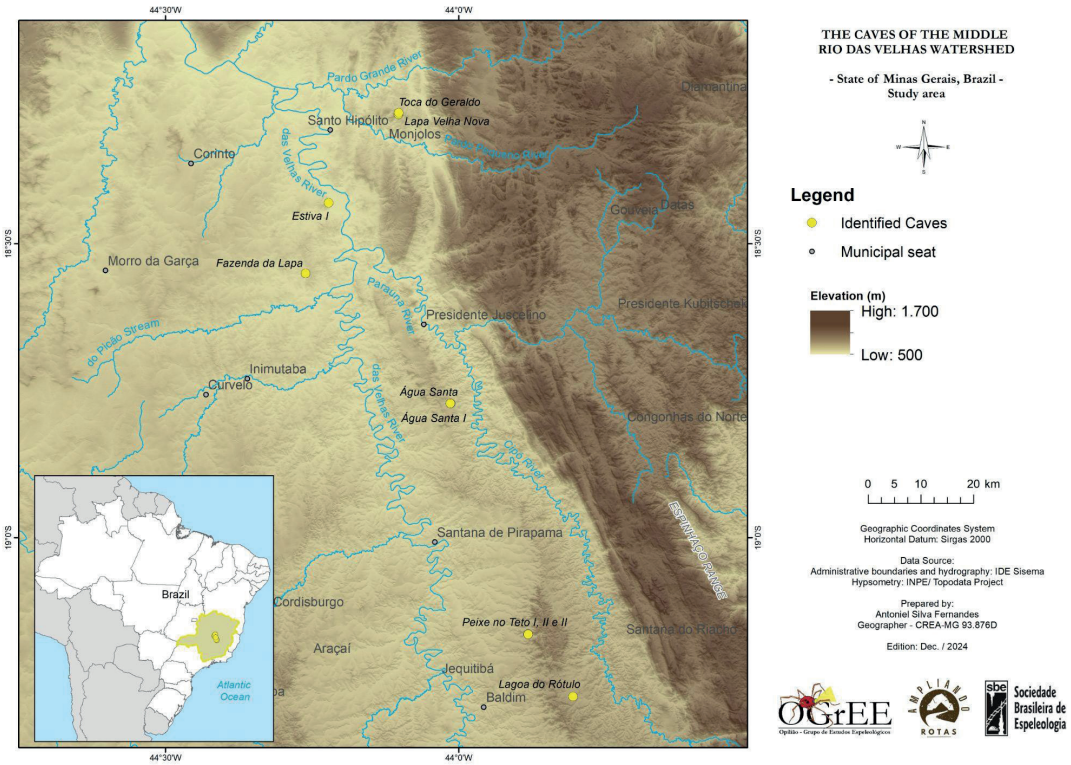

Figure 4: *Identified Caves. Source: from the authors, 2024.*

As an example of corrections to data inconsistencies, we note two caves located in Monjolos (red asterisks in Figure 6). The image also highlights the inconsistency between the two speleological databases (CNC and CANIE), showing duplicate records, coordinates with errors greater than 200 meters, incomplete names or even the absence of cavities of high speleological relevance. The region is part of the property known as "*Fazenda Velha*," and different speleological teams/groups that visited it at various times registered names and coordinates in different ways. Only after consulting references from works conducted in this region (GUIMARÃES, 2012), it was possible to conclude that the cave to the north (upper red asterisk) is the one commonly referred to as "*Gruta Velha Nova*," which was studied by *Sociedade Excursionista e Espeleológica* - SEE (the first speleological group in Brazil) on two occasions, and whose maps are part of its collection.

The point corresponding to this cave in the CANIE database is located 380 meters northwest of the original cave entrance, at the bottom of a sinkhole. In the CNC database, however, the name "*Velha Nova*" is not listed as a record for any cave in the municipality of Monjolos. The inconsistencies were identified and outlined in a report submitted to the SBE, in which we suggested the correction of the database.

Figure 6: *case of inconsistency, red asterisks caves discovered for this work, the river dashed in yellow has its sinkhole in the cave to the south, in the north, the direction, indicated by blue arrows, of the delineation of four well-defined sinkholes on the horizon.*

4. Discussion

During the topographic surveys, cultural elements were identified in the form of traces of religious activity inside some caves. For example, remains of animals possibly associated with African-origin religious ceremonies were verified in the *Fazenda da Lapa* cave, in Curvelo (Figure 7), in addition to the local report of catholic pilgrimages in the cave. A very rich biological heritage was also found in some cavities, observing small and medium-sized animals such as wild canines and felines and bats, in addition to species with a troglomorphic appearance. The marked presence of hydrological activity also highlighted the importance of karst systems for the preservation of water resources and for local and regional water security (Figure 8). In the *Água Santa* cave (Presidente Juscelino), for example, there was a small stream of crystal-clear water that cut through its wider hall in a west-east direction. Important archaeological remains were also found, such as in the *Peixe no Teto* cave system (Jequitibá), with well-preserved geometric, zoomorphic and anthropomorphic cave paintings (Figure 9).

Figure 7: *remains of animals possibly associated with African-origin religious ceremonies in the Fazenda da Lapa cave. Source: from the authors, 2024.*

Cave survey update also proved quite important for improving map quality, as it provided better detailing of some areas and the identification of others not represented in previous surveys that, in some cases, date back to 50 years ago. However, in general, the comparison of the maps showed a good agreement in terms of morphology and occurrence of elements inside the caves, such as speleothems and flora records, which suggests good accuracy in the mapping work, in addition to a reasonable good state of preservation of the caves along the years. However, it is worth noting that some of them contained residues inside, either left by visitors or brought from the external environment. In the most striking case, bottles of agricultural pesticides were observed close to a water stream in a cave.

Figure 8: *Hydrological activity inside the Toca do Geraldo cave. Source: from the authors, 2024.*

Figure 9: *new discoveries of geometric, zoomorphic and anthropomorphic cave paintings. Source: from the authors, 2024.*

In general, geolocation inconsistencies are due to data acquisition with no GPS equipment during older surveys. The discrepancy between the number of caves registered in the CNC - SBE and CANIE - ICMBIO/CECAV databases, in turn, is due to the unofficial nature of the first platform. Finally, the activities conducted through this project allowed group members to acquire expertise in speleological activities, thus providing a major contribution to the training of a new generation of cave scientists.

5. Conclusion

The project carried out by the Opilião Speleological Study Group (OGrEE) successfully contributed to the enhancement of speleological research and conservation in the karst region of the middle Rio das Velhas watershed. By identifying and mapping ten caves, six of which previously unregistered, and correcting inaccuracies in existing databases, the project addressed critical gaps in the documentation of speleological heritage.

The discoveries during this project underscore the diverse significance of the caves in this region, encompassing geological, hydrological, biological, cultural, and archaeological elements. These findings not only highlight the urgent need for conservation efforts but also emphasize the potential of these caves for advancing scientific research, education, and sustainable tourism.

Furthermore, the project demonstrated the importance of consistent and accurate documentation in national speleological databases, providing valuable contributions for their improvement.

This initiative exemplifies how targeted conservation actions — supported by collaborative efforts and robust methodological approaches — can strengthen the preservation of speleological heritage while fostering public awareness and scientific understanding.

As a secondary objective, the project was also important for the training and consolidation of speleologists who are members of OGrEE and participated in the execution of this project.

Finally, it is worth highlighting the importance of initiatives such as this one by institutions dedicated to the protection of speleological heritage. It is expected that new initiatives will be promoted in the near future, ensuring that the country's rich speleological heritage is safeguarded for future generations.

Acknowledgments

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The Sulfur and Edwards Mountain cave systems of Southern Kentucky, USA

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Abstract

Exploration activities since the 1960s have revealed world-class caves along the west-facing Cumberland Escarpment in southern Kentucky, U.S.A. When combined with expansive karst of the surrounding Interior lowland plateaus of the North American mid-continent, like those hosting Mammoth Cave, the caves of the Cumberland Escarpment have served as important benchmarks for exploration, conservation, and science. Multiple generations of cavers that began their career in the Cumberland Escarpment have become regular leaders in the National Speleological Society and its member grottos. The current generation of cavers fostering a renewal of cave exploration in southern Kentucky has unveiled important caves and revealed transformational science. Many classic caves to the region have been remapped, and more than 70 km of new passage have been discovered in existing and newly found caves. Technical advancements in single rope techniques and adoption of European style rigging methods have made otherwise un-explored passages accessible. In this way, cave explorers and scientists continue to uncover and map amazing caves, including 16.3 km beneath Sulfur Mountain where we feature the exploration of Bowman's Pit and its connection to Skert Well. At nearby Edwards Mountain we feature the exploration of 10.1 km of passage in Spelunger Cave.

Résumé

Les activités d'exploration depuis les années 1960 ont révélé des grottes de classe mondiale le long de l'escarpement de Cumberland, orienté à l'ouest, dans le sud du Kentucky, aux États-Unis. Lorsqu'elles sont combinées avec le vaste karst des plateaux de plaine intérieurs environnants du centre du continent nord-américain, comme ceux abritant Mammoth Cave, les grottes de l'escarpement de Cumberland ont servi de références importantes pour l'exploration, la conservation et la science. Plusieurs générations de spéléologues qui ont commencé leur carrière dans l'escarpement de Cumberland sont devenues des dirigeants réguliers de la National Speleological Society et de ses grottes membres. La génération actuelle de spéléologues qui favorise un renouveau de l'exploration des grottes dans le sud du Kentucky a dévoilé d'importantes grottes et révélé une science transformationnelle. De nombreuses grottes classiques de la région ont été recartographiées et plus de 70 km de nouveaux passages ont été découverts dans des grottes existantes et nouvellement découvertes. Les progrès techniques dans les techniques de corde à simple et l'adoption de méthodes de gréement de style européen ont rendu accessibles des passages autrement inexplorés. De cette manière, les spéléologues et les scientifiques continuent de découvrir et de cartographier des grottes étonnantes, notamment 16,3 km sous le mont Sulphur, où nous présentons l'exploration de la fosse Bowman et sa connexion avec le puits Skert. À proximité du mont Edwards, nous proposons l'exploration de 10,1 km de passage dans la grotte Spelunger.

Resumen

As atividades de exploração desde a década de 1960 revelaram cavernas de classe mundial ao longo da Escarpa Cumberland voltada para o oeste, no sul de Kentucky, EUA. Quando combinadas com o cárstico expansivo dos planaltos circundantes da planície interior do continente norte-americano, como aquelas que hospedam a Caverna Mammoth, as cavernas da Escarpa Cumberland serviram como referências importantes para exploração, conservação e ciência. Várias gerações de espeleólogos que começaram sua carreira na Escarpa Cumberland tornaram-se líderes regulares na Sociedade Espeleológica Nacional e nas grutas de seus membros. A atual geração de espeleólogos que promove uma renovação da exploração de cavernas no sul do Kentucky revelou cavernas importantes e revelou a ciência transformacional. Muitas cavernas clássicas da região foram remapeadas e mais de 70 km de novas passagens foram descobertas em cavernas existentes e recém-descobertas. Os avanços técnicos nas técnicas de corda única e a adoção de métodos de cordame de estilo europeu tornaram acessíveis passagens que de outra forma seriam inexploradas. Desta forma, exploradores de cavernas e cientistas continuam a descobrir e mapear cavernas incríveis, incluindo 16,3 km abaixo da Montanha Sulphur, onde apresentamos a exploração de Bowman's Pit e sua conexão com Skert Well. Na vizinha Edwards Mountain, apresentamos a exploração de 10,1 km de passagem na Caverna Spelunger.

1. Introduction

The authors of this paper are the third generation of organized cavers to actively work in the Cumberland Plateau of southeastern Kentucky. The first generation in the 1960s and 1970s included significant contributions by members of the Dayton Area Speleological Society (DASS) and Central Ohio Grotto (COG) of the National Speleological Society (NSS) and culminated in the surveys of some of the longest caves in the United States at that time--Sloans Valley Cave (39.6 km), Coral Cave System (36.3 km), and the Cave Creek System (24.1 km). All three of these cave systems

were south of the town of Somerset in Pulaski County Kentucky, which at that time was the southern terminus of quality highways.

The second generation in the 1980s and 1990s included more members of the Greater Cincinnati Grotto (GCG), the Miami Valley Grotto (MVG), and the Bluegrass Grotto (BGG) and saw systematic documentation on cave locations and cave maps. Coalitions of cavers formed to synergize efforts in specific areas and in response to specific actions. One coalition included the Southwest Ohio Regional Caving Association (SWORCA) that focused efforts east of the town of Mount Vernon in Rockcastle County Kentucky. These groups worked in the Crooked Creek watershed with the Goochland-Poplar Cave System (18.0 km) at its headwaters. A second coalition was the Sloans Valley Conservation Task Force that spearheaded efforts to end activities at the Dixie Bend Landfill adjacent to Sloans Valley Cave.

The third generation of organized southern Kentucky caving began at the turn of the new millennium and lends its origins to two discrete sets of paired actions and reactions. The first action-reaction pair was a government plan to build a new interstate highway (I-66) across southern Kentucky and the caver-led opposition to the cascade of impacts it would cause to caves in Pulaski County. This included Wells Cave (18.5 km) that became a NSS preserve in 2002. Cavers persevered and managed to reroute the proposal away from sensitive sites and significantly delay highway construction.

The second action-reaction pair was an observation that cave and karst data in Kentucky was decentralized with limited capacity to communicate the scale of statewide karst resources. This limited the capacity to develop organized responses to threats to caves, such as the proposal to build I-66 and the development of a major industrial hub on the sinkhole plain near Mammoth Cave. While attempts at a statewide database of caves occurred in both prior generations (by Roger Sperka in the 1970s and Angelo George in the 1980s) those earlier attempts were regional and managed by a single individual. The reactions were to develop statewide maps of dye traces, a geospatial inventory of sinkholes, and establish the Kentucky Speleological Survey (KSS) to aggregate, retain, and selectively disseminate cave locations and cave maps.

Parallel to these two action-reaction pairs at the turn of the 21st Century was the Annual Convention of the NSS, which was held in 2001 at Great Saltpetre Cave in Rockcastle County Kentucky and remains one of the largest NSS Conventions to date with more than 2,000 registered attendees. The efforts to host this convention led to an organization and caver fellowship that long outlasted the convention. Cavers of the regional grottos have subsequently secured ownership of Great Saltpetre Cave and the more than 130 ha of surrounding land. They also founded the Rockcastle Karst Conservancy that has since bought or established access to several important caves in southeast Kentucky.

Across all three generations there were sporadic efforts in Wayne County, Kentucky, which is south of the places and caves outlined to this point. Some of the reasons for this lack of attention were noted in the 18th ICS proceedings (FLOREA et al., 2022) and included the distance of travel from major metropolitan centers, the quality of road networks prior to the 1990s, and the difficulty securing access from landowners. Despite these challenges, large caves were known from initial surveys by dedicated cavers of the first and second generations, such as Lou Simpson and Bill Walden who were both recipients of the NSS Lou Bicking Award for exploration. These included Blowing Cave (8.2 km), Redmond Creek (7.4 km), Triple-S Cave (7.2 km), Wind Cave (4.8 km), and Burfield Hollow Cave (3.8 km)--these lengths are current and include resurvey or additional new survey.

This paper outlines the continuing generational legacy of cave exploration in Wayne County, Kentucky and highlights cave mapping and science thus far in the 21st Century. Many classic caves to the region have been remapped, and more than 70 km of new passage have been discovered in existing and newly found caves. We will focus our discussion on two cave systems from which we have revived regional interest and engaged new talent. The first is the sprawling Sulfur Mountain System (16.3 km), now the longest cave in Wayne County, and the second is the Edwards Mountain System (10.1 km), which has the potential to be the deepest cave in Kentucky at more than 150 m. Both cave systems have included adoption of European-style single-rope techniques, rescue caches, and in-cave camps. Both cave systems have also led to scientific findings that have been transformative to our understanding of caves in the Cumberland Plateau.

2. Historical Context

The colonial settlement of Wayne County, Kentucky began in the late 18th Century as settlers from Virginia traversed the Wilderness Road across Cumberland Gap, through the rugged hills and valleys of the Cumberland Plateau, and into the sweeping plains of the Bluegrass region. Some ventured south along the western margin of the Cumberland Escarpment and established communities, such as Monticello, on the sinkhole plains of the Pennyroyal Plateau (also known as the Highland Rim). Monticello, like most settlement communities, was situated along wildlife corridors (called traces) and near cave springs that were sources of potable water in a landscape with scarce surface water. The juxtaposition of tillable lands for crops on the sinkhole plain, the old-growth forests and sources of coal in the adjacent Cumberland Plateau, and the nearby Cumberland River made communities such as Monticello a bustling center for lumber and grain mills.

During the U.S. Civil War, confederate troops constructed an iron furnace adjacent to two travertine waterfalls along Beaver Creek in Wayne County. This supported nearby garrisons and engagements with Union Troops, such as at the Battle of Mill Springs. The furnace made cannonballs using smelted ore from veins of goethite in the overlying sandstone and conglomerate of Furnace Mountain. Along with charcoal from the plentiful forests, it is possible that sources of shallow oil were used for combustion. Colonial settlers to the region noted sulfurous smells arising from Beaver and Otter creeks during times of low flow. The smell came from hydrogen sulfide associated with seeps of petroleum rising through fractures in the streambed. Such was the naming origins for several local places in the 19th Century, such as Sulfur Mountain, Oilton, and Slickford.

Post Civil War industrialization in the U.S. sought sources of oil to drive heating and steam production for manufacturing, electricity, and the railroads. Accessible oil 'pools' were shallow in Wayne County (< 150 m) and spurred a flurry of well drilling and pipeline construction starting in 1898. By 1926, more than 4,000 oil wells had been drilled in the region and the shallow reservoirs were depleted. Remnants of the oil industry, including segments of pipeline, well pumps, and storage tanks, remain scattered in the forests and along the creeks.

Today, Monticello and Wayne County, like many rural areas in Kentucky, have higher average rates of poverty. Timber production and grain farming remain the largest industries. Land ownership is virtually all private and single-owner parcels greater than 500 ha are common. Some land ownership can be traced through a single family to the time of colonial settlement. In other cases, large timber companies have bought land to put into timed rotation for logging. Coopers supporting the booming bourbon industry demand stands of white oak that are native to the Cumberland Plateau.

3. Hydrogeologic Setting

Caves in southeast Kentucky are often associated with the incision of base level streams along the Cumberland Escarpment--a low-lying cuesta of gently dipping Carboniferous strata including 100 m of carbonates overlain by flysch and truncated by fluvial conglomerates (SIMPSON & FLOREA, 2009). Cave development progresses from vertical shafts that initiate at the carbonate-siliciclastic contact (BRUCKER et al., 1972) and through multi-level relict conduit networks perched above the active drainage system (SASOWSKY, 1994) that lead to springs at the base of the escarpment and carbonate sequence (CRAWFORD, 1984). The continued migration of knickpoints during Plio-Pleistocene interglacial periods is the guiding force behind the pace of incision (ANTHONY & GRANGER, 2007).

Topographic relief in Wayne County exceeds 300 m, ranging from 230 m-amsl on the Cumberland River to approximately 540 m-amsl on cliff-lined ridges. South of the town of Monticello, Beaver and Otter Creeks are major base level streams that collect karst groundwater from numerous springs. The bulk of cave exploration in Wayne County has focused on the headwater systems and tributaries of both Beaver and Otter Creeks and include segments of once more extensive integrated cave systems (FLOREA, 2015).

4. Sulfur Mountain System

Caves on Sulfur Mountain have been known for decades. A list of potential fallout shelters published locally in the 1980s in the Monticello newspaper included a note of a cave on Sulfur Mountain that would hold many people. Later in the 1990s, the same newspaper published a short article on two local arborists who discovered a pit with an extensive cave at its base. National press followed when cave explorers Alan Gennon, Joel Despain, and Shane Fryer from Western Kentucky University announced in 2001 that they had found the “biggest cave room in Kentucky” in a nearby cave--a claim since superseded by a room discovered in another Wayne County Cave. By this time, cavers largely from Ohio and led by Lou Simpson, who worked in the Black House Mountain area of northern Tennessee, moved their efforts to Wayne County. They rented the Hideout, a farmhouse that remains a base of operations to this day, and focused efforts toward the survey of the newly discovered Grayson-Gunnar Cave (11.4 km).

The list of leads to check grew exponentially through the late 1990s and early 2000s. This was, in part due to diligent efforts of brothers Greg and Pat Erisman, who spent years ridgewalking and lived nearby. Among their finds in the mid-2000s was a pit on the south flank of Sulfur Mountain at the contact between the Kidder Limestone and overlying Hartselle Formation. When they dropped the 24.4-m entrance shaft, they discovered large cave passages. Initials scratched into the walls made it clear that this was the cave mentioned in the newspaper article about the arborists. The nearby landowner, through which they obtained access, was the source of the cave name, Bowman’s Pit.

First author Florea started a comprehensive survey and study of Sulfur Mountain and associated caves starting in 2007. In Bowman’s Pit, five levels were quickly discovered that represent segments of the Early Pleistocene flowpath of Beaver Creek. As with all “Cumberland Style” caves (Sasowsky, 1994), the upper-level passages are hillside parallel and mark the progressive incision of the base level stream. These combined segments of cave comprise about 40% of the total survey. Connecting the primary passage levels and striking off in other directions are modern sub-drainages that convey hillside recharge through vertical shafts and descending canyons. These comprise another 40% of the known cave. All sub-basins have segments that are perched on the Lost River Chert at the base of the Ste. Genevieve Limestone. Where they break through, the cave rapidly descends through a series of waterfalls. Skert Well, another open-air shaft on Sulfur Mountain, is the best and most dramatic example.

Exploration of Skert Well began in earnest in Fall 2015 when Florea and others pushed a blowing and long overlooked lead 12 below the lip on a green shale in the Kidder Limestone. Three rappels and three traverse lines later, leaned over chert ledge into a dark gulf with the reverberating sound of a torrential waterfall—the Lost World. Further exploration included three additional drops through water into the Moonage Daydream Borehole, the only base level stream discovered in the Sulfur Mountain System that includes another 10% of the mapped cave. The Moonage Daydream Borehole remains an enigma; both ends of the survey end at a sump. Downstream, the water likely reappears

Figure 1: *Photos from Bowman’s Pit Cave in the Cumberland Escarpment of southern Kentucky, USA. (Top) Thunderdome, a 49-m vertical shaft (Jacob Leiber). (Upper middle) Traverse line across large room and into feeder canyon (Lee Florea). (Lower middle) Gypsum antlers in relict tier of cave passage (Jacob Leiber). (Bottom) Activity in camp (Lee Florea).*

after 120 m in a blue hole on Beaver Creek. Upstream, the magnitude of water and the trend of the passage direction suggests that it may be a piracy route for the valley to the north of Sulfur Mountain.

By 2016, more than 12 km of passages were surveyed. Rapid initial efforts transitioned into slow progress, and then a general hiatus. A blowing lead at the west end of Bowman's Pit became a focus Brian Devine and others, who at the end of 2016, used micro-shaving techniques to open the tight lead and discover a labyrinth of canyons and vertical shafts. In spring 2019, Bauer, Devine, and Nathan Canaris connected Bowman's Pit to Skert Well. The through trip includes 15 ropes and is the culmination of 2.5 years of route-finding, bolting, and creative rigging.

The eastern part of Bowman's Pit is where the remaining 10% of the 16.3-km current length has been added since 2017. It is also where Florea, Devine, and others established a fully stocked camp to aid exploration (Fig. 1). The route from the entrance shaft to the camp is approximately 2.5 km. One third of this route is walking, a second third is canyoneering, and the remaining third are sand crawls. The entire route is coated in gypsum. In some cases, this gypsum manifests as antlers more than 30 cm long (Fig. 1).

One noticeable characteristic of exploring Bowman's Pit is relative warmth and dryness. Hydration becomes a concern with the pace of caving and the lack of water. Partly guiding the location of the camp are nearby sources of water. Teams can now engage in trips longer than 36 hours, including two hours of time to rig and de-rig the entrance drop. With four hours or travel time each way to camp and an eight-hour period for food and rest, this leaves 18 hours or more for exploration, lead climbing, and survey. The training and lessons learned in the Sulfur Mountain System were excellent practice for the complexities of cave exploration on Edwards Mountain just 10 km to the south.

5. Edwards Mountain System

Compared to many areas in Wayne County, Edward's Mountain remained relatively unexplored by cavers until the 2000s, the lone exception being a sandstone cave (119 m) that received frequent local visitation. Rather, most cavers went to well-known caves nearby such as Triple-S, Blowing, Redmond Creek, and Wind Cave. The shift toward exploration occurred after Charles Gibbs, inventor of the Gibbs Ascender, purchased land adjacent to and on Edwards Mountain. Cavers soon reported several leads and mapped many caves on Gibbs property. One lead found by Paul Unger and others was a crevice with exceptional airflow on the saddle of a high ridgeline. The position of the crevice was tantalizing. First, it was in the Bangor Limestone above the Hartselle Formation. Second, it was on the flank of the Sunnybrook Anticline, one of few significant geologic structures in this region. Both features of the crevice offered a depth potential of 155 m, more than 30 m greater than anywhere else in Kentucky.

The crevice was widened in 2007 by Harry Goepel, Buddy Gibson, and the Erisman brothers. Intersecting vertical fissures descended 10 m through the Bangor Limestone to a balcony on the Hartselle Formation that overlooked a thundering darkness. This unassuming crack in the ground quickly opened to the top of a large chamber, 51 m high with a seasonal waterfall (Fig. 2). The cave was named Spelunger, a combination of the word Speleo and the name Unger.

Early exploration of Spelunger was primarily focused around the base of the entrance shaft. One set of explored passages were oriented east-west and included segments of upper-level, gypsum-encrusted borehole in the Kidder Limestone (Fig. 2). A second set of explored passages were accessed through another 10-m rope drop through breakdown and a waterfall at the base of the main shaft. This led to a set of north-south-oriented, middle-level, gypsum-encrusted borehole segments in the Ste. Genevieve Limestone. Exploration in these north--south passages concluded when the Erisman brothers, after dropping another 12 m shaft (the 'fourth drop'), encountered a 'funny smell' and were concerned that there could be bad air.

The first phase of exploration between 2007 and 2012 included a combination of full survey, line plots, and undocumented exploration. This early phase ended over concerns with bolt integrity and rope placement, and because exploration in Sulfur Mountain attracted most project cavers that came to the area.

Interest in Edwards Mountains revived in 2018 and second author Bauer took over project management at that time. Lessons learned from Sulfur Mountain, including strategic bolt placement and alpine rigging were utilized to revamp the entrance rigging. Bauer, Harry Goepel, Jonathan Carmen, and Jason Glancy spearheaded this effort and resurveyed the east-west upper levels.

Figure 2: *Photos from Spelunger Cave in the Cumberland Escarpment of southern Kentucky, USA. (Top) The entrance room with 51-m vertical shaft and waterfall (Jacob Leiber). (Middle) Upper level borehole (Jocob Leiber). (Bottom) Petroleum seep in lower stream level of cave (Lee Florea).*

In 2019, exploration of the north-south trending passages began in earnest. Florea, recalling prior work in Jugornot Cave (9.8 km) of Pulaski County, noted that the 5-levels of passages were stacked vertically, and that stacking was likely from the presence of a significant fault. Evidence of this fault, in the form of slickensides, was soon identified in the higher levels. In the lowermost level, 98 m below the entrance, a stream passage continues for nearly a kilometer in each direction of the drop where exploration ended in 2012. Upstream of this intersection are more than a dozen seeps of petroleum rising through the fault zone (Fig. 2). The hydrogen sulfide from these seeps was the source of the 'funny smell'. Downstream of this intersection, cavers followed the stream and adjacent crawls, bypassing several intersections, and turned around in walking virgin passage. The last trip in that part of the cave was in 2020.

Lowe Cave is the suspected resurgence of the Edwards Mountain System. It is 1.2 km from the current end of the downstream survey. The entire 45 m of this cave has been excavated by cavers that were following incredible airflow that rose through boulders in a small gully at the base of Edwards Mountain. More excavation is needed to break into the open cave.

Above the stream passage and to the north of the fourth drop are four other levels of dry cave that follow the faultline and generally parallel the adjacent hillside. Connections between these levels occur at shafts that punctuate the cave system. These north-trending passages are where exploration is presently focused and has yielded discoveries of large rooms and beautiful formations in places such as the Monsoon Room, Ginsberg Dome, Fisherman's Wife's Dream, and Treasure Island. A previously unchecked lead in the room with the entrance shaft has provided more direct access to these active leads. At present, Spelungers is 10.1 km long, and 105 m deep.

Increasing the depth is a primary goal. Several other caves and leads discovered and mapped by Florea, Bauer, and others along the west flank of Edward's Mountain likely connect to Spelungers. These include Green Garter Pit, Elimination Hole, and Lavonathon Cave. Green Garter Pit is a 5 m shaft in the Bangor Limestone with a waterfall that has incredible airflow rising through a breakdown choke. This pit is almost certainly the source for the waterfall in the Monsoon Room. Elimination Hole is a 19-m retreating shaft in the Bangor Limestone, surveyed to 46 m with two leads which require modification to continue. Lavonathan Cave is a 30-m-deep retreating shaft in the Bangor Limestone and on a fault near the northern crest of the Sunnybrook Anticline. It is 1 km north and 45 m higher in elevation than the northern terminus of the current survey in Spelunger. Due to the tight confines and danger of flooding in the stream crawl, continued exploration in Lavonathon is limited to the present 95 m of survey.

6. Concluding Notes

The caves of Sulfur and Edwards Mountains are examples of ongoing work in spectacular cave systems in the Cumberland Escarpment. Both cave systems have experienced a decade of exploration and scientific study. From that work, we have recognized the tiered nature of cave levels because of staged incision of base level steams in response to Pleistocene glaciation, associated passage shapes and organizations in response to faults and folds in the enclosing geology and observed the role of shallow petroleum in the chemistry of karst groundwater and the speleogenesis of these caves. More importantly, this work has heightened interest in the understudied karst of Wayne County, in southern Kentucky, USA. These caves were largely overlooked by earlier generations of cavers in the 1960s through 1990s because of road conditions, distance of travel, and lucrative caving to the north in Kentucky, southward into Tennessee, or westward toward Mammoth Cave. It is quite likely that future efforts by this and the next generation will greatly expand the surveys of these and other sizable caves in Wayne County. This next phase will require dedicated cavers willing to establish and maintain camps, become adept at complex vertical rigging and bolt climbing, and push through crawls in wetsuits for distances of more than 1 km.

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Vegetação como indicadora de áreas cársticas

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Resumo

A identificação de áreas cársticas nem sempre é visível a olho nu, e o uso de ferramentas de sensoriamento remoto pode ajudar na detecção do carste. O Índice de Vegetação por Diferença Normalizada (NDVI) é uma ferramenta útil para mapear áreas de carste enterrado, pois indica a densidade e a saúde da vegetação. Este estudo teve como objetivo analisar o NDVI em duas sub-bacias do carste carbonático nas cavernas Timor e Tarzan, localizadas na Reserva Legado Verdes do Cerrado, em Niquelândia-GO. Utilizaram-se imagens do satélite Landsat 8 entre 2020 e 2023, divididas em quatro períodos sazonais. Os resultados mostraram que os valores de NDVI variaram de -0,039 a 0,767 para a sub-bacia Timor e de 0,059 a 0,757 para a sub-bacia Tarzan. A caverna de Tarzan apresentou valores mais elevados e constantes de NDVI. A alta porosidade do carste facilita o acesso das raízes à umidade, resultando em maior NDVI. A análise das imagens permitiu identificar fitofisionomias de Cerrado Restrito nas duas áreas. O NDVI pode ajudar na compreensão da dinâmica ambiental e na preservação das áreas cársticas.

Abstract

The identification of karst areas is not always visible to the naked eye, and the use of remote sensing tools can help in detecting karst features. The Normalized Difference Vegetation Index (NDVI) is a useful tool for mapping buried karst areas as it indicates the density and health of vegetation. This study aimed to analyze the NDVI in two sub-basins of the carbonate karst around the Timor and Tarzan caves, located in the Legado Verdes do Cerrado Reserve, in Niquelândia-GO. Landsat 8 satellite images from 2020 to 2023 were used, divided into four seasonal periods. The results showed that NDVI values ranged from -0.039 to 0.767 for the Timor sub-basin and from 0.059 to 0.757 for the Tarzan sub-basin. The Tarzan cave had higher and more consistent NDVI values. The high porosity of the karst allows the roots easy access to moisture, resulting in higher NDVI values. Image analysis revealed Restricted Cerrado phytophysiognomies in both areas. NDVI can help understand the environmental dynamics and contribute to the preservation of karst areas.

1. Introdução

O carste se trata de um tipo de relevo caracterizado pela presença de cavidades formadas a partir de processos de dissolução e/ou erosão mecânica de rochas, como as carbonáticas, siliciclásticas e ferruginosas (AB'SABER, 1978). Cavidades como cavernas e dolinas representam ecossistemas únicos e delicados, do ponto de vista biológico abriga espécies adaptadas a condições específicas de escuridão e umidade e do ponto de vista hidrológico contribui para a rápida percolação de fluxos hídricos em subsuperfície alimentando os aquíferos subterrâneos. O carste e suas inúmeras feições subterrâneas apresentam delimitação difusa e de difícil identificação em diferentes escalas de observação e mapeamento. Entretanto, devido à interdependência dos sistemas da hidrosfera, litosfera, pedosfera, atmosfera e biosfera (RODRIGUES & TRAVASSOS, 2013) é possível elencar peculiaridades do carste que possam influenciar quaisquer uma das esferas citadas. Por exemplo, no carste desenvolvido sobre rochas carbonáticas é comum encontrar diferentes fitofisionomias de vegetação, como mata seca, xerófitas e floresta ombrófila destacando-se na paisagem em contraste às plantas presentes em outras litologias do entorno, evidenciando a relação entre litosfera e biosfera, assim como hidrosfera e pedosfera.

Por meio de sensores especializados e técnicas pertinentes ao sensoriamento remoto é possível captar informações em diversas faixas do espectro eletromagnético, permitindo a geração de imagens e dados precisos sobre características geográficas, vegetacionais, hidrográficas, ambientais e atmosféricas (SAUSEN, 2007).

Segundo SOUZA & FOLHARINI (2019), o Índice de Vegetação por Diferença Normalizada (NDVI) é uma medida amplamente utilizada no campo do sensoriamento remoto, especialmente em aplicações relacionadas à vegetação e ecossistemas terrestres. O NDVI proposto inicialmente por ROUSE et al. (1974) e citado por MOREIRA (2007) e PONZONI et al. (2012) é calculado a partir de dados de imagens de satélite, utilizando a diferença entre as reflectâncias na faixa do infravermelho próximo e do vermelho do espectro eletromagnético. Sua fórmula simples, (NIR - Red) / (NIR + Red), gera valores que variam de -1 a +1, onde valores mais elevados indicam maior vigor vegetativo.

O NDVI é utilizado para monitoramento de queimadas e focos de incêndio (LEAL et. al., 2019), para análise ambiental urbana como parâmetro de qualidade de vida (LIMA, AMORIM, 2011), para análise de modificações da cobertura vegetacional como indicador da influência de chuvas, secas, vazões e assoreamentos (AIRES, 2018). Na agricultura, o NDVI é utilizado para detectar infestação de pragas, zonas com deficiência nutricional ou fitotoxicidade (MOTOMIYA, 2007).

A utilização do NDVI para ambientes cársticos está presente em estudos como de Rodrigues e Travassos (2013), o qual, teve como objetivo identificar e mapear a ocorrência das matas secas, também conhecidas como florestas estacionais decíduas, associadas aos carbonatos do Grupo Bambuí, na região do carste de Santo Hipólito e Monjolos, no estado de Minas Gerais, no bioma Cerrado, numa transição entre as matas secas e os campos rupestres.

O mapeamento detalhado de áreas cársticas não apenas fornece uma compreensão profunda do potencial espeleológico de uma região, mas também permite identificar áreas críticas para a preservação da biodiversidade associada (MOMOLI, 2019).

Assim, considerando o tipo de vegetação como indicador da qualidade físico-química do substrato – rochas e solos – o NDVI pode apresentar potencial para localizar os corpos rochosos carbonáticos enterrados.

Desta forma o presente estudo busca, através da utilização do Índice de Vegetação por Diferença Normalizada (NDVI), identificar áreas de ocorrência de rochas carbonáticas sob áreas vegetadas por sensoriamento remoto em duas áreas cársticas localizadas no Legado Verdes do Cerrado, em Niquelândia - GO.

2. Materiais e Métodos

As cavernas do Tarzan e do Timor se localizam no Núcleo Engenho da Reserva Legado Verdes do Cerrado (RLVC)- Votorantim, na região centro-sul do município de Niquelândia – GO (Figura 1). A área possui 27 mil hectares sendo 80% com cobertura vegetal nativa do bioma Cerrado em elevado grau de conservação (CARDOSO, 2017) e 20% com uso agropecuário.

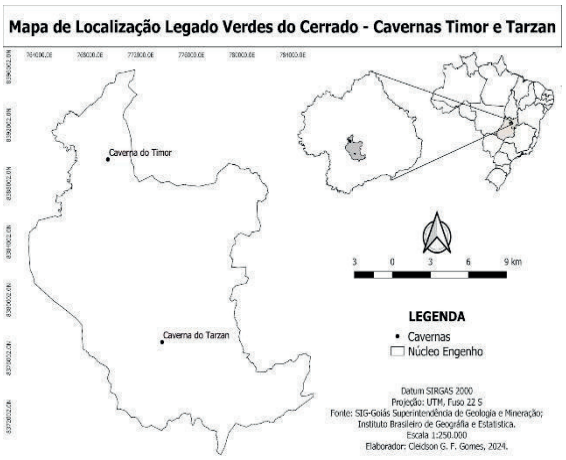

Figura 1: *Área de estudo: Cavernas Timor e Tarzan, no Legado Verdes do Cerrado, Niquelândia, GO.*

Na RLVC, as rochas do Grupo Paranoá apresentam sucessões rítmicas de metargilitos, ardósias, filitos carbonosos e quartzitos, entremeadas por lentes de rochas carbonáticas como metacalcários, mármores e dolomitos, onde o carste se desenvolve (MOREIRA et al. 2008) (Figura 2).

O relevo é composto por serras, montanhas e planícies (ZANCOPÉ et al., 2023) cujas altitudes variam de 556 a 1254 m e a vegetação é típica do bioma cerrado com (REZENDE, ALVES; 2017; FERREIRA et al., 2021).A pluviosidade média anual na RLVC é de 1787 mm, com temperatura média anual variando de 17°C a 34°C de acordo com mini-estação meteorológica instalada na área (MIRANDA et al. 2022).

Figura 2: *Cavernas do Timor e Tarzan, vista geral (A e C) e detalhe (B e D).*

O presente estudo faz parte do projeto "Espeleologia e Biodiversidade" financiado pela FAPEG/Votorantim, em andamento desde 2023. Estudos anteriores realizados no âmbito do projeto Qualidade dos solos das regiões cársticas, na RLVC (Chamada Pública 04/2018 n. 201810267001536) pelo mesmo grupo de pesquisa identificou que os solos do entorno das cavernas do Timor e Tarzan (MIRANDA et al., 2022) correspondem a Neossolo Litólico eutrófico, com textura franco-siltosa, característica essa que promove a alta porosidade e permeabilidade do solo. Os autores ainda apontam que tais características físicas associados a uma alta fertilidade são favoráveis ao desenvolvimento de vegetação florestal em ambos os maciços, apesar da baixa profundidade dos solos.

Figura 3: *Infográfico metodológico da pesquisa.*

Este trabalho teve um desenho metodológico dividido em três principais etapas (Figura 3). A primeira consistiu em uma revisão bibliográfica sobre o uso do sensoriamento remoto e métodos de índices biofísicos (NDVI), a segunda etapa, da delimitação das bacias hidrográficas onde se inserem as cavernas Timor e Tarzan e a determinação do período histórico a serem analisados. Já na terceira etapa foi realizada a confecção das matrizes ponderadas do NDVI e a redação final deste estudo. A seguir iremos detalhar os passos dois e três.

Na análise multitemporal foi feito o recorte dos últimos quatros anos (2020, 21, 22 e 23), sendo que para analisar as principais épocas da vegetação foram selecionadas imagens de quatro períodos de cada ano, sendo elas, o período chuvoso (janeiro/fevereiro), início da estiagem (Abril), período intenso de estiagem (Agosto) e início das chuvas (outubro/novembro).

A aquisição das imagens foi através do satélite LANDSAT 8 (OLI) órbita/ponto: 222/70 adquirida gratuitamente na homepage do Serviço Geológico dos Estados Unidos (disponível no link https://earthexplorer.usgs.gov/). Vale ressaltar que a seleção das imagens levou em consideração os critérios de menor excesso de brilho, menor quantidade de nuvens e maior normalidade espectral.

Quadro 1: *Correspondência entre coloração e valor dos pixels para as sub-bacias.*

Coloração dos NDVI's nas Sub-bacias					
Timor			Tarzan		
Valor Pixel	Cor	Cod./Cor	Valor Pixel	Cor	Cod./Cor
-0,039		#d7191c	0,059		#d7191c
0,076		#ed6e43	0,158		#ed6e43
0,191		#feba6f	0,258		#feba6f
0,306		#ffe8a5	0,358		#ffe8a5
0,421		#e6f5a8	0,457		#e6f5a8
0,536		#b3df76	0,557		#b3df76
0,652		#6abd58	0,657		#6abd58
0,767		#1a9641	0,757		#1a9641

O processamento das imagens se deu por meio do Sistema de Informação Geográfica QGIS 3.14, onde foram feitos os recortes das imagens selecionadas, a correção do fator de reflectâncias da superfície e a geração dos índices de vegetação, pois de acordo com SOUZA & FOLHARINI (2019), essa correção de reflectância se faz necessário para o "cálculo do NDVI visto que este processamento converte os números digitais (ND) das imagens em reflectância de superfície, permitindo a caracterização espectral de objetos" (p. 494).

Por último foi realizado uma padronização nas colorações dos pixels de acordo com o maior e menor índice alcançado nos último quatro anos para cada sub-bacia (Quadro 1), sendo que a variação dos pixels para a sub-bacia do Timor variou de -0,039 a 0,767 e da sub-bacia do Tarzan variou de 0,059 a 0,757.

3. Resultados

A análise multitemporal do NDVI, com o recorte de 2019 a 2023 em diferentes estações do ano revelou que os índices obtidos para a caverna Timor variaram de 0,195 a 0,612 e para a caverna Tarzan os valores ficaram em torno de 0,388 a 0,638 (Tabela 1).

Como esperado, os menores valores de NDVI foram observados no período seco, principalmente no mês de agosto, para todos os anos em ambas cavernas. E os maiores valores, em janeiro, no auge do período chuvoso.

Tabela 1: *Valores de NDVI para as cavernas Timor e Tarzan nos últimos 4 anos.*

ANO	Período	MÊS	TIMOR	TARZAN
2019	Chuvoso	Dezembro	0,302	0,606
2020	Início da seca	Abril	0,555	0,579
	Seco	Agosto	0,195	0,519
	Início das chuvas	Outubro/ Novembro	0,341	0,455
2021	Chuvoso	Janeiro	0,351	0,581
	Início da seca	Abril	0,396	0,571
	Seco	Agosto	0,213	0,432
	Início das chuvas	Outubro/ Novembro	0,256	0,638
2022	Chuvoso	Janeiro	0,612	0,616
	Início da seca	Abril	0,377	0,569
	Seco	Agosto	0,199	0,401
	Início das chuvas	Outubro	0,459	0,616
2023	Chuvoso	Janeiro	0,571	0,540
	Início da seca	Abril	0,471	0,542
	Seco	Agosto	0,286	0,388
	Início das chuvas	Novembro	0,548	0,588

Com aproximadamente 6,44 Km² a sub-bacia da caverna do Timor fica ao norte da RLVC e obteve valores de NDVI que variaram de -0,039 a 0,767. Autores como (SOUZA & FOLHARINI, 2019; TRENTIN et al. 2021; GAMARRA et. al., 2016 e CARVALHO JÚNIOR et al., 2008) apontam que índices de reflectância menores que zero correspondem ao fator de reflectância dos corpos hídricos. Contudo no caso da sub-bacia da caverna Timor esse valor negativo está associado a um foco de queimada, o qual foi registrado em agosto de 2020, entretanto vale ressaltar que esse dado não inviabilizou o processo de análise do local. A Figura 4 a seguir apresenta todos os dezesseis índices obtidos para a sub-bacia do Timor, entre dezembro de 2019 e novembro de 2023.

A porção central da sub-bacia do Timor, onde os NDVI's são baixos, corresponde a uma planície cultivada com grãos e onde durante a estação seca, se acumula a palhada ressecada do cultivo anterior. Nesta região, valores extremamente baixos de NDVI (0,076) foram observados, enquanto na região a montante do cultivo, onde se encontra a caverna do Timor, o valor mínimo do NDVI foi 0,195, em agosto de 2020. Como o NDVI reflete a densidade sazonal da biomassa, valores elevados indicam melhores condições hídricas para crescimento vegetal e, consequentemente, apontam para maior umidade retida no conjunto solo-rocha.

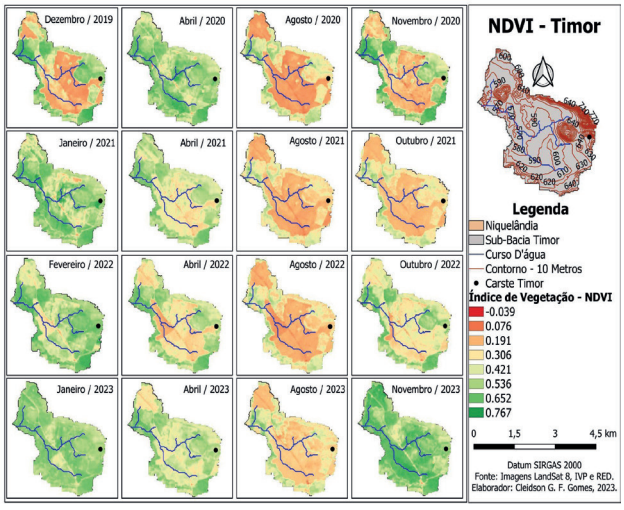

Figura 4: *Índices de Vegetação da Diferença Normalizada - Sub-bacia Timor, entre 2019-2023.*

A sub-bacia da caverna Tarzan fica localizada na região centro-sul da RLVC e possui aproximadamente 1,20 Km2 de extensão. Conforme demonstrado na figura 5, os índices obtidos para esta sub-bacia variaram de 0,059 a 0,757.

A região onde se encontra a caverna do Tarzan apresentou valores elevados de NDVI, durante todos os meses dos anos avaliados, em comparação à área cultivada do seu entorno. A topografia rebaixada neste local condicionou a concentração hídrica próximo à caverna, o que associado à elevada fertilidade natural do substrato do carste, favoreceu o estabelecimento das plantas

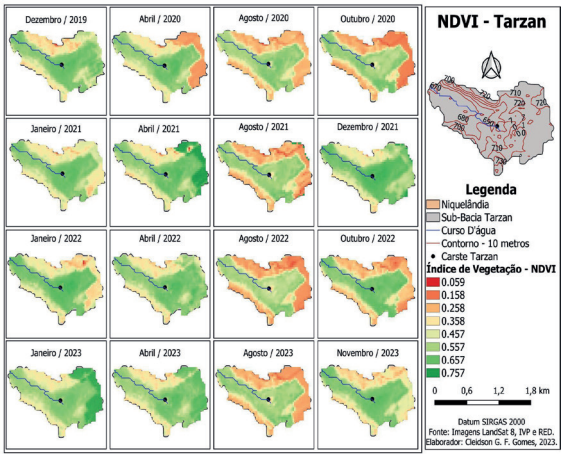

Figura 5: *Índices de Vegetação da Diferença Normalizada - Sub-bacia Tarzan.*

4. Discussão

De acordo com GAMARRA et al. (2016), a média do NDVI para a fitofisionomia de Matas do bioma Cerrado varia de 0,795 a 0,963, já o índice esperado para a fitofisionomia de Cerradão varia entre 0,685 a 0,821 e para a formação de Cerrado Restrito o NDVI esperado é de 0,468 a 0,661. Tendo em vista que a média dos NDVI's analisados foi de 0,382 e 0,540 para Timor e Tarzan respectivamente, podemos concluir que de acordo com o estudo citado, a fitofisionomia da caverna do Tarzan se comporta como Cerrado Restrito, resultado esse que corrobora com as análises feitas por Miranda et al. (2022), quando os mesmos apontaram que o solos do entorno das cavernas são classificados como Neossolo Litólico, que favorece a ocorrência da fitofisionomia do Cerrado Sentido Restrito.

Contudo não podemos descartar a hipótese de que a fitofisionomia da caverna Timor também seja de Cerrado Restrito, uma vez que, nos estudos realizados por GAMARRA et al. (2016), foram utilizadas imagens apenas de uma época do ano gerando assim valores mais elevados e com pouca variância.

Todos os valores de NDVI obtidos para a caverna do Tarzan foram maiores do que os calculados para a sub-bacia da Caverna do Timor (Figura 6). Destaca-se também que, a sub-bacia da caverna do Tarzan apresentou índice menor que 0,400 apenas no mês de agosto de 2023, refletindo o período de menor precipitação de chuvas que reflete no stress hídrico das plantas e consequente redução da biomassa.

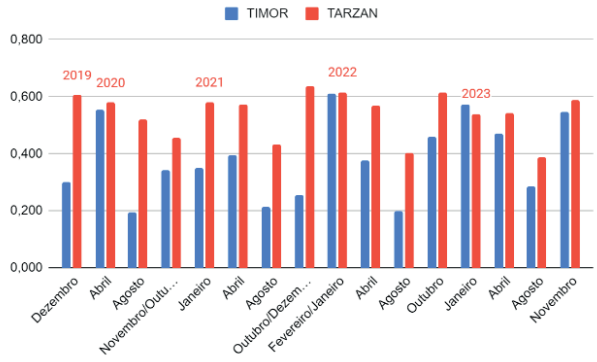

Figura 6: *Comparação entre os índices de NDVI das cavernas Timor e Tarzan.*

5. Conclusão

A análise do NDVI indicou diferenças importantes entre os terrenos cársticos e não cársticos adjacentes, cujos limites dificilmente são visualizados em campo, sendo uma ferramenta útil nas atividades de prospecção de cavernas e conservação da biodiversidade e do patrimônio espeleológico.

A fitofisionomia da sub-bacia do Tarzan pode ser caracterizada como Cerrado Restrito, e a sub-bacia do Timor, embora o índice NDVI médio tenha sido ligeiramente mais baixo, a hipótese de uma fitofisionomia de Cerrado Restrito também não pode ser descartada, pois as variações de NDVI ao longo do ano podem ter influenciado o resultado.

Sabemos que o mapeamento de vegetação em áreas cársticas é um processo complexo, dado que fatores como incêndios (observado em 2020) e variações climáticas ao longo do ano têm impacto direto sobre os índices de vegetação.

É importante destacar que a relação entre os solos cársticos e a vegetação está intimamente ligada à disponibilidade e qualidade dos solos, os quais são influenciados pelas características geológicas da região. Essa interação facilita a observação das mudanças na vegetação ao longo do tempo, que podem servir como indicadores das dinâmicas ambientais nas áreas cársticas.

Um próximo passo poderia ser a ampliação da análise para outros períodos e a inclusão de dados climáticos e topográficos mais detalhados, o que permitiria um estudo mais aprofundado sobre a relação entre a vegetação e os fatores ambientais. Dessa forma, este trabalho contribui para o entendimento da biodiversidade e da conservação das áreas cársticas, fornecendo dados valiosos para o monitoramento e a preservação das cavernas Timor e Tarzan no contexto da Reserva Legado Verdes do Cerrado.

Agradecimentos

Expressamos sinceros agradecimentos à Fundação de Amparo à Pesquisa do estado de Goiás- FAPEG e Reservas Votorantim-CBA pelo suporte financeiro do projeto de pesquisa Espeleologia e biodiversidade (Chamada 10/2022, número 202310267000407) e à equipe gestora e de campo do Legado Verdes do Cerrado.

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Expedition Sila 2023: explorations de cavites glaciaires au Groenland du Sud

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Abstract

Expedition SILA 2023: Glacial caves explorations in South Greenland. Over the past decade, the accelerated melting of glaciers, whether in the Alps or the Arctic, has become a fact of life for all to see. Despite the urgent need to understand the dynamics of mass loss in the planet's largest glaciers, modern glaciology still struggles to judge the proportion of melting that should be attributed to precipitation or rising temperatures. In the summer of 2023, a team of speleologists joined the sailing vessel Atlas in the Kujalleq region, a province of 31,000km2 located at the southern tip of Greenland, to continue locating and documenting caves and cavities of erosive origin in coastal zones (HAPKA 2021) and to travel up the region's many fjords, encountering the glacial fronts of the ice sheet and their sometimes titanic resurgences!

Résumé

Au cours de la dernière décennie, la fonte accélérée des glaciers, que ce soit dans les Alpes ou en Arctique, s'est révélée être une évidence que tout le monde peut constater. Malgré l'urgence de comprendre la dynamique de la perte de masse dans les glaciers les plus vastes de la planète, la glaciologie moderne peine encore à juger de la proportion de fonte que l'on doit accorder aux précipitations ou à l'élévation des températures. Au cours de l'été 2023, une équipe de spéléologues a rejoint le voilier Atlas dans la région du Kujalleq, une province de 31'000km2 située à la pointe Sud du Groenland, pour y poursuivre le repérage et la documentation de grottes et cavités d'origine érosive en zone côtière (HAPKA 2021) et pour remonter les nombreux fjords de la région, à la rencontre des fronts glaciaires de l'inlandsis et de leurs résurgences, parfois titanesques !

Resumen

Expedición SILA 2023: Exploración de cuevas glaciares en el sur de Groenlandia. En la última década, el deshielo acelerado de los glaciares, ya sea en los Alpes o en el Ártico, se ha convertido en un hecho evidente para todos. A pesar de la urgente necesidad de comprender la dinámica de la pérdida de masa en los mayores glaciares del mundo, la glaciología moderna sigue teniendo dificultades para juzgar la proporción del deshielo que debe atribuirse a las precipitaciones o al aumento de las temperaturas. Durante el verano de 2023, un equipo de espeleólogos se unió al velero Atlas en la región de Kujalleq, una provincia de 31.000 km2 situada en el extremo sur de Groenlandia, para proseguir la identificación y documentación de cuevas y cavidades de origen erosivo en las zonas costeras (HAPKA 2021) y remontar los numerosos fiordos de la región, ¡para encontrarse con los frentes glaciares de la capa de hielo y sus resurgimientos, a veces titánicos!

1. Introduction

Des expéditions ont été réalisées ces dernières années sur la calotte glaciaire du Groenland dans le but d'étudier ces sujets à travers l'exploration de moulins glaciaires par lesquels l'eau de fonte s'engouffre dans la glace. Mais d'autres types d'accès sont possibles, comme les crevasses, les rimayes, les rotures (espaces entre le flanc du glacier et la montagne), les cavités de décollement sous le glacier ou les porches glaciaires par lesquels l'eau refait surface. Tous ces accès permettent potentiellement de voir et d'étudier directement l'intérieur des glaciers [MOREAU 2009].

L'expédition tire son nom de Sila, la source de tous changement en langue inuite (d'après un conte groenlandais sur les changements climatiques). La logistique sur place était assurée par le skipper et photographe Arnaud Conne. Avec les navigateurs Angie Gartz et Alex Mansfield et le vidéaste Richard Mardens à son bord, le voilier Atlas (de l'association Atlas Expeditions) a traversé l'atlantique Nord, en ligne directe de Saint-Malo en France à Qaqortoq au Groenland, au début de l'été 2023 (ATLAS EXPEDITIONS 2019).

Arnaud Conne et Richard Mardens, dans le cadre d'un effort de captation visuelle des réalités du vaste territoire en changement que forme le Kujalleq, ont notamment collaboré à la documentation des travaux de recherche menés par les scientifiques du Green Fjord Project et le Laboratoire de Recherche sur les Environnements Extrêmes de l'Ecole Polytechnique Fédérale de Lausanne (GREEN FJORD PROJECT 2023-2024) qui visent à mieux comprendre comment le changement climatique affecte les écosystèmes des fjords du Sud Groenland et comment cela se propage à la biodiversité et aux moyens de subsistance.

Les spéléologues du projet « Ice Cave » (ICE CAVE 2018) explorent et documentent régulièrement les cavités de plusieurs glaciers suisses. Ils sont ainsi devenus de véritables spécialistes des cavités glaciaires. Il était donc naturel qu'un de leurs représentants, l'ingénieur Hervé Krummenacher, se joigne à l'équipe d'Atlas Expeditions pour assurer la sécurisation de la progression dans les cavités glaciaires groenlandaises. Roman Hapka a ainsi pu sereinement réaliser ses relevés topographiques.

Figure 1: *Le bateau Atlas au mouillage dans un fjord devant un front glaciaire. Le torrent est directement issu d'une source pénétrable du front glaciaire de l'Inlandsis (photo Arnaud Conne).*

2. Les buts de l'expédition

Depuis des siècles, les glaciers jouent un rôle crucial dans la vie des Suisses. Ils fournissent de l'eau pour l'agriculture, la biodiversité et la production hydroélectrique et sont une part non négligeable de l'attrait touristique du pays.

Bien que les glaciers suisses et groenlandais soient situés dans des régions géographiques très différentes, ils sont touchés par le changement climatique et font face à des problèmes similaires. Les explorations suisses au Groenland remontent au début du 20e siècle, lorsque des scientifiques et des explorateurs vaudois ont commencé à s'intéresser à cette île arctique reculée. On relèvera en particulier les premières documentations photographiques du glacier Eqip Sermia réalisées en 1912 par l'ingénieur vaudois Paul-Louis Mercanton (UNIL 2024).

Après ceux de l'Antarctique, les glaciers du Groenland sont les deuxièmes plus grands réservoirs de glace au monde. Ils sont particulièrement vulnérables au réchauffement climatique, car ils sont situés dans l'une des régions les plus touchées par les changements climatiques. Les scientifiques ont constaté que les glaciers du Groenland perdent en moyenne plus de 250 milliards de tonnes de glace chaque année en raison du réchauffement de l'atmosphère et des océans.

Les glaciers suisses, quant à eux, ont également connu une fonte rapide ces dernières décennies. On estime qu'ils ont perdu près de la moitié de leur volume depuis le début du 20e siècle, et que la fonte s'est accélérée au cours des dernières années. Les conséquences de la fonte des glaciers sont similaires pour les deux pays: elle entraîne une augmentation du niveau de la mer, menaçant les zones côtières et les îles basses à travers le monde. Elle a également pour conséquence une perte de biodiversité, car de nombreux organismes dépendent de l'eau froide et claire qui coule des glaciers. Enfin, elle affecte les industries locales telles que l'agriculture, le tourisme et la pêche.

Repérer et documenter les grottes érosives et les cavités glaciaires du Groenland du Sud grâce aux techniques spéléologiques peut contribuer à la compréhension de l'évolution des glaciers de la calotte groenlandaise. Nous avons d'une part l'évolution très lente de la formation de cavités par érosion dans les roches métamorphiques (principalement Granite et Gneiss), et d'autre part l'évolution rapide des cavités glaciaires en lien avec les eaux de fonte.

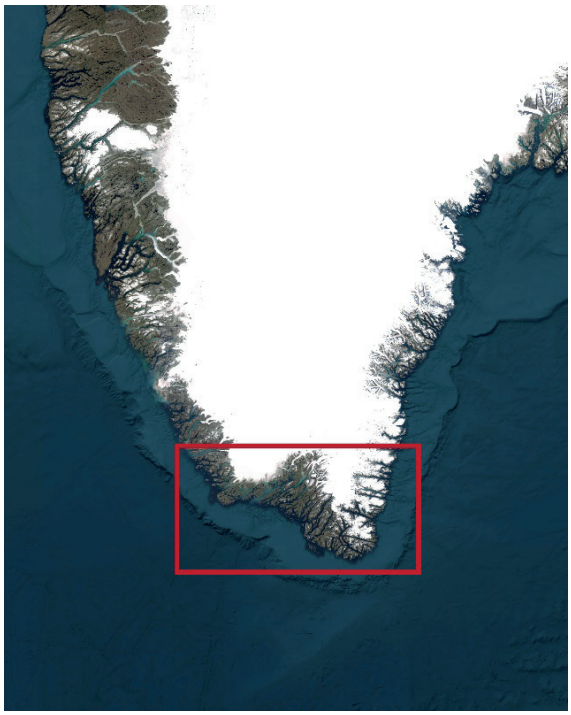

Figure 2: *La région du Kujalleq, une province de 31'000km2 est située à la pointe Sud du Groenland.*

3. Déroulement de l'expédition

Une centaine de sources potentielles avaient été repérées sur les images satellites, la plupart grâce aux cascades et rivières qui en sont issues. Une fois franchis les aléas maritimes, encore fallait-il les atteindre en progressant à terre entre falaises abruptes, pierriers géants instables et rivières déchaînées ou sur une surface de glace parsemée de crevasses et de moulins.

Du 5 au 23 août 2023, nous avons cherché avec l'Atlas à atteindre par voie maritime les fronts de vêlage de différents glaciers de la région du Kujalleq. La taille réduite du bateau nous a permis de nous faufiler au travers du maillage serré de la multitude d'îles et d'îlots encombrés d'icebergs qui constituent la côte du Groenland du Sud, et de remonter ainsi certains fjords sur plusieurs dizaines de kilomètres.

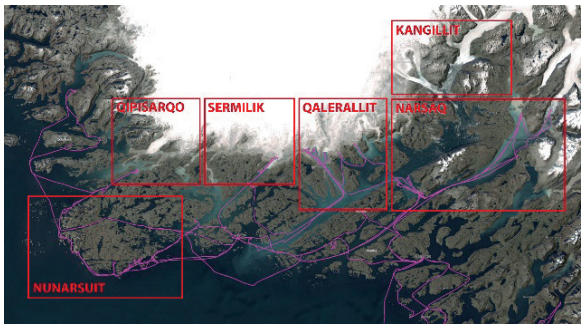

Figure 3: *Les 5 zones prospectées dans le Sud du Groenland.*

Cinq zones ont été prospectées, soit d'Ouest en Est:

- **la zone de Nunarssuit** où est situé le Cap Thorvaldsen et qui était déjà exempte de glace lors de la colonisation viking du Moyen-âge,
- **la zone de Qipisarqo**, riche de grandes zones marécageuses parcourues par des troupeaux de rennes,
- **la zone de Sermilik**, avec son front glaciaire très actif d'où s'échappe un véritable fleuve sous-marin,
- **la zone de Qalerallit** et ses cascades issues de multiples résurgences glaciaires,
- **la zone de Narsaq**, localité centrale au coeur des grands fjords

Figure 4: *Approche prudente des sources glaciaires dont les porches d'entrées sont souvent à moitié effondrés (photo Arnaud Conne).*

La zone de Nunarsuit

Le "Nunarsuit" ou "Cap Thorvaldsen", aussi nommé "Île de la désolation" par l'explorateur John Davis est l'un des points emblématiques du Groenland. Cette île aux montagnes majestueuses, qui souvent se profilent au-dessus du brouillard, devait déjà servir de marqueur paysager pour les Inuits et les colonies vikings du Moyen-âge qui s'étaient installées dans cette région déjà exempte de glace à l'époque.

En longeant la côte, nous repérons quatre cavités perchées dans les falaises entre 50 et 100 m au-dessus de l'océan. Il n'y a pas de roches karstiques au Sud du Groenland, celles-ci se rencontrent uniquement dans le Nord du pays. L'extrême Sud est constitué de roches granitiques très anciennes car remontant au Précambrien.

Les cavités rencontrées se développent horizontalement et l'origine de leur creusement reste à définir. Si l'on n'est pas très surpris de trouver des cavités au niveau de l'océan - que l'on peut qualifier de véritables grottes marines car apparemment creusées par les vagues - celles situées à plusieurs dizaines de mètres d'altitude témoignent peut-être de phénomènes d'érosion plus anciens, maritimes, glaciaires ou autres.

L'une d'elle, Malenefjeld Cave 1, s'enfonce linéairement de plus de 100 m dans une haute falaise granitique. La majestueuse entrée est haute de près de 40 m et large de 10 m. A proximité du terminus de la grotte un petit lac encombré de blocs de glace doit être franchi. Après un ressaut de 3 m occasionné par de gros blocs coincés, la galerie se pince.

Malenefjeld Cave 2, située à la même altitude (70m), à une quarantaine de mètres à l'Ouest de la première, a une morphologie identique mais n'est profonde que de 35 m.

Figure 5: *Les deux entrées monumentales des grottes marines de Malenefjeld Cave 1 et 2 du Cap Thorvaldsen (photo Arnaud Conne).*

La zone de Qipisarqo

Après avoir contourné le Cap Thorvaldsen, et croisé quelques-unes des baleines à bosse qui se nourrissent ici, nous nous dirigeons vers le Nord-Est pour tenter de rejoindre les fronts glaciaires de Qipisarqo, aux franges de l'Inlandsis. Nous devons laisser l'Atlas en raison des faibles profondeurs dues à une forte accumulation de sédiments à l'extrémité du fjord et poursuivre avec l'annexe. Le coin est riche en lacs peu profonds et nous rencontrons d'importantes zones marécageuses parcourues par des troupeaux de rennes. Après une marche d'approche de plusieurs kilomètres sur les moraines, nous parvenons enfin à la langue glaciaire. Aucune cavité importante n'est repérée, mais c'est la première occasion pour Hervé et Roman de monter sur la glace et d'approcher diverses petites résurgences, moulins et bédières, alors que Richard et Arnaud documentent la zone au moyen de leurs caméras et des drones.

La zone de Sermilik

Dès le début de l'expédition, il était apparu que le profond fjord de Sermilik serait incontournable vu le nombre d'objectifs potentiels repérés sur les images satellites. Encore fallait-il passer au travers des multiples icebergs produits par ce front glaciaire très actif. Cela se fait de manière plus aisée que prévu, mais une autre surprise de taille nous attend lorsque nous approchons les hautes falaises bleutées avec l'Atlas. L'eau bouillonne littéralement et de gros tourbillons emportent les icebergs et notre bateau. Un véritable fleuve sous-marin surgit à la base du glacier, faisant remonter des tonnes de sédiments riches en éléments nutritifs dont se nourrissent les poissons, ce qui attirent des myriades d'oiseaux de mer. A tout instant des blocs de glace se détachent des falaises et viennent frapper la surface de l'eau, mais c'est surtout la remontée spectaculaire et assez effrayante d'icebergs de glace dense arrachés à la base du glacier qui nous incite à la prudence.

Figure 6: *Un véritable fleuve sous-marin surgit à la base du glacier, faisant remonter des sédiments riches en éléments nutritifs ; une aubaine pour la faune (photo Arnaud Conne).*

Nous optons pour une option d'approche moins frontale en remontant à pied un important torrent qui s'échappe d'un sombre porche glaciaire sur la partie latérale du glacier. Pendant que Roman enfile sa combinaison étanche pour pénétrer dans le cours d'eau, Hervé et Arnaud observent suspicieusement la voûte de l'entrée qui semble très peu stable. L'appel des profondeurs est puissant et l'on voit sur plus de 50m à l'intérieur de la résurgence, mais la raison a le dernier mot et nous renonçons à poursuivre. Il faudra trouver un autre orifice pour accéder à la rivière souterraine.

Nous décidons de suivre le bord du glacier jusqu'à un canyon latéral et découvrons plusieurs regards qui nous conduisent sur l'amont de la rivière souterraine. Le plafond et les parois de glace sont parfois noires ou d'un bleu translucide, alors que le sol est constitué de roche en place ou de gros galets. Le grondement de l'eau couvre nos voix et malgré nos efforts nous n'arrivons pas à trouver un passage praticable. Soit le courant est trop fort, soit nous buttons sur de petits puits qu'ils seraient nécessaires d'équiper avec des cordes. La rivière principale semble nous narguer en disparaissant dans les profondeurs, vers l'aval et vers l'amont.

Le système de résurgences et de pertes glaciaires est suivi et documenté sur plus de 500 mètres. En revenant vers le rivage par la surface du glacier, nous rencontrons de profonds regards desquels le bruit de la rivière est bien audible.

Figure 7: *Progression prudente dans les entrailles de l'Inlandis (photo Hervé Krummenacher).*

La zone de Qalerallit

Les jours suivants, c'est le glacier de Qalerallit qui nous accueille. Nous voici arrivés au pays des cascades, car le relief s'avère plus abrupt et les diverses langues glaciaires s'enfilent entre les lisses parois granitiques. Les torrents issus des résurgences glaciaires sont déchaînés et la moindre chute s'avérerait fatale. Nous progressons donc très prudemment et évitons les entrées les plus vastes, de toutes manières inaccessibles vu la force du courant. L'une d'elle nous permet cependant d'effectuer une belle traversée sous-glaciaire d'une centaine de mètres dans une galerie de plus de 10 m de largeur. Cette Qalerallit Ice Cave donne une bonne image du potentiel spéléologique sous-glaciaire de la région.

Figure 8: *Qalerallit Ice Cave donne une bonne image du potentiel spéléologique sous-glaciaire de la région (photo Hervé Krummenacher.*

La zone de Narsaq

La petite ville côtière de Narsaq avec ses pimpantes maisons multicolores en bois est située au cœur du terrain sélectionné par le Green Fjord Project pour ses études. C'est la base que les scientifiques ont naturellement choisie pour leur travail. Ils y occupent la maisonnette de la "Narsaq International Research Station", à partir de laquelle ils déploient quotidiennement un ballon météo.

Arnaud est venu récupérer l'équipe des spéléologues composée d'Hervé et Roman à l'aéroport régional de Narsasuaq avec l'Atlas. Sur le chemin de Narsaq, nous effectuons un léger détour en nous enfilant dans le fjord de Qooqqup, qui charrie quantité d'icebergs de tailles diverses. L'Atlas se fraie un chemin à travers la masse glaciaire qui devient de plus en plus compacte et après une dizaine de milles, la progression devient impossible.

Nous envoyons le drone en direction du front glaciaire. Attirant notre regard, une vaste tache circulaire sombre se démarque à la surface du fjord, à la base des falaises de glace. Nous comprendrons plus tard, par analogie avec d'autres glaciers, que l'absence de glace à cet endroit est due à la remontée des eaux de fonte issues d'une importante source sous-glaciaire.

A Narsaq, nous récupérons Richard qui, lors de son séjour avec les scientifiques du Green Fjord Project à bord du brise-glace Adolf Jensen, a pu abondamment documenter les travaux de recherche menés aux marges du glacier géant du Kangillit. Là aussi, les vues aériennes révèlent la présence d'une importante résurgence sous-marine à la base du glacier.

Figure 9: *Une vaste tache circulaire sombre, indiquant la présence d'une importante source sous-glaciaire, se démarque à la surface du fjord à la base des falaises du glacier de Qooqqup (photo Arnaud Conne).*

4. Conclusion

Ces 18 jours de navigation à la recherche des sources glaciaires du Kujalleq nous ont permis de ressentir l'importance du phénomène de fonte signalé ces dernières années au Groenland par diverses équipes de recherches scientifiques.

Figure 10: *Le potentiel d'exploration sous-glaciaire au Groenland est gigantesque (photo Arnaud Conne).*

Notre espoir d'accéder aux tréfonds des glaciers en pénétrant par les sources n'a été que partiellement couronné de succès. En effet, l'ampleur des débits rencontrés au front des glaciers et la dynamique des masses de glaces en mouvement rendent toute tentative bien trop risquée. Nous avons tout de même pu explorer plusieurs orifices intéressants dans les parties latérales des glaciers, à l'interface avec la roche.

Le travail le plus spectaculaire a sans doute été la documentation des fronts glaciaires maritimes, au contact avec les courants générés entre eau de mer et eau douce par les énormes sources sous-marines là où la glace rencontre directement l'océan. Les recherches menées par les équipes du Green Fjord Project devraient permettre de mieux comprendre l'importance du brassage des eaux de fonte dans la biodiversité des fjords.

Le repérage et le recensement des grottes marines creusées dans les falaises bordant les îles et les fjords ont porté leurs fruits. Comme supposé lors du premier passage de l'Atlas en 2021, la région du Kujalleq ne recèle sans doute pas de cavités majeures. Mais les cavités rencontrées démontrent cependant que les phénomènes d'érosion n'y sont pas anodins et que la poursuite de leur documentation pourrait peut-être permettre d'éclaircir le mystère de leur positionnement à plusieurs dizaines de mètres au-dessus de la surface de l'océan.

Remerciements

Merci à nos sponsors: Induni, CP Comuni, Swiss Art Books, Aventure Verticale SF Tech, ainsi qu'à Paul Cohen et son épouse, résidents de Narsaq, qui nous ont généreusement approvisionnés en légumes frais et en bois et même fait notre lessive. Photo SILA2023- ATLAS EXPEDITIONS (Arnaud Conne, Hervé Krummenacher, Richard Mardens).

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Figure 11: *Relevé topographique d'une cavité glaciaire. Une fracture dans la glace de fond noirâtre laisse filtrer un pâle rayon de lumière (photo Hervé Krummenacher).*

Espeleo Colombia 2010-2019: 10 años de espeleología suiza en Los Andes

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Abstract

Espeleo Colombia 2010-2019: 10 Years of Swiss Caving in the Andes. In 2010, on the occasion of its 40th anniversary, the Spéléo-Club des Préalpes Fribourgeoises (SCPF), launched itself to conquer the South American abysses of Colombia through the Spéléo Colombia project. Following the discoveries made in 2011 in the El Peñon karst massif, located in the state of Santander, expeditions continued at a steady pace. 10 years later, more than 70 pits and caves have been discovered, explored and mapped in the adjoining massifs of El Peñon, Bolivar, Sabana Grande, La Belleza and Florián. The cavities explored are the longest and deepest in Colombia. Their total development reaches 30km, making this region the most important exploration area in Colombia; a real small speleological Eldorado with barely begun potential.

Résumé

Spéléo Colombia 2010-2019: 10 ans de spéléologie suisse dans les Andes. En 2010, à l'occasion de ses quarante ans d'existence, le Spéléo-Club des Préalpes Fribourgeoises (SCPF), s'est lancé à la conquête des abîmes sud-américains des Andes Colombienne au travers du projet Spéléo Colombia. Suite aux découvertes réalisées en 2011 dans le massif karstique d'El Peñon, situé dans l'état de Santander, les expéditions se sont poursuivies à un rythme soutenu. 10 ans plus tard, plus de 70 gouffres et grottes ont été découverts, explorés et topographiés dans les massifs mitoyens d'El Peñon, Bolivar, Sabana Grande, La Belleza et Florián. Les cavités explorées sont les plus longues et les profondes de Colombie. Leur développement total atteint 30 km, faisant de cette région, la plus importante zone d'exploration de Colombie ; un véritable petit Eldorado spéléologique au potentiel à peine entamé.

Resumen

En 2010, con motivo de su 40 aniversario, el Spéléo-Club des Préalpes Fribourgeoises (SCPF), inició la exploración y prospección sistemática de las cuevas, cavernas y simas (hoyos) de Colombia mediante el proyecto Espelo Colombia (Spéléo Colombia). Tras los descubrimientos realizados en 2011 en el macizo cárstico de El Peñón, situado en el departamento de Santander, las expediciones continuaron a un ritmo constante. Diez años después, más de 70 cuevas, cavernas, simas u hoyos y abrigos rocosos han sido descubiertas, exploradas y cartografiadas en los macizos carsticos de El Peñón, Bolívar, Sabana Grande, La Belleza y Florián. Las cavidades exploradas son las más largas y profundas de Colombia. Su desarrollo total alcanza los 30 km de longitud, lo que hace de esta región el área de exploración más importante de Colombia, un verdadero y pequeño « Dorado Espeleológico » con un gran potencial que apenas se empieza ha conocer.

1. Historia de las exploraciones espeleológicas en Colombia

Las cavernas colombianas ubicadas en las altas mesetas centrales o en las selvas bajas o bosques del sureste, eran conocidas por las culturas indígenas quienes las usaban como sepulturas y refugios. Las primeras descripciones de las cavidades, a menudo pintorescas, escritas por viajeros extranjeros, datan de mediados del siglo XIX. En 1878, Alexander von Humboldt publica un escrito sobre las fallas y cavernas de las Cordilleras. Diversas cavidades son mencionadas durante la primera mitad del siglo XX, pero es en 1940 que Luis Cuervo Márquez describe el famoso Hoyo del Aire de 120 m de profundidad, topografiado nuevamente durante la expedición Espeleo Colombia o Spéléo Colombia en 2011, al igual que lo desarrollado en otras cavidades. Durante los 30 años siguientes, diversos autores científicos se interesaron por los carst colombianos, pero es solamente en 1975 que un equipo de espeleólogos polacos explora 24 cavidades en la región de La Paz (Santander), con equipos modernos.

En 1977, inicia una misión de reconocimiento del carst colombiano por parte de franceses del Grupo Espeleológico de Niza. Durante los 3 meses de su presencia en Colombia, resultó un trabajo imponente de exploración y de compilación de datos de casi todo el país. Más de 100 cuevas y abismos o simas fueron explorados y topografiados. La región de La Hermosura (Bolívar), muy próxima a EL Peñón fue visitada por primera vez y dos abismos importantes, incluyendo el Hoyo del Águila (- 149 m, pozo de 120 m), fueron explorados.

Figure 1: *Ejemplo de la entrada de una cavidad en bosque húmedo altoandino.*

Figure 2: *Ubicación de los carst estudiados alrededor del Macizo de El Peñón, departamento de Santander, norte de Colombia.*

Otras fechas importantes son las 1981, 1983 y 1985, que incluyeron tres expediciones francesas, bajo el nombre de Colombia 81, Hermosura 83 y Hermosura 85. Las exploraciones del Hoyo de Águila y su vecino el Hoyo Hermosura continuaron, uniendo las dos cavidades y recorriendo la cavidad la más grande conocida hoy en día en Colombia, con casi 5 km de desarrollo a una profundidad de 193 m.

En 2010, se realizó la primera incursión solitaria por un miembro del Spéléo Club des Préalpes Fribourgeoises en los macizos de El Peñón y Bolívar. Después del reconocimiento de una decena de cavidades con un potencial interesante, el Club decide organizar una primera expedición formal: Speleo Colombia 2011. En esta ocasión, 5 km de pozos y galerías fueron topografiadas, lo que incentivó al Club para hacer de esta región lejana su terreno de trabajo en la región tropical. En 2016, la prospección se extendió a los macizos vecinos de Sabana Grande, La Belleza y Florián y las exploraciones comenzaron en 2018 y 2019 (Figura 1).

Así, anualmente se encontraron nuevos descubrimientos en esta región cárstica de los Andes colombianos de más de 1.000 km de superficie, con un desarrollo actual de más de 30 km. A esto, toca añadir más de 70 cavidades abismos, cimas u hoyos y cuevas o cavernas, detectados durante otras prospecciones, que aún no han sido exploradas.

2. Los sistemas cársticos andinos: entre los volcanes y la selva altoandina

Los macizos de El Peñón, Bolívar, Sabana Grande, La Belleza y Florián, están ubicados en el departamento de Santander en la Cordillera Oriental de los Andes colombianos a 150 km al norte de Bogotá. Las zonas de exploraciones están situadas entre 3.000 m y 400 m de altura sobre el nivel del mar. Estas altas mesetas calcáreas, particularmente escarpadas y silvestres, están poco habitadas y las escasas localidades existentes son de difícil acceso vía terrestre (pavimentada). Una de las pruebas más ciertas es que el Municipio de El Peñón existe desde hace apenas cincuenta años y la vía de acceso apenas tiene 10 años (Figura 2).

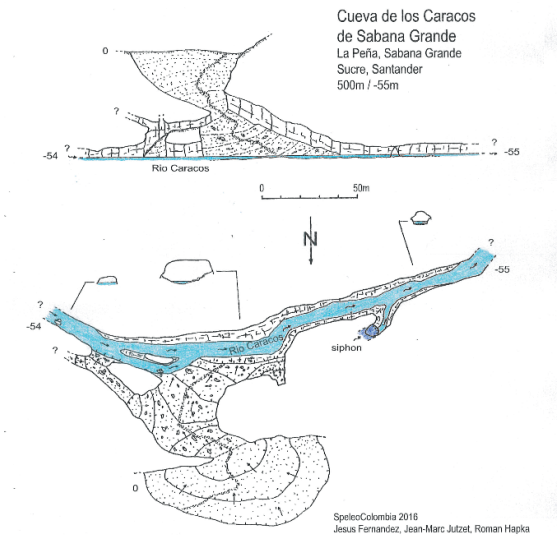

Figure 3: *Topografía de la Cueva de Los Carracos de Sabana Grande. El río -no explorado- prosigue río abajo y río arriba.*

A nivel litológico, las mesetas altas calcáreas prospectadas se extienden varios centenares de km entre las ciudades de Bogotá y Bucaramanga, a unas alturas entre los 50 y los 3000 m. s.n.m. Los carsts y todas las cavidades descubiertas se desarrollan entre el sistema calcáreo de la Formación Rosablanca del Cretácico inferior (Valanginiano superior y Hauteriviano inferior). En esta región, el espesor total de la formación puede alcanzar 400 m, y está compuesta de una sucesión de dolomitas gises, calizas grises, calizas morenas y de areniscas, para finalmente terminar en la cima nuevamente con piedra caliza o "coquillers" (HAPKA 2015). Estructuralmente, la zona está situada en la cima de un importante anticlinal con pliegues segundarios que forman las mesetas altas donde están ubicadas la mayoría de las cavidades. Para mayor detalle sobre la Formación Rosablanca y su geología, geomorfología y estratigrafía, se recomienda consultar a BOCHUD 2013, HAPKA 2015, HAPKA 2019, RODRIGUEZ-TORRES y LASSO C. A 2019

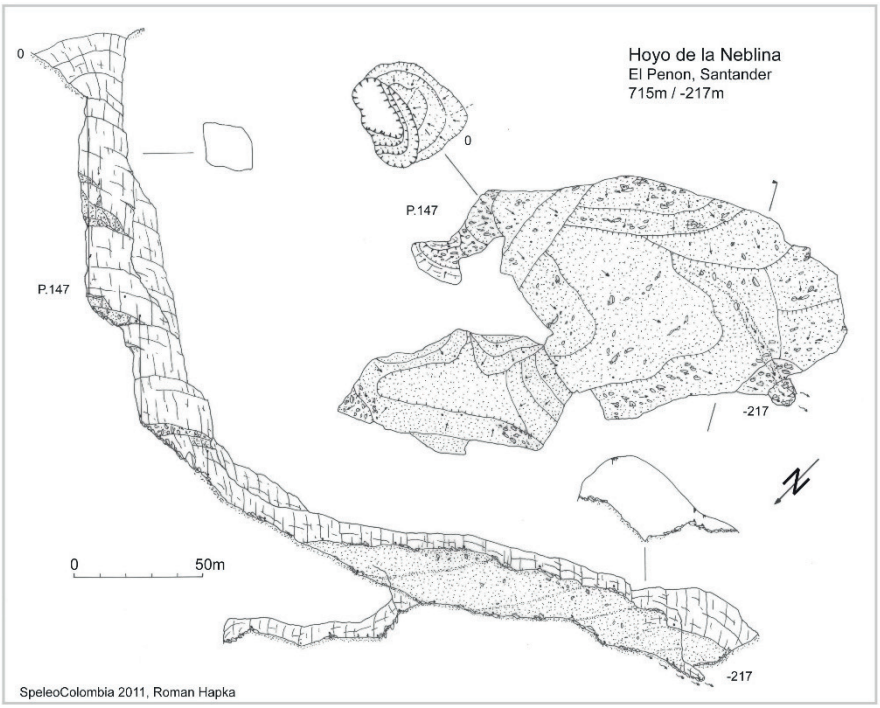

Figure 4: *Ejemplo de desarrollo de cavernas: topografía del Hoyo La Neblina (El Peñon).*

Se pueden diferenciar tres tipos principales de cavidades:

- Cavidades o pozos de "entrada" de 50 a 150 m de profundidad, que a veces dan acceso a grandes salas o importantes galerías horizontales (Figuras 4, 5 e 7).
- Cavidades horizontales con galerías amplias bien formadas y que presentan a veces dos niveles, de los cuales el primero es activo (figuras 3 e 6).
- Grandes abrigos o albergues bajo roca desde el pie de los acantilados, a veces con una quebrada o un río subterráneo que desaparece, más o menos rápidamente, en sifones o montones de piedras provenientes de un deslizamiento.

Con un desnivel de -219 m, el Hoyo de los Ocelotes es la cavidad más profunda descubierta hasta hoy. La red Hoyo Hermosura – Hoyo del Águila, es una cavidad con un desarrollo muy importante de unos 4936 m de longitud, y por último con 147 m, el pozo Hoyo de la Neblina, es el más grande de Colombia (Figura 4).

3. Conclusiones

Los resultados de las expediciones Espeleo Colombia han sido publicados en un número especial de Cavernes en 2015 (ver HAPKA 2015 para una mayor detalle), en diversas revistas internacionales y nacionales, así como, presentados en diferentes congresos y reuniones internacionales (BOCHUD et al. 2013, HAPKA 2019).

Las expediciones de Espeleo Colombia que se desarrollaron casi que anualmente desde 2010, se han dedicado a la prospección y a la exploración sistemática de los carsts altoandinos al sur del departamento de Santander. Casi una centena de cuevas y abismos (simas, hoyos), fueron explorados. Sin embargo, todavía no se ha descubierto la mayoría de los accesos hacia los colectores principales de estos sistemas, los cuales pueden alcanzar grandes profundidades. A pesar de la existencia de sifones, estrechamientos impenetrables o los deslizamientos a profundidades que sobrepasan los 200 m de profundidad, las exploraciones continúan. En efecto, los descubrimientos a lo largo de estas expediciones, se suceden casi que diariamente, testimonio de un formidable potencial de exploración a futuro.Lo que sigue se anuncia prometedor, ya que numerosas entradas importantes han sido señaladas por la población local o mediante entrevistas directas durante las prospecciones. Las primeras incursiones en zonas más bajas de los macizos, en zonas más cálidas, también han permitido acceder a grandes cavidades horizontales, vestigios quizás de antiguos salidas de rio subteranos. A partir de 2025, las futuras expediciones de Espeleo Colombia (Speleo Colombia), continuarán con las prospecciones y las exploraciones sistemáticas, para permitir un mejor conocimiento hidrogeológico de la región.

Figure 5: *Ejemplo de cavidades o pozos de profundidad: galería gigante (50 x 40 m) de la Cueva Brazuelos (Florián), con un pozo u hoyo de 122 m.*

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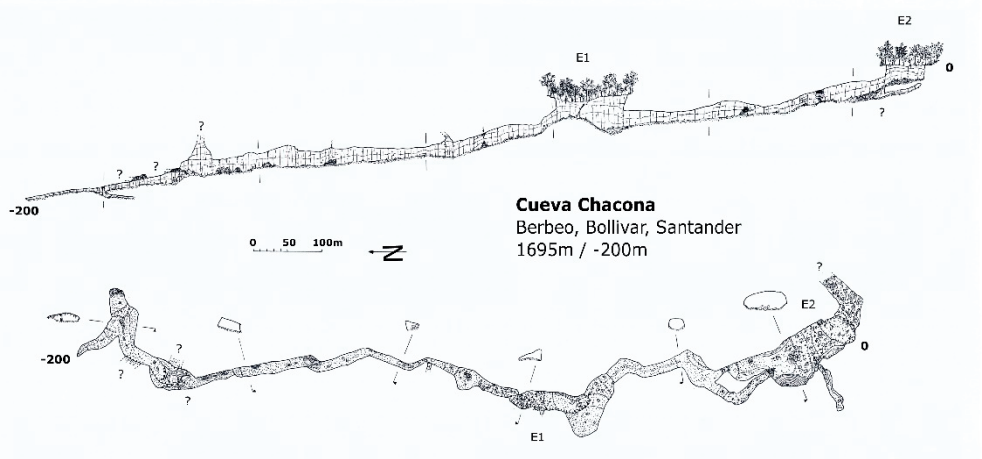

Figure 6: *Topografia de la Cueva Chacona (Bolivar): 200 metros de caída vertical sin usar cuerdas.*

Figure 7: *Grandes verticales de entrada de más de 150m son la seña de identidad del macizo de El Peñón.*

Typical of carbonate island cave in strike-slip fault setting: explored from Maratua Island. Indonesia

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Abstract

It is an open-shaped atoll on the submerged edge of the Mangkalihat Peninsula platform. A pop-up structure forms the island within a strike--slip fault. This paper describes the type of cave on the island. A field survey was conducted to gain insights into the cave's characteristics, including its type, morphology, and mapping. The survey found 13 caves that are controlled mainly by extension joints and faults. The cave formation is favored by flower structure due to the pop-up mechanism of the strike-slip fault.

1. Introduction

Maratua Island is (MI) an open atol that lies offshore of Kalimantan, Indonesia. It is an open-shaped atoll on the submerged edge of the Mangkalihat Peninsula platform (Park et al. 1982). The island was initially characterized by Molengraaff (1922) as an atoll resulting from diastrophism. A subsequent investigation was carried out by Kuenen (1933) as part of the Snellius Expedition. Kuenen (1933) proposed that Maratua Island is classified as an elevated coral. An investigation of Maratua Island was conducted later and published by Tomascik et al. (1997) in their book titled The Ecology of the Indonesian Seas. The book characterized Maratua Island as an elevated atoll featuring an open lagoon. The latest study by Haryono et al. (2021) suggests that a strike-slip fault controlled the formation of Maratua Island (Haryono et al., 2022).

The island showed six distinct geomorphological units: fringing reef, beach, marine terrace, karst ridge, structural valley, and lagoon. Additionally, caves exist within the karst ridge and along the coast, serving as submerged passages. Another remarkable geomorphological feature in the region includes three structural depressions with saline water found in the karst ridge (Haryono et al., 2018). This paper aims to describe the type of cave in the carbonate Island of strike-slip fault setting.

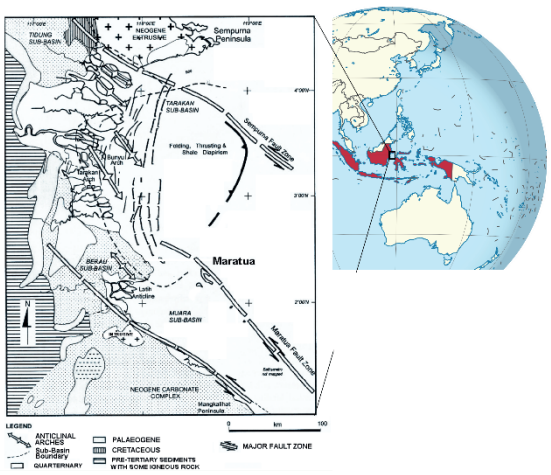

Figure 1: *Geological setting of the Maratua Island (simplified from Van Bemmelen 1970; Lentini and Daman 1996).*

2. Materials and methods

A series of steps were carried out during the data collection for the caves, beginning with gathering information on cave entrances, followed by conducting a cave survey. This survey aimed to gain insights into the cave's characteristics, including its type, morphology, and mapping. Teams of cavers utilized vertical gear for SRT (single rope technique) and tools for cave mapping to explore the cave. The research implemented the BCRA (British Cave Research Association) grade 3a for mapping caves, utilizing a clinometer and a laser distance-measuring device. The researchers engaged in cave diving to examine a submerged section of the cave. Through the mapping process, cave morphometry and other characteristics were analyzed. The plotting of cave entrances and their morphology was subsequently analyzed to identify patterns in cave occurrence, aiming to determine if they indicate various levels of occurrence that reflect the island's evolution (Haryono et al., 2022).

3. Results and Discussion

The caves located on Maratua Island exhibit unique and distinct shapes. The majority of these caves are controlled by structural factors (such as faults or joints) and feature narrow passages with tall ceilings. A small number of caves contain spacious chambers, such as Tangkapa Cave and Angkal-Angkal Cave.

Consequently, numerous caves are found at extended joint that align

with the NW–SE direction of the island's axis. A prime example of this kind of cave can be seen in Tangkapa, Angkal-Angkal, and Halo Tabung, where the widened joint are further developed by water that erodes the carbonate rocks to create caves. One cave, located in Gunung Putih at the island's highest point, has been dissected revealing stalagmite formations at the surface (Haryono et al., 2022). The visibility of the stalagmite is attributed to the partial unroofing of the cave, particularly in the karst ridge area. This unroofing resulted from the breakdown of rock masses along joint surfaces (Wang and Xiong 2020).

Table 1: *The Caves in Maratua Island. From: (Haryono et al., 2018).*

Nr. Cave Name	X	Y
1. Sembat	680678	241568
2 . Tangkapa	679625	242479
3 . Angkal-Angkal	679136	242826
4. Silandayan	676935	244428
5. Sipbig	677085	244183
6. Sukur	674758	247565
7. Mayat-Mayat	674554	248089
8. Pogah	675221	246891
9. Hapit Pogah	675187	246947
10.Organ	674445	248955
11 Jellau	676660	253437
12.Pahang	677594	251903
13.Penggunting	676793	244087

Phreatic caves and flank margin caves, typically found in carbonate islands with an eogenetic setting (Mylroie and Mylroie 2007), are relatively rare on Maratua Island. During the authors' fieldwork, the caves revealed a distinctive hydrological condition: some are filled with brackish to saline water, and tide fluctuations appear to influence the water levels. The only cave of flank margin origin identified on the island is Kepiting Kenari Cave. Additionally, caves have been located within the vadose zone, evidenced by the presence of vadose drips that create speleothems. The vadose drips originate from the joint system situated above the cave passage. Examples of features of this type include Jallau and Sembat caves. These caves were discovered at varying elevations, suggesting past water table levels (Haryono et al., 2022). The cave is highly connected with the sea water.

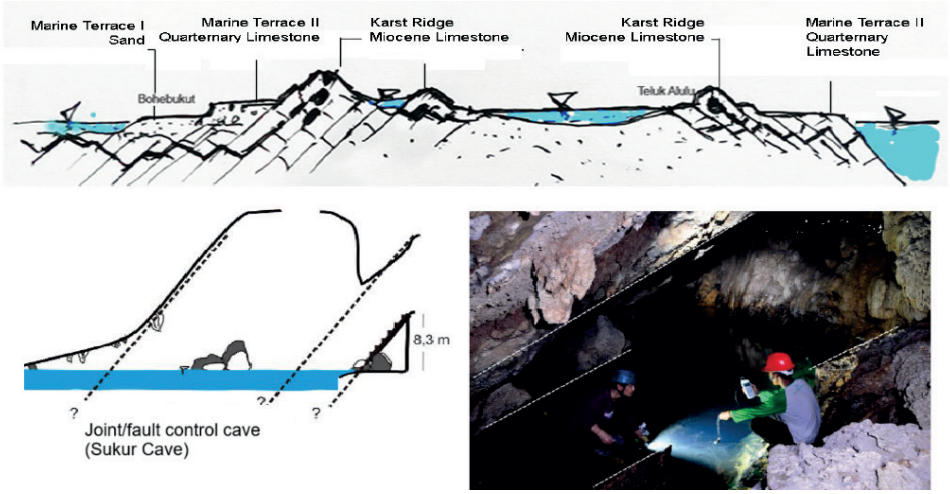

Figure 2 : *Cave types in the Maratua Island (Haryono et al., 2018, 2022).*

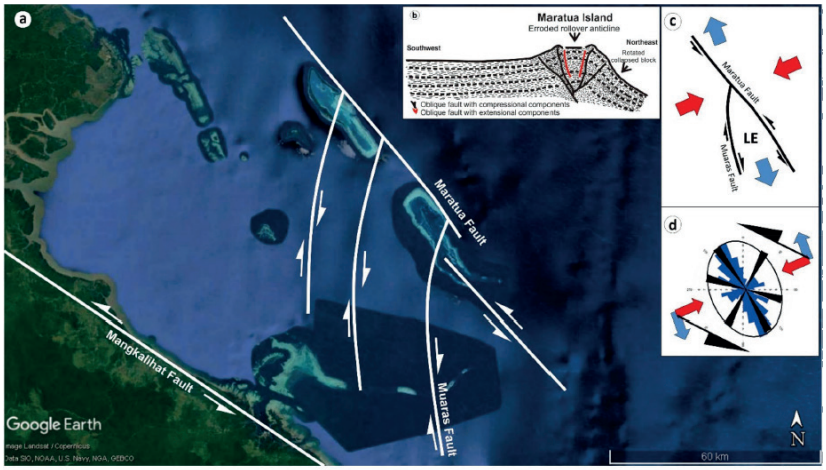

Figure 3: *illustrates the fault system surrounding Maratua Island, showing the connection between the left-lateral Maratua Fault (primary) and the right-lateral faults (subsidiary) as seen in a Google Image. b presents a flower structure model of Maratua Island. c indicates that the Muaras fault and other subsidiary faults facilitate the lateral movement of the southern block (this illustrates a kinematic model of the lateral escape (LE) block amidst the subsidiary and Maratua faults). d displays the strain ellipse for the kinematic model in (b), plotted alongside surface fracture data, where the majority of fractures recorded on Muaras reef indicate the primary extensional direction (Haryono et al., 2022).*

4. Conclusion

Strike-slip faults form a distinctive type of cave that is different from the carbonate islands previously proposed by Mylroie and Mylroie 2007. The cave formation is favored by the extention joint of the flower structure due to the pop-up mechanism of the strike-slip fault.

Acknowledgments

This paper is excerpted from previous papers by the authors (Haryono et.al, 2018; Haryono et.al, 2022) for issemination purposes, which were previously published in Environmental Earth Sciences and IOP Conf. Series: Earth and Environmental Science

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Exploring the Vanoise Karst: Marble Caves Beneath Active Glaciers

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Abstract

The Vanoise Massif (French Alps) presents a unique setting to investigate interactions between glacial dynamics and karstic processes. Recent speleological surveys (2022–2024) focused on high-altitude carbonate formations in the Col de la Vanoise syncline, where Jurassic and Cretaceous marbles exhibit complex karstification driven by ~1,000 m of glacial retreat since the early 20th century. The exploration and mapping of 2.6 km of galleries across 18 caves, with depths reaching 135 m, revealed subglacial losses, moulins, and fossil conduits, enabling the tracing of groundwater pathways to lower-altitude emergences. Hydrogeological analyses confirmed links between glacial meltwater infiltration and karstic outflows, while speleothem records provided insights into paleoclimate variability in glacial environments. A major discovery, Arcelin Cave, extends >2 km and hosts an active subglacial river, representing a pioneering example of such systems in the Western Alps and globally. These findings highlight the significance of glacially influenced karst networks and their role in high-mountain hydrology under accelerating climate change.

1. Introduction

The Vanoise massif, located in Savoie in the French Alps, is a remarkable natural area for its geological diversity, complex topography and karstic systems. Reaching a peak of 3,855 m at the Grande Casse, the massif is home to peaks exceeding 3,000 m, numerous glaciers and a wide variety of geological formations. Geographically, the Vanoise serves as a crucial transitional zone between the Briançonnaise coal zone and the lustrous shale (ELLENBERGER, 1958). The area surveyed generally consists of massive Jurassic (Malm) marbles and chlorite marbles from the Upper Cretaceous to the Paleocene. These marbles are mostly underlain by Triassic quartzites (lower impermeable level); the thickness of the marbles is variable and sometimes unknown.

The speleological history of the Vanoise is characterised by a succession of contributions since the 1970s. Since the inaugural explorations by the Spéléo Club de Pommard in 1976, and the subsequent detailed investigations conducted by the SGCAF and the Forez speleologists in the 1980s (DUCLUZAUX, 1993), there has been a gradual increase in the discoveries of karstic sinkholes and losses. Of particular note is the documentation of the areas surrounding the Col de la Vanoise refuge and the Arcelin plateau, which has revealed intricate underground water flows and conduits that are often challenging to penetrate due to glacial deposits (HOBLEA, 1997). From 2022 to 2024, a new speleological exploration campaign was conducted in the syncline of the Col de la Vanoise, located south of Pralognan-la-Vanoise, at an altitude ranging from 2,600 to 3,000 meters. The marble layers, though altered and karstified, are partially covered by recent glacial deposits. The sub-glacial losses, bedières and moulins observed in this area are indicative of karstic activity influenced by the glacial retreat of almost 1,000 m since the beginning of the XXe century, exposing ancient fossil conduits and beheaded caves. Tracing carried out from the losses near the Col de la Vanoise refuge has confirmed the hydraulic connection between the sub-glacial losses and the emergences located between 1,500 and 1,800 m, near the place known as 'Les Fontanettes' (RAMPNOUX and NICOUD, 1979; DUCLUZAUX, 1993).

This recent work, including tracing in 2024, has enhanced our comprehension of the groundwater dynamics in this karstic system. Continuous glacial melt, in conjunction with periods of warming, exerts a pivotal influence on the evolution of the caves and the formation of speleothems, the dating of which offers valuable insights into the reconstruction of Alpine paleoclimates. The objective of this publication is to present the results of the explorations carried out between 2022 and 2024, while building on previous work. The study of karst systems in the Vanoise massif, through the analysis of losses, sinkholes and underground circulation, offers new perspectives on the interactions between karst and glacial dynamics in a context of climate change.

2. Context

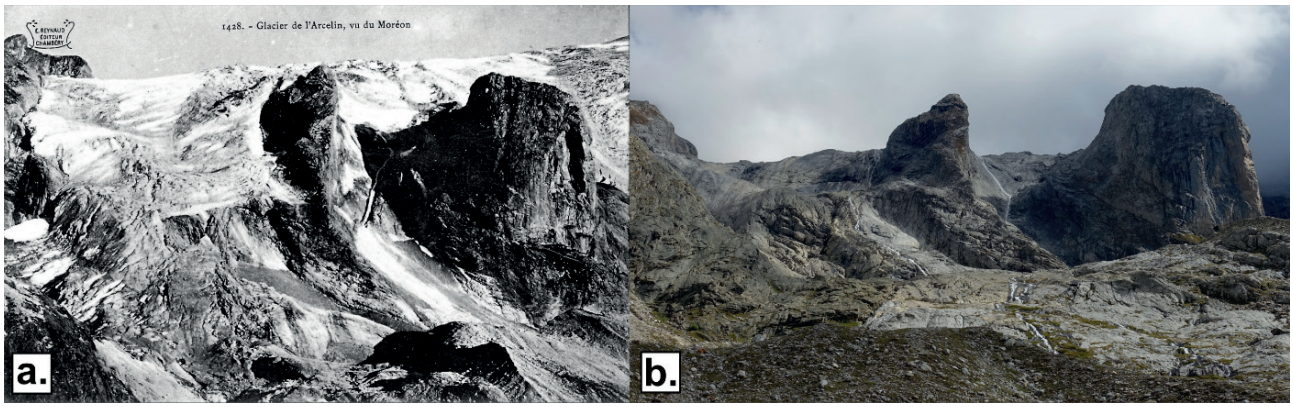

Figure 1: a. The Arcelin glacier at the beginning of the 20th century. b. Contemporary photograph showing the same view of the slabs at the front of Arcelin Glacier. Both pictures are from Bernard Vion.

Since 2022, a series of speleological expeditions have been undertaken in the Vanoise massif with the objective of enhancing our comprehension of high mountain karsts, with a particular emphasis on the repercussions of recent glacial changes. This endeavour has been informed by systematic surveys, exploration of new caves, and an integrated scientific approach encompassing hydrogeological studies and speleothem analyses. The rapid retreat of glaciers, as illustrated by the evolution of the Arcelin Glacier over the past century (Fig. 1), underscores the urgency of these investigations.

Glacial retreat and link with karstic environment

The interaction between karst landscapes and the cryosphere—Earth's ice-covered regions, such as glaciers and snowfields—is crucial for understanding environmental dynamics in high mountain regions. In high-altitude karst areas, the cryosphere directly affects underground hydrology, cavity formation, and landscape evolution. Glaciers and perennial snowfields act as water reservoirs, releasing meltwater that infiltrates karst systems through sinkholes and shafts, altering underground hydrological flows in a seasonal and sometimes unpredictable manner. The freeze-thaw cycle also causes cryoclasty, widening limestone fissures and promoting the development of lapiaz and dolines. Subglacial and periglacial cavities are influenced by glacier fluctuations, which can lead to the widening of galleries or the temporary clogging of conduits by sediment or ice.

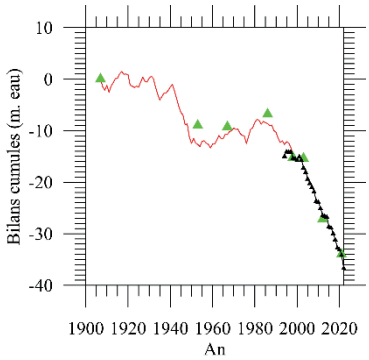

Figure 2: Reconstructed mass balance of the Gebroulaz Glacier (1905–2022). Data and figure: GLACIOCLIM.

Studying karst-cryosphere interactions is essential for understanding geomorphological processes in high mountains and the impacts of climate change on glacier stability, water resources, and karst network evolution.

The Vanoise mountain range, particularly the Gebroulaz Glacier (as an example), has been studied for years, with monitoring beginning in 1995 (Fig. 2). The mass balance of the Vanoise glaciers, like those across the Alps, shows a significant deficit. Given the projected disappearance of glaciers by 2050 (VINCENT et al., 2019), it is essential to understand their current hydrogeological functioning to anticipate potential regime shifts in the coming decades.

Origin of the project

The project was launched at the initiative of mountaineers, speleologists, local guides, and rangers from the Vanoise National Park (PNV) in 2021. A review of existing work, notably the synopsis by HOBLEA (1997), was undertaken, leading to the identification of key karstic regions of interest through a series of field observations.

These areas, which are primarily situated in the vicinity of the Col de la Vanoise, are characterised by the presence of sinkholes, losses and moulins, which have been exposed due to the retreat of the glaciers (Fig. 1).

Preliminary surveys, encompassing a visit to the Grand Marchet resurgence and the cave on the Arcelin glacier front, signified the project's inaugural stages. These investigations culminated in the establishment of an inaugural caving camp in 2022.

Constraints and terrain conditions

The Vanoise massif imposes significant climatic and logistical constraints, which must be considered when planning fieldwork in this area. In winter, the caves and moulins are often blocked by snow, making access perilous, and in spring and early summer the melting snow can disrupt explorations by saturating the caves.

Consequently, late summer and autumn are the optimum periods for prospecting, with more stable conditions and minimal snow cover.

Access to the exploration areas is possible via a three-hour walk and a 1,000-metre ascent from the Fontanettes car park in Pralognan-la-Vanoise. The proximity of the Col de la Vanoise refuge facilitates extended stays, thereby maximising the effectiveness of fieldwork.

2023: Further exploration

The encouraging results obtained in 2022 led to an extension of activities for the following year, with the primary objective being to continue prospecting the moulins and subglacial cavities, while deepening exploration of the identified sinkholes. Closer collaboration with the Vanoise National Park enabled the validation of the scientific approach and the sampling authorisation for calcite samples. These samples were collected as part of Alexandre Honiat's PhD thesis, which focused on the formation of speleothems in a glacial environment. Prior to the main camp in 2023, two scouting trips were conducted: In July 2023, the Petit and Grand Marchet cirques were explored, and the topography of the loss of the Petit Marchet was studied, along with the identification

of new entrances in the marbles. In August 2023: Surveys on the Col de l'Arcelin and the Vanoise glacier, locating several caves, including those explored in the 1980s (AR1, AR2 and AR3). The data collected enabled the search areas to be extended, particularly around the Pointe du Dard.

2024: New discoveries and further scientific research

In 2024, the focus of explorations was directed towards the Arcelin cave, where promising prospects had been identified in the preceding year. Despite the occurrence of initial snowfall, which rendered extensive prospecting challenging, the October camp was dedicated to climbing and topography within this cave. Concurrently, two scientific themes were initiated:

1. Hydrogeological tracing: This involved the implementation of artificial tracing between August and September 2024, with the objective of elucidating the subterranean circulation between glacial losses and karstic outcrops. The outcomes of this endeavour, meticulously documented in a dedicated report, substantiate the correlation between these elements.
2. Speleothem studies: The process of sampling and instrumentation within the Arcelin cave has facilitated the investigation of speleothem formation conditions within a subglacial environment. This research aims to reconstruct the glacial paleoclimates of the Alps.

3. Exploration

Name	X	Y	Z	Development (m)	Height Difference (m)
Arcelin 1988					
colAR1	325525	5027289	2600	41	26
colAR3	325440	5027344	2565	129	62
Arcelin 2022 (AR)					
AR1 **Arcel1**	325573	5027449	2530	2022	135
AR3	325991	5027256	2791	14	13
Arcelin 2023					
AR12	325909	5026904	?	21	12
Rocher du Génèpy 2022 & 2023 (G)					
G1 **Marbrimba**	326617	5027246	2946	131	117
G2	326528	5027262	2875	19	18
G3	326196	5027362	2793	23	22
G4	326115	5027348	2791	56	42
G8	326055	5027677	2665	35	42
G9	326083	5027653	2743	10	10
G11	326061	5027632	2725	6	6
G13	326077	5027637	2731	11	10
G14	326073	5027628	2737	17	15
G17	326075	5027281	2799	8	7
G18	326068	5027239	2855	8	8
Col de la Vanoise (CV)					
CV3	326432	5028768	2475	26	15
CV5	326829	5028478	2505	10	3
	Total Cave Development:			**2587**	
Moulins 2022 (M)					
M1	326772	5026609	3043	35	30
M2	326614	5026804	2987	75	42
M4 M5 M6	326017	5027115	2862	517	64
Moulins 2023					
M11	326985	5026342	3055	65	60
M12	326090	5026478	3055	89	51
	Total Development:			**3368**	

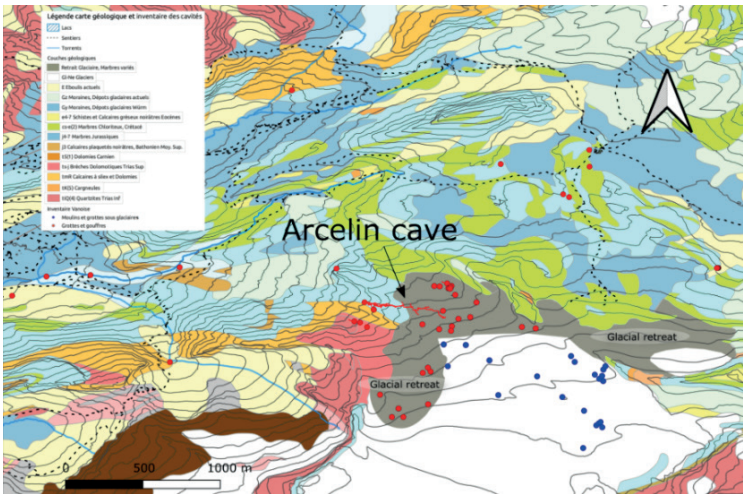

Figure 3: Table: Summary of cavities explored during the 1988-2022-2023-2024 expedition. Map: Geological map of the prospecting area with the location of the entries identified by the cyan dot. The glacial retreat (interpretation) can be identified in grey and the actual glacier in white. BRGM data.

Marble and Arcelin caves

A total of 18 caves have been mapped (Fig. 3) and more than 50 entrances have been discovered. The caves in the area are predominantly formed by the fracturing of the marble layers, leading to the formation of numerous single pit blocks by ice and/or sediment. The majority of these caves are vertical in nature, with a maximum depth of -135 recorded for Arcelin and -117 for Marbrimba. There is negligible horizontal development, with the exception of Arcelin.

Arcelin Cave is a fractured alpine karst network characterised by a succession of shafts, meanders and fossil galleries (Map: Fig. 4) Recent explorations have revealed new developments and significant environmental changes, including the disappearance of the fossil ice between 2023 and 2024. From the upper entrance, a series of shafts and meanders descend for more than 60m, culminating in a funnel where a narrow passage discovered in 2023 has allowed further exploration. A fossil gallery displays sedimentary deposits and ancient glacial formations that have now disappeared. The lower entrance opens onto a maze-like network marked by typical forms of erosion and a small temporary lake linked to melting snow.

Exploration in 2024 allowed us to go beyond the previous terminus by crossing a 90° constriction, revealing a gallery with active erosion features, a 30 m deep diaclase and a 9 m shaft leading to a gallery with an unexplored active river from the meltwater of the glacier. This is a major discovery for the western Alps.

Moulins and Ice caves (between the glacier and bedrock)

The Arcelin glacier constitutes the eastern and northern part of the extensive Dômes de la Vanoise ice cap. This glacial plateau, situated at an altitude of between 2,900 and 3,200 metres, is supported by a carbonate bedrock foundation and encompasses an area of approximately 3 km^2. Exploration of moulins has enabled descent to a maximum depth of 60 metres reaching contact with the bedrock. While few visible emergences are evident at the glacier's forefront, exploratory endeavours have revealed contact caves extending over several hundred metres between the ice and the bedrock. Under-ice karstic losses have also been observed. The caves and moulins under the glacier are undergoing rapid evolution due to the substantial ablation of the glacier.

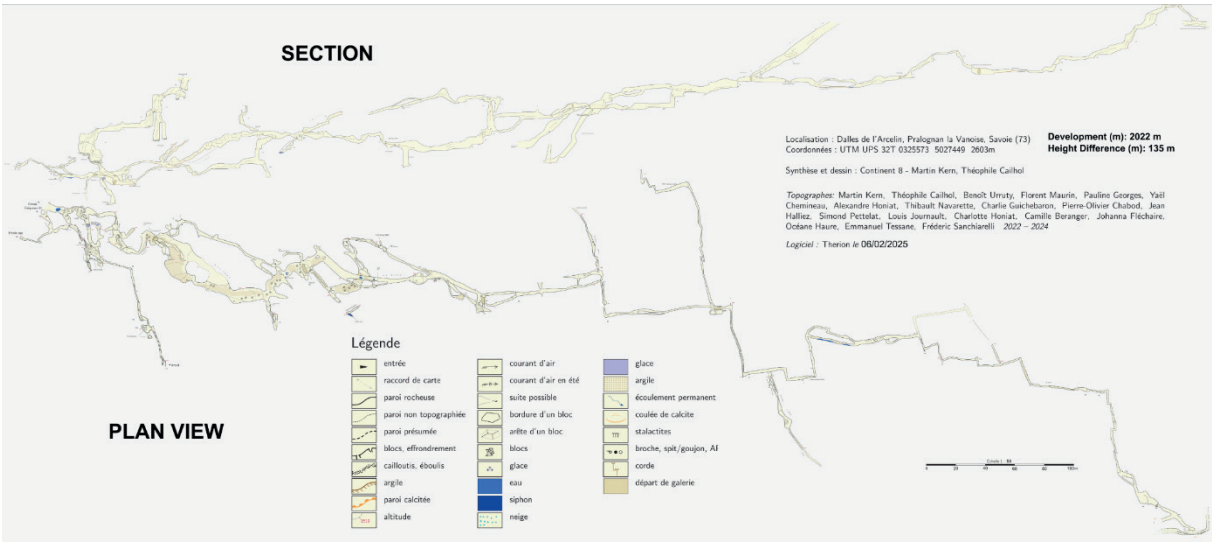

Figure 4: Topography of Arcelin cave. The section on the upper part and the plan view on the lower part are presented.

4. Key scientific work

Karstology and geological observation

The surveyed area includes regions that were previously covered by glaciers, such as carbonate outcrops around the northern edge of the Vanoise glaciers. Between the Pointe du Dard and the Pointe de la Réchasse, the glacier rests on carbonate bedrock (Geological map: Fig. 3).

Glacial deposits are extensive, covering much of the syncline base. Furthermore, sub-glacial calcite crusts (Fig 5.a) and breccias (Fig 5.b) have been exposed by glacial movement at the front of the Arcelin glacier, and karstic conduits have been eroded, forming unroofed caves.

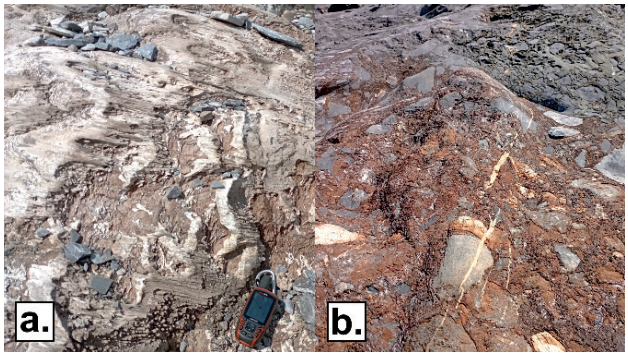

Figure 5: Sub-glacial calcite crusts. b. Breccias.

Subglacial speleothems and paleoclimatology

Subglacial speleothems—carbonate formations within caves overlain by glaciers—challenge conventional assumptions about speleothem growth, typically associated with warm, humid conditions and soil cover. However, evidence from temperate-based glaciers demonstrates their formation beneath ice. This process is driven by sulfide oxidation in the host rock, generating sulfuric acid that dissolves carbonate bedrock (instead of the classical carbonic acid dissolution), leading to calcite precipitation within cave environments. Such mechanisms have been documented in high-alpine caves (SPÖTL et al., 2024), including Milchbach (LUETSCHER et al., 2011), Melchsee-Frutt, Sieben Hengste (Switzerland), Spannagel Cave in Austria (SPÖTL and MANGINI, 2010), and now Arcelin Cave in France (this study).

These formations serve as archives of paleoenvironmental conditions, recording episodes of basal melting beneath temperate glaciers. Their presence indicates past glacier thinning or retreat, enabling meltwater infiltration into underlying karst systems (ATKINSON et al., 1983; SPÖTL et al., 2024).

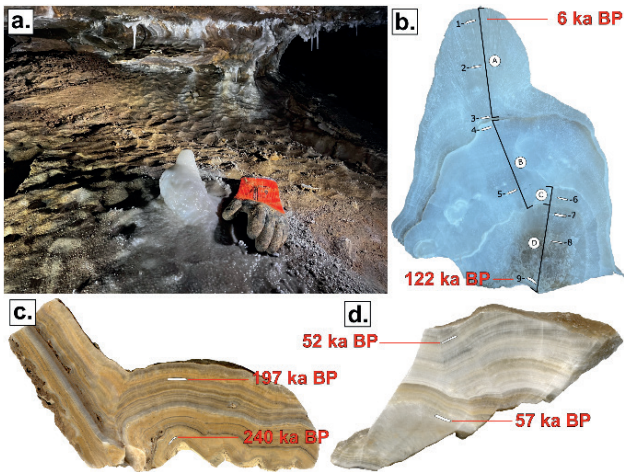

Figure 6: (a)Stalagmite A1S extracted from the terminus room 2023 of the Arcelin cave. (b) Stalagmite A1S. (c) Flowstone AR1. (d) Flowstone AR3. For (b,c & d) Section cut, polished and dated by the U/Th method for the top and bottom (preliminary). The successive growth periods are labelled A, B, C and D respectively (b).

The 2024 Vanoise expedition builds on previous research, focusing on stalagmite A1S in Arcelin Cave (Fig. 6a, b), which records growth spanning Marine Isotope Stages (MIS) 1–5, punctuated by multiple hiatuses. In 2023, analyses of two flowstones (named AR1 and AR3) revealed continuous deposition during MIS 3/4 (Fig. 6d) and 7 (Fig. 6c), reflecting shifts in glacial and periglacial hydrology. In summary, the growth periods of glaciers occur primarily under favourable climatic conditions, such as interglacial or interstadial periods, where the glacier is able to maintain a stable warm base. These findings serve to confirm the hypothesis that subglacial speleothems are capable of growth in both warm and cold conditions, with the caveat pertinent to the other parameters being the altitude at which they are found. To further investigate these processes, a comprehensive cave monitoring program has been implemented, deploying temperature loggers, drip loggers, and glass plates to track modern calcite precipitation across key chambers in Arcelin Cave.

These new datasets will help our understanding of subglacial speleothem formation and paleoclimatology of glaciated karst environments.

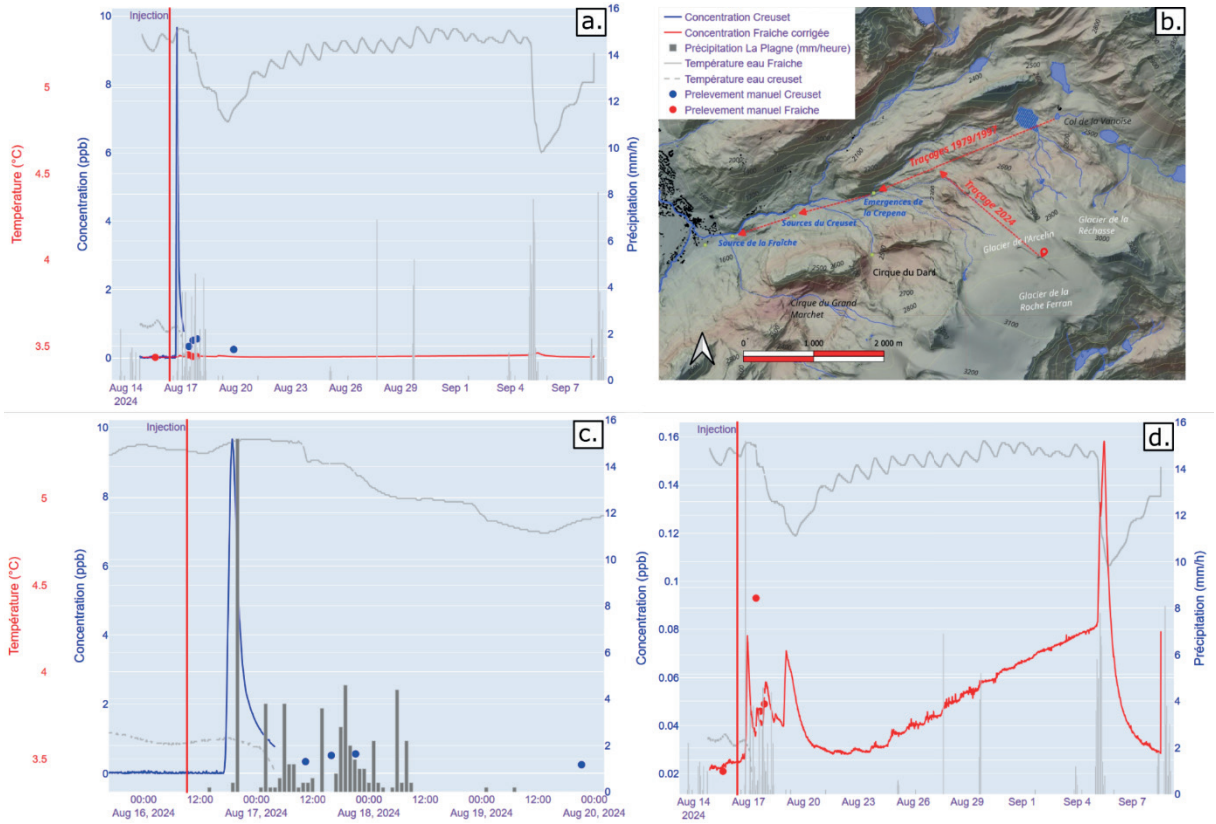

Figure 7: *Tracer Injection and Restitution Data (legend for a, b and c located in the upper left part of the map) a. Tracer concentration curves for the Creuset and Fraîche springs, showing early arrival at Creuset with higher peak concentration. b. Map of the Glacier of Arcelin and the Fontanettes area, indicating the injection site (Moulin M2) and monitored springs with inferred flow paths. c. Temporal distribution of tracer restitution events and their relation to rainfall, showing episodic signals influenced by precipitation. d. Long-term temperature and flow dynamics at the springs, illustrating variations in meltwater contributions and karstic system response over time.*

A hydrological tracer experiment on the Glacier of Arcelin

In August 2024, a hydrological tracer experiment was conducted on the Glacier of Arcelin in Vanoise National Park, France, with the objective of elucidating subsurface hydrological connections between glacial meltwater and karstic springs in the Fontanettes area, with a particular focus on the Creuset and Fraîche springs. This study is of particular importance in the context of climate-driven glacier retreat, which is projected to cause the glacier's disappearance by 2050. On 16 August 2024 at 09:30 AM, fluorescein tracer was injected into Moulin M2, a crevasse reaching the bedrock at a depth of 42 meters. (Fig. 7b). Tracer detection was monitored at six observation points, including the Creuset and Fraîche springs, located 3.5 km and 4.4 km from the injection site, respectively. At Creuset, the tracer appeared after 7.5 hours, travelling at a velocity of 470 m/h, with a peak concentration of 10 ppb of fluorescein (Fig. 7a). In contrast, at Fraîche, the tracer emerged after 11 hours, exhibiting a velocity of 398 m/h and a peak concentration that was one order of magnitude lower than that observed at Creuset (i.e., 10 ppb). These findings underscore the pre-eminence of Creuset as the predominant outlet for meltwater, with Fraîche contributing a negligible amount. Temporary outlets such as Crépéna also exhibited episodic tracer signals during periods of high-water levels, thereby highlighting the intricate dynamics of the karst system (Fig. 7c). This experiment emphasises the accelerated infiltration and subsurface transport of meltwater through high-capacity karstic conduits, in addition to the system's vulnerability to external inputs, including precipitation. Long-term discharge and temperature data (Fig. 7d) further elucidate seasonal variations driven by meltwater and rainfall. These findings are of critical importance for the effective management of water resources in Pralognan-la-Vanoise, a region heavily reliant on these springs, and for a comprehensive understanding of the impacts of glacial retreat on alpine hydrology.

5. Conclusion and perspective

The 2022–2024 explorations in the Vanoise massif have significantly advanced our understanding of high-altitude karst dynamics and glacial interactions. During this period, the exploration team successfully mapped 18 caves, discovering over 50 entrances and uncovering a total of 2.6 km of galleries. Of particular note is Arcelin Cave, which has been identified as a remarkable example of karstic phenomena, reaching a maximum depth of 135 meters over an area of 2 km. This cave is notable for its discovery of an active subglacial river, a ground-breaking finding that has significant environmental and scientific implications for the Western Alps and other glacier-covered area. Key findings also include hydrogeological tracing that confirmed subsurface water connections, and the discovery of subglacial speleothems, providing valuable insights into past glacial climates. These discoveries highlight the dynamic role glaciers play in shaping subterranean water systems. As glaciers continue to retreat, the rapid evolution of these caves underscores the importance of ongoing exploration and monitoring. Subsequent expeditions, with a projected duration until at least 2027, will concentrate on first the exploration, then extending paleoclimate research and enhancing our comprehension of alpine hydrology, with a particular emphasis on the pivotal relationship between glaciers, groundwater, and karst networks in the context of climate change.

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Ultima Patagonia 2023; an outsized expedition

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Abstract

Located at 50° S in Chilean Patagonia and explored by Centre Terre since 1997, Madre de Dios (MDD) archipelago is one of the southernmost karst regions on Earth. Ultima Patagonia 2023 is the 9th expedition led by Centre Terre and the second one in which members of the Kawésqar community, whose traces have been found in caves, took part. This edition of unprecedented logistical complexity saw three teams working simultaneously during the first month of the expedition (one on the glaciers, one on the north of the MDD Island and one film team), while during the second month two teams worked simultaneously from two different base camps on Madre de Dios Island. In terms of glacier exploration several dozens of moulins were explored, almost reaching the depth of 100 m in two of them. On the limestone massifs of MDD, the -300-meter mark was surpassed in two new caves, and several new siphons were explored. In all, seven major underground systems were discovered and explored in both sectors, totaling more than 7500 m of cave surveyed. Scientific work both in caves and on the surface was carried out, as well as educational school projects in France and Chile.

1. Introduction:

The Ultima Patagonia expedition 2023 (UP2023) is the 9th expedition to Chilean Patagonia by the Centre Terre team since 1997, not including the reconnaissance expedition in 1995. The 2023 edition overcame many challenges, starting with an interminable period of maturation between its launch at the beginning of 2020 and its actual realisation: the Covid pandemic dictated its tempo. As early as March 2020, the first worries appeared when the reconnaissance team (for what was then the UP-2021 project) had just sailed from the bay of Puerto Eden, since France had just been placed under strong confinement. The UP-2021 expedition had to be postponed until 2022. However, by the end of September 2021, sanitary conditions were clearly not in place to guarantee a possible departure in early 2022. Everything fell apart again. Despite all these setbacks, the machine was relaunched for the first quarter of 2023. Unfortunately, these three years changed everything: the team, the list of partners, the filming project and above all the financial aspects. Inflation had a severe impact on every item of expense (flights fares, freight transportation, cost of hiring boats, of petrol on site, of land transport, to the cost of accommodation) and the budget skyrocketed from €250,000 to €360,000.

UP2023 is first and foremost an expedition under the Franco-Chilean flag, officially launched from Puerto Edén, the home village of the Kawésqar people, who for thousands of years have traveled and tamed this hostile environment, and with whom Centre Terre has succeeded in creating a very strong bond. It is also an expedition that, for the first time since 2000, has managed to carry out simultaneous explorations and scientific work from two particularly remote base camps: one in the Estero Calvo, located in a glacial zone on the Southern Patagonian Ice-sheet; and another one in the *Estero Egg* in the north of Madre de Dios Island, where until then only short excursions had been made.

The team was also able to return to the central part of Madre de Dios Island thanks to the shelter built in the Seno Barros Luco in 2017. Finally, various verification, measurement and sampling operations were carried out on the southern part of the island, which had been explored between 2000 and 2010 from the Guarello mining base. This 2023 edition is also marked by the quantity and diversity of the participants: 48 in total, from 7 different nationalities (France, Chile, Marocco, Canada, Switzerland, Spain, Ukraine). Among the team members there were 12 scientific participants covering several fields of expertise such as marine biology, geography, karstology, geology, archaeology, geomorphology, meteorology, microbiology, paleoclimate, the study of avifauna and subterranean fauna.

UP2023 ensured the continuity of previous projects led by Centre Terre, under the umbrella of the *Fédération Française de Spéléologie*. It led a major school project involving 24 French primary and secondary schools.

The paper presents the main results from the exploration of limestone islands, a brief overview of the range of scientific work undertaken and the actions led by Centre Terre concerning the school program.

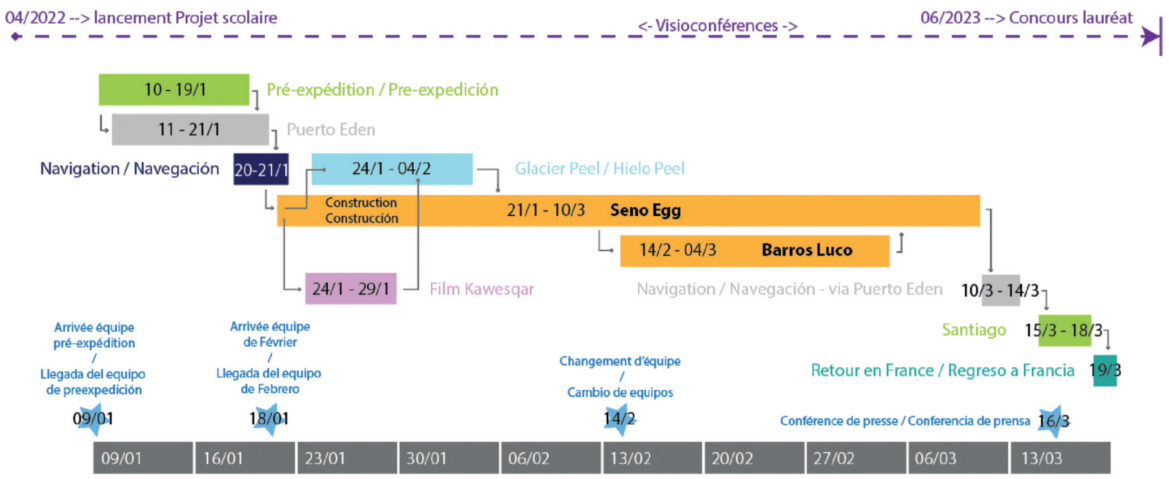

Figure 1: *Timeline of the UP2023 Expedition.*

2. Exploration

To facilitate the consolidation of cave survey data, a *Therion* database for the Patagonian karst was created to host all survey data and drawings from previous expeditions. Moreover, a set of uniquely identified cadastral units now allows specific subregions and karstic catchments of MDD to be queried and visualized. A summary of the exploration results from the glacier exploration which took place in *Estero Calvo*, Bernardo O'Higgins National Park, is given in a companion abstract (RACINE et al., 2025). Below is a brief overview of notable UP2023 exploration results on the limestone karst of MDD.

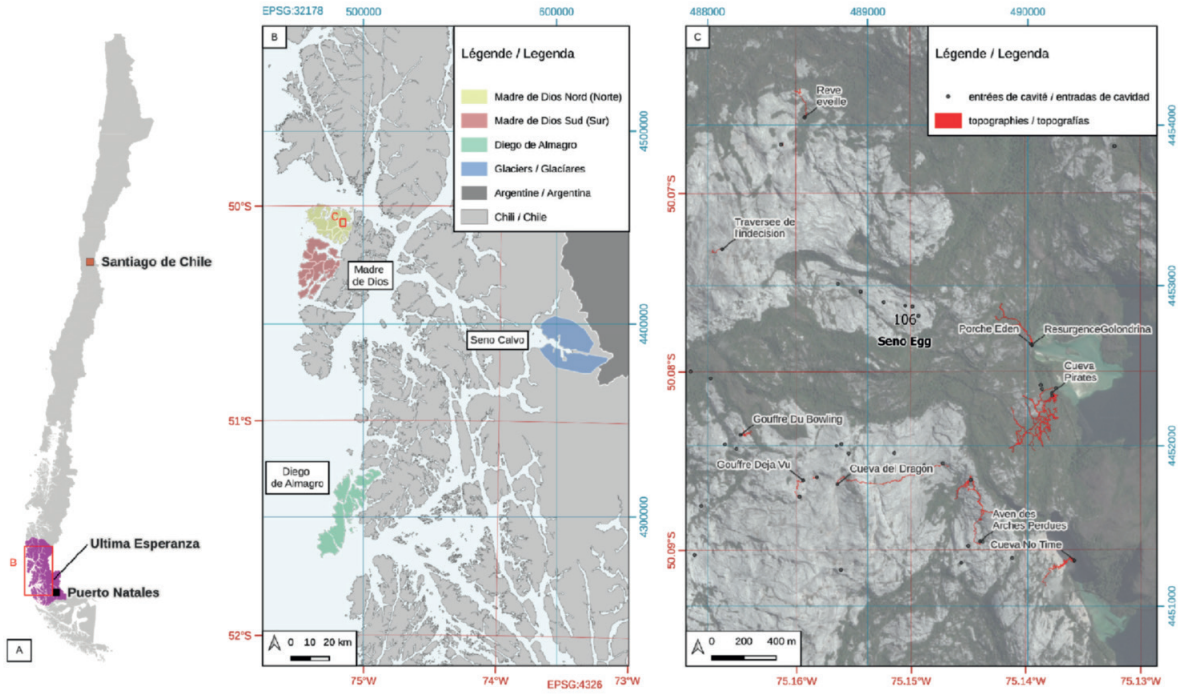

Figure 2: *Location of the expedition targets a) in Chile, b) cadaster for the exploration zones since 1995 c) Zoom on the Egg estuary area and overlay of cave passages.*

2.1. Exploration at the *estero* (estuary) *Egg*

Exploration logistics in the Egg estuary, on the northern rim of MDD island, were greatly simplified by the design and building of a wood and corrugated iron cabin during the first days of the expedition. This served as an all- round weatherproof headquarters, kitchen and communal area. While part of the team explored the glaciers of the Calvo estuary, another roamed from the cabin to the surrounding the karst plateau above the Egg estuary and began exploring some of the many pits opening on the bare marble.

Nearby, the epi-phreatic maze of the Pirates cave (first explored in 2006, later extended by Oxford university cavers to over 1.8 km) was further explored and mapped to a length of 3954 m, making it the longest cave on Madre de Dios Island. With its portal cave entrance opening 10 m above sea level and located only five minutes by boat from the camp, it was the ideal foul weather exploration option. Another notable cave of

the plateau is the Lost Arches cave, which over the course of the expedition was pushed to a depth of 306 m, hitting a permanent siphon, and in which a total of 1431 m were surveyed. From a depth of about 220 m and downwards, the general character of the cave changed from mainly vadose shaft series to wide open galleries with similar morphologies to those located in the epi-phreatic zone of Pirates cave. As ever, the final days of the expedition saw some new findings, including one large streamway explored for about 400 m upstream from a porch near sea-level. Many tantalizing leads remain in this aptly named No-Time cave. Diving took place over several outings at the main submarine resurgences of the Egg estuary. At the resurgence of Pirates cave, more than 200 m of guideline was put down in the entrance sump, with one exit to an air pocket lying closer than 10 m away from the closest surveyed point in Pirates cave, and an upstream continuation. At the nearby Golondrina resurgence, the entrance sump, reaching a maximum depth of 38 m, was dived to open and continuing passage beyond, which lie at the heart of the estero Egg massif. In total 676 m were surveyed in that cave.

2.2. Exploration in the *Seno* (inlet) Barros Luco

Using the cabin built in 2017, used again in 2019, a splinter team revisited the Barros Luco area to finish some of the open leads left there, as well as to find new entrances.

Setting up some advanced campsites on the plateau to further explore inland, the team returned to Jackpot cave, which had been left as a wide-open stream passage. Despite many setbacks due to horrendous weather conditions, the team surveyed several hundred metres, pushing the cave to a depth of 303 m, for a total length of 1350 m. During the exploration, a scientific team carried out detailed observations and sampling of sedimentary deposits therein.

Another team continued the exploration of the 3 Entrances +1 cave, concluding some of the more obvious question marks, while in a low-lying maze-like network of phreatic conduits, the Ancient System, no less than 710 m of passages were surveyed, for a modest height difference of 34 m. The return to Barros Luco was thus an all-round success and allowed longstanding question marks to be fully investigated.

Map n°	name	X	Y	Z	development	Height difference
				Egg		
106001	Cueva Pirates	490220	4452363	10	3954	154
106002	Cueva No Time	490289	4451286	70	437	105
106022	AvenDesArchesPerdues	489704	4451405	358	1431	306
106023	GouffrePlusPlus	487708	4451733	238	133	88
106028	Perte Sous Le Lac Turquoise	488683	4451804	272	15	50
106033	GouffreDuBowling	488207	4452069	294	221	66
106055	Perte25MetresNageLibre	488575	4451682	262	77	41
106056	PerteChampis	487409	4451595	210	34	27
106057	GouffreDuDejaVu	488596	4451785	280	151	34
106058	Perte du Disto	487919	4451318	240	200	40
106059	El Pozo Granizo	487642	4450792	281	81	81
106060	Puits de l'Arche	489099	4452897	201	32	21
106061	ResurgenceGolondrina	490023	4452633	0	676	78
106062	GrandeFailleDuBoutDuMonde	488459	4453880	244	56	43
106063	TraverseeDeLIndecision	488092	4453227	280	108	19
106064	Reve Eveille	488605	4454050	145	331	124
106065	PorcheEden	490023	4452633	5	76	29
106066	Casablanca	490551	4450456	10	73	17
106067	Resurgence des Pirates	490177	4452360	0	155	27
				Barros Luco		
107028	Gouffre Jackpot	482804	4447950	369	1350	303
107039	Grotte de l'Ancien	482166	4447844	330	710	34
				Trois Entrées		
109015	Grotte des 3 entrees + 1	485649	4444763	53	3258	114
				HPS-35		
402001	Perte3-HPS35	600151	4384623	439	30	20
402003	Perte5-HPS35	600145	4384573	446	65	50
402005	Perte7-HPS35	600144	4384403	460	115	75
402006	Moulin de la Science	599747	4384126	494	14	5
402010	Perte de Rascarcapac	600721	4383564	492	65	50
402016	Perte15-HPS35	600162	4383677	539	15	15
402019	Perte11-HPS35	599981	4383590	533	7	7
402026	Perte-??	600640	4384856	451	180	120
				HPS-31		
403003	Perte3-HPS31	602692	4391550	270	15	10
403005	Perte5-HPS31	602660	4391355	213	10	10
403007	Perte7-HPS31	602597	4391224	178	25	20
403008	GrotteLapisLazuli	602192	4390803	27	80	5

Table 1: *Summary of cavities explored during the 2023 expedition.*

3. Key scientific highlights

3.1. Climate and rainfall

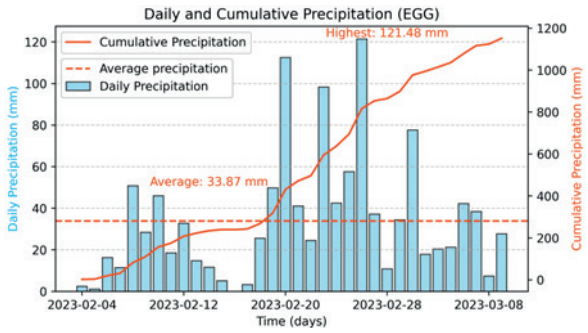

Figure 3: *Daily and cumulative precipitation at the EGG base camp between 4th of February and 9th of March 2023.*

During the 2023 expedition at the "Estero Egg base camp", climate surveys were conducted to measure key parameters such as temperature, atmospheric pressure and rainfall. These data provide an in-depth perspective on local variations in the context of climate change in southern Patagonia. The recorded temperatures demonstrate modest daily variations, with an average day-time temperature of 10°C and night-time temperature of 4°C observed during the expedition. The total precipitation recorded amounted to approximately 1,000 mm over the course of the month, with a mean daily precipitation of 34 mm. It is noteworthy that certain days witnessed intense rainfall, with a maximum of 120 mm in a 24-hour period. This volume represents a 25% increase compared to the rainfall recorded during the same period in 2017: 800 mm (MOREL, 2017). The Pluvimate (from Driptych company), used for this study, employed a stalagmate that works as a drip-counting system, recording every impact of water droplets that fall on its lid as an 'event'. There is no need to empty a container, but the water can be collected for calibration purposes for later chemical analysis, with a few modifications. Cumulative rainfall is obtained by integrating the intensity readings. The user can define the sampling interval, which can vary from a few minutes to several hours or days. Typical time resolution is 10 minutes, allowing up to 7 months of data to be recorded. This technology, which has been adapted to the rigorous conditions of Patagonia, facilitates the accumulation of precise data over several months.

Cave micro-climate and past climate

Monitoring work in some caves was started in 2019 in order to provide anchor point for past climate reconstructions using speleothems. The data-loggers were collected in 2023 and are the subject of a companion paper (HONIAT et al., 2025).

3.2. Dissolution-disaggregation process of dolomitic marbles

Figure 4: *Sand dolines on the upper western karst: A. Large sandy doline. B. Temporarily lacustrine depression with sandy fill. Typical forms of desquamation on the western karst: C. Circular hollow morphologies. D. Circular desquamation.*

The northern karst of Madre de Dios (Egg sector) is highly singular. In fact, we witness dissolution-disaggregation of the same type as that encountered in the erosion of the dolomites and dolomitic limestones that gave rise to the dolomitic sands. But here the associated morphologies are different: instead of the classic ruiniform relief, we see an association of dissolution grooves, hydrographic systems that can each exceed several hectares, a desquamation of the surface and sandy deposits present all the way from the endokarst to the resurgences (MAIRE, R. 2024).

Examination of thin sections and polished sections of marble from the Egg estuary plateau reveals facies generally containing large dolosparite-type crystals. On the surface, their dissolution-disaggregation results in forms of desquamation, followed by sandy deposits in rocky depressions and corridors. This process also gives rise to residual forms such as 'arches' and 'lobos' (sea lions). Dolomitic sands are present on the exokarst, as residual deposits at the lowest level of dissolution dolines, in the endokarst, as lateral deposits in cave stream notches, and above all at the outlets in the form of sandy deltas. One of them, the 'Las Golondrinas' delta, has a volume of several hundred thousand m^3. The precise granular erosion-dissolution balance is an area of research.

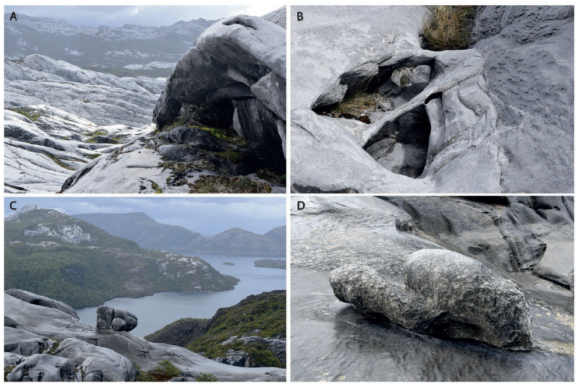

Figure 5: *Examples of residual forms of alteration: A. Large arch located near the Lost Arches cave; B. Small arches; C and D. Residual 'lobos' (sea lions) on the karstic surface.*

3.3. Prospecting for fauna and its importance in preserving the environment

Bat diversity and activity

During the Ultima Patagonia 2019 and 2023 expeditions, the possible presence of previously unknown bats was studied both on the Tempanos glacier and in the Madre de Dios archipelago. Ultrasonic detectors were installed at various sites. A total of 90 recordings were obtained for bats in 2019 over 26 nights of monitoring and 119 recordings in 2023 over 43 nights of monitoring.

A single male of the species *Histiotus magellanicus* was captured using mist nets in the 3 Entrances +1 cave on the night of 21 February 2023 by researcher Gonzalo Ossa. The individual was recaptured after 2 hours, being the only bat observed in the area. This study provides, for the first time, information on the presence of bat species both in the southern ice fields and on Madre de Dios Island. These data are relevant because they show a connection between the northern and southern populations on the Pacific side.

Subterranean fauna

During our expeditions, we sampled the caves in search of cave fauna, and our investigations highlighted its great poverty. This could be explained mainly by the glacial heritage of the archipelago and the lack of nutrients in the cave habitats. Nevertheless, apart from a few troglo-xene species regularly present, we were able to discover some species of interest. The terrestrial fauna is particularly poor. To date, only one Rhagidiidae mite, discovered in 2023 in the Pirates' Cave, can be considered truly troglobitic, but its determination to the species level could not be made, due to a lack of specialist. Similarly, an Isotomidae springtail collected in 2023 at the Pirates' Cave and at the spring of Golondrina could be troglobitic or troglophilic, but the absence of data outside these caves does not allow us to conclude on its status. This species will be described by Louis Deharveng. The aquatic fauna is significantly richer, even if here again the lack of specialists means that many of the species discovered could not be described. Among the stygobionts, a new species of Phreatogamaridae amphipod, *Ruffia patagonica*, was discovered in the anchialine cave at the end of the seno Eleuterio. Our 2023 investigations allowed us to discover a new species of Anaspidacea from the hitherto monospecific family Patagonaspididae. It is currently being described by Marcela Peralta, from the University of Tucumán, in Argentina.

Microbiological studies

Since the 2019 expedition, the bacterial diversity in Barros Luco inlet has been analyzed. Samples were collected from Jackpot Cave at depths of 145 and 170 meters, and genomic DNA was extracted for microbiological analysis. Sequencing of the bacterial 16S rRNA gene revealed the presence of sulfur- and nitrite-oxidizing autotrophic bacteria (family *Nitrosococcaceae*), bacteria capable of obtaining energy from methane (order *Methylomirabilales*), bacteria with denitrification activity and the ability to degrade aromatic compounds (genus *Polaromonas*), among others. These results suggest that, due to the low organic matter characteristic of cave depths, bacteria might obtain energy from inorganic sources such as H_2S or NO_2-, as well as from the oxidation of atmospheric gases like CH_4 in the cave depths. Currently, the DNA sequences are being processed using bioinformatics analyses to identify changes in microbial communities from the 2023 expedition, as well as analyzing samples from the exploration of new microbial communities in other areas of Madre de Dios Island.

Terrestrial observations

The observation of certain terrestrial species is important for environmental preservation. One of them is the bumblebee *Bombus Dahlbomii*, also known as the 'red bumblebee', endemic to Chile. This bumblebee is notable for its essential role as a pollinator, maintaining a crucial

link with many native plants. Unfortunately, in 2016, it was included on the 'Red List' of the International Union for Conservation of Nature (IUCN), being declared the 'first insect in danger of extinction in Chile'. Researchers Jaime Neira, Gonzalo Ossa and Matias Vargas have observed and confirmed its presence in the Barros Luco inlet and the Egg estuary during UP2023. Other unexpected species were observed such as the Neovison mink, also known as the 'American mink'. It is one of the most damaging invasive species for biodiversity and ecosystem conservation.

During this expedition, birds were once again the species most frequently observed. 14 bird species associated with the aquatic environment (open sea, coast or shore) were regularly observed as well as 16 terrestrial species. However, it is worth noting the presence of a pair of Cocoi Herons at the Egg base camp. Common further north in Patagonia, this species is not known to occupy the Magallanes region. Its presence could not be studied in more detail.

Revealing Patagonia's biodiversity using environmental eDNA

Each species has its own DNA sequence. By sampling the DNA of an environment, it is possible to reveal most of the species present in a place. On the other hand, the use of eDNA in this region remains a challenge, as many species have not yet been sequenced. At present, many identifications are limited to the genus or even the family. 20 seawater samples were taken. In all, 24 fish families were detected, 14 for birds, 8 for mammals and 1 family in the Chondrichthyan class. The group with the most species detected was fish, with 65 species, followed by birds, with 22 species, mammals, with 20 species, and chondrichthyans, with 1 species. Among the interesting results, a species of chimera was present at the estero Egg. Detected under the genus *Callorhinchus*, it is most likely the species *Callorhinchus callorynchus*, a species found in Patagonia and fished all year round in Argentina and Chile. It is threatened by overfishing, particularly trawling and driftnets. Another interesting finding is the Dragonfish of the *Bathydraconidae* family, detected at several sites. Little is known about their biology. 2 species from this family have been detected in Guarello area: *Gerlachea australis* and *Parachaenichthys charcoti*. This is very surprising, as these species are normally restricted to the coasts of Antarctica (their known distribution area). So, either the species detected here are very similar to the two detected, but still unknown or absent from the genetic database, or these little-studied fish have a much wider distribution than previously estimated.

3.4. Archeological observations

Since the 2000 expedition, Centre-Terre have inventoried, mapped and described more than twenty archaeological sites, mainly located in caves close to the shore: habitat sites or shelters, burials, rock paintings, etc (LAMOTTE D., 2019). During this expedition we revisited one of the major discoveries made in 2006 in the Pacific cave with members of the Kawésqar community. Several advanced motifs (anthropomorphs, sun wheels, geometric signs) painted in ochre or drawn with charcoal adorn the walls of this cave (JAILLET et al. 2009). The works discovered constitute one of the rare caves with parietal artistic manifestations of this people. Our visit was meant to enable our Kawésqar companions to re-visit places filled with the history of their ancestors. During UP2023 we inventoried a few more site with traces of occupation like the Ancient cave.

4. The school program and the promotion of caving in Chile

From 2008 to 2017, the Centre Terre explorers, supported by the French Ministry of Sports and Education, invited primary and secondary school classes to share in remote the Ultima Patagonia (UP) scientific and speleological expeditions. Under the implication of José Mulot, both teacher and explorer with Centre Terre, the educational dimension of the project grew. In 2016, the Centre Terre

association obtained accreditation from the French Ministry of Education.

For UP2023, the school program officially started in April 2022. A total of 24 schools comprising a total of 40 classes and 942 pupils, have officially signed up; to which we may add an unknown number of other school teachers who have used the resources of the Centre Terre school space on environmental, scientific or sporting themes (https://www.centre-terre.fr/projet-scolaire-up2023-presentation.php). Centre Terre member gave more than 15 talks to classes, either by videoconference or in situ, to make the link between learning and exploration in the field. Other classes in Switzerland and Chile also took part in the school projects proposed by the UP2023 expedition throughout 2022-2023.

In August 2017, fostered by Centre Terre, the *Asociación Espeleológica de Patagonia* was created in Chile. It is a non-profit organization whose main aim is to develop caving in Chile. One of the aims of the *Asociación Espeleológica de Patagonia* is to disseminate the work that Centre Terre has been developing and to convert this knowledge of a unique territory into a powerful educational tool. The *Cuerdas y Más* educational initiative (led by Natalia Morata) uses caving to bring the children from Puerto Eden closer to their territory and has allowed a wonderful cultural exchange to blossom between them and the CM1 and CM2 pupils of the Lorp-Sentaraille primary school (France), who are also following Centre Terre's expeditions through the educational project with the French Ministry of Education.

Figure 5: *Picture of all UP2023 participants: Bruno Peyronnet, Jérôme Krumenacker, Gilles Santantonio, Caroline Boghossian, Laurence Boudoux d'Hautefeuille, Arnauld Malard, Jules Clouzeau, Christian Chauvin, Alexandre Andrieu, Florian Rives, Christine Magot, Mehdi Boukhal, Katerina Medvedieva, Didier Lamotte, Clément Chaput, Franck Bréhier, Denis Morales, Bernard Tourte, Cédric Roques, Raphaël Seguin, David Meunier, Alexandre Honiat, Natalia Morata-Calvo, Amandine Dransart-Laborde, Laurent Mestre, Marie Eveillard-Buchoux, Olivier Guérard, Jessica Morin--Buote, Gwladys Fontanieu, Charlotte Honiat, Tanguy Racine, Sébastien Verlhac, Joël Trémoulet, Michel Philips, Christophe Rognon, Nicolas Fouilland, Gonzalo Ossa, Jaime Neira, Matias Vargas, Jérémie Prieur-Drevon, Richard Maire, Carlos Placido, Florian Chenu, Sylvain Boutonnet, Lionel Ruiz, Serge Caillault, Francisco Arroyo and Maria Isabel Tonko.*

5. Summary and perspective

The UP2023 expedition represents a significant advancement in the exploration and scientific study of the unique karst systems and biodiversity of the Patagonian Madre de Dios archipelago. This edition consolidated previous exploration survey and data into a comprehensive Therion database. The exploration of the northern part of Madre de Dios permitted the observation of new landscape morphologies due to the presence of dolomitic marbles, and expanded the knowledge of the longest cave systems, such as the Pirates Cave (almost 4km in development) and the Lost Arches cave (300 m of depths).

In the realm of biodiversity, critical observations, such as the confirmation and identification of bat presence and the unexpected detection of Antarctic species in local waters, underscore the importance of ongoing research.

Additionally, the educational and cultural exchange programs, supported by Centre Terre and the Asociación Espeleológica de Patagonia, have strengthened awareness and appreciation of the Patagonian underground and its conservation. By linking science with education, the UP2023 expedition not only deepens our understanding of Patagonia's unique subterranean environment but also inspires future generations to engage in its preservation.

Acknowledgments

A very large network of partners supported this UP2023 expedition. We thank our institutional and private partners from France, Austria, Switzerland, Denmark and Canada. We especially thank the French Federation of Speleology (FFS), and the Chilean authorities for all the necessary authorizations, particularly the Ministry of National Assets of Chile, the French Embassy in Chile, the Gobierno Regional de Magallanes y la Antárctica Chilena, Corporación Nacional Forestal (CONAF).

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The importance of protected spaces for the conservation of karst heritage: a participatory experience at RPPN Fazenda Serra Negra (MG)

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Abstract

Quartzite formations are structures that are highly susceptible to chemichal dissolution and the consequent formation of karstogenic features, such as caves, skinholes, pipes and shelters. Sharing the geomorphological context of the Serra da Mantiqueira, Serra Negra has several cataloged caves, but there are areas that have been little explored, largely due to the significant spatial expression of the geomorphological unit mentioned, in addition to being an area with the presence of private proprierties, steep slopes and difficult access. Therefore, this work aims to carry out a participatory mapping with local residents to locate the natural underground cavities and ancient trails locate in the RPPN Fazenda Serra Negra. To this end, a participatory workshop was held in which the organizers brought a previously articulated cartographic base with the aim of allowing participants to locate caves and the paths to the cavities according to their local knowledge. After this, fieldwork was carried out to verify whether the caves and paths indicated by the participants were real and whether the paths were still in a condition suitable for exploration purposes. This technique will be of utmost importance for the full identification of the karst geomorphological elements of the RPPN, as well as assisting the owner in the management of the property.

Resumo

As formações quartzíticas são estruturas bastante susceptíveis à dissolução química e consequente formação de feições carstogênicas, como cavernas, dolinas, pipes e abrigos. Partilhando do contexto geomorfológico da Serra da Mantiqueira, a Serra Negra possui diversas grutas catalogadas, mas existem áreas pouco exploradas, em grande parte devido à significativa expressão espacial da unidade geomorfológica aludida, além de figurar como uma área com presença de propriedades privadas, declivosas e de difícil acesso. Sendo assim, este trabalho visa realizar um mapeamento participativo com moradores da região para localizar as cavidades naturais subterrâneas e as trilhas antigas situadas na RPPN Fazenda Serra Negra. Para tanto, foi realizada uma oficina participativa na qual os organizadores levaram uma base cartográfica previamente articulada com o inuito de os participantes localizarem cavernas e os caminhos até as cavidades de acordo com os seus conhecimentos locais. Após esse momento, foi realizado um trabalho de campo para averiguar se as grutas e os caminhos apontados pelos participantes são factuais e se os caminhos ainda estão em condições de trânsito para fins exploratórios. Essa técnica será de suma importância para a plena identificação dos elementos geomorfológicos cársticos da RPPN, assim como auxiliar a proprietária na gestão da propriedade.

1. Introduction

A Serra Negra é uma estrutura quartzítica que pertence ao conjunto das Cristas Quartzíticas Festonadas da Mantiqueira Meridional (MARQUES NETO, 2017), que estão inseridas nas cadeias montanhosas da Serra da Mantiqueira, que segundo RICCOMINI (1989), possui sua gênese relacionada ao processo de rifteamento continental do sudeste brasileiro, que soergueu boa parte da fachada atlântica brasileira. A geologia da Serra Negra apresenta quartzitos de granulação grossa, com intercalações de gnaisses e xistos, (ROCHA et al. 2024) estando associada às rochas metamórficas do Grupo Andrelândia (PINTO et al. 1991).

Nesse contexto, desde o começo da década de 90, pesquisas tem versado acerca do fenômeno da carstificação nos quartzitos de Ibitipoca, que partilha do mesmo contexto geológico e espeleológico da Serra Negra. Sendo assim, alguns trabalhos com foco na espeleologia vêm sendo elaborados na Serra Negra, com destaque para UAGODA (2006), que explorou a geomorfologia cárstica do local e identificou inúmeras cavidades na porção da serra pertencente ao município de Rio Preto, além de KHALED et al. (2023), que lista uma base de dados com 43 cavidades localizadas e cadastradas até o ano de 2023.

Um dos objetivos principais deste trabalho é identificar grutas, cavernas e cavidades naturais subterrâneas na RPPN Fazenda Serra Negra (figura 1), utilizando como subsídio a oficina de cartografia participativa. O trabalho também visa contribuir para a base de dados de cavidades naturais subterrâneas e antigos caminhos da Serra Negra, sendo que muitas regiões da RPPN permanecem inexploradas devido à topografia acidentada e à dificuldade de acesso, sendo um trabalho preliminar que utiliza a cartografia participativa para criar bases para levantamentos

exploratórios subsequentes.

Neste contexto, a RPPN Fazenda Serra Negra aparece como uma das áreas prioritárias para estudos prospectivos. A cartografia participativa, técnica utilizada neste trabalho, visa integrar conhecimentos locais às práticas científicas para identificar cavidades naturais subterrâneas e trilhas históricas, fornecendo subsídios para a proprietária executar da forma mais proficiente possível o manejo e a gestão do seu território, resguardando a relevância ambiental e histórica do local.

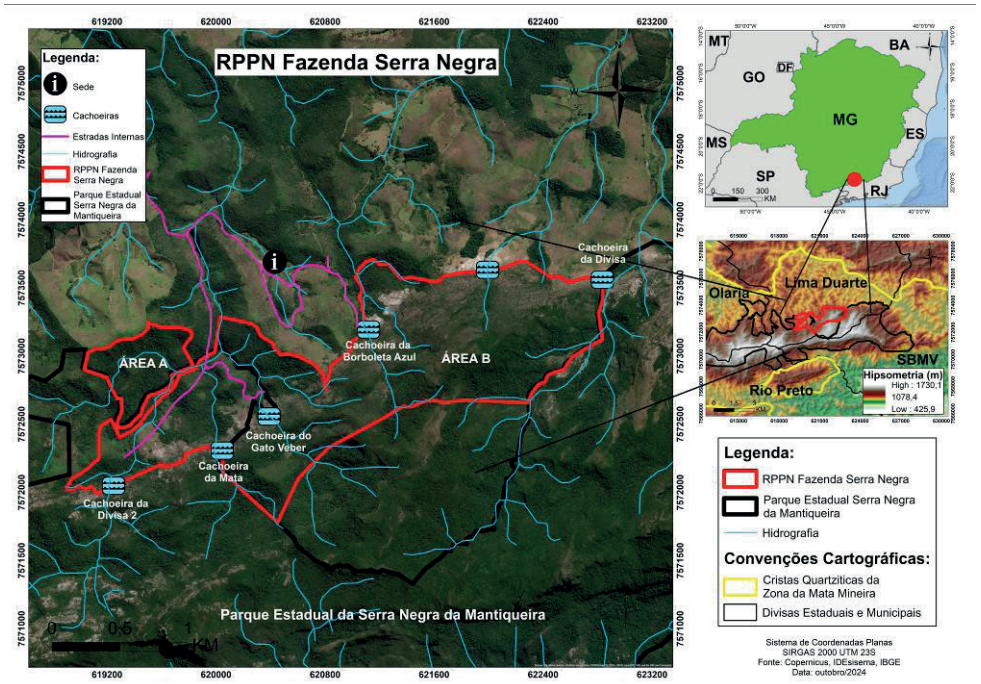

Figura 1: *RPPN Fazenda Serra Negra : base cartográfica levada para a oficina para ser construído um mapa de caráter coletivo. Fonte: Os autores.*

2. Materials and methods

A iniciativa de realizar uma oficina de cartografia participativa para identificação de cavidades naturais subterrâneas e trilhas antigas na RPPN foi levada em consideração devido à topografia acidentada do local, bem como o desconhecimento preciso da localização das feições cársticas e das antigas trilhas de acesso. Sendo assim, o primeiro passo para a realização da oficina foi pensar em uma data para sua realização, e, posteriormente, selecionar, juntamente com a proprietária, os moradores que frequentavam a região da RPPN antes do local se tornar uma reserva, podendo assim ser formalizado o convite para os partícipes de interesse.

Subsequentemente foi confeccionada a base cartográfica para ser levada à oficina, em consonância às propostas metodológicas de DA SILVA & VERBICARO (2016), que detalham a metodologia do mapeamento participativo com imagem de sensoriamento remoto. Esta metodologia é realizada primeiramente com a confecção de uma carta-imagem produzida por meio do cruzamento de dados cartográficos, com as imagens de sensoriamento remoto de boa resolução espacial, a fim de que sejam impressas em formato A1 e levadas à oficina.

Inicialmente, a proprietária forneceu aos organizadores uma planta cadastral da Fazenda Serra Negra que possuía a real demarcação da RPPN, assim como a localização e o nome das cachoeiras do local, as vias internas, e algumas infra estruturas de médio a pequeno porte. A planta cadastral foi georreferenciada no Qgis e levada ao software ArcGIS 10.3, para que essas informações da planta pudessem ser vetorizadas e transformadas em *shapefile* a fim de ajudar na construção da base cartográfica a ser levada na oficina. Somadas a essas informações, o *shapefile* do Parque Estadual da Serra Negra da Mantiqueira foi obtido no site do IDEsisema (https://idesisema.meioambiente.mg.gov.br/webgis).

O modelo digital de elevação foi obtido no site (https://portal.opentopography.org), junto ao satélite Copernicus, da União Europeia, e usado para a elaboração dos mapas de hipsometria. A ferramenta *Hillshade* foi utilizada para a elaboração do relevo sombreado, e a ferramenta *Slope* para gerar o mapa de declividade. Os produtos cartográficos em questão foram levados à oficina em forma de mapa junto das informações da planta cadastral para auxiliar na interpretação.

O Google Earth Pro foi outro software importante para o êxito dos procedimentos, já que todas as camadas selecionadas para estarem na base cartográfica a ser levada à oficina foram exportadas do ArcGIS ao Google Earth Pro a partir da ferramenta *Layer to KML*. O referido software é importante pois permite a visualização do modelo digital de elevação juntamente ao uso e cobertura vegetal da superfície, facilitando a todos os participantes a visualização e a interpretação do mapa e dos elementos propostos a serem identificados.

No âmbito da oficina de cartografia participativa na RPPN Fazenda Serra Negra, após a chegada dos participantes locais, uma roda de conversa foi formada, com a exposição dos mapas ao centro. No início da oficina, foi proposto, juntamente com os participantes locais, a elaboração de uma simbologia, criando uma legenda com diferentes cores para as classes identificadas: linha verde para caminhos e trilhas antigas, ponto marrom para cavernas, grutas e cavidades. A oficina foi dividida em duas partes: uma caminhada para visualização em campo da morfologia de parte da RPPN e uma sessão dedicada à identificação das cavidades e trilhas, utilizando a base cartográfica confeccionada pelos organizadores. O Google Earth Pro foi fundamental para que o grupo e os participantes se localizassem com precisão, correlacionando o mapa à realidade do terreno.

Posteriormente à oficina, já em ambiente de gabinete, os organizadores puderam identificar os locais apontados pelos participantes no mapa da oficina pelo Google Earth com a ajuda da análise remota, podendo assim, reproduzir o mapa feito na oficina em software ArcGIS (figura 2). Subsequentemente, utilizando as imagens de satélite como

ferramenta de análise, as cavidades apontadas pelos participantes da oficina, além de alguns locais da RPPN que aparentam possuir feições cársticas, puderam ser divididos em « *locais com evidências de cavernas no relevo por análise remota* » e « *locais sem evidências de cavernas no relevo por análise remota* », ajudando o grupo à organizar melhor os dados obtidos em oficina. Essa distinção se deve pelo fato de que algumas localidades apontadas pelos participantes não terem sido reconhecidas pelos propositores da oficina a partir das imagens de satélite, carecendo de prospecções futuras.

Ainda, um trabalho de campo foi feito para averiguar a existência dessas grutas e caminhos que foram apontados pelos participantes. O mapa gerado em conjunto com a comunidade foi exportado para o aplicativo Avenza, podendo ser acessada nossa localização em tempo real dentro do mapa. Com auxílio do aplicativo Wikiloc, o percurso realizado foi gravado, e pontos puderam ser marcados.

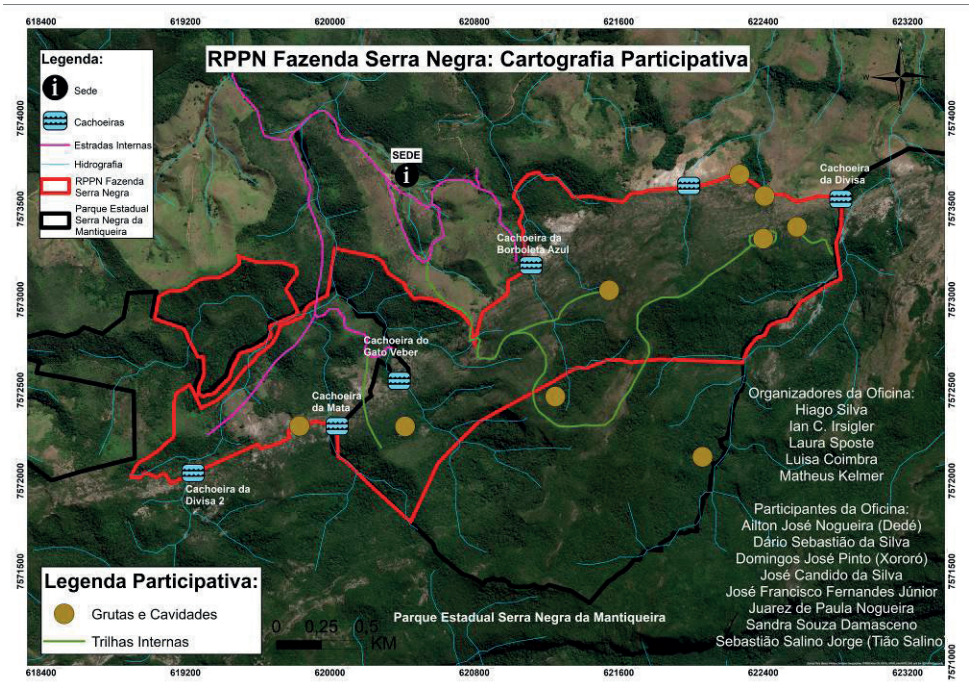

Figure 2: *RPPN Fazenda Serra Negra - Resultado do mapeamento participativo para identifiação de grutas, cavernas e trilhas antigas. Fonte : Os autores e os participantes da oficina.*

3. Results

No decorrer da oficina, os moradores relataram as mudanças ocorridas nas terras do parque, da RPPN e adjacências ao longo das últimas cinco décadas, destacando que a criação da RPPN Fazenda Serra Negra contribuiu para a preservação da biodiversidade local, com a restauração da vegetação original. Durante a visualização dos mapas, os locais deliberaram entre si sobre quais áreas eles consideravam pertencentes a RPPN Fazenda Serra Negra, e puderam visualizar a real delimitação da RPPN pelo mapa que os organizadores levaram.

Seguindo a oficina, foram mostradas as cachoeiras da reserva no mapa de localização. Assim, os participantes recapitularam através de suas memórias, suas andanças por essa área no passado e relataram a existência de grutas na área. As cachoeiras foram pontos referenciais importantes para os moradores da comunidade local se situarem no mapa a partir de locais que eles conhecem na realidade, e a partir do relato dos participantes, descobriu-se que a cachoeira do Gato Veber, é popularmente conhecida como cachoeira do Barrinho. Uma gamela (alto topográfico), foi apontada no topo da Serra Negra, a montante da cachoeira do Gato Veber (Barrinho), e que se situa no topo da Serra Negra, no divisor das águas que drenam para vertente norte, e águas que drenam para a vertente sul da serra, ficando situada no topo da Serra Negra próximo às RPPN's adjacentes. Ao todo, foram identificadas na oficina nove cavidades naturais subterrâneas (figura 2).

Uma possível gruta (Toca do Barrinho) foi identificada subindo a serra pela drenagem acima da cachoeira do Gato Veber (Barrinho), que evidencia na imagem de satélite diversos paredões rochosos, sendo assim presumível a existência de cavidades, porém não no local indicado pelos participantes. Uma outra cavidade foi identificada no talude situado entre a cachoeira da Mata e a cachoeira da Divisa 2, havendo pouca evidência no relevo da própria, mas tendo sido relatada por um dos participantes como sendo um abrigo.

No topo da RPPN há um reduto de mata fechada, onde foi relatada a existência de uma ou mais grutas, tendo sido apontada por "Tião Salino" a localização aproximada dela. No mesmo contexto florestal foi relatada a existência de uma árvore enorme que é utilizada por caçadores para descanso, sendo um marco referencial importante para a RPPN. O fato de ser um local de reduto de mata fechada dificulta a visualização com base nas imagens de satélite do Google Earth.

Uma outra cavidade apontada pelos participantes se localiza em zona de cabeceiras de sistemas de drenagem local, de onde é possível avistar a sede da RPPN, e que apresenta uma expressão morfológica de afloramentos e taludes rochosos. A gruta apontada, observada da sede da RPPN, aparenta se tratar de uma expressiva cavidade natural na forma de uma dolina de dissolução em encosta, a exemplo do que foi encontrado por UAGODA (2006), sendo o local de mais fácil acesso a partir da RPPN entre aqueles relatados. Sendo assim, o local em questão foi alvo da primeira campanha de campo, tendo sido encontradas algumas cavidades, inclusive uma pequena gruta denominada de FSN01 (figura 3). Ainda, na medida que os participantes iam externando os conhecimentos acerca das feições cársticas, sincronicamente informavam sobre os acessos às localidades relatadas, tendo sido apontado um caminho que atravessa a serra horizontalmente pela parte central da vertente, caminho esse que dá acesso a gruta FSN01 citada acima. A antiga trilha

mostrou um grau de dificuldade considerado difícil pelos participantes da expedição, já que, em muitos pontos, a mesma pôde ser identificada. No entanto, na maioria dos pontos, foi observado que a vegetação estava se regenerando, uma vez que poucas pessoas caminharam pela área após ela se tornar RPPN. Além disso, a Serra Negra possui uma área de topografia acidentada, o que dificulta a realização de prospecções, justificando a necessidade do trabalho.

Já perto da divisa leste da RPPN, foi relatado a existência de quatro cavidades. Duas situadas no pé da serra, já no setor intermontano, e duas situadas na zona interfluvial, havendo bastante evidências no relevo a partir das imagens de satélite, já que morfologias de dolina foram identificadas pelo Google Earth. Uma dessas duas grutas do topo da serra, foram reconhecidas como "Gruta do Mata Cachorro", "pelo fato de cachorros já terem caído dentro da cavidade e precisarem de ajuda para ser retirados de lá" e a partir do relato de "Tião Salino", "houve um homem que morou por muito tempo em alguma gruta do topo da RPPN para fugir da polícia. O rapaz fez uma espécie de grades e portas de bambu para fechar a entrada da gruta e se proteger das onças (*Puma concolor*), que possuem forte presença na região. Ele se alimentava basicamente de palmito (muito comum na região) e recolhia sal nos cochos de gado.» Se a existência dessas cavidades nos limites interfluviais for confirmada, as cavidades intermontanas (que estão alinhadas com as grutas do topo) podem se tratar do mesmo eixo de dissolução na condição de ressurgência das cavidades interfluviais.

Por fim, para chegar a essas grutas dos limites interfluviais da RPPN, foi apontado um caminho principal que liga a sede da RPPN ao topo da estrutura quartzítica que permeia a RPPN Fazenda Serra Negra, fazendo um percurso pelos limites interfluviais da serra até as grutas do topo. Esse caminho pode ser comparado aos caminhos de cavaleiros que MENCK (2023) propôs, na qual são antigos caminhos que sobem a Serra Negra pela face norte ou pela face sul, e que estruturam a rede de caminhos antigos como um todo. Um outro percurso relatado para chegar a essas grutas dos limites interfluviais remete à subida da crista por um caminho que parte da porção à montante da cachoeira da Divisa 2, e onde é dispersada uma drenagem perene a partir do topo, tendo sido ainda relatada a presença de uma pequena cavidade ao lado do rio, mas provavelmente fora da RPPN.

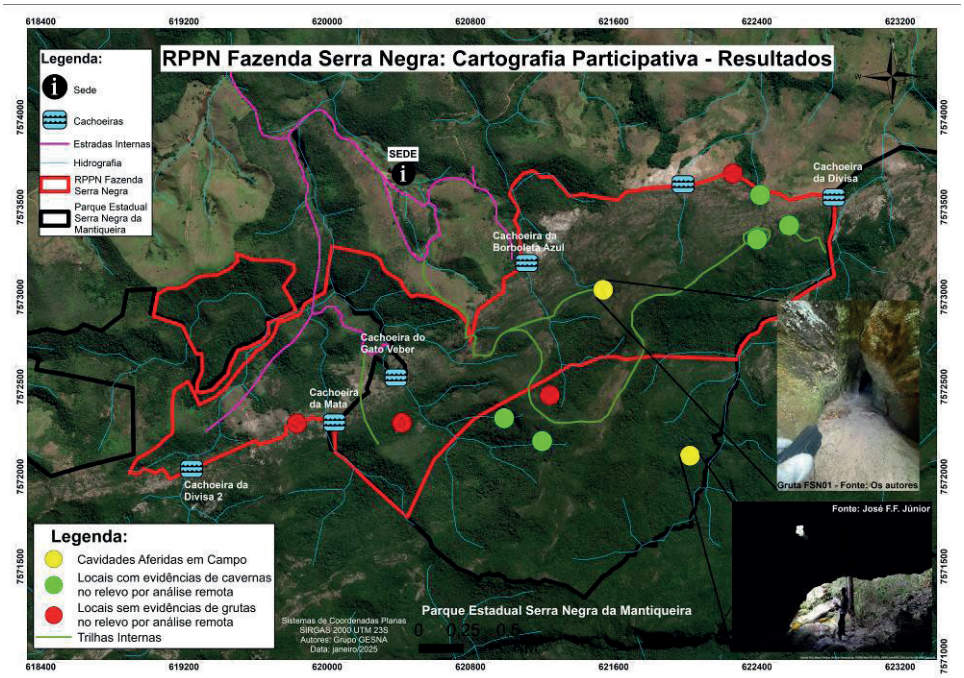

Figure 3: *RPPN Fazenda Serra Negra - Resultado do mapa feito oficina pós tratamento. Fonte : Os autores.*

4. Discussion

O conhecimento popular repassado durante a oficina na RPPN das feições cársticas presentes no local foi de suma importância para a elaboração do planejamento em campo, com foco nas grutas demarcadas e representadas no mapa pelos participantes. Considerando que o grupo propositor não possui um grande conhecimento dos atrativos da RPPN, os caminhos recomendados durante a atividade foram seguidos em campo. A realização dessa oficina permitiu que os organizadores tivessem maior contato com os moradores locais, estabelecendo laços iniciais importantes para futuras pesquisas e para a consolidação das conversas sobre as cavidades da região, que em grande número ainda não localizadas e cadastradas por pesquisadores atuantes na área.

A oficina de cartografia participativa se mostrou bastante eficiente para identificar e localizar cavidades em um local determinado, para o qual foi organizada uma expedição de campo. Entretanto, alguns desafios foram notados diante da realização da atividade, como por exemplo, a diferença terminológica entre o grupo organizador e os moradores da comunidade local. Para os moradores, as cavernas são morfologias muito comuns, algumas vezes sendo mencionadas como "tocas", até mesmo havendo dificuldade em reconhecer as cavidades pelo nome de "grutas e cavernas", sublinhando as diferenças entre termos técnicos e termos populares que procedimentos de troca de saberes procuram convergir.

Entre a cachoeira do Gato Véber e a cachoeira da Borboleta Azul, se situa um dos principais caminhos apontados pelos moradores, pelo qual foi localizada uma gruta, denominada por FSN01. Também foram identificados dois pequenos abrigos e uma pequena fenda no talude. Essas cavidades são morfologias associadas à dissolução química e a processos físicos do quartzito, condições essas que favorecem a formação das feições cársticas, pelas quais a alteração das juntas e abertura de condutos é seguida de processos de desplacamento e queda contribuindo com sua evolução. Sendo assim, a partir da amostragem de cavidades em um local visitado, presume-se que a RPPN Fazenda Serra Negra possa ter as nove cavidades naturais subterrâneas apontadas pelos

participantes, ou até mais do que isso.

Ainda, se os vestígios de ocupação humana forem confirmados nas grutas dos limites interfluviais da RPPN, o local se torna um importante sítio para estudos arqueológicos, já que a partir dos relatos dos participantes da oficina, existiu um homem que morava dentro de uma dessas cavidades e alterou a entrada da gruta para servir a fins próprios de moradia e proteção, contribuindo com os levantamentos arqueológicos em cavidades naturais subterrâneas na Serra Negra e região, já abordados por KHALED et al. (2023) em levantamentos pretéritos. A oficina de cartografia participativa se mostrou eficiente, portanto, no levantamento de dados arqueológicos e históricos utilizando as memórias culturais dos participantes, que preservam suas memórias através do tempo e relembram de eventos que se passavam em outras épocas, já não mais compatíveis com os costumes da atualidade.

5. Conclusion

Os resultados obtidos apontam que a área possui um enorme potencial espeleológico, tendo sido constatado em campo o que foi apontado na oficina, junto aos participantes. A ida a campo possibilitou o reconhecimento de uma gruta e algumas cavidades. Contudo, devido ao elevado grau de dificuldade para acessar o interior da RPPN em função da vegetação densa e da declividade do terreno, novas expedições se fazem necessárias para uma análise mais abrangente da área, o que poderá auxiliar a proprietária na compreensão e assimilação dos atrativos de sua propriedade. Dessa forma, os resultados dão respaldo aos proprietários e gestores na cobrança junto aos órgãos competentes por uma maior rigidez na geoconservação do patrimônio, que já sofreu intervenções físicas de caçadores e peregrinos que por ali circularam (ou ainda circulam), exercendo a prática ilegal da caça de animais silvestres.

No que tange aos resultados obtidos durante a oficina com os moradores locais, o mapa gerado deu conta de representar os grandes atrativos espeleológicos apontados pelos participantes e trazendo os conhecimentos tradicionais para o plano cartográfico. O sucesso da primeira expedição está diretamente ligado ao êxito da oficina e aos saberes dos participantes, pois a área escolhida foi descrita pelos locais durante a oficina com riqueza e precisão de detalhes, o que possibilitou o reconhecimento da gruta mencionada e visitada em campo durante a confecção do mapa participativo.

Por fim, os resultados obtidos confirmam a premissa de que o conhecimento popular tradicional alinhado ao saber científico pode gerar novos conhecimentos para fins de aproveitamento mútuo, aprofundando os estudos das formações cársticas em quartizito da região e fomentando a preservação e valorização dos saberes tradicionais, que remontam há décadas e que através da oralidade e exercício de suas memórias e vivências foram de suma importância para o avanço científico e para reafirmar entre os partícipes a importância da conservação de seu patrimônio ambiental.

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Expedition to new hypogenic caves in Northern Namibia

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Abstract

Since the early 1990s, the Association for Speleology in Upper Styria, Bad Mitterndorf, Austria has repeatedly set off on expeditions to Namibia. In 2016, research in the Otavibergland gained momentum again with the rediscovery of the hypogene cave "Blowing Hole". In 2020, cooperation with the University of Innsbruck began and a preliminary joint research trip in 2022 was followed by a longer expedition which took place in spring 2023. Large entrances in the remote Kaokoveld region found by plane during a preliminary expedition in 2018 were examined and surveyed. Following a brief overview of the landscape and caves exploration history in the Otavibergland and Kaokoveld of Namibia, we describe the 2023 expedition, its speleological results as far as already available. In all, 14 caves were explored for a combined total of 1 400 m surveyed, with the largest Omuhako yielding a length of 505 m and depth of 54 m. The observed forms of hypogenic cave formation are discussed. Systematic cave documentation allowed the beginning of a cadastre for Namibian caves to be created.

1. Introduction

Namibia is one of the least densely populated countries in the world and one of the most arid. Perennially running rivers are confined the borders of the country, for instance the Orange and Kunene rivers at the South-African and Angolan borders, respectively. The Kaokoveld area is located in the north-western corner of the country, in the Kunene region between the towns of Opuwo and Sesfontein (Fig. 1). The Otavi mountains are located between the towns of Otavi and Tsumeb, at the border between the Oshikoto and Otjozondjupa regions.

The geological makeup of the Kaokoveld and Otavi mountain land were extracted from the 1:25 000 maps provided by the Geological Survey of Namibia (MILLER, 2008). In the north-western part of the country are extensive outcrops of karstified carbonate rocks, forming an arc-shaped mountainous region known as the Otavi fold belt (GOSCOMBE et al., 2005). In the northern limb of this mountain belt forming the bulk of the Kaokoveld, the main carbonate sequences are represented by the Maierberg formation, which corresponds to a post-glaciation single deposition event (HOFFMAN et al., 1998). During the late Proterozoic period, before hard-shelled organisms began to appear in the fossil record, the characteristic reef-building organisms were cyanobacteria, forming organo-sedimentary structures called stromatolites. These organisms build laminated growth structures (finely laminated, pillar shapes, cusps, etc.) and the sedimentary fabrics visible in the field arise as a result of sediment trapping and binding by organic mats. The well bedded platform carbonates of the Elandsoek and Hüttenberg formations are mainly comprised of 1-m scale sedimentary cycles (HOFFMAN et al., 2021a). The collective thickness of these units varies between 0.75 km in the Kaoko belt and 2.5 km in the Otavi Mountain Land. The Elandsoek and Hüttenberg formations mostly comprise a succession of grainstones and mostly silicified ribbonites, which are facies of made of laterally linked stromatolite structures (Fig. 2b). These horizons are easily distinguished in the field, owing to the preferential silicification giving them a characteristic buff colour, in contrast to the surrounding light grey limestone. Many caves explored during the expedition, especially the ones located on the westernmost ridges of the Kaoko belt are developed within either the Elandshoek or the Hüttenberg formations.

Despite the extensive exposure of carbonate rocks in the eastern part of the Kaoko Belt, epigene karst is little developed to absent, as a result of the very arid climate (Fig. 2a). Subsurface karst expressions under the form of large chambers (the Orumana sinkhole or Omuhako main chamber for instance) are present, however, testifying to locally intense dissolution. The currently accepted speleogenetic model for these cavities was first put forward by MARTINI et al. (1999). Based on several years exploring the region, the authors recognised the hypogenic origin of many of the caves found in the region. The speleogenetic origin rests on several key observations (MARTINI & MARAIS, 2002):

- absence of surface karst morphologies at mega-scale, i.e., no dolines, no blind valleys, dendritic valley networks
- absence of relationship between the surface drainage and cave entrance location (for instance, the Orumana sinkhole)
- presence of key morphologic indicators within the caves, upwards terminating alcoves, niches, cupolas, e.g. at Temple of Doom cave
- presence of low salinity and low temperature calcite spar, and baryte in one cave (Temple of Doom)

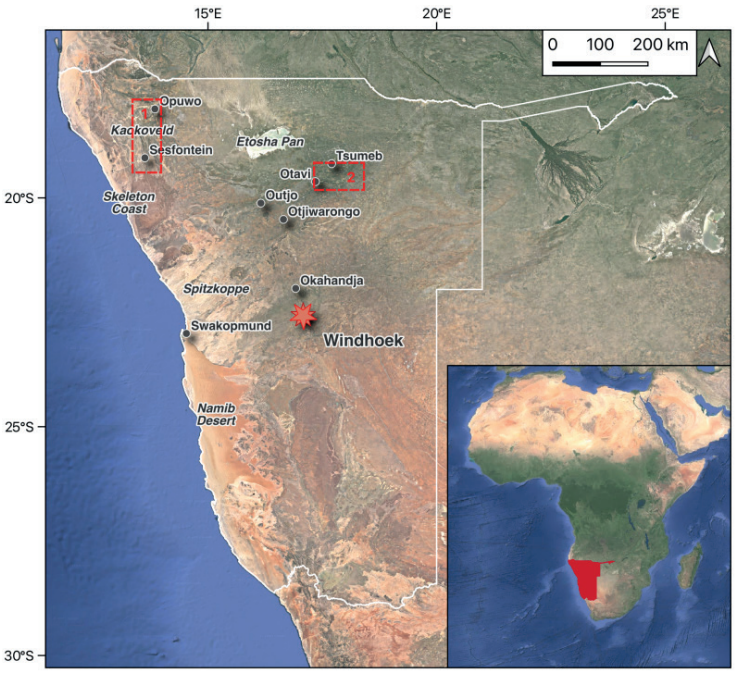

Figure 1: *Map of Namibia and caving areas visited: 1) Kaokoveld, 2) Otavi Mountains. © Google Satellite 2023.*

2. Prior explorations

Exploration of the caves in the Otavi mountains has a history spanning a little more than a century (WOLF, 1992; JEUTTER et al., 1998; JEUTTER et al., 2015). However, in the Kaokoveld area, pioneering cave explorations were primarily led by SWAKNO (Suid Wes Afrika Karst Navorsing organisasie), a Windhoek-based scientific-oriented caving association. Beginning in the early 90's, under the leadership of Eugene Marais, and other members like Jaques Martini and John Irish, the group used aerial photography and stereoscopy to identify caving prospects of Kaokoveld. This led them to find the major sinkholes later named Orumana and Parakietgat. SWAKNO led further cave expeditions over Namibia in the following years, but the next visit to Kaokoland took place in 1994. The group explored various other significant sinkholes: Columbarium, Arboretum and Hermitage caves. A striking finding at the time was Temple of Doom cave, significant for its hypogene solutional morphology and baryte deposits, as well as descending the 130 m deep Wow Gdoom pothole. The latter is one of the deepest caves in the country and the deepest in Kaokoveld. More recently, two expeditions were carried out in Kaokoveld 2015 and 2018 by members of the Gloucester Speleological Club, led by Mark Tringham, in cooperation with the Integrated Rural Development and Nature Conservation (IRDNC). These expeditions to Kaokoveld were mounted on the hope of finding systems with extensive horizontal development in formations equivalent to those known elsewhere in the country where the major cave systems of Dragon's breath and Arnheim had been discovered. Over the course of those two expeditions, the team used satellite imagery, documented 1.1 km of new cave passages in 23 caves. The two most significant findings with respect to length were Ondimba ja Omungongo (358 m) and Oktjakateta (138 m).

The 2023 expedition to the Kaokoveld area aimed at precisely locating and reaching the entrances located in 2018 during an aerial survey conducted by André Schoeman and Peter Jeutter. The flight over the Kaokoveld range focussed foremost on a N-S oriented series of carbonate outcrops spanning 18.5°S to 19° S, from Sesfontein in the South, and Omuhiva in the North. This allowed two dozen potential entrances seen from the air to be roughly located. Since these entrances could only be reached by driving gravel roads, then by hiking across country, the teams travelled up to Kaokoveld in 4x4 drive vehicles. The main expedition objectives for this area were to explore and map the caves reached, producing high standard plans, elevation views, as well as extensive photo documentation. The main speleological results of this 2023 expedition are presented hereafter.

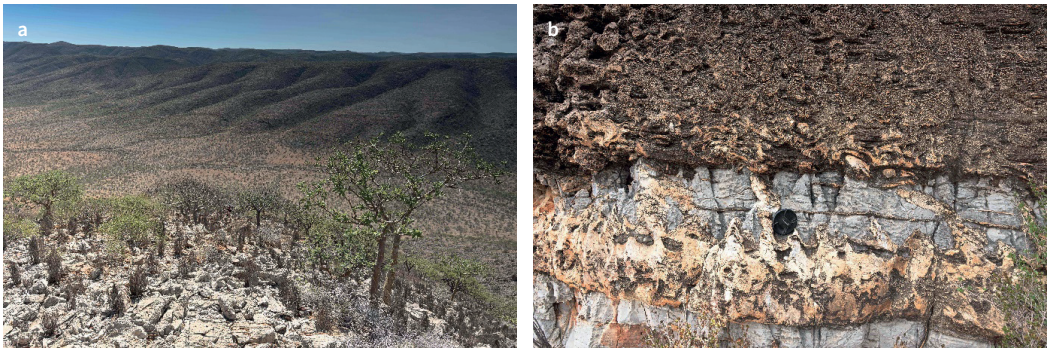

Figure 2: *a) absence of surface karst and dendritic valley networks on carbonate bedrock in the valley between Sesfontein and the village of Otjikondavirongo, b) outcrop of stromatolitic limestone of the Elandsoek formation, camera lens cap for scale. © Tanguy Racine.*

3. Results

The summary of total surveyed passage for the 2023 Namibia expedition is given in Table 1. Of the 26 entrances located during the reconnaissance flight, only 5 could be visited due to access constraints. In total, over 1400 m of passages were surveyed in caves of varying dimensions, though none was larger than Omuhako cave (505 m surveyed), or deeper than the already explored Wow Gdoom pot. Two large portals were revisited by drone to confirm their general dimensions but on balance were deemed to remote to investigate during the 2023 expedition. All new caves were added to a dedicated page on the Spelix database containing all other known and surveyed caves of Namibia.

Along the N-S oriented westernmost outcrop of Elandsoek and Hüttenberg formations, three key sites were surveyed and are described below. The largest (Omuhako cave) was found by local shepherd: its entrance is obscured by an eponymous tree. A short series of shafts drops into the large, main chamber of the cave. Two branches with abundant epigenetic speleothems (Fig. 4a) lead off to the north and south, according to the strike of the steeply dipping limestone strata. Some flowstones are several metres thick. Collaroid growths were observed on almost all of the other speleothems present. As the cave was home to a bat roost with several dozen individuals at the time of exploration, m-thick guano deposits are abundant and ubiquitous. The deepest pit surveyed is Starling shaft, at 68 m depth, the only cave where a pool of standing water could be observed. The cave of Three Guardians (Fig. 3) shares many of the same characteristics, in that a) the main passage development guided along the N-S strike of the Elandsoek / Hüttenberg formations, b) the cave geometry is a single pit leading to guano floored passages, home to bat roosts, c) epigene speleothems like stalactites, flowstones and stalagmites have developed, but do not appear to be active at present, d) their location, size and orientation does not match any surface expression of epigene karstification, but appears to be lithologically controlled. Hydrological activity in these caves seems to be controlled by infiltration and fracture flow, but at the time of the visit, the water balance precluded any active drips from being spotted. Perhaps one of the more peculiar findings of the 2023 is the short cave named Jeweller's chamber. After a 4 km hike in a dry canyon north of the Sesfontein settlement, a small downclimb from the entrance yields access to the cave's only chamber. Two generation of speleothems could be observed. The first are exposed in the lower part of the chamber, and are comprised of scalenohedral calcite crystals ranging from 5-10 cm in size (Fig. 4b). The second, directly overlying the first are massive flowstone deposits of epigene origin, associated with arrays of stalactites and stalagmites. The far side of the chamber is made up of an ascending chimney home to a bat roost.

In the Otavi mountain land, the Blowing Hole, which was re-located and surveyed on the Nosib/Atoon back in 2016 farm had also been equipped with temperature data loggers. Explorations at depth greater than 45 m require the use of additional oxygen (JEUTTER et al., 2023). Upon retrieval of these loggers in 2023, some 130 m of new continuing cave were surveyed at a depth of 30-35 m. This series of passages is heavily imprinted by epigene speleothems. The general morphology of the cave is undulose and overprinted by cupolas. These morphologies bear no relation to the lithological makeup of the host rock, having dissolved equally the massive limestone but also the mega-breccia bedrock.

Cave name	Length *(new)* (m)	Depth (m)	Altitude (m asl)
Omuhako Cave	505 *(505)*	54	1452
Cave of the Three Guardians	145 *(145)*	47	1483
Gecko Canyon Motel	13 *(13)*	1	918
Jeweller's Chamber	41 *(41)*	19	1037
Dwarfbeak Cave	17 *(17)*	8	1406
The Pigeonhole	15 *(15)*	10	1415
Starling Shaft	135 *(135)*	68	1459
Orutura Cave	23 *(23)*	2	1480
Blowing Hole (Nosib/Atoom)	415 *(130)*	62	1465
Porcupine Cave	85 *(85)*	8	1397
Leopard Cave	26 *(26)*	6	1434
Himba Village Cave	65 *(65)*	13	1405
Parrot Portal caves 1+2	150 *(150)*	40	938
Khoekhoe-kai//om Cave	80 *(80)*	25	1519
Total	*1430*		

Table 1: *Length and depth of passages newly surveyed during the Namibia 2023 expedition*

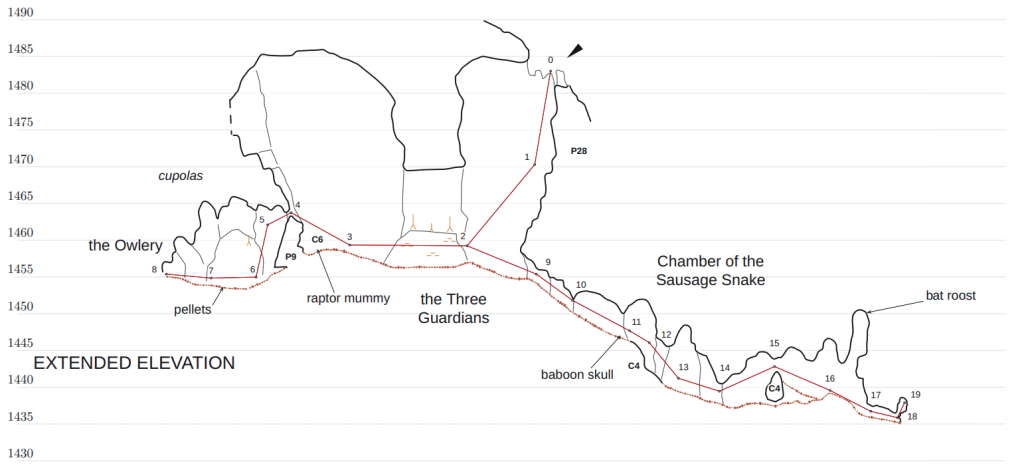

Figure 3: *Extended profile of Three Guardians cave, highlighting the general morphology of the ceiling.*

4. Discussion

The speleogenetic clues for the hypogene origin of the caves explored are of a morphological nature. At macroscale, we only observed lithologically controlled, isolated cavities, with no obvious signs of epigenetic water flow (tubes, shafts, tree-like or branching network organisation). There appears to be a total lack of relation between the cave entrance location and local topography or drainage. No surface karst features were noted in the Kaokofeld: entrances are linked to mechanical collapse features. The Omungongo cave was described as having a complex 3-dimensional maze of dry passages of phreatic origin, upwards terminating passages and successions of dome-like chambers (TRINGHAM, 2015). For comparison, during the 2023 expedition, phreatic mazes were observed in two parts of Omuhako cave in the north and west, at depths between 45 and 50 m. Upwards terminating chimneys or cupola-like morphologies were found in the cave of the Three Guardians, for instance in the Owlery and in the deeper sections. Although no evidence of water flow was recorded in the Kaokoveld caves, epigenetic karst development certainly played and continues to play a role in the recent history of these caves, as demonstrated by the abundance of speleothems linked to the fracture networks along which preferential recharge occurs. The detailed observations of sequences of speleothem deposition and concomitant sedimentation in the cave of the Otavi mountain land contrast these findings, because they suggest that active water flow played a role in deposition and removal of sediment from somewhat far flung sources. We also note the likely overprint of original dissolution morphologies by biocorrosion. In many places, ascending, blind chimneys are actively occupied by bat roosts, and thick accumulations of guano are present on the floors, while some speleothems have a corroded surface suggesting that they are imprinted by biocorrosion. In this, the speleological findings of the 2015, 2018 and 2023 cave expeditions to Namibia agree with the model of hypogene origin for the caves of Northern Namibia (MARTINI et al. 2002).

With respect to caving potential, entrances to the caves often result from the collapse of large underground chambers. Elsewhere in the piedmont of the Otavi mountains are several cenotes (for instance Guinas Lake) which formed by the collapse of subaqueous chambers (MARTINI, 1991; JEUTTER et al., 1996). The famous Dragon's Breath cave is one example where the chamber's ceiling is still preserved (JEUTTER, 1996) This is also the case in three of the caves explored in the Kaokoveld and presented above. However, since those caves open at higher elevation, guano deposits prevented access deep enough to reach the water table.

Figure 4: *a) abundant speleothems in and fine reddish sediment fill Martian Chamber in Omuhako cave, b) calcite crystals from Jeweller's chamber, © Tanguy Racine.*

5. Conclusion

In the Kaokoveld there remain several cave entrances known to the local people which were not yet investigated. The general cave morphologies suggest that even small entrances may lead to bigger caverns. Horizontal cave development is not well developed, and is usually limited to small sections of phreatic mazes on the outskirts of larger chambers. Although there is potential in theory for > 400 m deep caves between the hillcrests where carbonates outcrop and the altitude of perennial springs, breakdown features and guano deposits usually close up the cave passages before they reach a great depth. The deepest cave in the area remains the Wow Gdoom pot at a depth of 130 m.

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Uso de sensor LiDAR como ferramenta para otimização de prospecção espeleológica em áreas remotas

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Resumo

Em busca de novas técnicas que auxiliem a execução de trabalhos de prospecção em áreas remotas, foi conduzido pela Brandt Meio Ambiente e pela Vale S.A um projeto piloto que contou com dados obtidos por um perfilamento a laser, executado por aeronave tripulada, na etapa de planejamento de campo. A partir destas informações, de precisão centimétrica, foi construído um modelo preditivo relacionado ao potencial espeleológico da área proposta a instalação de PDE N5 Sudeste, que orientou as tomadas de decisão durante a prospecção espeleológica. Da mesma forma, tal planejamento foi conduzido utilizando-se de dados secundários em escala regional, para fins comparativos. Em ambos os casos, foi elaborada uma amostragem com a mesma extensão, considerando os resultados da avaliação de potencial e as particularidades paisagísticas da área de estudo. Após o trabalho de campo, observou-se uma efetividade significativamente superior quando utilizadas as informações obtidas pelo sensor LiDAR, que resultou em uma amostragem final de 44 km e 75 cavidades identificadas.

Abstract

Use of LiDAR sensor as a tool for optimizing speleological prospecting in remote areas. In search of new techniques to assist in the speleological prospecting in remote areas, Brandt Meio Ambiente and Vale S.A. conducted a pilot project that included data obtained by laser profiling, performed by a manned aircraft, in the field planning stage. Based on this information, with centimeter precision, a predictive model related to the speleological potential of the area proposed for the installation of PDE N5 Sudeste was constructed, which guided decision-making during the speleological prospecting. Likewise, this planning was conducted using secondary data on a regional scale, for comparative purposes. In both cases, a track with the same extension was prepared, considering the results of the potential assessment and the landscape particularities of the study area. After the field work, significantly higher effectiveness was observed when using the information obtained by the LiDAR sensor, which resulted in a final sample of 44 km and 75 new caves.

1. Introdução

A prospecção espeleológica é, comumente, a primeira iniciativa adotada por uma equipe de trabalho que tem como objetivo investigar uma determinada área em busca de cavidades. Ela deve ser, preferencialmente, precedida por um estudo de gabinete, como uma avaliação de potencial espeleológico, que utiliza dados secundários como fonte para a construção de modelos preditivos capazes de orientar as iniciativas das equipes de campo, aumentando assim a assertividade e consequentemente a produtividade do trabalho. Porém, a disponibilidade de dados secundários de boa qualidade, que possibilitem a condução de um bom planejamento, não é uma realidade no Brasil. Informações relacionadas a geologia, geomorfologia, hidrografia, uso e ocupação dos solos, dentre outras, são geralmente construídas em escala regional pelos órgãos governamentais competentes ou até mesmo pelas universidades. O emprego destes dados em avaliações cujo o objeto tem uma abrangência local, reduzem muito a qualidade da avaliação de potencial, tornando-a genérica e pouco eficaz. Assim, como alternativa a utilização de informações inadequadas ao planejamento de estudos de prospecção em áreas com abrangência local, foi proposto pela Brandt Meio Ambiente e pela Vale S.A a realização de um ensaio técnico na área proposta à instalação de pilha de deposição de estéril (PDE) N5 Sudeste, que contou com a execução de um sobrevoo de aeronave tripulada embarcada com um sensor LiDAR RIEGL LMS-Q780 e uma câmera RGB, com o objetivo de produzir bases de alta precisão que permitam um bom planejamento de campo. Para a área em questão, foi obtida uma nuvem de pontos que permitiu a construção de um modelo digital de terreno (MDT) e um modelo digital de superfície (MDS), ambos com resolução espacial de 10 cm ou 0,1 m. Além disso, foi obtido um mosaico de ortofotos, de mesma resolução espacial. Estes dados foram tratados e utilizados como referência na condução dos estudos de campo, cujos resultados serão apresentados neste trabalho.

A área proposta a instalação da PDE N5 Sudeste está localizada no Complexo Minerador de Serra Norte, inserido no município de Parauapebas, região sudeste do estado do Pará, Brasil (Fig. 1).

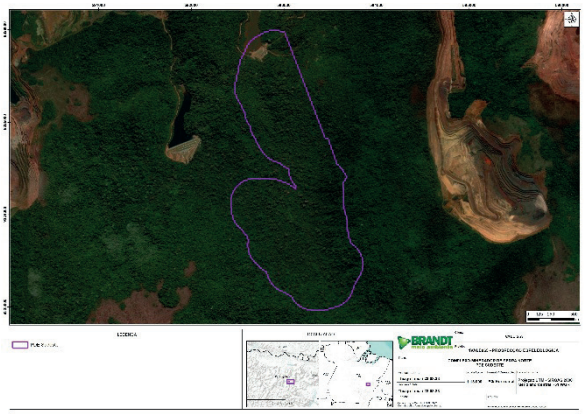

Figura 1: *Localização da área proposta a instalação da PDE N5 Sudeste.*

2. Materiais e métodos

O sobrevoo da área proposta a instalação da PDE N5 Sudeste foi realizado em 31 de maio de 2023 com o uso de um sensor LiDAR RIEGL LMS-Q780, embarcado em um avião Embraer Seneca III prefixo PT-VBA homologada para SAE – Serviços Aéreos Especializados e certificada pela ANAC através do SEGVOO 001 número H20-1517-0 para sensores digitais e laser aerotransportado (Fig. 2).

Figura 2: *Aeronave Embraer Seneca III.*

O *laser scanner* RIEGL LMS-Q780 (Fig. 3) é capaz de realizar até 266.000 coletas por segundo em relação à superfície alvo e opera a uma altitude máxima de 4.572 metros. Seu processamento em múltiplos intervalos de tempo (MTA – *Multiple Time-Around Processing*), a digitalização por eco e a análise a partir de diferentes formas de ondas é ideal para uma operação com amplas variações altimétricas, tornando o RIEGL LMS-Q780 o equipamento adequado para a execução de levantamentos em áreas de relevo complexo.

Figura 3: *RIEGL LMS Q780.*

Após o recebimento da área proposta para este estudo, a equipe responsável pelo levantamento definiu o plano de voo para a execução do perfilamento a laser. Após o voo, todos os dados foram tratados em *softwares* de modelagem específicos – permitindo a produção de modelos da superfície e do terreno local (MDS e MDT).

Tais produtos subsidiaram a realização das análises preditivas apresentadas neste trabalho, permitindo avaliações com foco na declividade das vertentes (Fig. 4), na forma das escarpas locais, a presença ou não de depósitos de tálus e a existência de trilhas em meio a floresta ombrófila. Todos os produtos cartográficos foram elaborados utilizando *softwares* como o ARCGis PRO, da ESRI e o *Cloud Compare* V2.13.1 (Kharkiv – Mar 20, 2024).

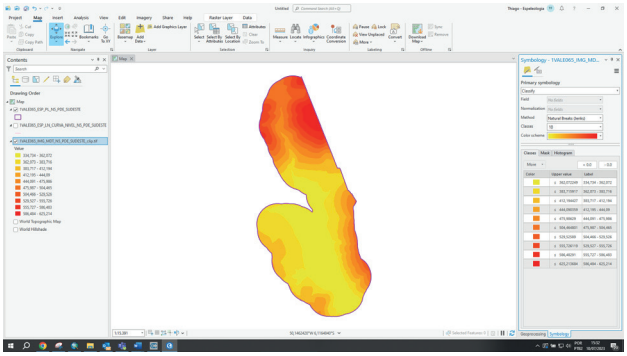

Figura 4: *Declividade das vertentes locais.*

3. Resultados

O sobrevoo executado na área proposta à instalação da PDE N5 Sudeste resultou na aquisição de uma nuvem de pontos colorizada em RGB e a um conjunto de imagens posteriormente ortoretificadas (Fig. 5).

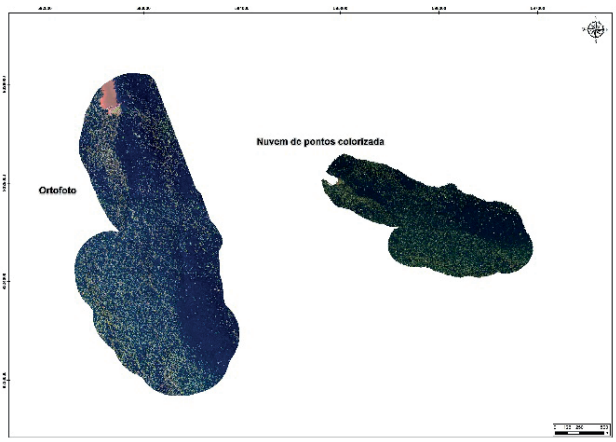

Figura 5: *Ortofoto e nuvem de pontos colorizada em RGB.*

A partir destas informações, foram produzidas bases que permitiram uma análise paisagística integrada que subsidiou o planejamento das atividades de prospecção. Dentre estes produtos, destacam-se: modelo digital de terreno (MDT) (Fig. 6), modelo digital de superfície (MDS), declividade do terreno, hidrografia e curvas de nível com equidistância de um metro.

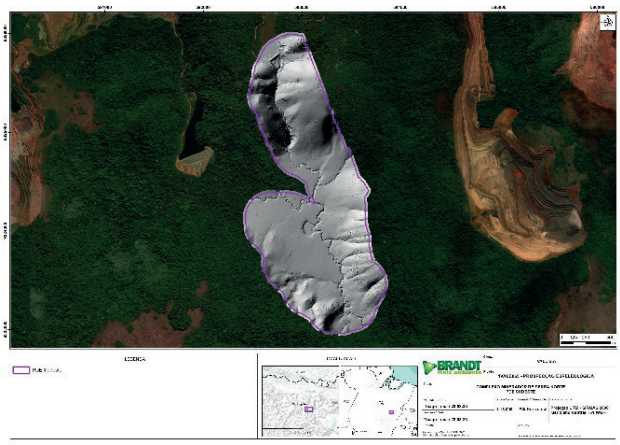

Figura 6: *MDT com filtro hillshade da área proposta a instalação da PDE N5 Sudeste.*

As investidas de campo foram planejadas com base no mapa de potencial espeleológico multicritério, elaborado a partir de uma álgebra de mapas conduzida no *software* ArcGIS PRO, da ESRI. Os atributos da paisagem local que alimentaram esta avaliação foram: geologia, hidrografia, pedologia, uso e ocupação do solo e declividade do relevo. Ressalta-se que parte destes atributos foram mapeados de forma primária pela equipe técnica da Brandt, o que evitou o *input* de informações representadas em uma escala inadequada para esta análise. Assim, com os resultados da avaliação de potencial espeleológico em mãos (Fig. 7), foi possível priorizar, em campo, porções da área de estudo cuja vocação para a ocorrência de cavernas era apontada como alta.

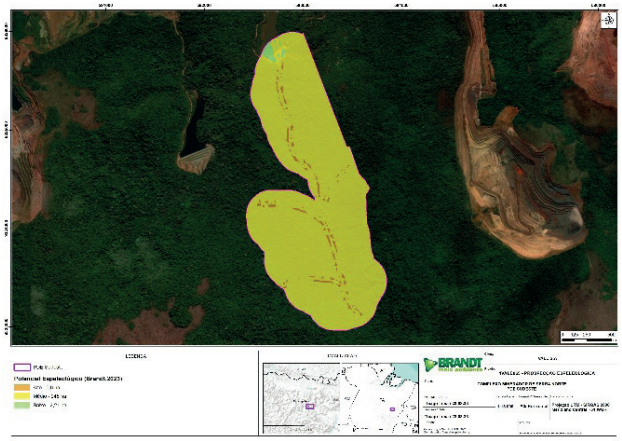

Figura 7: *Mapa de potencial espeleológico da PDE N5 Sudeste.*

A prospecção espeleológica da área proposta a instalação da PDE N5 Sudeste foi executada por uma equipe de campo no período de 05 de agosto a 22 de setembro de 2023. Quando consolidados os caminhamentos realizados, obteve-se um total de 44,9 km de trilhas efetivas, o que resultou em uma densidade superior a 17,7 km/km²[1].

A amostra planejada após o tratamento dos dados obtidos pelo sobrevoo e a consolidação da avaliação de potencial espeleológico multicritério contemplou de forma adequada cada uma das classes de potencial obtidas (Fig. 8), resultando em um total de 75 novas cavidades cadastradas (Fig. 9).

Complexo Minerador Serra Norte - PDE N5 Sudeste				
Classe de Potencial	**Área (km²)**	**Área (ha)**	**Track (km)**	**Densidade (km/km²)**
Baixo	0,02	2,21	0,07	3,50
Médio	2,45	245,00	43,00	17,55
Alto	0,06	5,60	1,84	32,86
TOTAL	**2,53**	**252,81**	**44,91**	**N/A**

Figura 8: *Amostra de caminhamentos executados durante a prospecção espeleológica divididos por cada uma das classes de potencial espeleológico identificadas pela análise multicritério e densidade de caminhamento por classe de potencial.*

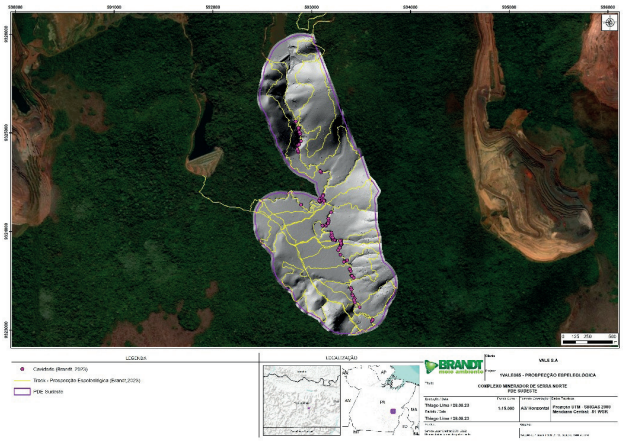

Figura 9: *Resultado final obtido pela prospecção espeleológica da área proposta a instalação da PDE N5 Sudeste.*

4. Discussão

Tradicionalmente, os estudos de prospecção espeleológica consideram, em sua etapa de dimensionamento, o uso de bases secundárias – informações estas relacionadas a estudos pretéritos, comumente elaborados em escalas regionais. Por se tratar de um levantamento direcionado, frequentemente executado em áreas de abrangência local, as análises preditivas conduzidas com bases regionais são inadequadas para um bom encaminhamento da prospecção, do ponto de vista produtivo. Além disso, o planejamento de uma prospecção espeleológica em uma área remota, amplamente vegetada por floresta ombrófila, como é o caso da área proposta a inserção da PDE N5 Sudeste, torna-se inviável do ponto de vista prático sem a utilização de informações de melhor resolução espacial. A PDE N5 Sudeste teve seu planejamento de campo elaborado com base tanto nas informações geoespaciais de abrangência regional quanto nas bases obtidas pelo sobrevoo executado com os sensores LiDAR e RGB, para efeito comparativo – considerando-se para ambos os casos, um trajeto amostral com 21 km de extensão. Porém apesar de ambos os trajetos terem a mesma extensão, o planejamento elaborado com os dados oriundos do sensor LiDAR permitiram uma leitura muito mais efetiva da paisagem local, possibilitando que a equipe vistoriasse porções da paisagem de maior potencial espeleogenético, à saber: talvegues de fluxo perene e/ou intermitente, escarpamentos contínuos, e os lineamentos realçados pela metodologia proposta vinculados a drenagens, fraturas variações litológicas que por sua vez suportam os depósitos de tálus. Já o planejamento estabelecido com base nos dados regionais, prioriza de forma concreta a execução de uma amostra de caminhamento randômica, sem um direcionamento geomorfológico ou espeleológico efetivo (Fig. 10).

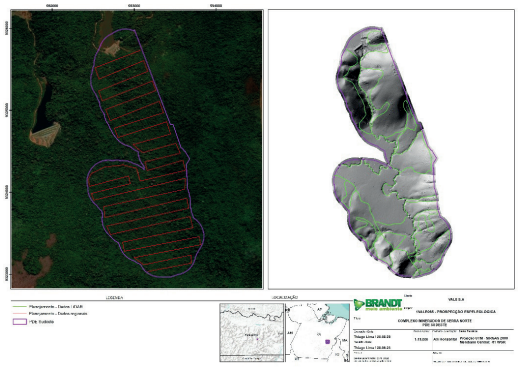

Figura 10: *A esquerda, planejamento de prospecção executado com base em dados geográficos de abrangência regional. A direita, planejamento de prospecção executado com base em dados geográficos obtidas de sobrevoo com uso de sensores LiDAR e RGB.*

Quanto ao tempo de execução, o planejamento proposto sem os dados obtidos pelo sobrevoo demoraria cerca de 37% a mais de tempo do que a amostra efetivamente executada, com as informações dos sensores LiDAR e RGB. Tal acréscimo de tempo não só representa um maior custo operacional efetivo, mas também uma maior exposição da equipe aos riscos naturais da área de estudo em questão. O MDT elaborado a partir da nuvem de pontos permitiu a visualização de acessos e trilhas em meio a floresta ombrófila que são invisíveis a partir do uso de uma imagem de satélite comum, ou mesmo uma fotografia aérea (Fig 11). Estes acessos permitiram que a equipe transitasse com mais segurança e rapidez pela área, vistoriando formas de relevo de maior potencial espeleológico, trazendo assim um melhor resultado ao trabalho.

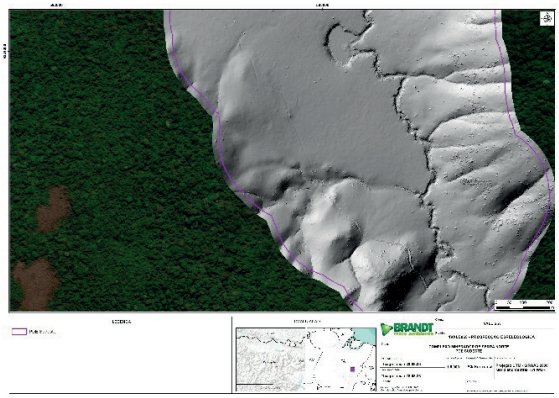

Figura 11: *Trilha pretérita em meio a floresta ombrófila, identificada no MDT com filtro hillshade.*

5. Conclusão

Conclui-se, portanto, a partir da experiência obtida com o projeto PDE N5 Sudeste, que o emprego de tecnologias relacionadas ao imageamento aéreo e ao perfilamento com uso de sensores LiDAR, para estudos que visam a investigação espeleológica em áreas naturais e remotas, é sim capaz de trazer ganhos operacionais, financeiros e técnicos. Uma leitura eficaz da paisagem resulta em um planejamento que preserva a integridade física da equipe em campo, reduz o tempo de execução, direciona as tomadas de decisões e aumenta significativamente a confiabilidade trazida pelo resultado final – que garante a amostragem das porções mais susceptíveis a espeleogênese da área estudada.

Agradecimentos

Agradecemos a AEROSAT Engenharia e Aerolevantamentos LTDA pela parceria, a Brandt Meio Ambiente LTDA pela iniciativa de condução do projeto e a VALE S.A pelo apoio institucional e financeiro.

Notas

1 | Para obter-se o valor aqui citado como “densidade de caminhamento”, aplicou-se a metodologia utilizada para determinar a densidade de corpos d’água (drenagens), onde se divide a distância total das drenagens que compõe a “bacia foco” do estudo pela área total dela, em hectares.

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The latest explorations of Czech and Slovak Speleological Societies in cave systems in Riviera Maya, Mexico

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Abstract

Czech and Slovak Speleological Societies have continued their long term project for exploration and documentation of underwater cave systems in so called „Riviera Maya“ in Quintana Roo, Mexico. Three expeditions were organized betwen 2022 and 2024 to the area and several new cenotes and caves was explored. Thanks to discoveries of 3,386 m of new passages in Yum Kaax Cave system it was extended to 12,802 m and now is the longest dry cave system in the area. In total more than 8 km of new cave passages was discovered and documented.

1. Introduction

A total of 22 speleological expeditions was organized by Czech and Slovak Speleological Societies between 2003 and 2021 to the Yucatan Peninsula in Mexico. In area between villages Chemuyi and Akumal, located on eastern coast in Quintana Roo state, they explored hundrets of cenotes and discovered significant underwater and dry caves there in total lenght of 140 km. The most important undrewater cave system explored and surveyed by members of Czech and Slovak Speleological Societies during that period are Sistema K´oox Baal, Sistema Sak Kay, Sistema Tatich, Sistema Cangrejo-Ich Kin, Sistema Tatich and Sistema Joolis. The most important dry cave system discovered by Czech and Slovak Speleologist in same time is Sistema Yum Kaax. MOTYCKA (2022). From 2022 to 2024 exploration continued mainly in Sak Kay and Yum Kaax cave systems and several smaller caves. Following members participated - Dusan Hablovic, Zdenko Hochmuth, Petr Chmel, Vit Kaman, Radek Jancar, Karol Kyska, Miroslav Manhart, Libor Matuska, Lada Matuskova, Zdenek Motycka and Jan Sirotek., MOTYCKA (2024).

2. Yum Kaax and Sak Kay Cave Systems

The first entrance to the Yum Kaax Cave system was discovered in 2017 and till the end of 2021 extensive labyrint of corridors in total lengh of 9, 416 m was discovered and documented. Exploration continued in 2022, when another 1,771 m of new spaces was discovered including two new halls - Nem Tu and Cirgulo (Fig.1). In 2023 new parts were discovered in nortwest part of the cave in total lenght of 920 m (Fig. 2). In 2024 another 695 m in central part, so the Yum Kaax is now 12,802 m long and is the longest dry cave in Akumal area (Fig.3). In 2023 documentary movie about Yum Kaax exploration and its beuties was filmed. SIROTEK, MOTYCKA (2023).

Sak Kay Cave system was discovered in 2014 and till the end of 2017 in total 11,638 m of underwater passages was discovered and documented, MOTYCKA (2023). Between 2022 and 2024 several revisional dives were realized and 2,054 m of new corridors was discover and mapped. The total lengh of Sak Kay Caves system is now 13,692 m. Some passages of both systems are very close to each other and it is only matter of time, when both caves will be interconnected to one system.

Figure 1: *The Nem Tu Hall in Yum Kaax Cave System, Mexico (photo by J. Sirotek).*

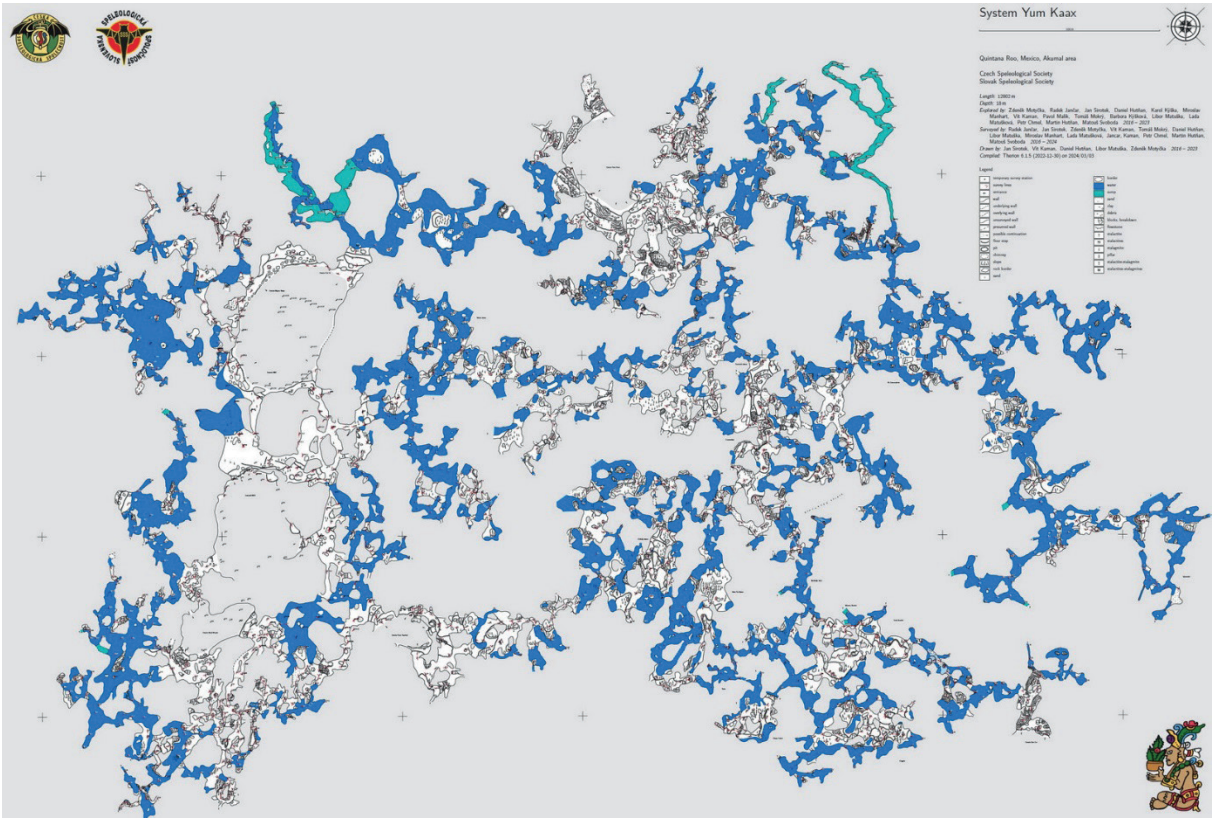

Figure 3: *The map of Yum Kaax Cave System at the end of 2024, Mexico.*

Figure 2: *Newly discoverd corridor in Yum Kaax Cave System, Mexico (photo by J. Sirotek).*

Figure 5: *Exploration in Thum Ben Ha Cenote, Mexico (photo by K.Kyska).*

3. Exploration in other caves

Beside exploration in Yum Kaax and Sak Kay, several new cenotes were also explored between 2022 and 2024. Together with Robbie Schmittner the new cenote called Mehaguya was explored and 873 m of underwater passages was discover (Fig. 4). In previously known cenote Thum Ben Ha new parts in lenght of 700 m were discovered (Fig.5) so the cave is now 1,478 m long (Fig. 6). Near Akumal two cenotes were explored and mapped – Yot is 346 m long and Fis Spa 314 m long.

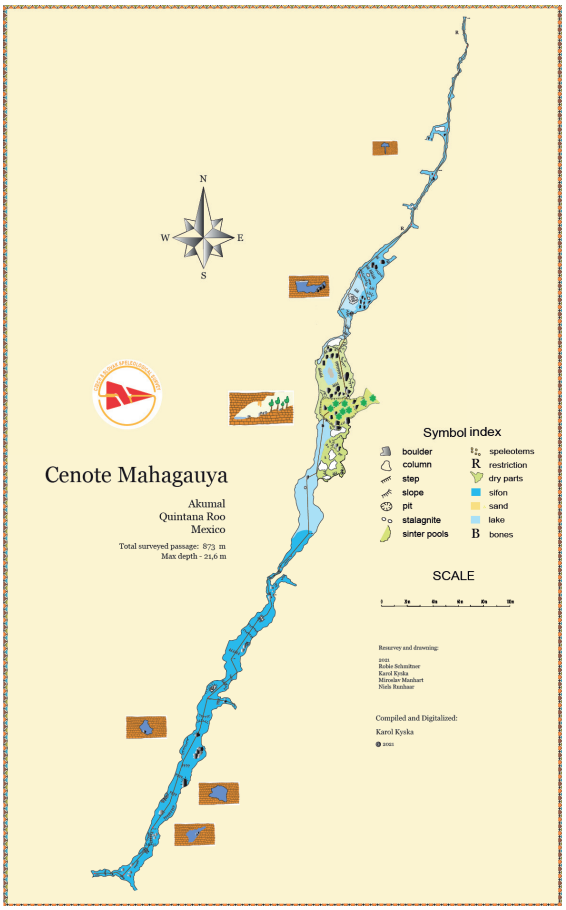

Figure 4: *The map of Cenote Mahagauya, Mexico.*

In 2024 exploration in central part of peninsula started and near Hunuku one new cave Grotte Xchayil was discovered and 210 m of cave passages surveyied (Fig. 7). Also huge cenote with same name was explored nearby and final depth of – 51m was reached (Fig. 8).

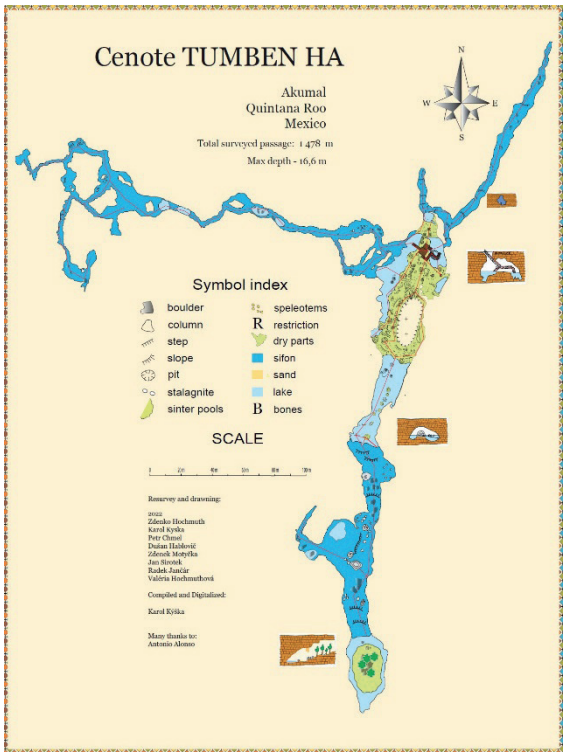

Figure 6: *The map of Cenoto Thum Ben Ha, Mexico.*

4. Conclusion

Between 2022 and 2024 three expeditions to Yucatan Peninsula were organized by Czech and Slovak Speleological Societies. In total 3,386 m of new cave passages were discovered in Yum Kaax Cave system, which is now 12,802 m long and 2,054 m of cave spaces were discovered in Sak Kay Cave system which is now 13,692 m long.

In other caves altogether 3,272 m was discovered. In total 8,712 m of new cave passages were discovered and documented by members of these three speleological expeditions.

Figure 7: *Before diving in Grotte Xchayil (photo by Z.Motycka).*

Figure 8: *Large cenote Xchayil (photo by Z.Motycka).*

Acknowledgments

Special thanks to Jim Coke, Jorge Gonzales Pacheco, Jacobo Pacheco, Robbie Schmittner, Dennis Niedermaier and Manuel Orvañanos for their support, help and friendship.

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Prospecção Espeleológica com o Uso de Drones: Caracterização de Áreas, Identificação de Riscos e Potenciais Espeleológicos

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Resumo

A prospecção espeleológica é fundamental para a identificação de cavernas e o planejamento de expedições, pesquisas e ações de conservação. Tradicionalmente realizada por métodos convencionais, essa atividade enfrenta desafios logísticos e riscos operacionais. A introdução de drones (Remotely Piloted Aircraft System - RPAs) tem se mostrado uma ferramenta complementar à prospecção convencional, possibilitando mapeamentos precisos e reduzindo os perigos associados à exploração. Esses equipamentos capturam imagens aéreas detalhadas e fornecem dados geoespaciais essenciais para a classificação de áreas com diferentes potenciais espeleológicos. No entanto, seu uso deve obedecer a regulamentações, como o Regulamento Brasileiro da Aviação Civil (RBAC-E nº 94) da ANAC e as diretrizes do DECEA, que estabelecem regras sobre categorias de drones, altitudes permitidas e autorizações em espaços controlados. Além de facilitar a identificação de feições geomorfológicas indicativas de cavernas, os drones contribuem para a segurança das equipes ao mapear áreas de risco, como encostas íngremes e terrenos instáveis. Os resultados obtidos demonstram ganhos expressivos em eficiência operacional, segurança e precisão na análise geoespacial, reforçando seu papel complementar na prospecção espeleológica. Contudo, desafios como a autonomia limitada da bateria e dificuldades em ambientes fechados ainda precisam ser superados. A incorporação de sensores avançados e inteligência artificial pode ampliar as aplicações dos drones, consolidando-os como ferramentas inovadoras e estratégicas para a espeleologia moderna.

Abstract

Speleological prospecting is essential for identifying caves and planning expeditions, research, and conservation actions. Traditionally carried out using conventional methods, this activity faces logistical challenges and operational risks. The introduction of drones (Remotely Piloted Aircraft System - RPAs) has proven to be a complementary tool to conventional prospecting, enabling precise mapping and reducing the dangers associated with exploration. These devices capture detailed aerial images and provide geospatial data essential for classifying areas with different speleological potentials. However, their use must comply with regulations such as the Brazilian Civil Aviation Regulation (RBAC-E No. 94) by ANAC and DECEA guidelines, which establish rules regarding drone categories, permitted altitudes, and authorizations for controlled spaces. In addition to facilitating the identification of geomorphological features indicative of caves, drones contribute to team safety by mapping hazardous areas such as steep slopes and unstable terrain. The results obtained demonstrate significant gains in operational efficiency, safety, and accuracy in geospatial analysis, reinforcing their complementary role in speleological prospecting. However, challenges such as limited battery autonomy and difficulties in enclosed environments still need to be overcome. The incorporation of advanced sensors and artificial intelligence may expand the applications of drones, consolidating them as innovative and strategic tools for modern speleology.

Resumen

La prospección espeleológica es esencial para identificar cuevas y planificar expediciones, investigaciones y acciones de conservación. Tradicionalmente realizada mediante métodos convencionales, esta actividad enfrenta desafíos logísticos y riesgos operacionales. La introducción de drones (Sistema de Aeronaves Pilotadas a Distancia - RPAs) ha demostrado ser una herramienta complementaria a la prospección convencional, permitiendo una cartografía precisa y reduciendo los peligros asociados con la exploración. Estos dispositivos capturan imágenes aéreas detalladas y proporcionan datos geoespaciales esenciales para clasificar áreas con diferentes potenciales espeleológicos. Sin embargo, su uso debe cumplir con regulaciones como el Reglamento Brasileño de Aviación Civil (RBAC-E nº 94) de la ANAC y las directrices del DECEA, que establecen normas sobre categorías de drones, altitudes permitidas y autorizaciones para operar en espacios controlados. Además de facilitar la identificación de características geomorfológicas indicativas de cuevas, los drones contribuyen a la seguridad de los equipos al cartografiar áreas de riesgo, como pendientes pronunciadas y terrenos inestables. Los resultados obtenidos demuestran importantes mejoras en eficiencia operativa, seguridad y precisión en el análisis geoespacial, reforzando su papel complementario en la prospección espeleológica.

No obstante, siguen existiendo desafíos como la autonomía limitada de la batería y las dificultades en entornos cerrados. La incorporación de sensores avanzados e inteligencia artificial podría ampliar las aplicaciones de los drones, consolidándolos como herramientas innovadoras y estratégicas para la espeleología moderna.

1. Introdução

Segundo o Centro Nacional de Pesquisa e Conservação de Cavernas (CECAV, 2010), a definição mais amplamente aceita para cavernas é a de cavidades naturais formadas em rocha abaixo da superfície terrestre, com dimensões suficientes para permitir a entrada de seres humanos. Essa definição é reconhecida pela União Internacional de Espeleologia (UIS) e reforça a importância dessas formações para estudos científicos, ambientais e de conservação. Nos últimos anos, a espeleologia tem ganhado destaque no Brasil, impulsionada tanto por avanços científicos quanto por regulamentações que visam à proteção do patrimônio espeleológico (CECAV, 2019).

A prospecção espeleológica é a fase inicial de qualquer atividade exploratória e consiste na investigação preliminar de uma área para identificar possíveis cavernas e formações subterrâneas. Essa etapa é essencial para o planejamento de expedições, pesquisas científicas e ações de conservação, fornecendo informações sobre acessibilidade, segurança e potencial científico das cavidades identificadas. No entanto, o trabalho de campo em áreas de difícil acesso apresenta desafios logísticos e riscos consideráveis para os pesquisadores, exigindo a adoção de métodos mais seguros e eficientes.

Nesse contexto, a incorporação de novas tecnologias tem revolucionado a prospecção espeleológica, proporcionando maior precisão na aquisição de dados e reduzindo os riscos inerentes à exploração manual em ambientes subterrâneos complexos. Dentre essas inovações, areonaves pilotadas remotamente (RPAs), popularmente conhecidos como drones, têm se destacado como uma ferramenta essencial. Conforme Skrypitsyna (2022), os drones permitem a captura de imagens aéreas detalhadas, o mapeamento de áreas de difícil acesso e a obtenção de informações geoespaciais com alta precisão.

Yepes & Barone (2018) e a Agência Nacional de Aviação Civil (ANAC, 2017) apontam que os drones são aeronaves não tripuladas que podem operar de forma autônoma ou ser controladas remotamente por um operador. Sua versatilidade os torna úteis em diversas aplicações, incluindo a espeleologia, onde contribuem para a identificação de áreas de risco, o mapeamento de regiões de maior potencial espeleológico e o refinamento da prospecção, tornando as expedições mais seguras e eficientes.

Diante desse cenário, o presente estudo tem como objetivo explorar o potencial dos drones na prospecção espeleológica, analisando seus avanços tecnológicos e os desafios operacionais envolvidos. Além disso, busca-se desenvolver protocolos de segurança e estratégias de integração dessa tecnologia aos métodos tradicionais de exploração, promovendo o desenvolvimento de novas abordagens para o estudo e conservação de cavernas.

2. Materiais e Métodos

Legislação Aplicável ao Uso de RPA (Drones) na Prospecção Espeleológica

Para a operação de aeronaves remotamente pilotadas (RPAs) em atividades de prospecção espeleológica no Brasil, é necessário observar a legislação vigente, que regula desde a classificação dos drones até os requisitos operacionais e de segurança. As principais normas aplicáveis incluem:

1. Regulamento Brasileiro da Aviação Civil Especial – RBAC-E nº 94 (ANAC)
    - Estabelece requisitos para a operação de drones civis no Brasil.
    - Classifica as RPAs em três categorias com base no peso máximo de decolagem (PMD):
        - Classe 1: acima de 150 kg.
        - Classe 2: entre 25 kg e 150 kg.
        - Classe 3: até 25 kg.
    - Define regras de voo, como:
        - Operação em Linha de Visada Visual (VLOS) e Além da Linha de Visada Visual (BVLOS).
    - Restrições de voo próximas a terceiros e requisitos de segurança operacional.
    - Exige registro da aeronave junto à ANAC e cumprimento de requisitos de certificação para operações acima de 400 pés AGL.
2. Código Brasileiro de Aeronáutica – Lei nº 7.565/1986
    - Regulamenta o uso do espaço aéreo brasileiro.
    - Determina que a navegação aérea e o tráfego aéreo são submetidos à fiscalização da autoridade aeronáutica.
    - Proíbe o transporte de materiais perigosos sem autorização especial.
3. ICA 100-40 – DECEA
    - Regula o acesso ao espaço aéreo por aeronaves não tripuladas.
    - Estabelece a necessidade de autorização para operações em áreas restritas e controladas.
    - Determina o uso do sistema SARPAS para solicitação de voos e avaliação de risco operacional.
4. ICA 100-12 – DECEA
    - Estabelece as diretrizes das regras e obrigações dos pilotos de aeronaves durante a realização de atividades de voo. É conhecido como “Regras do Ar”.

Como existem diversas exigências para cada tipo de voo, no Brasil é comum a utilização da seguinte configuração para realização de atividades de complementação de prospecção espeleológica por voo de RPA:

Drone Classe 3, com peso de decolagem de até no máximo 25 kg.

Voo em Linha de Visada Visual (VLOS)

Voo a altura máxima de 400 pés AGL (a se orientar pela altura do solo no ângulo nadiral)

Voo somente realizado por piloto habilitado e com cadastro no Sistema SISANTE.

Presença do protocolo do sistema SARPAS, que por sua vez é vinculado ao DECEA, autorizando o voo no espaço aéreo previamente delimitado para realização da atividade

Voo somente em áreas fora da Zona de Tráfego aéreo e fora da zona de aproximação e decolagem (ZAD) de aeroportos.

Utilização de drones homologados pela Anatel e pela ANAC.

Para realização de aerofotogametria, a empresa ou responsável pelo voo deve possuir o registro no sistema SISCLATEN, que por sua vez é vinculado ao Ministério da Defesa, e em caso de áreas maiores que quinze quilômetros quadrados, a autorização AVOMD emitida no mesmo sistema SISCLATEN.

Termo de anuência para sobrevoo de pessoas e propriedades, emitidos pelos proprietários dos locais a serem sobrevoados e por pessoas que estiverem abaixo do RPA. Porém, por questão de segurança, o mais comum é não permitir a presença de pessoas abaixo do RPA durante o voo.

Essa configuração atende as regras estabelecidas pela legislação vigente para a maioria dos voos em atividades de complementação da prospecção espeleológica, e permite a realização de fotos e vídeos em ângulos Nadiral e Obliquo, que trazem diversas informações acerca da área sobrevoada pelo RPA.

Figure 1: *Piloto de RPA preparando RPAs para voo (Cada equipamento é operado por um piloto diferente ou em momentos diferentes).*

A partir dos dados coletados em campo pelo RPA, (Fotos 3D, panoramicas, obliquas ou nadirais, vídeos, ortofotos ou modelos digitais de elevação), o material é processado de acordo com a proposta de cada trabalho, e avaliado pelo analista ambiental responsável pelo estudo, que define a melhor maneira de apresentar o resultado obtido de acordo com as características de cada projeto.

Figure 2: *Foto Obliqua efetuada por um RPA DJI Mavic Air 2.*

3. Resultados

A utilização de Veículos Aéreos Não Tripulados (RPA's), popularmente conhecidos como drones, na prospecção espeleológica proporcionou resultados significativos na caracterização da área de estudo e no planejamento das atividades de campo. As imagens aéreas de alta resolução capturadas pelos drones permitiram a identificação de diversas feições geomorfológicas indicativas de potencial espeleológico, bem como a avaliação de áreas de risco para as equipes de exploração.

Classificação do Potencial Espeleológico

Com base na análise das fotos, ortofotos e dos modelos digitais de elevação gerados a partir dos dados coletados pelos drones, foi possível classificar a área de estudo em zonas de alto, médio e baixo potencial espeleológico:

Alto Potencial: Foram identificadas áreas com afloramentos rochosos significativos, presença de dolinas e outras depressões fechadas, além de lineamentos estruturais que podem indicar a existência de cavernas subterrâneas.

Médio Potencial: Regiões com características geomorfológicas menos pronunciadas, porém com indícios de processos cársticos superficiais, como pequenas depressões e fraturas na rocha.

Baixo Potencial: Áreas predominantemente cobertas por solos ou antropizadas, sem evidências claras de feições associadas à formação de cavernas.

Figura 3: *Vista aerea de afloramento calcario rochoso, caracterizando alto potencial de cavernamento.*

Identificação de Áreas de Risco

A análise topográfica detalhada proporcionada pelo RPA possibilitou a identificação de áreas de risco que poderiam comprometer a segurança das equipes durante a prospecção em campo:

Encostas Íngremes: Mapeamento de declividades acentuadas que representam risco de deslizamentos ou quedas.

Terrenos Instáveis: Identificação de solos suscetíveis à erosão ou colapso, especialmente em proximidades de cursos d'água ou em áreas com histórico de instabilidade geológica.

Acessos Difíceis: Locais onde a densa vegetação ou obstáculos naturais dificultam o acesso seguro das equipes.

Figura 3 : *Vista aera de afloramento calcario rochoso, caracterizando alto potencial de cavernamento.*

Figure 4: *Area de baixo potencial espeleológico.*

Figura 5: *Area com inclinação alta, ausencia de aflorametos e solo expesso. Vossoroca de grande extenção.*

4. Discussão

A aplicação de *Remotely Piloted Aircraft System* - RPAs, ou drones, na prospecção espeleológica tem se mostrado uma abordagem inovadora e eficaz, trazendo avanços significativos na caracterização de áreas de estudo e no planejamento de atividades de campo. Os resultados obtidos neste estudo corroboram com achados de pesquisas anteriores, evidenciando as vantagens e desafios associados ao uso dessa tecnologia.

A classificação do potencial espeleológico em zonas de alto, médio e baixo potencial, baseada na análise de ortofotos e modelos digitais de elevação gerados pelos drones, permitiu uma avaliação detalhada das feições geomorfológicas da área de estudo. Essa abordagem é consistente com as práticas descritas por Petráček et al. (2023), que destacam a eficácia dos drones na exploração de ambientes subterrâneos, permitindo a identificação de características superficiais que podem indicar a presença de cavernas subterrâneas.

A identificação de áreas de risco, como encostas íngremes, terrenos instáveis e acessos difíceis, é fundamental para garantir a segurança das equipes de prospecção. A análise topográfica detalhada proporcionada pelos drones facilita essa identificação, permitindo o planejamento de rotas mais seguras e a mitigação de riscos associados às atividades de campo. Conforme discutido por Petráček et al. (2023), a capacidade dos drones de mapear terrenos complexos e de difícil acesso é uma vantagem significativa na exploração espeleológica.

Os benefícios observados, como a eficiência operacional, a segurança aprimorada e a precisão dos dados, estão alinhados com as vantagens apontadas por Petráček et al. (2023). A redução do tempo necessário para levantamentos iniciais e a diminuição da exposição das equipes a ambientes potencialmente perigosos são aspectos destacados em ambos os estudos. Além disso, a geração de modelos tridimensionais detalhados do terreno auxilia no planejamento preciso das rotas de prospecção e na identificação de pontos de interesse, conforme observado por Petráček et al. (2023).

No entanto, é importante reconhecer as limitações e desafios associados ao uso de drones na prospecção espeleológica. Fatores como a autonomia limitada da bateria, as restrições de voo em ambientes fechados ou com cobertura vegetal densa e as dificuldades de comunicação em terrenos acidentados podem impactar a eficácia das operações. Petráček et al. (2023) também apontam para a necessidade de desenvolver sistemas autônomos mais robustos e estratégias de cooperação multi-robô para superar essas limitações.

Benefícios Observados

A aplicação de drones na prospecção espeleológica trouxe diversos benefícios, alinhados às observações de Petráček et al. (2023) sobre a eficiência dos RPA's em ambientes subterrâneos:

Eficiência Operacional: Redução significativa do tempo necessário para o levantamento inicial da área, permitindo uma cobertura mais ampla em menor período.

Segurança: Diminuição da exposição das equipes a ambientes po-

tencialmente perigosos, uma vez que a avaliação preliminar é realizada remotamente.

Precisão dos Dados: Geração de modelos tridimensionais detalhados do terreno, auxiliando no planejamento preciso das rotas de prospecção e na identificação de pontos de interesse.

Esses resultados corroboram a eficácia do uso de drones na prospecção espeleológica, destacando-os como ferramentas valiosas para a caracterização de áreas de estudo e para o planejamento seguro e eficiente das atividades de campo.

5. Conclusão

A utilização de RPAs na prospecção espeleológica mostrou-se uma ferramenta inovadora e eficiente, permitindo a caracterização detalhada das áreas de estudo e o planejamento estratégico das atividades de campo. A classificação das zonas de potencial espeleológico em alto, médio e baixo, baseada na análise de imagens aéreas e modelos digitais de elevação, possibilitou uma identificação mais precisa das áreas com maior probabilidade de ocorrência de cavernas. Esse método se mostrou alinhado com estudos anteriores, como os de Petráček et al. (2023), que destacam a eficácia dos RPAs na exploração geoespacial de terrenos cársticos.

Além disso, a capacidade dos drones de identificar áreas de risco, como encostas íngremes e terrenos instáveis, contribuiu significativamente para a segurança das expedições, reduzindo a exposição dos pesquisadores a ambientes potencialmente perigosos. A análise remota do terreno permitiu um planejamento mais preciso das rotas de prospecção, minimizando riscos e otimizando a eficiência do trabalho de campo.

Os benefícios observados neste estudo, incluindo maior precisão dos dados, eficiência operacional e segurança aprimorada, reforçam o potencial dos drones como uma ferramenta complementar indispensável na espeleologia. No entanto, desafios como limitações na comunicação em ambientes fechados e a necessidade de treinamento especializado para a operação dos equipamentos ainda precisam ser aprimorados.

Diante dos resultados positivos, recomenda-se a continuidade de pesquisas voltadas à integração dos drones com outras tecnologias, como sensores LiDAR e inteligência artificial, para aprimorar ainda mais a prospecção espeleológica. Dessa forma, o uso de drones pode contribuir não apenas para a descoberta de novas cavernas, mas também para a conservação e gestão sustentável do patrimônio espeleológico.

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Shpella e Valbones - The deepest cave of Albania (Prokletije Mountains)

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Abstract

The Albanian Alps are the highest part of the Dinaric Mountains range. Their morphology resembles alpine massifs, and this means that the difference in levels between the holes and the drainage zone exceeds 1500 m. This gives hope for finding deep caves. The other reason, why we focused our efforts there, is because of the small amount of research and information of this area, and little knowledge of the Valbona Valley caves and karst, limited to a few previous exploratory expeditions. In 1993, an Italian expedition from the Circolo Speleologico Romano club operated in the Valbona area, and in 2007, a Slovak expedition visited two caves near the village of Dragobi.

Polish exploration of the Albanian Alps since 2007 has focused on the massifs surrounding upper part the Valbona River valley. During this time, among other things, we discovered and measured the deepest cave in Albania and the Prokletije Mountains - Shpella e Valbones (-725 m deep, and 2411 m long).

Scientific research was carried out in parallel on biospeleology, chiropterology, geomorphology, microclimate, paleozoology, etc. The preliminary results of the research turned out to be very interesting.

1. Introduction

Area of activity

The study area is located in the Albanian Alps (Prokletije, Bjeshket e Nemuna) in northern Albania. It is cut into two parts by the Valbona River. The Valbona flows out in a large spring (approx. 1300 m a.s.l.) from the southern slopes of the Maja Jezerce massif west of the Rrogam village, to join the Drin River after approx. 50 km near the town of Lekbibaj (approx. 200 m a.s.l.). The Valbona River changes its direction several times as it flows through the study area. First, it flows directly to the E, to change direction to the NE below Rrogam village, and from the village of Cuka Dunishes it takes a decisive SE direction. The upper part of the valley, up to the Valbona village (approx. 900 m a.s.l.) is a typical glacial U-shaped, valley. The Valbona River flows here deep in the rock rubble lining this entire section.

The glacier in the Valbona valley was the second longest in the Prokletije Mountains and measured about 9.5 km (M. Milivojevic, L. Menkovic, J. Calic 2008).The river appears on the surface only below the village of Valbona and here the valley has the character of a deep V-shaped river valley until it leaves the mountains. The closest northern and southern surroundings of the upper Valbona valley are the highest peaks of the Albanian Alps and the entire Dinaric Alps - Maja Jezerces 2694 m a.s.l., Maja Brykare te Hapta 2625 m a.s.l., Maja Kollates 2551 m a.s.l., Maja Rosit 2525 m a.s.l., Maja Ismet Sali Brucaj 2521 m a.s.l., Maja Pecmares 2468 m a.s.l. Between these last two peaks there is a large depression zone, the partially deepened Gropa Harushes valley (on average about 2100 m a.s.l., which is the main area of cave exploration.

Geology

The Albanian Alps area is formed by the geological and tectonic Albanian Alps Zone and has the shape of a rhombus limited by the towns of Shkodra (SE), Bajram Curri (NE), Vermosh (NW), Hani and Hotit (SW). The oldest sediments of this area come from the Permian period and are shales, sandstones, limestones and conglomerates. The Triassic sediments are mainly limestone rocks of terrigenous origin, limestones, but also dolomites, calcareous shales and tuffs. In the area of activity of Polish expeditions, three tectonic units meet; the Valbona Subzone, which forms the W-E axis, and to the N and E of it the Malesia e Madhe Subzone, to the north (around the Cerem Valley), the Gashi zone (non-karst rocks) overlaps the Valbona subzone. The central part of the Valbona Subzone is formed by the Valbona microblock. This unit entirely coincides with the area of the most intensive exploration activities coordinated by the FSP. The Valbona microblock is mostly composed of limestones from the Triassic period. On the northern side of the valley, limestones from the Cretaceous and Jurassic periods can also be found, but they are in a definite minority. In the Triassic limestones of this area, there are inserts containing bauxites and bauxite clays, these deposits were subject to exploitation.

The rock layers here form a large anticline with a W-E axis, the core of the anticline is made up of Upper and Middle Triassic rocks, while the arms are made up of Cretaceous and Jurassic rocks as well as Maastricht flysch (Shyqyri 2015)

In the Albanian Alps there is a fracture system consisting of two groups: NE-SW structures related to the Pyrenean phase and NW-SE resulting from neotectonic deformations. These discontinuities are important for the mechanical transport of rock fragments and drainage of surface waters. It was found that young faults determine the development of the majority of caves in this area. Therefore, the underground karst forms are of erosional-tectonic origin, while the karst relief on the

surface is dominated by corrosive forms. (Shanov 1993)

Carbonate massifs are intensively karstified. The crests of the ridges and the top surfaces of the mountains are characterized by surface karst forms in the form of karrs, sinkholes, dolinas and pits. Karst forms are almost invisible on the slopes. Underground karst, as shafts and pits, developed mainly due to subglacial runoff and nival waters. Caves are characterized by a weak development of flowstone forms. However, traces of paleokarst and possibly hydrothermokarst can be traced in the massif (Ridush et al 2024).

Climate

There are no studies on weather and climate conditions directly for the area of scientific and exploration activities. The nearest measurement stations are located in the towns of Bajram Curri (approx. 300 m a.s.l.) outside the mountain area and Bogë (approx. 900 m a.s.l.) - a station inside the mountain massif, on the other side of the ridge. Comparing with the station in Bogë, an average annual temperature of approx. 9,0 ^{0}C can be expected in the Valbona valley. The range of expected temperatures is from -20,0 0C in winter to approx. +35,0 0C in summer. Precipitation occurs mainly in the September-January period and can reach an average annual amount of up to 2280 mm (Iballe station). In winter, snow cover in the valleys lasts for about 100 days, and in the summit zones for > 250 days. The thickness of the snow cover in the mountains reaches even several meters (Kukes 160 cm). A distinctive feature of the Albanian Alps area is the heavy rainfall in the September-December period. At that time, 24-hour maximums of rainfall were recorded at the Bogë station 420,0 mm, 345,0 mm at the Shkodra station and 310,7 mm at the Puke station (Muçaj et.al 2010).

2. Exploration

Polish expeditions to Albanian Alps, organized by Mariusz Polok, was conduct since 2007 in cooperation with the Caving Club „AVEN" in Sosnowiec. After 2010, the organization and coordination of exploratory activities was taken over by the Polish Speleology Foundation (Fundacja Speleologia Polska). Activity was concentrated mainly in two massifs:

- hanging valley located between the peaks of Maja Cet-Harushes (2422 m a.s.l.), Maja Ismet Sali Bruce (2527 m a.s.l.) and Maja Malgashit (2319 m a.s.l.),
- Maja Isuf Demes (2243 m a.s.l.) and Maja Gjarprit Ceremit (2142 m a.s.l.),
- reconnaissance on north part of Maja Rosit (2522 m a.s.l.) and hanging valley Gropa e Rupes.

The activity of 13 expeditions in the years 2006 - 2014 resulted in the discovery of 141 new caves. Most of them are up to 50 m long, mostly vertical. The deepest - Shpella Sportive, located in the Maja Malgashit massif, was 256,6 m deep and 772,5 m long.

In September 2020, a small exploration and inventory team consisting of Ewelina Raczynska and Michal Macioszczyk operated in the Maja Gjarperit Ceremit massif.

Team verified 11 previously known holes, of which 2 was considered as needing to be checked with less snow cover on entrance. Additionally, team discovered 27 new caves, 20 of which require further exploration.

In 2021 was initiated Project Valbona aimed for continuing exploration of the caves in the upper part of Valbona Valley in a modified format. What was new, was the invitation to cooperate with scientists representing various fields and Figure 1: Map of activity area showing discovered caves. conducting parallel exploration and scientific research. Four expedition were organized by Polish Speleology Foundation, led by Michał Macioszczyk. Our activity focused on two areas of alpine karst. The most interesting area turned out to be suspended valley area in between Maja Cet-Harushes, Maja Ismet Sali Brucaj and Maja Malgashit.

The 2021 expedition focused on continuation of exploration in previously known caves, with particular emphasis on Shpella Sportive and surface exploration of a previously unknown part of the massif. The most promising result of the surface activity was the new Shpella e Valbones cave. It was measured to - 395 m deep.

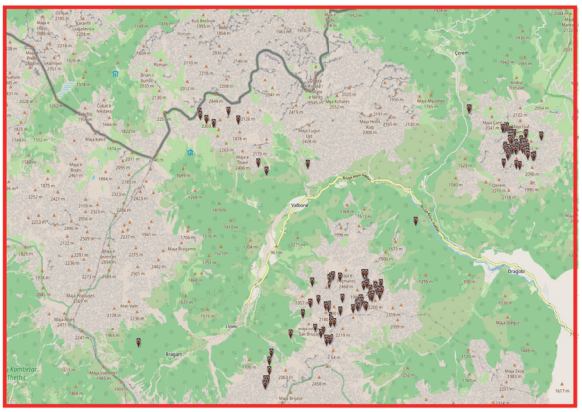

Figure 1: *Map of activity area showing discovered caves.*

During the next expeditions, 2022 and 2023 the exploration activities have allowed us to reach a depth of 725 m and 1931 m long. The goal for 2024 was primarily to check several new unexplored places, including wells and corridors leading from a huge chamber at a depth of 400 m, named after our Albanian hosts Gjoni Hall. Currently it is the second largest cave hall in Albania (388 000 m3). The Gjoni Hall is also the place of our bivouac, where a six-person team, can comfortably spend the night in quite good conditions. It is also worth noting that since 2023 the bivouac has had radio communication with the surface. Teams operating on the new branches spend two to four nights in the bivouac, then return for a few days "to the surface" and, for those willing, shifts underground again. The effect of 2024 exploration activities in Shpella e Valbones was the discovery of a large number of new corridors, thanks to which cave changed its character from a typical vertical cave to an increasingly interesting cave system. Exploration will continue with the expeditions planned in the coming years as the exploration team still sees many opportunities. It is currently the deepest cave in Albania and the deepest cave of Prokletije Mountains.

In addition, during the „Project Valbona" expeditions, 58 new caves have been discovered elsewhere in the area, several of them will be the subject of further exploration action.

Albania, Valbone's river valley - main caves explored in the years: 2006 to 2024

	by lenght			*by depht*	
1	Shpella e Valbones (AL-R-110)	2 411,0 m	1	Shpella e Valbones AL-R-110	727,3 (-725,0; +2,8) m
2	Shpella Sportive (AVL-R-70)	772,5 m	2	Shpella Sportive AVL-R-70	275,2 (-256,6;+18,6) m
3	Shpella Haxhise	365,0 m	3	AVL-C-19	-109,4 m
4	AVL-R-09	142,7 m	4	AVL-K-43	-65,0 m
5	AVL-C-19	131,8 m	5	Shpella Akult AVL-R- 52	-64,3 m
6	Shpella Akult (AVL-R- 52)	127,9 m	6	AVL-C-12	-63,8 m
7	AVL-C-12	118,6 m	7	Shpella ë GegHysenit	-60,1 m
8	AVL-R-50	113,9 m	8	AVL-C-17	60,1 (+0,2, -59,9) m
9	AVL-R-57	102,2 m	9	AVL-R-57	-55,6 m
10	AVL-C-22	100,0 m	10	AVL-R-76	-55,0 m
11	Sh. Kolapsa (AL-R-97)	98,0 m	11	AVL-R-50	-54,1 m

Figure 2: *List of deepest and longest caves documented by FSP expeditions.*

3. Science

A novelty in the expeditions to Albania since 2021 was the invitation to participate by scientists representing ISEZ PAN (Institute of Systematics and Evolution of Animals Polish Academy of Science), Department of Natural History, Upper Silesian Museum in Bytom, Department of Geography Chernivtsi University (Ukraine) and Forest Research Institute who conducted geological, morphological, paleozoological, biospeleological and chiropterological research. The preliminary results of the research turned out to be very interesting.

3.1. Biospeleology

In the caves and tunnels of the Valbona Valley, 102 specimens of arthropods were collected: among this 19 beetles, 44 flies, 3 crickets, 5 millipedes 16 Opinions, 6 spiders, 2 springtails, 1 tick.. The vast majority have been identified as species, among which there are many typical troglobiontic forms. Five of them are new for Albanian fauna: Gymnomus cassius, Gymnomus ceianui, Trichocera (Saltrichocera)maculipennis , Clinocera sp. and Macrochatetosoma bertiscea

3.2. New knowledge on the occurrence of bats in the Valbona Valley

Analyzing the available literature, it can be observed that data on the occurrence of bat species in mountainous and high-altitude regions of Albania are scarce. To expand the knowledge on the ecology of bats in mountainous areas, chiropterological studies have been conducted in the Valbona Valley and surrounding mountains since 2021. This study presents new findings on the presence of bat species in this area in the context of existing knowledge about the chiropterofauna of Albania. Research conducted in August from 2021 to 2024 included bioacoustic analyses, bat netting, and exploration of underground structures such as caves and mine shafts. A total of 46 bats representing 11 species were caught in chiropterological nets: *Rhinolophus hipposideros, Myotis emarginatus, Myotis alcathoe, Myotis nattereri, Myotis blythii, Hypsugo savii, Plecotus auritus, Plecotus macrobullaris, Plecotus austriacus/ kolombatovici, Vespertilio murinus*. Preliminary bioacoustic studies additionally detected 12 other species (apart from the netted ones): *Rhinolophus ferrumequinum, Myotis daubentonii, Myotis mystacinus/ brandtii, Nyctalus noctula, Nyctalus leisleri, Pipistrellus kuhlii, Pipistrellus pipistrellus, Pipistrellus pygmaeus, Barbastella barbastellus, Eptesicus serotinus, Eptesicus nilssonii, Tadarida teniotis*. In total, the presence of 23 bat species was documented. Analysis of the available bibliography on the zoogeography of bats in Albania revealed 17 new species for the region. Bioacoustic studies enabled the examination of bat activity in various environments, such as caves at different altitudes (between 1900 and 2300 meters above sea level), areas covered with dwarf pine, grass, scree, and near a waterbody at 2100 meters above sea level. The results indicate the highest bat activity near the waterbody and in rocky areas with cave openings. Although bats above 2000 meters do not use caves as summer shelters, they likely find refuge in rock crevices. The highest bat activity in caves was noted in those located below 200 meters, such as the Haxhise Cave, which serves as a swarming site. Studies conducted in the valley floor showed that recently installed street lighting has reduced bat activity in illuminated areas. However, activity remains relatively high in wet and unlit areas.

3.3. Paleozoology

The study aimed to detect the presence of faunal remains in the sediments and of the possible ancient human activity in caves. Our research involves shallow excavation of cave sediments and their geological description, collection of faunal remains from the cave floor, and sampling of fossil fauna samples, if any are found. The subfossil remains of at least five individuals of a wild goat, similar to Alpine ibex (Capra cf. ibex), were found in two caves Spella Haxhice and Shpella Sportive. One of them was dated to the Early Meghalayan (Holocene) age. The current scientific problem is that the systematic position of this extinct population is unclear. The future genetic analysis will reveal its genetic relationship with the other extant populations from Alps, Pyrenees, or Caucasus. This almost complete skeleton of an adult male, was trapped in a narrow gap between two large blocks. The bones were covered with fresh, mild dripstone calcite, similar to Mondmilch. At present, this species is absent in the local faunal list, and the remains are of great scientific interest.

To assess the biodiversity of the karst region, reconnaissance surveys of key areas were also carried out:

- in the Valbona River valley – hornbeam-beech and beech-fir forests; xerophytic meadows;
- on mountain ranges – outcrops of bedrock Triassic limestones with sparse moss-herb vegetation; high-altitude meadows in the nival-karst basin, karst plateau.

Among the important preliminary results, it should be noted that a greater diversity of molluscs is characteristic of mountain biotopes, especially for the karst plateau. Further research and analysis of the species composition will allow us to draw conclusions about the ecological composition of the molluscan fauna. It is also important to understand to what extent the mollusc species that inhabit mountain biotopes are typical for the region, and whether there are relict or endemic species among them.

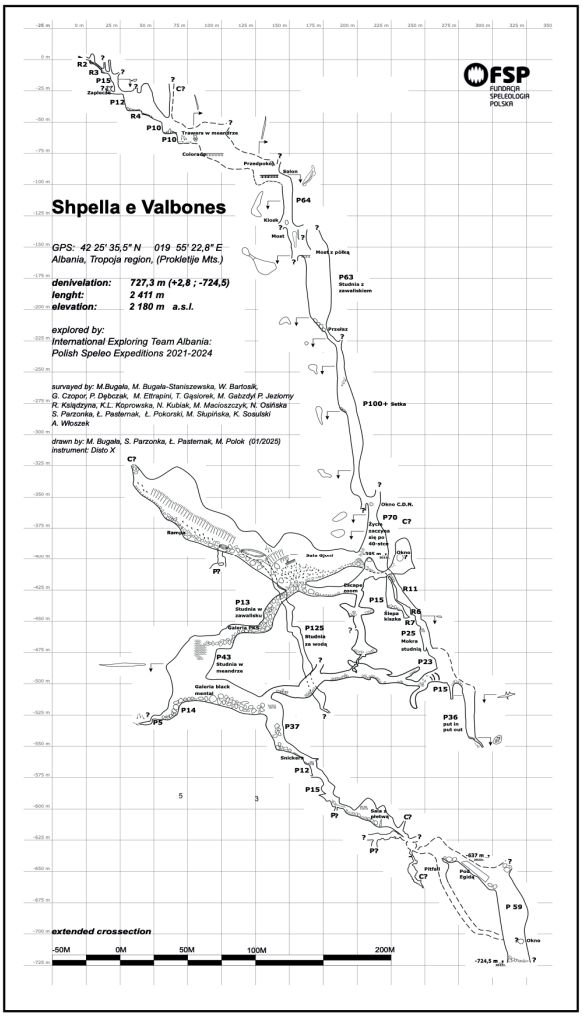

Figure 3: *Shpella e Valbones cross section.*

3.4. Caves microclimate

The air temperature in caves depends on many factors, including geographical location and elevation above sea level, the number and arrangement of openings, the development and volume of corridors and their position in relation to the terrain. Temperature measurements in caves were taken in two ways: long-term temperature measurements performed using temperature and humidity recorders. In this method, the recorders worked continuously for a period of 30 to 360 days, and also, supplementarily, as one-time current measurements of air temperature, conducted during exploration in new caves, or during visiting caves already known. In caves with ice cover, ice temperature measurements were taken using a drill-probe dedicated by the manufacturer, which allowed for measuring ice temperature at a depth of 5 cm from its surface. The results of research on the temperature of the Valbona Valley caves cover the period of four consecutive measurement seasons from 2021 (August) to 2024 (August). During this period, the temperature was recorded with Benetech GM1365 recorders and a DT11 thermometer (2021-2023). Benetech recorders, in difficult cave conditions, did not meet expectations regarding the durability of measurements. The recorded periods reached a maximum of 5 months of measurement continuity. Therefore, in 2023, Hobo U23 Pro v2 (Onset) recorders were introduced to the measurements, which solved the existing problem of the continuity of temperature recording. Starting from the 2023 season (August), measurements are carried out continuously.

The average annual temperatures (AAT) in selected caves, ranged from -0.210C in the Akullt cave to 5.390C in the Haxhise cave. For the Sportive cave, at the *Razors* point, which is located deep (-129m, 130 m from entrance) inside the cave, measurements were taken in two seasons. In 2021, the AAT obtained for this season was 2.110C. In the 2022/2023 season, it was is 2.160C. At the second, located in the Sportive cave, point, *Hanging Stone* (-6m, 60m from entrance), as a result of the full annual cycle of measurements, AAT was 1.470C. In the Valbones cave, measurements were taken at the *Biwak* point at a depth of about 400m.. The AAT for this season was 2.400C.

The annual temperature amplitude(TA) and its dynamics were characterized by significant diversification in the studied caves. The observed TA values ranged from 0.10C to as much as 8.39°C. The greatest variability in the temperature course was recorded in the Sportive cave, at the *Hanging Stone* point, this TA value reached 8.39°C. In the same cave, at the *Razor* point, located about 230 m into the cave, an TA of 0.10C, and 0.40C was recorded for the 2021 and 2022/23 seasons. In the other caves, the TA values were not as spectacular. For the Haxhise cave, it was 0.800C, and in the Sportive cave it was 2.30C. The lowest TA value was recorded at the *Bivouac* measuring point (-400m) in the Valbones cave where it was 0.100C.

Extreme annual temperatures(T_{max}, T_{min}) for the studied caves, the maximum annual air temperatures are observed in late autumn. In the Haxhise cave, T_{max} was 5.670C and was observed on November 18, 2023, respectively for the Sportiva Cave, at the Hanging Stone measurement point, T_{max} was 4.820C, observed on October 28, 2023. In the Akullt cave, the Tmax was measured on November 3, 2023, when it reached a value of 0.77^{0}C. In turn, the lowest temperatures, in the annual cycle, fell in January and February and were observed, respectively, in the Haxhise cave T_{min} = 4.87^{0}C on February 4, 2024, in the Sportiva cave T_{min} = -3.57^{0}C on January 13, 2024, and in the Akullt cave T_{min} = -1.53^{0}C was recorded on January 30, 2024.

Figure 4: *Ice in Shpella Akult, photo Alberto Righetto.*

4. Discussion and future work

After 17 expeditions, the consistent exploration of the caves of the upper part of the Valbona valley - the Valbona Project - it has only been possible to partially describe and understand this high-mountain karst area. The total lenght of surveyed passage it's almost 8 km in 199 caves. The deepest cave we have explored - Shpella e Valbones with a depth of -725 m is currently the deepest cave in Albania and the entire Prokletije massif. It has the potential to be deepened to over -1000 m and in the coming years we will try to achieve this. Equally important to the exploration of the caves are the parallel scientific studies, which we have partially described in the article.

We are planning further work because the massif to the south of the Valbona River contains the tracks of paleokarst. In some dolinas, there are outcrops of calcite crystals that, due to their habitus, could be considered of hydrothermal origin. In the same dolinas, one can observe the outcrops of "fossil flowstone", remnants of an ancient unroofed cavity.

Quartz sand and silicate pebbles were collected in the Spella Valbones Cave. Nowadays, no rocks that could be the source of these sediments are bedded close to the karst massif. That means that the massif's karstification started in time when it was in another tectonic position, most likely in the Miocene.

To reconstruct the climate history of the last centuries, several cores of the old-growing trees (species of pines) were collected.

There is a lot of work ahead of us to understand and describe this interesting karst area. We are open to cooperation. If you would like to support our activities, please contact us.

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- the Albanian Speleological Scientific Didactic Association, especially prof. Perikli Qirjazi and the secretary of the Association Etmond Cauli, thanks to which we obtain permission for exploration and scientific activities in the area of Valbona Valley National Park
- the Jubani family, who help us organize the transport of equipment to the upper base and host us in their Guesthouse Kol Gjoni.
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Session 09

EXPLORATION, SPELEOLOGICAL TECHNIQUES, AND MATERIALS

09:3: Topography, Mapping, 3D Scanning, and Documentation

3-D LIDAR mapping and visualization of Las Cabachuelas cave systems in Morovis, Puerto Rico

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Abstract

In the Puerto Rico archipelago, there are around 2,000 to 3,000 caves in the three karst formation zones of the island. Among these zones are the northern limestone zone, the southern limestone zone and the scattered limestone including the adjacent islands of Mona, Monito, Caja de Muertos and Vieques. The Las Cabachuelas Natural Reserve (RNLC) is part of the northern limestones and is in the municipality of Morovis, Puerto Rico. The RNLC cave system consists of approximately more than 60 caves. Our study consists of the acquisition of high-resolution cave geometric data with light detection and ranging (LIDAR). So far, we have around 12 caves mapped using the Geoslam Zeb 1 Horizon LiDAR for a total distance of approximately 1.5 km with more than 200 million data points collected. These three-dimensional maps are used for scientific research, education and outreach, cave printing, ecotourism and security. Another use for this data is the creation of visualizations for computers and virtual reality for the enjoyment of everyone, including people with disabilities and difficulties accessing caves.

Resumen

En el archipiélago de Puerto Rico existen alrededor de 2,000 a 3,000 cuevas en las tres zonas de formación kársticas de la isla. Entre estas zonas se encuentra la zona de caliza del norte, la zona caliza del sur y la caliza dispersa incluyendo las islas adyacentes de Mona, Monito, Caja de Muertos y Vieques. La Reserva Natural Las Cabachuelas (RNLC) es parte de las calizas del norte y se encuentra en la municipalidad de Morovis, Puerto Rico. El sistema de cuevas de RNLC consites en aproximadamente más de 60 cuevas. Nuestro estudio consiste en la adquisición de datos geométricos de cuevas de alta resolución con detección de objetos mediante láser (LiDAR: light detection and ranging). Hasta el momento tenemos alrededor de 12 cuevas cartografíadas utilizando el Geoslam Zeb 1 Horizon LiDAR para una distancia total de aproximadamente 1.5 Km con mas de 200 Millones de datos. Estos mapas en tres dimensiones sirven para investigaciones científicas, educación y extensión, impresión de cuevas, ecoturismo y seguridad. Otra utilidad de estos datos son la creación de visualizaciones para computadoras y realidad virtual para el disfrute de todos, incluyendo personas con impedimentos y dificultades para el acceso de cuevas.

1. Introduction

Organized cave exploration involves the physical pursuit of the discovery of caves and cave systems, and scientific field documentation that can be in the form of GPS location, karst formations, cave speleothems, and survey documentation (KAMBESIS, 2007). The survey presents to the explorer the necessary information about safe passage features, and symbols can represent specials features such as: pictographs, speleothem, bats roost areas, unhealthy cave regions, and sensible cave areas. A survey promotes responsible caving, integrating science, tourism and exploration to preserve the cave environment (NSS, 2016).

In the Puerto Rico archipelago, there are around 2,000 to 3,000 caves in the three karst formation zones of the island. Among these zones are the northern limestone zone, the southern limestone zone and the scattered limestone including the adjacent islands of Mona, Monito, Caja de Muertos and Vieques. Las Cabachuelas Nature Reserve is in Morovis and Ciales, PR (Figure 1) and was declared as a preserved site in February 2012 due to its natural and historical value. The northern part of the municipality of Morovis is part of the Northern Karst Belt Zone of Puerto Rico. The reserve consists in approximately a cave system of 60 caves. Las Cabachuelas has been one of the most significant places for understanding of the first inhabitants of Puerto Rico, as well for the study of regional paleoenvironments in the Caribbean. Recent evidence from radiocarbon dating has identified cave art (pictography and pyrography) in dating to 400 CE. (RODRIGUEZ-RAMOS, 2017). Geologically, the reserve is in the Lares Limestone formation. NELSON & MONROE 1966 describes this formation as a massive hard crystalline pale orange to nearly white locally coralline limestone, and surface and groundwater dissolution processes created the caves.

Figure 1: *Location of Las Cabachuelas Nature Reserve in Morovis, Puerto Rico.*

2. Materials and methods

Light Detection And Ranging (LiDAR) was used to create 3-D cave maps. LIDAR is a surveying method that measures distance to a target by illuminating the target with pulsed laser light (infra-red) and measuring the reflected pulses with a sensor. The Geoslam ZEB1 (3-D Laser Mapping) handheld mobile LiDAR was used to obtain the measurements. Figure 2 show the system. Mobile laser scanning system that uses relative measurements to the environment that travels. The system maps the area in around the same time it takes to walk. The data acquisition speed is 43,200 pts/s with a range of 30 m. The field of view: 270^0 by 100^0 and its source is a 905 nm laser diode (infra-red). The data processing consists in that the system estimate the trajectory (position and orientation) using simultaneous localization and mapping (SLAM). After the processed point cloud, the data is clean for non-cave elements such as exterior trees, roots, etc. The clean data then was used for the map. The tridimensional cartography was created using point cloud routines in MATLAB (pcread and pcshow).

Figure 2: *Geoslam Zeb1 handheld mobile lidar.*

3. Results

Las Cabachuelas Nature Reserve region consists of approximately 60 caves. For this study we created the cave maps for 10 caves: Cristales Cave, Gemelos Cave, Corazón Cave, Buruquena Cave, Catedral Cave, Estancita Cave, Espiral Cave, Dos Tres Pisos Cave, Palomas Cave and Lagartijos Cave. A total of approximately 0.77 Km were cartographied and 136.5 million data points collected. The maps created can be used to develop ecotourism guided routes, cave safety management and develop mitigation plans for karst biodiversity and land protection. These three-dimensional maps are used for scientific research, education and outreach, cave printing, ecotourism and security. Another use for this data is the creation of visualizations for computers and virtual reality for the enjoyment of everyone, including people with disabilities and difficulties accessing caves.

Figure 3 show example of the resulted raw data collected for 6 of the caves mapped. In the figure, a scaled map, top profiles and side view are show for those caves. Each gray dot represent a geometrical measurement of the cave, this maps area a 10% illustration of the total collected data for the cave.

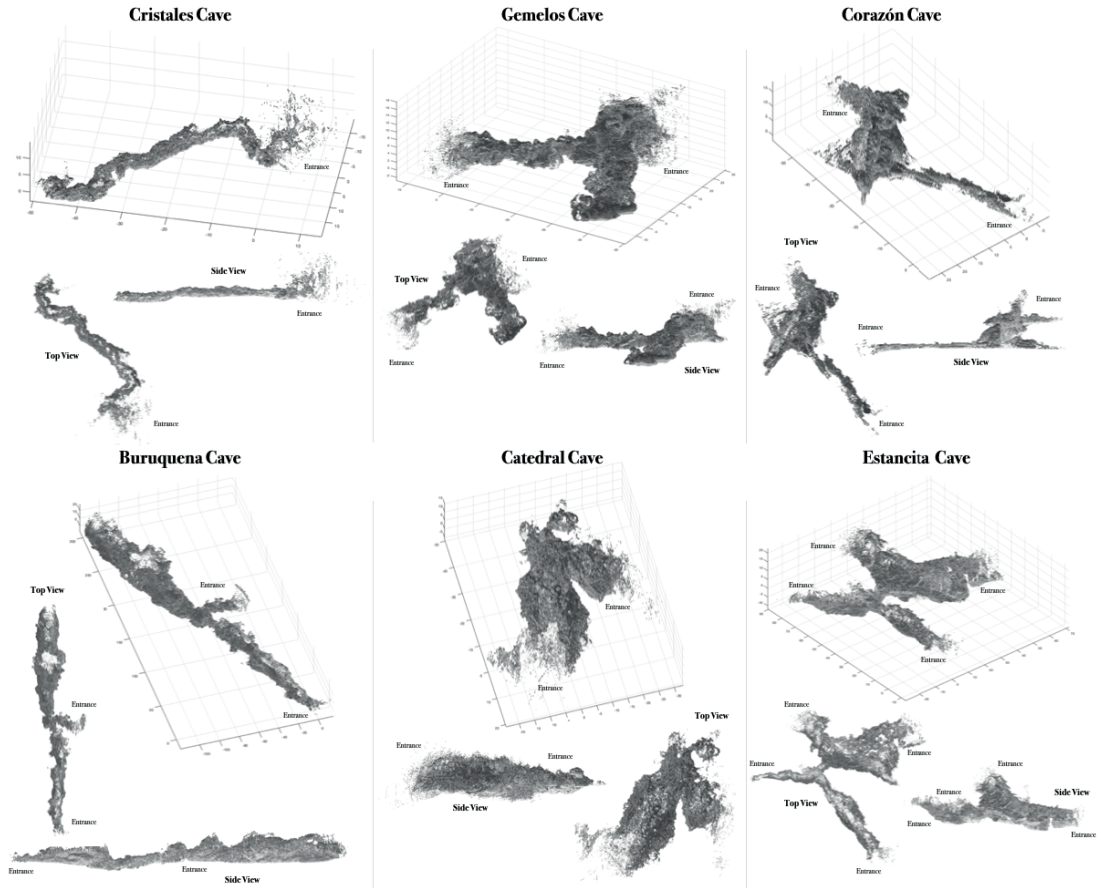

Figure 3: *Some examples of the results of LIDAR measurements for 6 caves in Las Cabachuelas Nature Reserve.*

4. Discussion

Normally, we try to create cave models using 2-D collected data (distance between stations, azimuth and inclination) and a software. An example is caveGEOmap developed by our research group (ACOSTA-COLON & CANDELARIA, 2018). Processing and collecting 2D data to 3D models have its challenges, one of them is the time that takes to collect all the data needed for a good model. For this study, we used the Geoslam ZEB1 LiDAR and it provide us with millions of data points and creates a 3-D point cloud that was used to create a cave model. This LIDAR use slam technology and data time collection takes the same time that we walk the cave. Figure 4 present a summary of the data collected and estimated lineal distance for all the caves of this study. The largest caves were Buruquena Cave (323m) while the smallest was Palomas Cave (18 m). The etymology of the word Cabachuelas come from cava (*caves*) and *chuelas* (*diminutive suffix*), small caves.

Cave Name	Total Collected Data (In millions)	Estimated Lineal Distance (m)
Cristales	6.5	67
Gemelos	14.0	39
Corazón	13.9	44
Buruquena	32.4	323
Catedral	12.9	50
Estancita	20.7	94
Espiral	9.5	54
Dos Tres Pisos	8.5	31
Palomas	8.6	18
Lagartijos	9.5	50
Total	136.5	770

Figure 4: *Summary of LIDAR results for all the caves studied at Las Cabachuelas Nature Reserve.*

Additionally, after collecting the LiDAR data, the high-resolution data was used to create a virtual mesh to build the cave. The data was processed using MeshLab and Cloud Compare to create a polygon mesh (a collection of vertices, edges and faces that create a geometrical model). Then the mesh is used as an object in Unity or Unreal Engine to create a virtual cave that a user can be submerged inside using Meta Quest (or Oculus) VR headsets. This virtual model can be used for education, research and enhance participation for disabled persons. Figure 5 present an example of the products that can be obtained after the data collection.

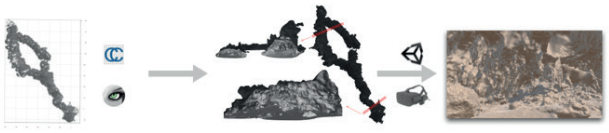

Figure 5: *An example of the process to obtain a cave virtual model from LIDAR data.*

5. Conclusion

Our study was to visualize the Las Cabachuelas Cave System in Morovis, Puerto Rico. The study consisted in the development of 10 caves maps that can be used for research, education, ecotourism and other applications. Additionally, we developed virtual caves environment obtained from real data by using underground LiDAR. In these days, virtual reality is a useful instrument to do activities and exploration that are difficult for an audience. Virtual Reality also is increasing as a tool to develop accessibility and inclusion of people with disabilities, elderly, children and others. The visualization of Las Cabachuelas cave system will provide additional awareness for karst system and caves in Puerto Rico, promoting their protection and conservation.

Acknowledgments

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Espeleotopografia: análise comparativa de topografia convencional e laser scanner nas cavidades NAWS_0072 e N4QS_0073, Serra Norte, Parauapebas - PA

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Resumo

Tradicionalmente, a topografia convencional em cavernas é realizada de forma manual, um método que exige tempo para as especificações e detalhamento do levantamento topográfico, conforme a BCRA – 5D (Classificação de detalhe para mapeamento topográfico de cavernas, conforme a British Cave Research Association). Em contrate a isso, o uso de geotecnologias como o Laser Scanner em estudos espeleológicos tem se tornado cada vez mais necessário em trabalhos topográficos, devido à sua precisão, velocidade e segurança na coleta de dados. Partindo desse entendimento, este trabalho tem como objetivo avaliar as diferenças entre os métodos aplicados, com foco em precisão, detalhamento e eficiência. Para essa análise, foi utilizado a topografia de duas cavidades, a N4WS_0072 e N4WS_0073, localizadas no município de Parauapebas – PA. Para a comparação de dados, ambas foram topografadas utlizando o método convencional e Laser Scanner. Para tal, foi feita a sobreposição dos dados da linha de parede a partir da topografia convencional e a nuvem de pontos oriunda da tecnologia Laser Scanner. Os resultantos apresentaram discrepância nos dados de área, volume, desenvolvimento e desnível. No entanto, ambos os métodos são eficientes e, em alguns casos, até se complementam em situações especificas, especialmente em contextos onde os recursos tecnologicos não estão disponveis ou em situações especificas em que se mostram adequados.

Abstract

Traditionally, conventional topography in caves is performed manually, a method that requires time for specifications and detailing of the topographic survey, according to BCRA. In contrast, the use of geotechnologies such as Laser Scanner in speleological studies has become increasingly necessary in topographic work, due to its precision, speed and safety in data collection. Based on this understanding, this work aims to evaluate the differences between the applied methods, focusing on precision, detail and efficiency. For this analysis, the topography of two cavities, N4WS_0072 and N4WS_0073, located in the municipality of Parauapebas - PA, was used. For data comparison, both were topographically performed using the conventional method and Laser Scanner. For this purpose, the wall line data from the conventional topography and the point cloud from the Laser Scanner technology were superimposed. The results showed discrepancies in the area, volume, development and unevenness data. However, both methods are efficient and, in some cases, even complement each other in specific situations, especially in contexts where technological resources are not available or in specific situations in which they are appropriate.

Resumen

Tradicionalmente, la topografía convencional en cuevas se realiza de forma manual, método que demanda tiempo para la especificación y detalle del relevamiento topográfico, según el BCRA. Por otra parte, el uso de geotecnologías como el Láser Scanner en estudios espeleológicos se ha hecho cada vez más necesario en los trabajos topográficos, debido a su precisión, rapidez y seguridad en la toma de datos. Partiendo de esta base, este trabajo pretende evaluar las diferencias entre los métodos aplicados, centrándose en la precisión, el detalle y la eficiencia. Para este análisis se utilizó la topografía de dos cavidades, N4WS_0072 y N4WS_0073, ubicadas en el municipio de Parauapebas - PA. Para la comparación de datos ambos fueron topográficos utilizando el método convencional y Laser Scanner. Para ello se superpusieron los datos de

las líneas de pared de la topografía convencional y la nube de puntos de la tecnología de escáner láser. Los resultados mostraron discrepancias en los datos de área, volumen, desarrollo y desnivel. Sin embargo, ambos métodos son eficaces y, en algunos casos, incluso se complementan en situaciones específicas, especialmente en contextos donde no se dispone de recursos tecnológicos o en situaciones específicas en las que éstos resultan apropiados.

1. Introdução

O uso de geotecnologias em estudos ambientais tem se tornado cada vez mais necessário, devido a sua precisão, velocidade e segurança na coleta de dados. A aplicação e a adaptabilidade dessas tecnologias, aliadas ao rigor metodológico, têm sido amplamente empregadas em pesquisas espeleológicas sobre tudo em levantamento topográfico.

Tradicionalmente, a topografia de cavernas é realizada de forma manual, com uso de instrumentos como bússolas, clinômetro e trena, o que exige tempo e especificações quanto à precisão e ao nível de detalhamento, gerando a necessidade de otimizar o processo aquisição de dados. A tecnologia LIDAR (Light Detection and Ranging) surge a partir dessa necessidade de se obter dados robustos e de alta precisão.

O uso de laser scanner na topografia de cavernas tem revolucionado a forma como esses ambientes complexos e de difícil acesso são mapeados e mensurados. O scanner à laser supera essas restrições ao permitir a coleta rápida de dados geométricos, mesmo em áreas de difícil acesso ou instáveis, o que reduz significativamente os riscos aos profissionais.

Essa tecnologia, que emprega o princípio de emissão de feixes de luz laser para capturar milhões de pontos em alta resolução, possibilita a criação de modelos tridimensnais detalhados das formações internas das cavernas (ARAUJO et al. 2015) ; (MARQUES et al. 2019).

1.1. Área de estudo

As cavidades N4WS_0072 e N4WS_0073, ilustradas na (figura 1), estão localizadas no município de Parauapebas, no estado do Pará. Essas cavidades foram selecionadas para este estudo por terem terem sido topografadas utilizando tanto a metodologia convencional quanto o Laser Scanner, possibilitando uma comparação detalhada entre os dados obtidos por ambas as técnicas. O principal objetivo deste trabalho é avaliar as diferenças entre os métodos aplicados, com foco em precisão, detalhamento e eficiência.

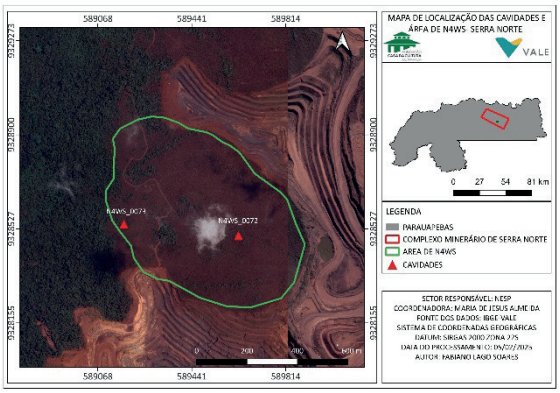

Figura 1: *Localização das cavidades de estudo.*

2. Materiais e Métodos

2.1. Topografia convencional de cavidades

Para a aquisição de dados utilizando a metodologia convencional, é necessário contar com uma equipe composta por diferentes profissionais, sendo um desenhista (responsável pelo desenho e detalhamento da caverna, planejamento e orientação metodológica dos procedimentos técnicos) ; um instrumentalista (encarregado da coleta de medidas, utilizando trena a laser para distancias, bússola para azimutes, e clinômetro para declividade); um anotador (responsável por registrar os dados espeleométricos na ficha topográfica); e um apontador de trena (responsável por auxiliar nas observações e realizar o registro fotográfico das atividades).

No mapeamento espeleológico, os dados topográficos são levantados utilizando trena a laser e bússola com clinômetro de visada. Esses dados servem com base para a confecção dos croquis em papel milimetrado, com o auxilio de escalímetro e transferidor. As informações coletadas são registradas na ficha de topografia, sendo levadas em consideração tanto a morfologia da cavidade quanto os depósitos sedimentares mais importantes (clásticos, químicos, orgânicos, entre outros).

A metodologia aplicada segue as configurações definidas pelo sistema **British Cave Research Association (BCRA)** no nível de detalhe 5D (quadro 1 e 2), que oferece o detalhamento máximo das características morfológicas, hidrogeológicas e geoespeleológicas, entre outras.

Quadro 1: *Graus de precisão do método BCRA para a linha central da topografia.*

Grau	Descrição
1	Esboço de baixa precisão, sem medições tomadas em campo.
2	A ser usado, somente se necessário, para descrever um esboço com precisão intermediária entre os Graus 1 e 3.
3	Levantamento magnético de baixa precisão. Ângulos horizontal e vertical medidos com precisão ± 2,5º e distâncias medidas com precisão ± 50 cm; erro de posição da base menor que 50 cm.
4	A ser usado, somente se necessário, para descrever um levantamento que, apesar de mais preciso que o Grau 3, não tenha alcançado os requisitos do Grau 5.
5	Levantamento magnético. Ângulos horizontal e vertical medidos com precisão ± 1º,distâncias medidas com precisão de1 cm e erro de posição da base menor que 10 cm.
6	Levantamento magnético com precisão maior que a de Grau 5.
X	Levantamento topográfico utilizando-se teodolito ou Estação Total ao invés de bússola

Quadro 2: *Graus BCRA para registro de detalhes de conduto.*

Grau	Descrição
A	Detalhes das galerias baseados na memória.
B	Detalhes das galerias estimados e anotados na caverna.
C	Medidas de detalhe realizadas apenas nas bases topográficas.
D	Medidas de detalhe realizadas nas bases topográficas e entre elas, de modo a representar mudanças morfológicas na galeria.

2.2. Topografia com Laser Scanner

Esse método de topografia é desenvolvido por uma equipe de profissionais, neste estudo foi utilizando o aparelho portátil Scanner a laser GEOSLAM – ZEB REVO, trena a laser e bússola SUNTON. Incialmente, é feita a exploração dos condutos da caverna para observar a morfologia e planejar estratégias de trabalho que garantam o melhor trajeto para levantamento topográfico, otimizando o tempo e garantindo a qualidade dos dados coletados. Após a coleta, os dados são processados e consolidados, gerando nuvens de pontos que passam por georreferenciamento, tornando-se aptas para análises e cálculos espeleométricos.

O processo de digitalização 3D segue etapas bem definidas, sendo: aquisição de atributos geomorfométricos das cavernas, geração de nuvens de pontos para detalhes da morfologia, georreferenciamento e criação de modelos numéricos em malhas com precisão centimétrica ou milimétrica, dependendo da configuração e velocidade de leitura do equipamento. Os dados resultantes são compatíveis com plataformas GIS e podem ser exportados para softwares CAD, após o devido processamento.

OS dados obtidos por meio do escaneamento a laser serão processados no Sofware CloudCompare para a realização da limpeza da nuvem de pontos removendo assim ruídos e imperfeiçoes. Em seguida, é aplicada uma reamostragem da nuvem de pontos para uniformizar os dados por meio da ferramena Cloud Subsampling do software e CoudCompare, que permite ajustar a densidade dos pontos de acordo com as necessidades do projeto (Figura 2). Esse procedimento garante a eficiência no processamento e na analise posterior, sem comprometer a precisão dos modelos gerados.

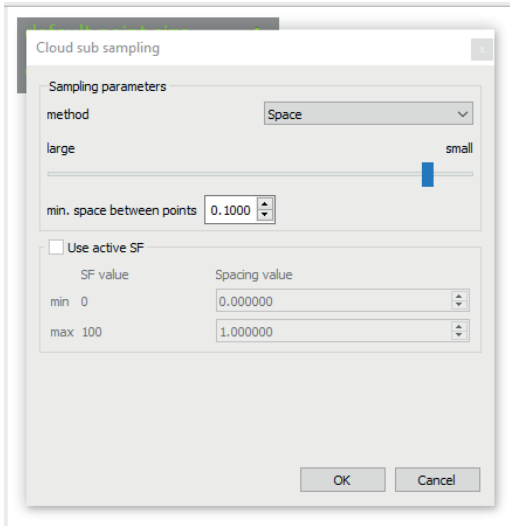

Figura 2: *Representação da re-amostragem da nuvem de pontos.*

Para obtenção do cálculo de volume e extração da planta baixa, perfis e seções, a nuvem de pontos é transformada em malha através do cálculo das normais aplicando o comando *local modern sur-face: triangulation*, minimum spanning tree *knn* = 3, coforme demonstrado na figura 3.

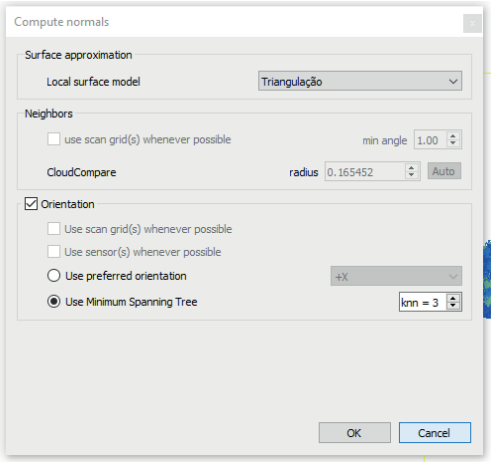

Figura 3: *Representação do comando para cálculo das normais.*

Após o cálculo das normais o sólido é gerado com a utilização da ferramenta Poisson Surface Reconstruction, com parâmetro Octree Depth. E a partir da obtenção do sólido, é calculado o volume e extraído os demais dados representativos como planta baixa, perfil/perfis e seções. Após a extração dessas informações, os dados são trabalhados no software *AutoCad* onde é montado o layout do mapa.

3. Resultados

O mapeamento convencional destas cavidades, baseado nas conveções do método ***British Cave Research Association*** (BCRA) em nível de detalhe 5D, foi realizado no ano de 2009. Deste então, observa-se que houve avanços significativos na metodologia de trabalho, incluindo a inserção do ponto zero, indicação de tetos baixos e condutos inacessíveis. Essas informações impactam diretamente nos dados espeleométricos, aprimorando a precisão e o detalhamento das informações. Por outro lado, o mapeamento com scanner a laser foi realizado recentemente, em 2023, utlizando o modelo ZEBO REV HORIZON, destcando-se pela aplicação de tecnologia mais avançada para coleta e processamentos de dados espeleométricos.

Com o objetivo de realizar uma análise comparativa entre o os dados gerados, foram avaliados os mapas finais (Figura 4). Observa-se que os contornos das cavernas, representados pelas linhas em preto no modelo 5D, não exigem precisão ao modelo mais recente obtido pelo Laser Scanner, representado pela nuvem de pontos na coloração rosa. Essa discrepância evidencia as limitações da metodologia convencinal em caputrar detalhes com o mesmo nível de exatidão forncecido pela tecnologia de scanner a laser. Os gráficos apresentados na figura 5 sistematizam essa discrepância. A coluna azul representa os dados obtidos pelo mapeamento convencional 5D, enquanto a coluna cinza corresponde aos resultados gerados pelo Laser Scanner. Essa comparação visual evidencia as diferenças entre os dois métodos, permitindo identificar as limitações do mapeamento convecional frente à tecnologia e ao detalhamento fornecido pelo escaneamento a laser.

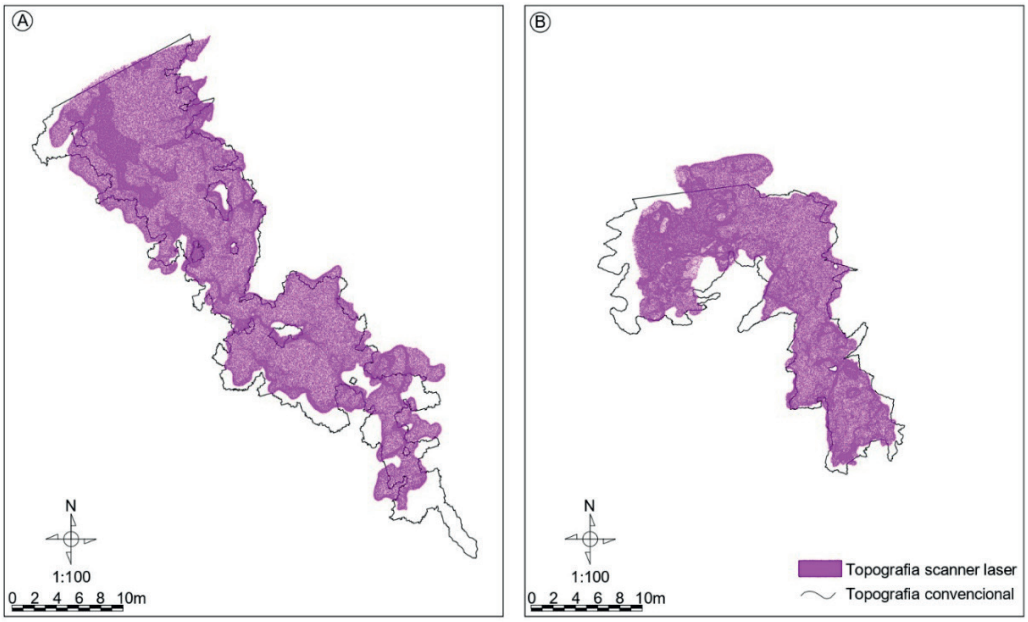

Figura 4: Mapas topográficos. (A) Mapa de N4WS_0072, com a sobreposição da linha de parede interna em preto, elaborada em 2009, com a malha da nuvem de pontos gerada pelo scanner a laser em 2023. (B) Mapa de N4WS_0073 Mapa de N4WS_0072, com a sobreposição da linha de parede interna em preto, elaborada em 2009, com a malha da nuvem de pontos gerada pelo scanner a laser em 2023.

4. Discussão

A comparação revela diferenças significativas de área, volume, desenvolvimento e desnível destas cavidades, conforme organizado nos gráficos exposto na figura (5). Na cavidade **N4WS_0072**, o desenvolvimento apresentou diferença de 30,59m, o desnível 1,16m, Área 41,38m² e volume 399,90m³. Já na cavidade **N4WS_0073**, as diferenças de 16,06m no desenvolvimento, 2,32m no desnível, 47,05m² na área e 279,74m³ no volume. Esta análise evidencia a disparidade em atributos gerados pelos diferentes métodos de mapeamentos. O Método que utiliza o scanner a laser demosntra maior precisão, pois é capaz de captar elementos essenciais para o cálculo das variaveis, como contornos detalhados, níveis do salão, pilares internos, áreas de teto baixo e contornos inferior e superior ; Simões (2019). Muitas vezes, esses elementos não são acessecíveis ao pesquisador durante o mapeamento convencional devido a limitações físicas e biologicas, Fernandes et al.,(2023). No entanto, o método de elaboração 5D não é descartado, pois tambem desempenha um papel significativo nas pesquias, especialmente em contextos onde os recursos tecnologicos não estão disponveis ou em situações especificas em que se mostram adequados. Ambos os métodos se complementam, contribuindo de maneira relevante para o avanço dos estudos espeleológicos assim visto por Da Silva Assunção et al., (2015).

A figura 6 apresenta, de forma sintetica e em percentuais, as diferenças nos dados de área, desnível, volume e desenvolvimento obitidos em comparação as duas metodologias aplicadas.

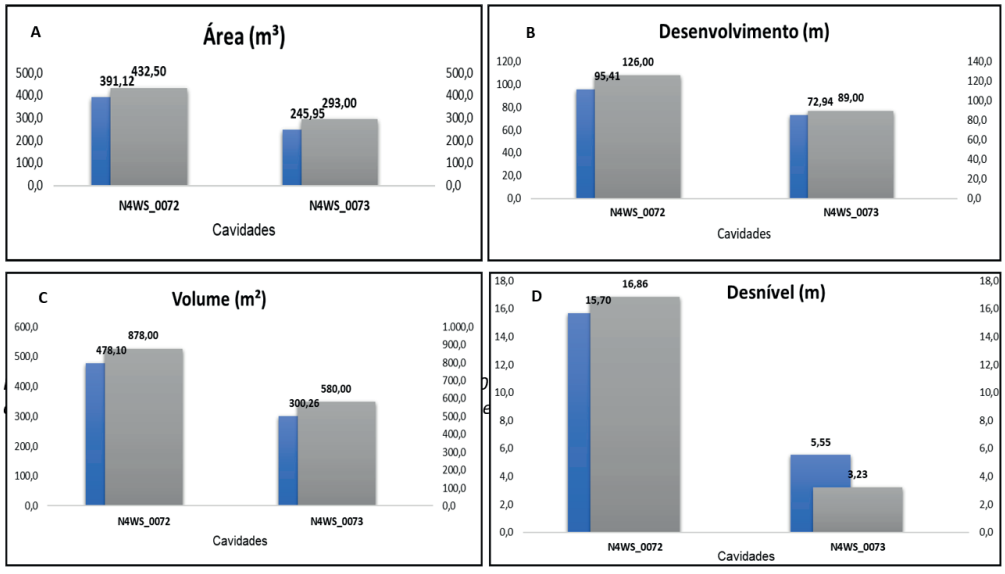

Figura 5 : Dados espeleométricos das cavidades N4WS_0072 e N4WS_0073 em coloração azul, método BCRA- 5D em coloração cinza, scanner a laser – (A) Área , (B) Desenvolvimento, (C) Volume e (D) Desnível.

N4WS_0072			
Área	Desnível	Volume	Desenvolvimento
9,57%	6,88%	45,54%	24,27%
N4WS_0073			
Área	Desnível	Volume	Desenvolvimento
16,05%	41,80%	93,17%	18,04%

Figura 6: *Dados espeleométricos das cavidades N4WS_0072 e N4WS_0073, diferença em percentuais na compração de dados entre as metodologias.*

5. Conclusão

Fica evidente, através deste estudo de caso, que no método de mapeamento com uso de scanner a laser, os dados espeleométricos obtidos, principalmente volume são mais precisos. Além da agilidade na coleta das informações, ganho de tempo, e maior exatidão em relação ao método convencional. O uso de tecnologia tem se tornado mais popular devido a sua economia de custo e agilidade na coletas de informações. A análise deste trabalho, demostra a diferença entre os dois métodos aplicados, apresentando área, volume, desnivel e desenvolvimento discrepantes no qual os scanners a laser oferecem precisão e velocidade, já o método 5D, analises mais complexas e dinâmicas. No entanto é importante observar que, apesar da topografia convencional ser mais demorada e menos precisa, ambos os métodos se complementam, contribuindo de maneira relevante para o avanço dos estudos espeleológicos.

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Vale do Rio Gameleira – Redescobertas Espeleológicas no P.A. Gameleira e Entorno

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Resumo

A região do estudo encontra-se na área do Planalto Central Brasileiro, no município de Flores de Goiás, em região próxima da divisa dos estados de Goiás e Minas Gerais. Ambos cadastros nacionais, CNC e Canie, apresentam registros de cavidades na região do Vale do Rio Gameleira, com nomes das cavidades idênticos na identificação, entretanto com localizações não coincidentes. O estudo se propôs à confirmação desses registros, de modo a corroborar como hipótese a importância de redundância das informações em ambos os cadastros, passando por suas validações e consequentemente o aumento do conhecimento espeleológico. Além desses, a oportunidade para trazer em evidência a maior relevância das cavidades presentes na região, sejam por suas formações geológicas, aspectos arqueológicos ou diversidade biológica. Como resultado do projeto, foram confirmadas a localização de 5 cavidades, integradas e corrigidas informações entre os cadastros nacionais, efetuado o mapeamento de precisão, coletado dados possíveis de avistamento, registros arqueológicos e fotográficos.

Abstract

The study region is located in the Brazilian central area (Planalto Central), in the municipality of Flores de Goiás, in a region close to the border of the states of Goiás and Minas Gerais. Both national caves registries, CNC and Canie, present records of cavities in the Gameleira River Valley region, with identical cavity names in the identification, however with non-coinciding locations. The study had the objetive to confirm these records, in order to corroborate as a hypothesis the importance of redundancy of information in both caves registries, with validation process and consequently increasing speleological knowledge. In addition to these, the opportunity to highlight the greater relevance of the cavities present in the region, whether due to their geological formations, archaeological aspects or biological diversity. As a result of the project, the location of 5 cavities was confirmed, information was integrated and corrected between national registries, precision mapping was made, speleological, archaeological datas and photographic records were collected.

1. Introdução

A região do Vale do Rio Gameleira se encontra em área próxima da divisa dos estados de Goiás e Minas Gerais, distante cerca de 300km da capital federal. O local de estudo está situado no município de Flores de Goiás-GO, próximo ao distrito de Goiaminas, este pertencente ao município de Formoso/MG, na região de entorno do Projeto de Assentamento (P.A.) Gameleira. O município de Flores de Goiás encontra-se na porção nordeste do estado de Goiás, o qual está inserido no limite leste da Faixa de dobramentos Brasília (em contato com o cráton São Francisco), pertencente à Província Tocantins (MOREIRA, M. L. O. et al., 2008).

A região apresenta afloramentos calcáreos ao sul do Rio Gameleira, enquanto ao norte está a extensa Serra Geral do Goiás, prolongando-se até a divisa com Estados da Bahia e Goiás. Está inserida na unidade de relevo Chapadas do Rio São Francisco (IBGE, 2006) e integra a Sub-bacia do Tocantins.

A área já foi prospectada nos anos de 2010, mais precisamente em 2014, tendo pontos de cavidades registrados nos cadastros nacionais espeleológicos - Cadastro Nacional de Informações Espeleológicas (Canie), gerido pelo Centro Nacional de Pesquisa e Conservação de Cavernas - ICMBIO/CECAV, e o Cadastro Nacional de Cavernas (CNC) gerido pela Sociedade Brasileira de Espeleologia (SBE). Apesar de constarem na região objeto do estudo a presença de 25 cavidades cadastradas no Canie e 44 cavidades cadastradas no CNC não coincidentes geograficamente, não houve estudo que possibilite a convergência dos registros para redundância das informações em ambos os cadastros.

A proposta do projeto foi de investigar a confirmação de localização de 5 cavernas que se localizam na região do entorno do Projeto de Assentamento Gameleira (P. A. Gameleira), em área rural denominada de Fazenda Sete Rios, promovendo além de sua confirmação entre CNC e Canie a prospecção e seu mapeamento.

O escopo tratou-se da conferência das 5 cavernas registradas para a Fazenda Sete Rios de acordo com Canie, bem como as 3 cavernas coincidentes em nomes registradas na mesma região para o CNC. Destaca-se que não foram localizados mapeamentos nos cadastros consultados das cavernas na área de objeto específico do estudo (cavernas Sete Rios I a V do Canie e Sete Rios I a III do CNC) que possam trazer maior conhecimento sobre o patrimônio espeleológico da região.

O trabalho foi realizado pelos membros associados do Espeleo Planalto Central (EPC), grupo localizado em Brasília-DF – Brasil, formado em setembro de 2021, e dedicado a pesquisa e proteção das cavidades naturais subterrâneas, divulgação e incentivo à espeleologia, bem como a congregação de espeleólogos e demais interessados.

2. Materiais e Métodos

Para os trabalhos de campo foram utilizados EPI convencionais de espeleologia, como botas, macacões, capacetes, lanternas, perneiras, luvas. Para as prospecções também foram utilizados repelentes, protetores solares, telas de proteção contra vespas e abelhas, e facão para transpor áreas com vegetação mais densa.

Para localização em campo foi utilizado equipamento GPS marca Garmin modelo GPSMAP 65. Foram gravados os caminhamentos e a marcação dos pontos de localização ocorreram o mais próximo possível das bocas para amarração à linha de trena do mapeamento espeleológico. Quando da existência de mais de uma boca na caverna optou-se pela marcação do ponto na boca mais próxima aos acessos mais fáceis ou de melhor referência para o caminhamento em mata, sendo a topografia da caverna iniciada por esta base topográfica.

Para o mapeamento foram utilizados equipamentos analógicos e digitais, conforme a seguir:

- Bússola Suunto KB-14/360R
- Clinômetro Suunto PM-5/360
- Trena Laser Bosh GLM40
- BRIC5

Para o mapeamento digital em campo foi utilizado o software Topodroid versão 6.2.44-34, instalado em tablet proprietário de membros do grupo. Para a finalização digital dos mapas foi utilizado o software Adobe Illustrator e Photoshop, os dados espeleométricos foram calculados por meio do software Compass versão 5.24.2.26.228.

Para localização das cavernas na região foram previamente carregados em aparelho GPS a localização das cavernas constante nos cadastros do CNC e Canie. Quando confirmada a localização da caverna foram tomadas as anotações para preenchimento de ficha de cadastro das mesmas, confirmada sua localização e iniciado o mapeamento em campo. Em escritório foram tratados os dados de campo e efetuada a digitalização dos mapas das 5 cavernas objeto do projeto.

3. Resultados

Na execução do projeto foram realizadas 6 saídas de campo, e 03 reuniões de alinhamento e planejamento das atividades, além de treinamento para utilização de equipamentos. Para execução das atividades de escritório foram distribuídas atividades e responsabilidades entre os integrantes do projeto. As reuniões ocorreram em ambiente virtual. Todas as atividades de campo ocorreram no ano de 2024, entre os meses de abril a setembro com uma incursão a campo por mês.

A região prospectada se apresenta em vegetação típica do Bioma Cerrado, as cavernas foram localizadas na região da Fazenda Sete Rios, em área privada, próxima de pasto e sem indícios de degradação.

Figura 1: *Feições geomorfológicas encontradas na região de estudo (acervo EPC - agosto 2024).*

As prospecções concentraram-se na época de estiagens ao longo de 2024, a fim de facilitar o caminhamento em mata e também para que o deslocamento de carro não fosse interrompido em virtude de pontes precárias, que podem apresentar instabilidade nos períodos de forte chuvas. A figura 1 a seguir demonstra ponte de madeira típica da região que foi substituída recentemente por ponte em concreto, garantindo maior segurança nos deslocamentos.

Figura 2*: Pontes de acesso à região. À esquerda ponte de madeira em condições precárias, à direita nova ponte em concreto (acervo EPC).*

As cavernas encontradas se apresentaram em rocha calcárea, com espeleotemas típicos tais como, estalactites, estalagmites, escorrimentos, cortinas, além de fauna característica de cavernas, tais como morcegos, aranhas e amblipígeos. Alguns gotejamentos encontrados, porém, sem indícios de elementos permanentes de hidrologia em todas as cavidades exploradas. Corroborando registro de pinturas rupestres em cavernas próximas da região, foram identificadas pinturas rupestres nas cavidades exploradas pelo projeto, as quais foram registradas junto ao IPHAN.

Ao longo das prospecções além das confirmações dos pontos das cavidades foram identificadas também alguns abrigos de pequenas dimensões, poços de pequena profundidade e outros que por necessitarem de acesso por meio de técnicas verticais não foram explorados.

A figura 3 ao final apresenta so resultados comparativos em visão espacializada dos registros presentes no CNC e Canie, juntamente com as confirmações efetuadas pelas expedições do EPC. Foram confirmadas as localizações das 5 cavidades registradas no Canie, sendo que apenas a caverna denominada Sete Rios III coincidiu em localização para ambos os cadastros. As cavernas Sete Rios I e II do cadastro no CNC não foram localizadas nas coordenadas geográficas registradas. As localizações cadastradas de ambas se encontram em região de solo sem presença de rochas aparentes. Nas proximidades a equipe não localizou indícios de presença de cavernas em diferentes momentos de prospecção.

A confirmação das localizações e mapeamento efetuados permitiram o aumento do grau de precisão no Canie, passando as cinco cavernas ao nível III, maior grau de validação graças aos mapeamentos efetuados.

Outro destaque foi a presença confirmada de figuras rupestres na região, sendo as cavernas Sete Rios III, IV e I confirmadas com essas

tipologias com equipe convidada do IPHAN (Instituto do Patrimônio Histórico e Artístico Nacional). Os registros encontrados foram de pinturas rupestres e ferramentas líticas, nas três cavernas III, IV e I, as quais, apesar da denominação não sequencial, estão próximas, uma ao lado da outra, separadas por curto trecho de mata (vegetação de cerrado denso em estágio de regeneração, pois elas se encontram no fundo de uma área de pastagem, onde o pasto encontra o afloramento carbonático).

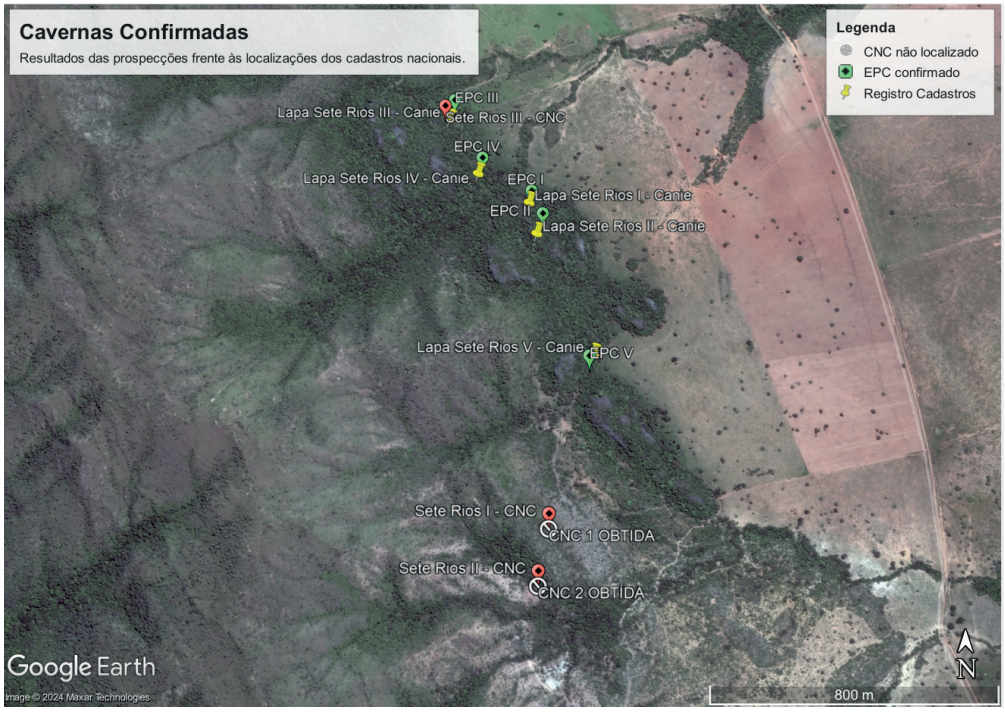

Figura 3: *Mapa com a disposição dos pontos de cavernas nos cadastros nacionais e confirmação de localizações pelo EPC no âmbito do projeto (Fonte Google Earth adaptado EPC).*

4. Discussão

Como resultado do projeto as coordenadas das cavernas Sete Rios I e II no CNC foram corrigidas, e além dessas foram cadastradas as cavidades Sete Rios IV e V no CNC, que constavam apenas no Canie, assumindo os registros GO-887 e GO-888 respectivamente. As cavernas já registradas no Canie passaram de nível de validação nível I para nível III com a topografia amarrada em localização geográfica.

A caverna com maior desenvolvimento encontrado foi a Sete Rios IV, sendo a Sete Rios I com maior boca, e aparentemente maior volume apesar de não apresentar zonas afóticas.

A menor caverna foi a Sete Rios V, que apresentou entrada rastejante acompanhando o mergulho da rocha no solo.

Figura 4: *Visão de dentro com entrada de luz pela maior Boca da Caverna Sete Rios I (acervo EPC).*

A identificação de pinturas rupestres e demais achados arqueológicos nas Cavernas da Lapa Sete Rios I, III e IV, aumentam sua relevância para região. Os indícios encontrados foram cadastrados junto ao Iphan e o grupo acompanhou técnicos do instituto em vistoria de campo.

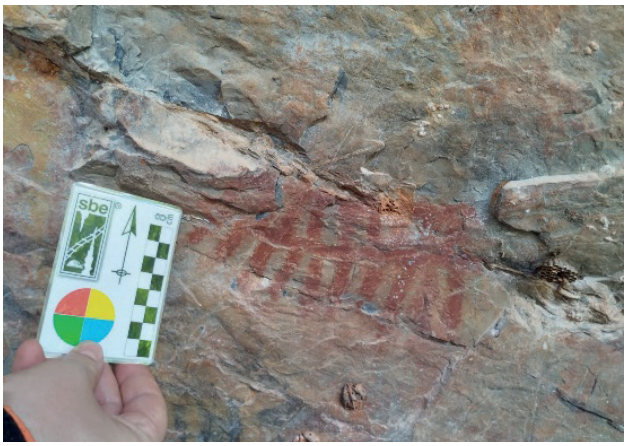

Figura 5: *Exemplo de figura rupestre presente na boca da Caverna Sete Rios III (acervo EPC).*

Os resultados das localizações das cavernas frente as prospecções do EPC pelo projeto estão ilustradas na Figura 3 da seção anterior e os resultados do mapeamento de cada cavidade são apresentadas na Tabela 1 ao final.

Dentre os objetivos do projeto com as prospecções, trabalhos de campo e escritório podem ser sintetizadas os seguintes resultados:

i. Identificado e confirmado que as coordenadas dos cadastros da Lapa Sete Rios III coincidem entre o CNC e Canie, confirmando ser a mesma cavidade.

ii. Confirmado que as localizações das cavidades Lapa Sete Rios I e II do CNC estão em local sem presença de cavidades naturais, sendo corrigidas suas informações de localização naquele cadastro.

iii. Confirmada existência da Lapa sete Rios I, II, III, IV e V de acordo com coordenadas e cadastro no Canie.

iv. Registradas as presenças de pinturas rupestres e material lítico nas Lapas Sete Rios III, IV e I, aumentando sua relevância para região. Os indícios encontrados foram cadastrados junto ao Iphan.

v. Aumento da relevância das cavernas na região com exploração de seus condutos, mapeamentos efetuados, descrição de faunas e espeleogêneses encontradas, e dos achados arqueológicos registrados.

vi. Destaca-se o treinamento e aperfeiçoamento adquirido pela equipe nas campanhas de campo, a qual está executando prospecção com uso de aparelho de GPS, leitura de mapas e imagens, e capacitada para topografia de cavernas com equipamentos tradicionais e digitais.

A topografia efetuada com consequente mapas produzidos pelo grupo EPC permitiu ampliar o conhecimento do valor espeleológico das cavernas da região, suas dimensões, avistamento de fauna típica do ambiente cavernícola, dentre a coleta de mais informações que podem oportunizar maior proteção a essas cavidades. Ainda há muitos registros de cavidades na região do P.A. Gameleira a serem estudados, registrados e apresentados a comunidade.

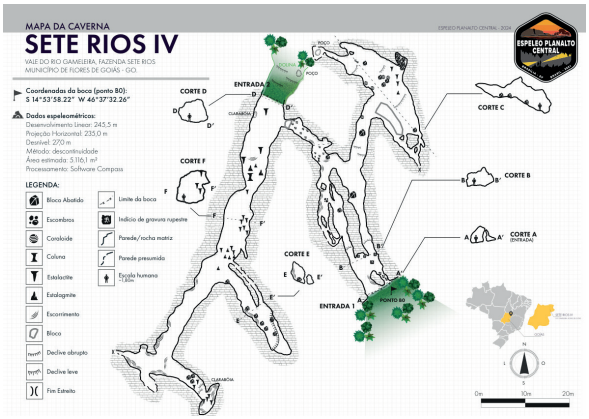

Figura 6: Mapa finalizado da Caverna Sete Rios IV (acervo EPC) ilustrando o material final produzido.

Todos os mapas produzidos no projeto conduzido pelo EPC estão disponíveis para acesso público em formato PDF no website: https://espeleoplanaltocentral.org.br/mapas/

A tabela 1 a seguir apresenta síntese dos principais dados espeleológicos coletados no levantamento das 5 cavidades exploradas e mapeadas.

Tabela 1: Principais dados espeleológicos das cavidades exploradas.

Dados Espeleológicos	Sete Rios I	Sete Rios II	Sete Rios III	Sete Rios IV	Sete Rios V
Confirmação Canie	Sim	Sim	Sim	Sim	Sim
Confirmação CNC	Não	Não	Sim	Cadastro efetuado	Cadastro efetuado
Rocha	Calcárea	Calcárea	Calcárea	Calcárea	Calcárea
Hidrologia presente	Não	Não	Não	Não	Não
Espeleotemas observados	Estalactites, estalagmites, colunas, cortinas.	Escorrimentos, cortinas e coralóides.	Estalactites, estalagmites, escorrimentos, cortina.	Estalactites, estalagmites, pequenas represas de travertinos, coraloides e escorrimentos.	Escorrimentos, cortinas, coraloides.
Fauna observada	Quirópteros, aracnídeos.	Suindara, aranhas, formigas e cascas de caramujos.	Quirópteros, aracnídeos, anuro, cobra e Amblipigio.	Quirópteros, aracnídeos, anuro, cobra e Amblipigio.	Quirópteros, aracnideos e formigas.
Indícios arqueológicos	Sim	Não observado	Sim	Sim	Não observado
Mapeamento	Realizado	Realizado	Realizado	Realizado	Realizado
Desenvolvimento Linear (m)	118,5	25,4	194,9	245,5	15,4
Projeção Horizontal (m)	114,3	24,4	187,9	235,0	14,4
Profundidade (m)	13,3	11,2	12,1	27,0	9,3
Método	continuidade	continuidade	descontinuidade	descontinuidade	descontinuidade
Área estimada (m²)	3.330,3	363,7	3.124,2	5.116,1	197,0
Grau BCRA	4D	4D	4D	4D	4D

5. Conclusão

A execução do projeto permitiu ampliar o conhecimento espeleológico das cavernas da região localizadas próximas ao P.A. Gameleira no município de Flores de Goiás/GO, tendo como amostras as cavernas localizadas na Fazenda Sete Rios, permitindo ampliar a relevância das cavernas na região devido aos achados arqueológicos encontrados.

A prospecção e comparação entre os cadastros nacionais permitiu concluir da importância da redundância de informações, a fim de poder garantir a preservação de informações mesmo em caso de indisponibilidade dos cadastros, uma vez que durante boa parte do período de execução do projeto o Canie se apresentou indisponível enquanto ocorriam suas manutenções, enquanto isso, constatou-se que os registros no CNC se apresentaram incompletos ou com necessidade de apuração das localizações inseridas. Foram notadas instabilidades e detalhes complexos nas duas plataformas, que foram felizmente resolvidos conforme demandas aos administradores dos dois sistemas.

Afirmar que um cadastro poderia ser melhor que outro seria um equívoco, uma vez que localizações imprecisas podem também ocorrer no Canie, ao passo que o CNC também pode apresentar indisponibilidades (o que já ocorreu em outros tempos). Além disso, em que pesem ambos cadastros objetivaram o registro das cavidades em território nacional, os

públicos que utilizam podem ser distintos entre consultorias ambientais e grupos de espeleologia, podendo haver complementação entre ambos os cadastros para melhor inventário do patrimônio espeleológico brasileiro.

Portanto, sobretudo é importante buscar meios para que os cadastros se retroalimentem entre si, podendo servir inclusive para efeitos de confirmação e validação de informações espeleológicas nacionais, que possam atuar com fidedignidade na geração de informações para promoção de políticas públicas, preservação e estratégias de uso sustentáveis.

Além disso, o engajamento dos trabalhos com a comunidade, contando inclusive com a participação de moradores locais em atividades de campo, oportunizou a conscientização e valoração do patrimônio espeleológico local.

Agradecimentos

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Speleological regionalization of Slovenia: methodology and application

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Abstract

Geospatial analysis of cave data in a country is based on cave coordinates. In addition, predefined regions, if available, are useful both for a non-professional caver and a karst scientist. In Slovenia, the national Cave Registry contains data on more than 15,000 caves, but so far there were no such regions although several general regionalizations had been published. We have developed a methodology for a regionalization that is specifically dedicated to speleological use. This includes guidelines for region sizes, shapes and how the boundaries should be drawn. Several problematic cases are discussed in more detail. Based on this methodology, we divided Slovenia in 64 speleological regions, grouped into five macroregions. An elementary morphometric analysis is also included in the paper.

1. Introduction

In regional geography, one of the key concepts is regionalization of the area under study into well-defined units that share common properties. The area under study often overlaps with national borders, while the internal boundaries of the regions are defined according to the desired motivation of the study. In speleology and karst studies, such a regionalization should be based on natural features such as lithology, cave density and topography, with limited regard to social indicators, if any. From a practical point of view, the regions should at least be of comparable sizes, and the boundaries should be reasonably generalized. The regions can all be at the same level, but it is often advantageous to have at least some hierarchical structure (macro-/microregions), although this should not be too complex.

There are cases of country-wide speleological regionalization. In Poland, the territory is divided into eight primary speleological regions and forty smaller subregions, based on physical geography and geological characteristics. Cave data in the online Polish Cave Database are organized according to these regions (PIB, 2025). In Australia, caves are categorized according to administrative divisions (states and territories) and further divided into 338 cave regions. Each region corresponds to a localized cluster of caves, with an associated coordinating club responsible for exploration, research, and conservation. The Australian Cave Database facilitates searches by states and regions (ASF, 2025). In Russia, the Cave Atlas classifies cave regions based on tectonic, lithological, and geomorphological factors. The largest regions are identified as nine speleological provinces, which are subdivided into multiple speleological regions and smaller areas (Shelepin et al., 2019).

Slovenia can be considered as an example of regionalization for a combination of characteristics. Although it is a small country (20,271 km^2), it lies at the crossroads of four major European regions: Alps, Dinaric Alps, Mediterranean and Pannonian Basin (Perko et al., 2020). Several regionalizations have been published, starting with Melik (1954), followed by Ilešič (1958) and Gams (1983), just to name a few. The regionalization by Perko (1998), which is widely used and has been taught in schools across the country, is characterized by a clear division into 48 regions of relatively equal size, which are grouped into four macroregions.

With regard to geological, hydrogeological and geomorphological characteristics, a number of typifications of the Slovenian karst have been made (e.g. Gams 1965, 1974, 2004; Habič 1969, 1982; Mihevc 1998; Stepišnik 2024). The karst is principally divided into three relatively well distinguishable spatial units: Alpine, Dinaric, and Subalpine / isolated / intermediate karst. Unlike previous typifications, Stepišnik (2024) distinguishes four types of karst in Slovenia: deep karst, shallow karst, fluviokarst, and glacial karst. However, the typifications were made on a small scale (to be used at the national level only) and the distribution of caves was not considered.

When a regional overview of caves is needed, Perko's system is sometimes used (Tičar, 2021), although it has some disadvantages for its application in speleology. The system was developed on the basis of a broad selection of features of physical geography – which is appropriate for geography in general. However, some of them are rather irrelevant for speleology: climate, pedology or land use. As a result, the distribution of caves by region is extremely inhomogeneous: The Julian Alps region, for example, contains 2700 caves, while a quarter of the regions have less than 15 caves each. In addition, some important cave clusters are inconveniently divided between two or more regions. Therefore, the existing regionalization systems are essentially not used in the general (non-professional) caving and speleological communities.

The national library of cave data in Slovenia is called the Cave Registry, which is jointly managed by the Speleological Association of Slovenia and the Karst Research Institute of the Research Centre of the Slovenian Academy of Sciences and Arts. Current Cave Registry database (2024) counts 15,486 caves. Although the database contains 37 attributes for each cave, the geolocalization information is limited to coordinates (in various geodesic systems), the national topographic map sheet number

(admittedly, quite outdated in the age of online maps) and administrative unit name (municipality). Apart from the coordinates, these data can give a rough indication of the cave location but are practically useless for analytical work. In the Slovenian Cave Registry, a cave is defined as a natural underground space that is large enough for human entry. To be included in the registry, a cave must have a minimum length of 10 meters.

Based on the explanation given above, there is a need for a regionalization, adapted for speleological use. It would help the non-professional cavers to categorize the thousands of caves in a meaningful geographical context. For an experienced GIS user, standardized geospatial units, as opposed to those arbitrarily defined by individual authors, would allow for more consistent comparisons. This paper is based solely on speleological regionalization of Slovenia. However, we believe that the developed methodology can also be used in other countries, with some compromises due to differences with Slovenia.

2. Methodology

We set a series of concepts upon which we built our regionalization; they are briefly discussed in each of the following paragraphs.

1. **The audience.** This regionalization is aimed at two groups of audiences: the professional karst researchers and the non-professional cavers. An appropriate compromise is necessary, especially considering the limited geological knowledge of a typical caver. Crucial lithological boundaries should be respected (e.g. karst in limestone-flysch contact), but in less obvious cases (e.g. Jurassic-Cretaceous limestone) topographic features should be favoured. Sometimes, it is difficult to decide which criterion is more appropriate (Fig. 1a).

2. **Targeted region area.** Preferably, the individual regions should be easily recognizable from the terrain, such as a karst plateau or a mountain ridge, or at least share general topographical features, e.g. a series of low hills. The other important parameter is uniformity of lithology, although this is less relevant in poorly karstified areas. The regions should be roughly comparable in size, but this requirement must be flexible enough to allow for smaller areas in highly karstified areas (e. g. Mount Kanin). On the other hand, areas that are predominantly non-karstified can be grouped clearly in one large region. Another criterion is the number of caves per region, although this can be misleading as it may be a consequence of incomplete exploration rather than a natural feature. Admittedly, the two criteria (area and number of caves) can hardly be fulfilled simultaneously, but at least a trend can be set. Even if »a cave« is often considered pointwise, it is not sufficient to simply put groups of caves in one region. If possible, the entire extent of the passages should preferably be included in one region so that a cave is not divided into two regions (Fig. 1b). Keeping proven hydrologically connected areas in one region is desirable but often difficult (Petrič et al., 2020), particularly in cases of dubious tracer tests.

3. **Boundaries.** If possible, they should follow the boundaries between karstified and non-karstified areas: alluvial valley bottoms, non-carbonate belts or at least poorly karstified areas (dolomite rather than limestone). The boundaries of karst, or karst in different lithologies were taken from Gostinčar and Stepišnik (2023), where applicable. In the absence of clear lithological boundaries, a belt of low cave density can be taken; however, it may may well be a consequence of inadequate exploration, as stressed in the previous paragraph. Purely man-made boundaries are not acceptable (political borders, roads or similar infrastructure). However, a road often follows a natural passageway so it may be considered in the absence of more appropriate criteria. Whatever the background, a reasonable generalization of boundaries must be made and keep the overall shape of the region compact, without enclaves or the like.

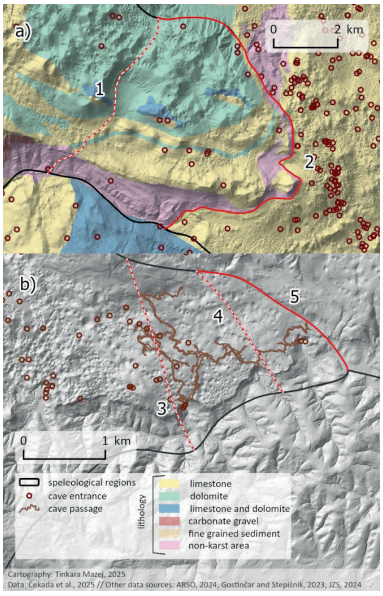

***Figure 1** : Two cases where it is difficult to decide between contrasting concepts where the boundary should be placed (black: non-problematic, red full: accepted option, red dashed: cancelled alternatives). (a) Contrast between 1 – terrain (a dry valley) and 2 – lithology; (b) Joining a hydrologically connected area: 3 – shortest line, inconveniently crossing a group of caves, 4 – a more appropriate shortcut, but crossing a passage within a cave system, 5 – following the joint to fully include the cave system.*

4. Relation to existing regionalizations. The regionalization of Slovenia by Perko (1998) was taken as a basis. In cases where an existing region was too large or contained too many caves it was divided into several smaller regions. On the other hand, in predominantly poorly karstified areas, several regions were combined into one. The boundaries were often slightly adjusted to better conform to the terrain or lithology as Perko's regionalization was constructed based on spatial data on smaller scale. There are several regions in Perko's system, which are distinctly non-karstified. If we had kept them, they would have just added up the number of regions without any speleological value. On the other hand, we might have divided them into neighboring karst regions; that would be somehow artificial, influencing a net reduced cave density of these regions. We decided to keep only the larger regions, provided they are distinctly different from the surrounding area (alluvial plain, flysch mountains). If there were neighboring similar non-karst areas we joined them together.

A polje is by definition a karst phenomenon, but the polje floor is usually devoid of caves so it remains an open question, does it merit to have a region on its own in a speleological regionalization. In Fig. 2 there is an example of a polje, surrounded by three well-defined mountainous regions, divided by non-problematic boundaries (shown in black). From a broad geographical point of view, a polje is inevitably connected to the spring and ponor caves located at the polje perimeter. Thus, a boundary

of the polje region should include all these caves and possibly some immediate surroundings (dashed green line). However, from the caving point of view, it does not make sense to draw an artificial line somewhere at the slope above the polje; the mountain region does not stop 50 m above the polje floor. Therefore, a better delineation of the polje would follow the foothills, assigning all the caves into the mountain region including the spring/ponor ones (dashed blue line). We may choose to cancel the polje region altogether, which should in any case be done in those poljes which are too small to merit a region anyway. The division of the polje among the neighboring mountain regions can be drawn at the center line (black dashed), or we may choose to assign the whole polje floor to one region only. This is justifiable if there is a physically much more discrete border on one side of the polje. In the presented case we decided to divide the polje at the center line.

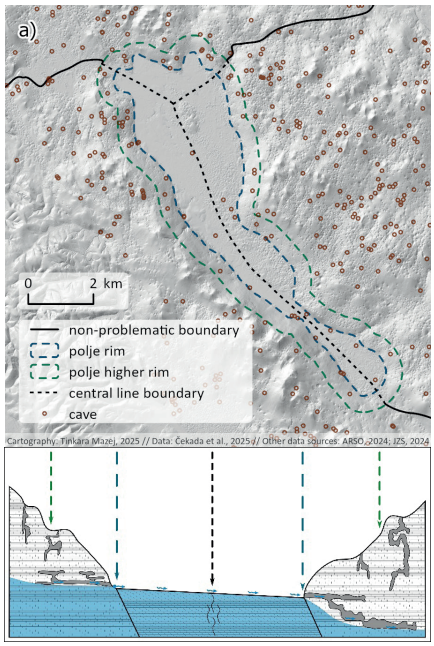

Figure 2: Possible boundaries of regions at a polje: (a) a case point, Dobrepolje, central Slovenia, (b) schematic cross-section in perpendicular direction.

3. Results

Based on the methodology described in the previous section we divided the territory of Slovenia in 64 speleological regions. They were grouped into five macroregions, in accordance with existing general regionalizations mentioned in the introduction. The map is shown in Fig. 3.

The Alpine macroregion could be easily divided into regions using the boundaries of individual mountain ranges, which predominantly follow the valleys. It includes Mount Kanin, which is the smallest region in the country (34 km^2) but currently counting 856 caves, it has by far the highest cave density at 25.1/km^2. In contrast, the Prealpine macroregion is characterized by discontinued patches of karst with isolated small groups of caves. The boundaries of the regions were drawn somewhat more arbitrary. However, the Dinaric macroregion, which contains 51 % of caves in the country, is a continuous karst area, but could be relatively conveniently divided in regions of similar sizes. The Submediterranean macroregion is a continuation of the latter, nevertheless it is interrupted by three large flysch regions. The Subpannonian macroregion is practically devoid of karst; therefore, the entire Northeastern part of the country was included in one region covering 14 % of the national territory. Additional data on area, caves and karst for each macroregion is shown in Table 1.

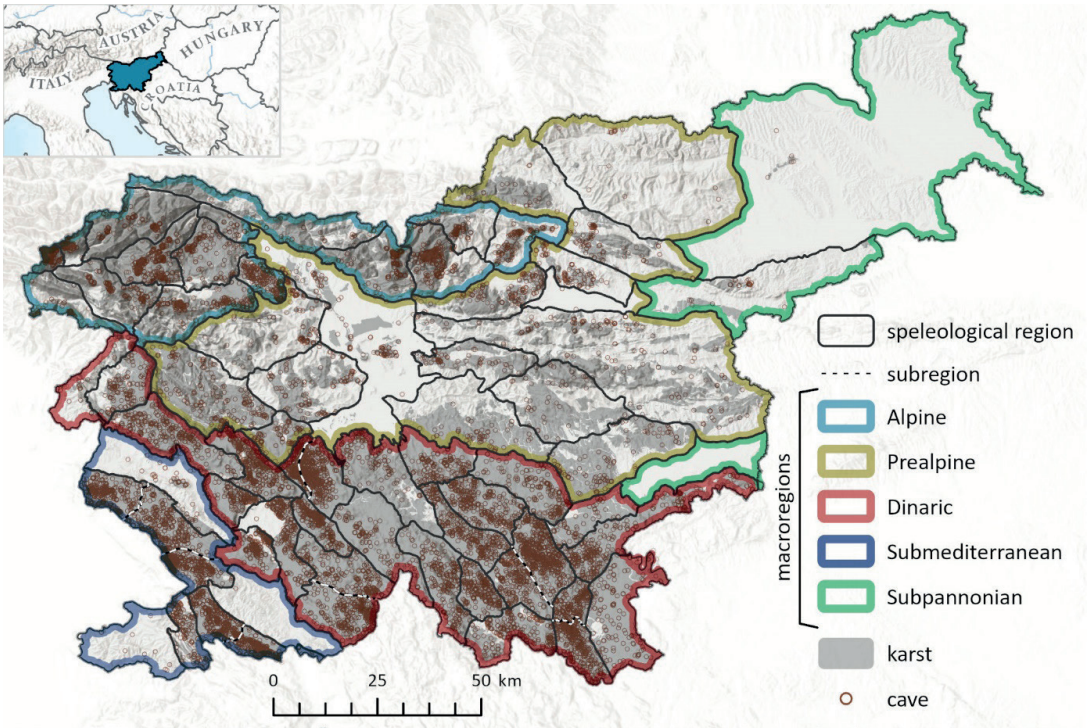

Figure 3: The 64 speleological regions of Slovenia, as constructed following the methodology.

macroregion	average region area [km²]	average no. of caves per region	cave density [km–²]	share of karst [%]
Alpine	179	250	1.39	74
Prealpine	455	89	0.19	37
Dinaric	211	331	1.57	92
Submediterranean	270	386	1.43	45
Subpannonian	1195	12	0.01	2
Slovenia (total)	316	242	0.76	50

Table 1: *Average morphometric values of the speleological regions of Slovenia, presented separately per macroregions.*

The values presented in columns 2 and 3 of Table 1 are based on our regionalization; if we had opted for overall larger or smaller regions, they would be different. However, relative values from columns 4 and 5 are not affected by a particular division. Therefore, these two values are presented in the chart in Fig. 4 (note the y axis is in logarithmic scale). Each point shows one region, where the symbol colors indicate the macroregions. The regions in the Dinaric macroregion are by far the most homogeneous: they have a karst share above 70 % and a cave density between 0.5 and 4.5/km2(there is one isolated outlier at 30 % karst). In the Prealpine macroregion the karst share is evenly spread almost throughout 0–100 % with the cave density in the range of 0.1–1/km2. The Alpine and the Submediterranean regions, on the other hand, are less homogeneous with few similarities among the respective regions.

We insisted on not dividing compact, geographically well homogeneous regions, even if they contain too many caves. From the caver's point of view, it becomes too complex to manage a region with almost a thousand caves. An extreme case is the Kras region (from where the term karst originates) with currently 1223 caves. For planning purposes only, we decided to subdivide six regions with the highest number of caves in two or three subregions. In contrast to regional boundaries, the subdivision boundaries were in most cases drawn following roads. If necessary, additional subdivisions can be made, without compromising the 64 regions which are based solely on geographical features.

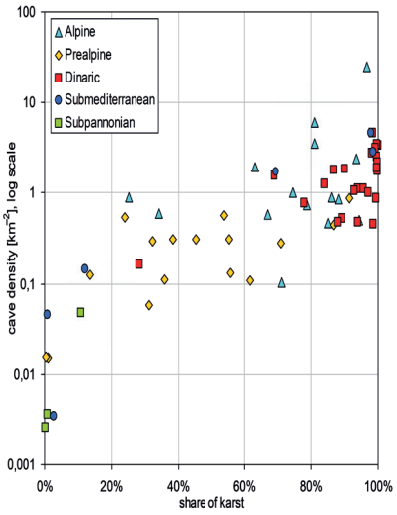

Figure 4: *Distribution of all 64 speleological regions of five macroregions, based on share of karst and cave density.*

4. Conclusion

The 64 speleological regions constructed in this work successfully address the main motivation: to set up a convenient geospatial system of cave distribution in Slovenia. The five macroregions allow a broad generalization based on the established macroregions. On the other hand, the option of subregions in those regions with a large number of caves allows for a flexible subdivision when necessary. The system is simple enough to be used by the general non-professional caving community and is a useful tool for karst researchers.

Although the methodology developed in this paper applies only to Slovenia, it can also be extended to other countries. We believe that similar dilemmas will be encountered such as the ones presented in more detail: caver/professional, terrain/lithology and other difficult boundary choice cases such as poljes.

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Potencial Científico e Conservação da Gruta da Onça Goiana: Primeira Abordagem Espeleológica

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Resumo

A exploração, registro e estudos em cavidades caracterizam um esforço coletivo de cientistas e grupos de espeleologia no Brasil e no mundo. Em "Contribuição do GREGEO na Documentação e Qualificação da Gruta da Onça Goiana em Campinorte, Goiás, Brasil" o Grupo de Espeleologia da Geologia da UnB aborda, metodicamente, o registro e qualifica de maneira multidisciplinar a Gruta da Onça Goiana, trazendo a região para o mapa de interesse de espeleólogos e destacando-a como um ponto de altíssimo potencial científico e importante interface biológica e geológica na área que se insere.

Abstract

The exploration, recording and study of caves is a collective effort by scientists and speleology groups in Brazil and around the world. In "Contribuição do GREGEO na Documentação e Qualificação da Gruta da Onça Goiana em Campinorte, Goiás, Brasil" (GREGEO's contribution to the documentation and qualification of the Onça Goiana Cave in Campinorte, Goiás, Brazil), the UnB Geology Speleology Group takes a methodical approach to the registration and multidisciplinary qualification of the Onça Goiana Cave, bringing the region onto the map of interest for speleologists and highlighting it as a point of very high scientific potential and an important biological and geological interface in the area in which it is located.

1. Introdução

As atividades de prospecção e documentação de cavidades desempenham um papel fundamental no Grupo Espeleológico da Geologia da Universidade de Brasília (GREGEO-UnB), contribuindo tanto para a produção científica quanto para a proteção do patrimônio espeleológico.

Em 2024, o GREGEO organizou uma expedição ao município de Campinorte, em Goiás, com o objetivo de cadastrar e topografar uma cavidade localizada em uma propriedade privada. Durante a expedição, foi aplicada a metodologia de qualificação de cavernas proposta por MENIN & BACCI (2022), na qual 14 critérios são avaliados coletivamente para o cálculo de quatro Valores Espeleológicos e um Alerta de Conservação. Esse mecanismo não apenas auxilia na caracterização da cavidade, mas também fornece subsídios para o desenvolvimento de estratégias de geoconservação, divulgação espeleológica e uso educativo da caverna.

Diante disso, o presente trabalho reúne os dados coletados em campo durante a prospecção, apresentando o cadastro da cavidade, seu mapa topográfico parcial e sua qualificação segundo os critérios estabelecidos.

1.1. Área de estudo

A Fazenda Moura está situada no distrito de Colinaçu, a aproximadamente 46 km da cidade de Campinorte, no noroeste do estado de Goiás (Fig. 1). As atividades econômicas são predominantemente pecuárias, sendo que as áreas de Reserva Legal correspondem a porções delimitadas para a proteção de nascentes e da vegetação nativa em propriedades rurais FLORESTAL, (2017).

A paisagem vegetal da região sugere a presença de mata seca decidual, uma formação característica de áreas acidentadas com afloramentos calcários. Essa vegetação é composta por árvores eretas que podem atingir até 25 metros de altura, além de arbustos e epífitas em menor proporção RIBEIRO & WALTER (2008). Dentre as espécies de destaque, a gameleira (Ficus sp.) se sobressai, crescendo entre os blocos de rocha SHINZATO (1998).

De acordo com MOREIRA et al., (2008), a rocha predominante na área de estudo pertence ao Grupo Serra da Mesa na unidade PP4smbc, composta por lentes de calcixisto e mármore.

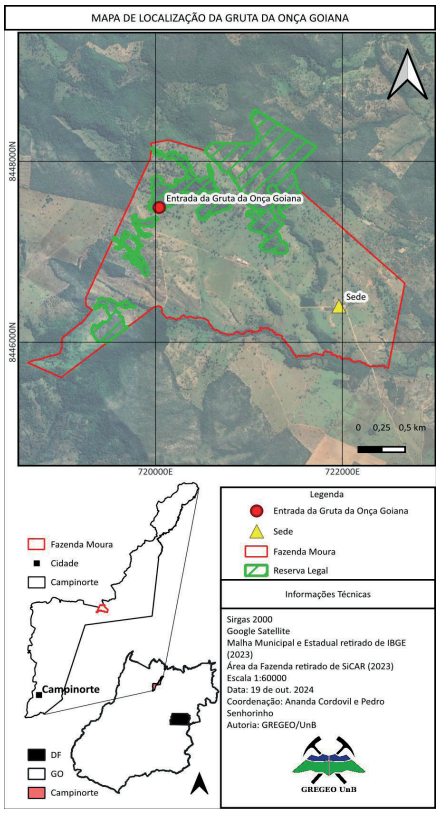

Figura 1: *Mapa com a delimitação e indicações da sede e cavidade na Fazenda Moura.*

2. Materiais e métodos

A coleta de dados foi realizada em duas expedições, ocorridas entre os dias 18 e 21 de outubro e 14 e 17 de dezembro de 2024, na Fazenda Moura, localizada no município de Campinorte, Goiás.

O estudo foi estruturado em três etapas principais: pré-campo, campo e pós-campo, com metodologias distintas aplicadas à prospecção, topografia e qualificação da Gruta da Onça Goiana.

No pré-campo da primeira expedição, foram reunidas referências bibliográficas sobre o contexto geológico da região. Além disso, foi elaborado um mapa base no software QGIS 3.34.10, utilizando imagens do Google Satélite para a delimitação da área de estudo.

A prospecção foi realizada ao longo da primeira expedição, em dois dias de campo, com a participação de dez integrantes do GREGEO. O trabalho iniciou-se com informações fornecidas por funcionários da Fazenda Moura, que indicaram a localização da caverna e de uma dolina. A partir dessas indicações, a equipe percorreu a área, registrando o trajeto e coletando coordenadas e altitudes dos pontos de interesse no mapa base, utilizando o aplicativo Avenza 5.3.3.

Na segunda expedição, realizada em dezembro, foi conduzida a topografia da Gruta da Onça Goiana, desta vez com quatro integrantes do GREGEO. Para a obtenção dos dados topográficos, utilizou-se o aplicativo TopoDroidX 6.2.95 para a construção do croqui e o registro das informações espeleométricas. As medidas angulares foram obtidas por meio do aplicativo Dioptra 1.0.10, enquanto as medições de distância foram realizadas com uma trena a laser, com alcance de 40 metros. A finalização do mapa foi realizada no software CorelDRAW, utilizando os dados coletados em campo e símbolos espeleológicos para a inserção da legenda.

Para a qualificação da caverna, adotou-se a metodologia de Menin & Bacci (2022), que estabelece 14 critérios avaliados em campo por meio de um formulário digital. Os critérios considerados foram: (1) Espeleometria, (2) Fósseis, (3) Espeleotemas, (4) Arqueologia, (5) Conhecimento histórico, (6) Conhecimento científico, (7) Uso turístico, (8) Beleza cênica, (9) Exemplo pedagógico, (10) Utilidade de campo, (11) Fragilidade, (12) Vulnerabilidade, (13) Estado de conservação e (14) Vínculo regional.

A integração desses critérios resultou na atribuição de Valores Espeleológicos, classificados como Valor Científico, Valor Pedagógico, Valor Histórico-Cultural e Valor Turístico. Além disso, foi gerado um Alerta de Conservação, indicando a necessidade de medidas para a preservação do patrimônio espeleológico.

Por fim, na etapa de pós-campo, os dados de prospecção extraídos do Avenza e as informações topográficas coletadas no TopoDroid foram compilados para o cadastramento da cavidade no Cadastro Nacional de Cavernas (CNC) da Sociedade Brasileira de Espeleologia (SBE) e no Cadastro Nacional de Informações Espeleológicas (CANIE) do Instituto Chico Mendes de Biodiversidade (ICMBio).

3. Resultados

3.1. Prospecção

A prospecção realizada no morro identificou a entrada da cavidade e uma dolina de colapso com 3 m de diâmetro e 8 m de profundidade, além de outras feições características do epicarste como paredões, blocos abatidos, mata seca e gameleiras (Fig. 2).

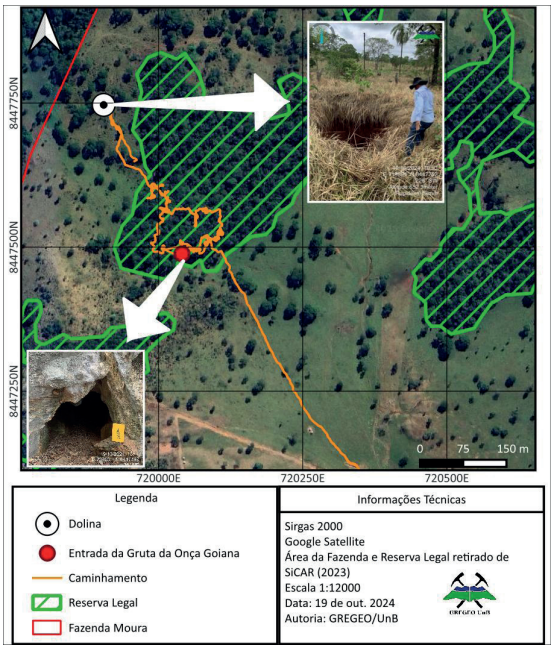

Figura 2: *Mapa de caminhamento da prospecção.*

3.2. Cadastro

A cavidade nomeada "Gruta da Onça Goiana" possui entrada principal no ponto 720040 E e 8447488 S, da zona 22 L, mais uma entrada de difícil acesso e uma claraboia, respectivamente nas seguintes coordenadas 720047 E e 8447498.08 S, 720030 E e 8447495 S foi registrada sob os números: 033374.07731.52.04706 no CANIE do ICMBio; e GO-889 no CNC da SBE.

A escolha do nome da cavidade foi baseada em relatos de onças-pardas e onças-pintadas frequentemente avistadas nas proximidades, além da presença de carcaças e ossos identificados nas zonas fótica e de penumbra da caverna (Fig. 3).

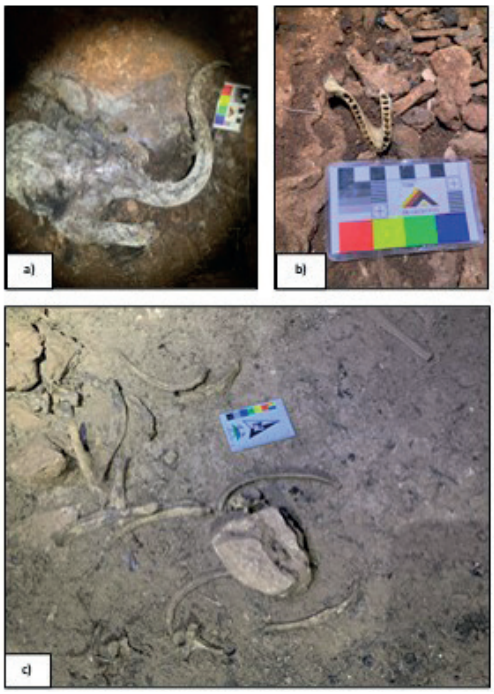

Figura 3: *Carcaças e ossos encontrados na gruta, escala 8 cm. a) Metade de um Tamanduá-mirim em estado de putrefação; b) Arcada dentária; c) Ossos de costela.*

3.3. Topografia

A cavidade possui uma entrada principal com teto baixo de aproximadamente 1 m de altura e largura, utilizada para acessá-la e iniciar a topografia. A entrada dá acesso a um conduto que exige rastejamento. À direita, no primeiro salão, há uma segunda entrada localizada no alto, acima de uma parede de blocos abatidos, apresentando um desnível superior a 3 m, por onde ocorre a entrada de luz. Essa entrada não foi utilizada para acessar a cavidade, pois requer acesso vertical. Na base da parede formada pelos blocos abatidos, se nota a carcaça do tamanduá-mirim e demais ossadas. Adiante, à esquerda, no mesmo salão, encontra-se uma claraboia com abertura inferior a 50 cm, que constitui uma terceira entrada e também necessita de acesso vertical.

A caverna abriga uma grande população de morcegos, cuja presença é evidenciada pela abundância de guano. No mapa, o guano está representado por manchas de cor marrom (Fig. 4).

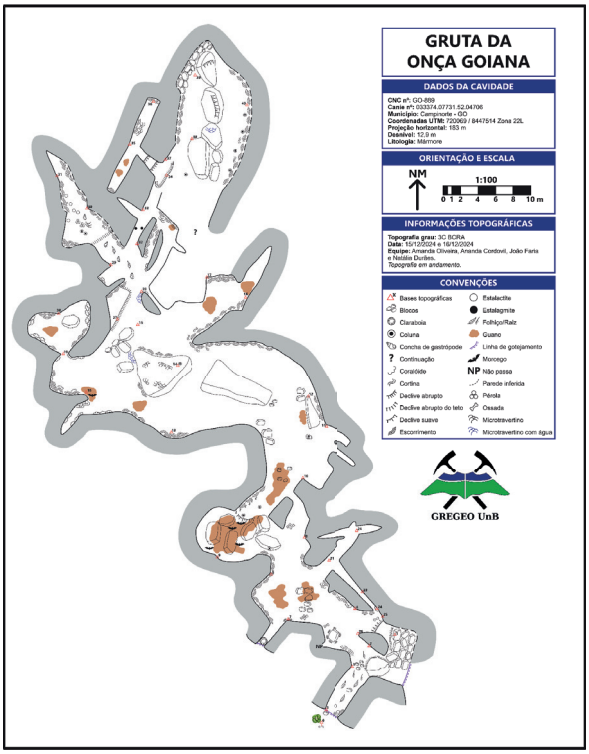

Figura 4: *Mapa topográfico. Escala 1:100 m.*

A topografia da caverna não foi concluída devido ao tempo limitado da expedição. Até o momento, a Gruta da Onça Goiana apresenta uma projeção horizontal de 183 metros, com uma área de 1.046 m^2, um volume de 3.691 m^3 e um desnível linear de 12,9 metros.

Os condutos da caverna seguem uma morfologia curvilínea a reticulada, caracterizada por múltiplas passagens interconectadas e presença de pilares rochosos. Dentre os espeleotemas identificados, destacam-se colunas, escorrimentos, estalactites, estalagmites, bolos de noiva, coraloides, travertinos, pérolas, entre outros.

3.4. Qualificação

O resultado do preenchimento do formulário de qualificação das cavernas foi organizado em uma planilha, contemplando os 14 critérios avaliados, cuja análise resultou na atribuição dos Valores Espeleológicos e do Alerta de Conservação.

O formulário obteve um total de 12 respostas e, com base nesses índices, foi possível estruturar os dados em um gráfico, representando as médias obtidas para cada critério avaliado (Fig. 5).

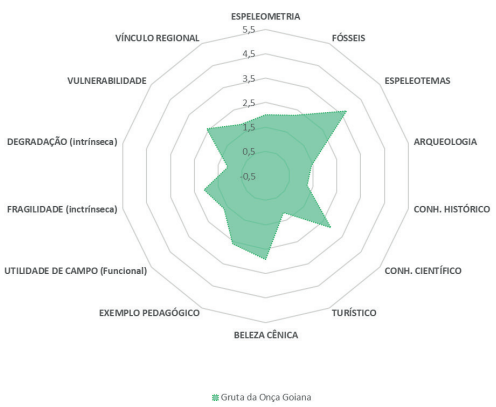

Figura 5: Gráfico com as médias de acordo com cada critério observado.

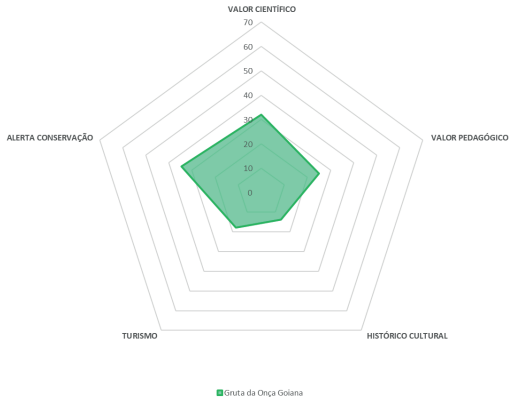

Figura 6: Gráfico com os Valores Espeleológicos e o Alerta de Conservação analisados na Gruta da Onça Goiana.

Os critérios que se destacam são Espeleotemas, Conhecimento científico, Beleza cênica e Exemplo pedagógico, fundamentados pela abundância de ornamentação na caverna.

Os critérios que obtiveram menores indicadores foram sobre o Uso turístico, Degradação e Conhecimento histórico.

Em se tratando dos quatro Valores Espeleológicos e o Alerta de Conservação, foram verificados que a Gruta possui indicativos maiores para o Valor Científico e para o Alerta de Conservação (Fig. 6).

O Valor científico e o Alerta de Conservação são influenciados pela concentração de espeleotemas como colunas (Fig. 7a), escorrimentos (Fig. 7a), pérolas (Fig. 7b), cortinas (Fig. 7c) e travertinos (Fig. 7c) e, também, pela presença de morcegos na cavidade (Fig. 7d).

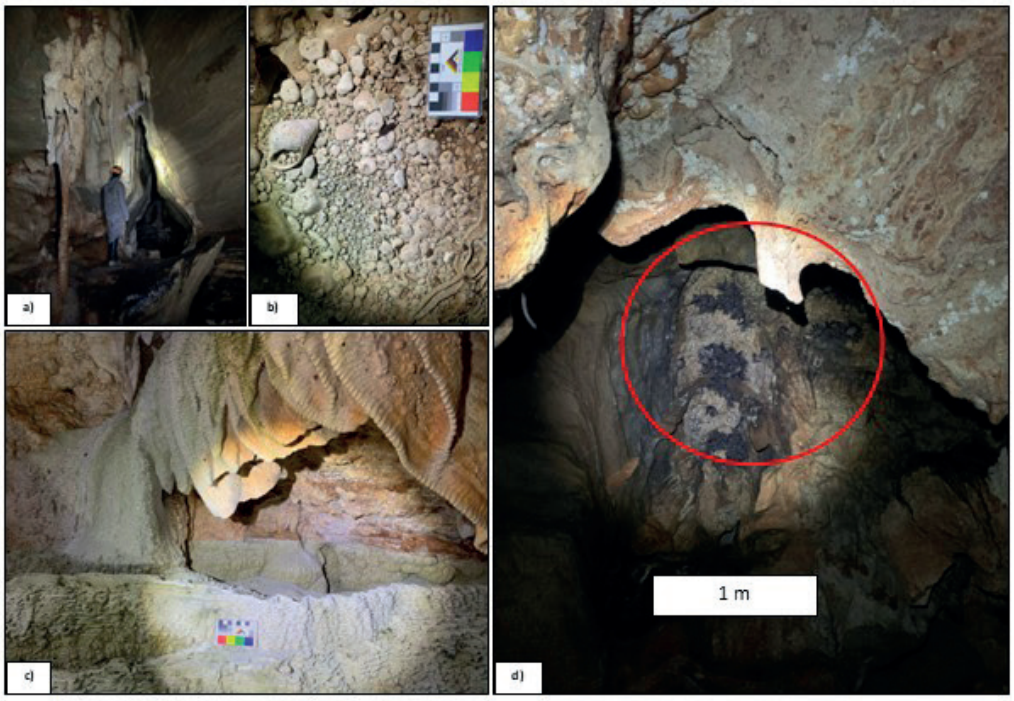

Figura 7: Características que indicam o Valor Científico e o Alerta de Conservação. a) Coluna e escorrimentos. b) Pérolas, escala 8 cm. c) Travertinos e cortinas, escala 8 cm. d) Concentração de morcegos, escala informada.

4. Discussões

A atividade de prospecção revelou alto potencial espeleológico na região. Relatos de moradores locais e trabalhadores da Fazenda Moura sobre outras cavernas na região indicam a possibilidade de ampliação da área de estudo.

Além disso, a litologia da rocha encaixante exposta na região, a presença de feições cársticas, e o panorama da flora, caracterizado por vegetação de mata seca e gameleiras, são fatores que reforçam a probabilidade de ocorrência de novas cavidades.

A topografia preliminar destacou as informações espeleométricas da gruta a cavidade com maior extensão topografada na região de Campinorte.

Em face disso, a gruta possui desnível baixo, com orientação horizontalizada e condutos em padrão curvilíneo e reticulado. Isso evidencia uma formação preferencialmente epigenética, fortalecida por espeleotemas de água circulante. São observadas também, grandes salões e condutos com tetos altos e não apresentou fluxo hídrico constante e

pouca presença de sedimentos.

A qualificação para conservação da caverna indicou que a Gruta da Onça Goiana se destaca pelos critérios relacionados a Espeleotemas, Conhecimento Científico e Beleza Cênica. Esses fatores exercem influência direta sobre o Valor Científico e o Alerta de Conservação.

Por outro lado, a análise apontou menores resultados para os critérios de Uso Turístico, Degradação e Conhecimento Histórico, evidenciando que esses aspectos apresentam menor representatividade na qualificação da caverna.

O Valor Científico se destacou pela necessidade de aprofundar o conhecimento sobre a gênese espeleológica, química, climática e morfológica da cavidade. A futura exploração científica da Gruta da Onça Goiana poderá contribuir para diversos estudos, especialmente nas áreas de sedimentologia, paleoclima e processos geomorfológicos da região. Além disso, a análise da fauna local, evidenciada pela presença de ossos e restos de animais, reforça a relevância desse critério, impulsionando novas investigações.

Quanto ao Alerta de Conservação, foi observada uma fauna abundante, incluindo colônias estáveis de morcegos e uma grande quantidade de guano depositado. Esses animais, embora frequentemente associados a doenças como a histoplasmose e a raiva, desempenham um papel fundamental no equilíbrio ecossistêmico da caverna e do meio epígeo. Essa condição também ressalta a necessidade de adotar certas precauções antes de um eventual retorno para uma exploração mais detalhada da caverna.

Além disso, a presença de restos de animais nas zonas fótica e de penumbra, possivelmente resultado da predação por um animal de maior porte, sugere que a cavidade possa estar sendo utilizada como refúgio ou abrigo para predadores, reforçando sua importância ecológica.

Por outro lado, os critérios que obtiveram menores pontuações foram Uso Turístico e Conhecimento Histórico. Esses resultados estão relacionados ao fato de a gruta estar isolada em uma propriedade privada, com poucos relatos conhecidos, restritos a moradores e trabalhadores da Fazenda Moura. Além disso, a caverna está inserida em uma Área de Reserva Legal da propriedade rural e apresenta pouca intervenção humana direta, o que indica um baixo nível de degradação.

O cadastro da cavidade em Campinorte destaca a importância do conhecimento sobre o patrimônio espeleológico como um passo essencial para sua conservação. Nesse contexto, se sugere a ampliação da área de pesquisa, possibilitando comparações com outras cavidades da região. Essa abordagem permitiria um estudo mais abrangente, integrando os resultados da qualificação para uma visão geral do patrimônio espeleológico local.

5. Conclusões

As expedições do GREGEO à Gruta da Onça Goiana consolidaram a primeira documentação formal desta cavidade, buscando contribuir para a espeleologia e para a proteção do patrimônio natural da região de Campinorte, Goiás.

A prospecção confirmou a existência de uma caverna formada em mármore, com domínios xistosos do Grupo Serra da Mesa. Embora a topografia não tenha sido concluída devido ao tempo limitado da expedição, as informações preliminares e o mapa inicial revelaram a disposição dos condutos seguindo um padrão curvilíneo ampliado, além de condutos menores com padrão reticulado.

Na execução das expedições, foram constatados espeleotemas variados, blocos abatidos e alta atividade biológica, evidenciada por uma colônia expressiva de morcegos e restos de presas de grandes predadores. Além disso, a identificação de outras feições cársticas e relatos de moradores sugerem um potencial ainda maior para a exploração espeleológica no entorno.

A qualificação da cavidade apontou para um elevado valor científico e um alerta de conservação, destacando a importância do monitoramento contínuo e da conscientização sobre o impacto das atividades humanas na área.

Para os membros do GREGEO, a expedição foi fundamental para o aprimoramento das metodologias de campos e técnicas de prospecção e topografia, exigindo o uso de equipamentos como trena a laser, bússola e aplicativos adaptados para a espeleologia. Esse aprendizado consolidou a formação técnica dos participantes e de futuros profissionais capacitados na área.

Agradecimentos

Aos participantes do GREGEO que contribuíram diretamente com essas expedições e com os bons momentos que tivemos em campo: André Andrade, João Faria, Eduardo Moura, Gabriela Lehmkuhl, Luiz Lima, Diogo Almeida e Rodrigo Pinheiro. Ao senhor Adão Moura que nos hospedou e viabilizou alimentação servida pela senhora Elielma Oliveira durante os dias das expedições. Aos conselhos do senhor Aderaldo Silva, morador e trabalhador na Fazenda, para encontrar a Gruta da Onça Goiana. À Prefeitura de Campinorte que colaborou com a logística para execução da expedição por meio de incentivos da senhora Andreia Oliveira, presidente do Conselho Municipal de Turismo e vice-presidente do Conselho Municipal de Meio Ambiente, e da senhora Rosângela Barcelo, Vereadora e Subprefeita de Colinaçu, Goiás. E, por fim, aos motoristas que nos acompanharam nas duas expedições: senhor Heder Gonçalves e senhor Denivaldo Faria.

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A photographic approach of glowworms in New Zealand caves

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Abstract

Anyone who has had the opportunity to visit caves in New Zealand, whether as a caver or a tourist, is bound to be fascinated by the glowworms whose unreal lights illuminate some of the caves. But taking photos that reveal both their bluish light and their environment is a real challenge, requiring the use of specific photographic techniques.

Résumé

Quiconque a l'occasion d'aller dans des grottes de Nouvelle Zélande, en tant que spéléo ou bien en tant que touriste, ne manquera pas d'être fasciné par le spectacle des glowworms dont la lumière irréelle illumine certaines cavités. Mais faire des photos qui révèlent à la fois leur lumière bleutée et leur environnement est un vrai défi qui a demandé de mettre en œuvre des techniques spécifiques.

1. The glowworm, a fascinating creature

Glowworms are among the most surprising underground wonders to be seen. Although only a few cavers know about them, the general public had the opportunity to discover them, along with other emblematic New Zealand sites, in one of the "Lord of the Rings" films. But there's every chance that viewers thought it was a digital effect, not suspecting that nature can be far more inventive than cinematic special effects. These glowworms illuminate the ceilings and walls of some of New Zealand's caves, where they are endemic, creating a magical atmosphere.

In fact, a real tourist industry has developed around the glowworm caves, particularly in the Waitomo area. Thousands of tourists flock to take a boat trip or float down the river on rubber inner tubes, all illuminated by thousands of bluish light dots. This unreal light is reflected on the dozens of threads bearing strings of droplets that each glowworm produces, just as the tassels of a chandelier diffuse its light. But although the sight is fantastic, the animal itself is anything but attractive. In fact, it's rather repulsive: it has all the appearance of a maggot, except that it emits a light at the end of its abdomen (which immediately makes it much more interesting). Bioluminescence is created by a chemical reaction: the larva emits a beautiful greenish-blue light thanks to a luminous device located at the end of its body (Malpighian tubules modified with a tracheal reflector).

It's the larva of an insect, the keroplatid dipteran (Arachnocampa luminosa). This is found only in a few caves in New Zealand and Australia (in other parts of the world, what are known as glowworms are actually coleoptera). This larva needs very high humidity, which is why it is most frequently found near underground rivers, or outdoors in damp, protected places. It weaves a small silken tube in rock hollows, in which it lives and produces up to 70 sticky threads that can be 50 cm long, in order to trap the flying insects on which it feeds.

The life cycle of the glowworm comprises four stages. The eggs, incubated for around 20 days, hatch into the larva, which spends 6 to 8 months feeding. Then, over a period of 8 to 14 days, the larva gradually transforms into a pupa with legs, wings and a head, before finally emerging from its tube and flying away. During the adult stage, it no longer produces light or feeds. It reproduces, lays eggs and dies within 2 to 3 days, if it doesn't end up trapped in the threads of other glowworms.

If watching glowworms in a cave, standing still in the dark or sitting in a boat gliding silently over the water, is a wonderful experience, taking pictures of them is another story altogether, made up of many failures and disappointments.

2. First encounter

We were lucky to see glowworms for the first time in 2017, during a week of underground photography organized by Phill Round of the Auckland Speleological Group, just before the Sydney International Congress. He had obtained permits for several glowworm caves in the Waitomo area (Spellbound cave, Waipuna cave, Hollow hill cave). Our first observation was that their light, although clearly visible in the dark after a short period of eye adjustment, requires a long exposure to photograph them. To take a whole wall, the exposure time is around 4 minutes at f4 and ISO 3200. The use of a tripod is of course essential. The "Noise Reduction" function, which reduces noise after a long exposure, is not recommended, as it may remove the glowworms from on the image, interpreted as sensor overheating. The second observation was that the larva hates movement and light. After two or three photos with second-curtain synchronization, it extinguishes its light ... and it's too bad for the photographer if he hasn't yet found the right exposure. As for macro shots, the mere fact of approaching them with our lamps immediately causes them to stop glowing. So we had to make do with photos of the larva without its light. In conclusion, even though I brought back a few satisfying photos of glowworms, I was still frustrated at not being able to capture them up close with their light, and at not having any large views.

Photo 1: *First encounter - Macrophotography of a glowworm. The larva and threads are clearly visible, but it unfortunately extinguished its light as soon as we got close*

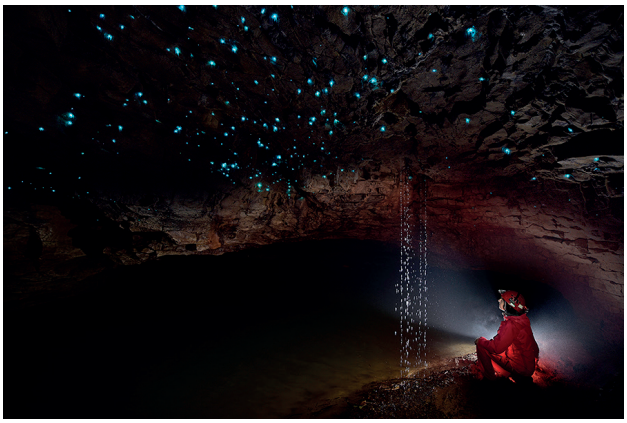

Photo 2: *First encounter - Photo of a glowworm-covered ceiling above the final sump of Spellbound cave, with second curtain synchronized backlight. We neglected to turn off our headlights while preparing the shot, so a large number of glowworms had dimmed their lights.*

3. Same player shoot again

In December 2024, we went back to New Zealand with the aim of both photographing glowworms again and discovering the country's marvelous natural landscapes. This time, however, I had to work out a strategy for photographing them while they glow. First of all, it was clear that we had to approach them as unobtrusively as possible. So we used low-powered headlamps with an inactinic red light. This meant setting up the camera on a tripod in near-darkness, with all the risks that this entailed when handling the equipment. The strategy was to first shoot the glowworms with just the light they emit, and then use flashes to light up the scene. With the camera on a tripod, it would then be a simple matter of superimposing the shots in post-processing. Finally, to reduce our presence next to the animal, exposure was first determined by bracketing (a series of photos taken at varying exposures) with sensitivity set to maximum (ISO 51200) and maximum aperture (f 2.8) to keep exposure time as short as possible. We should point out that in the case of such photos with bright dots on a black background, automatic exposure setting by the camera is not an option. All I had to do then was define the right exposure from this series of shots, using a sensitivity that would be acceptable in terms of the noise in the photo. This involved converting the shooting parameters (shutter speed, aperture and sensitivity) based on the chosen EL Index. For example, 4 seconds at f2.8 and ISO 51200 becomes 4 minutes at f4 and ISO 3200.

I chose a color temperature of 5400 K, corresponding to what I saw on my camera screen. It was important to check this on site, as the memory may not be accurate when the photos are processed on the computer later on. It also revealed that people's perception of blue-green is very diverse. A lower color temperature would have added more yellow, making the glowworms appear greener.

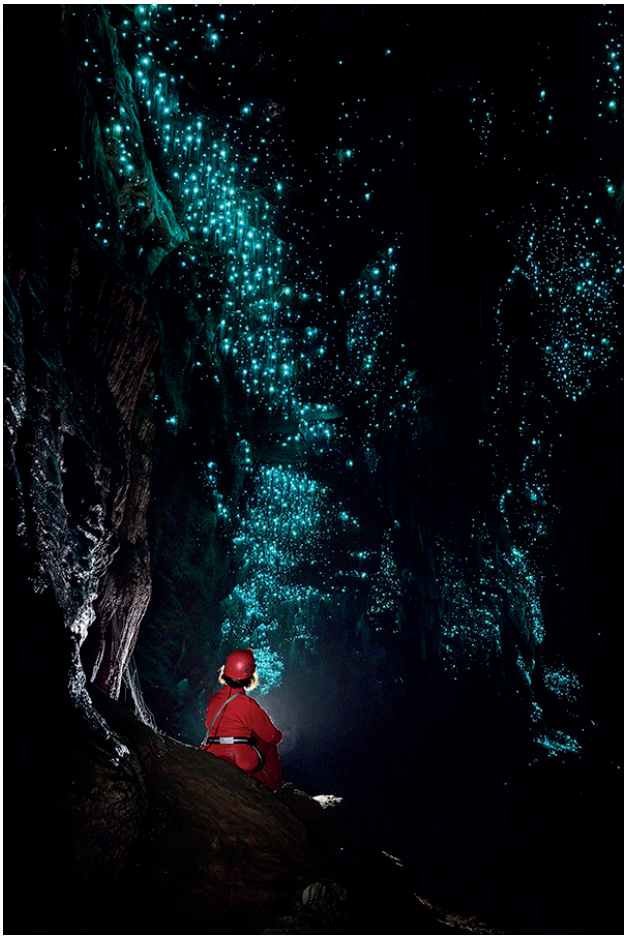

Photo 3: *Photo resulting from the superimposition of two shots: the first one just for the glowworms on the ceiling, and the second one taken with two electronic flashes (backlight and snoot on the model).*

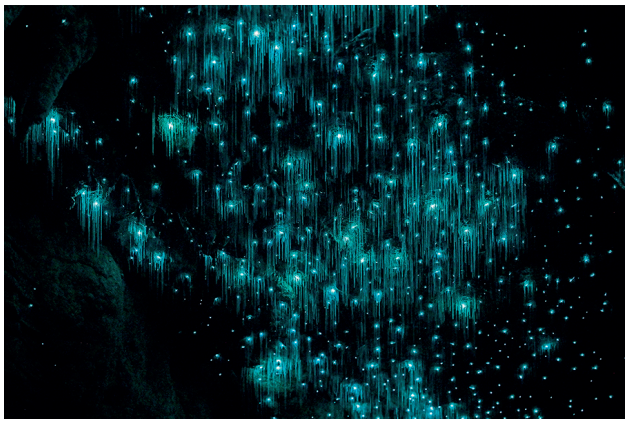

Photo 4: *This photo shows how the threads reflect the glowworms light, thus creating a unique magic atmosphere. Without the threads, they would appear as mere blue dots.*

The first outing was to a cave on private land in the Waitomo area. Kevin, a friend of Phill Round, had obtained the necessary permit from the owner. The cave is a beautiful river sink into a high vertical entrance which ends after a hundred meters on a sump above which there was a large colony of glowworms. We only photographed the whole passage with glowworms on the ceiling, as they were too high for macro shots. The strategy worked well, so we took separate shots of the glowworms and of the overall scene with the model, and then superimposed them in Photoshop.

The second cave was Spellbound. The owner, Peter Chandler, had kindly opened it to us between 7 and 9 a.m. before the tourists arrived. This time, the aim was to take a photo with the model in a small boat on the river under the glowworms. The set-up was a little more complicated, and the resulting commotion caused some of the glowworms to extinguish their light at the time of the photo.

The last cave was Okupata cave in Tongariro National Park. Surprisingly, it's an open-access cave that is a river sink. The trunks stuck to the ceiling show that it's not a good place to venture into during floods. We were able to go in on our own and spend all the time we needed. The small stream runs through passages just a few meters wide and under a ceiling low enough to allow a close-up view of the glowworms. It was a favorable configuration. But setting everything up in the dark in a small space, with our feet in the water, was quite a challenge. And the larva doesn't like the feel of a macro lens just a few centimeters away, especially as you need to focus manually, the autofocus being unable to focus on the tiny glowing part. But with patience, we were able to find two more tolerant individuals. After taking a long exposure photo of the larva, we then took several shots, varying the position of the flash. All that remained was to combine them so as to have the glowworm, its threads and the environment in the same image. Several final photos were then possible, depending on which element we wanted to emphasize.

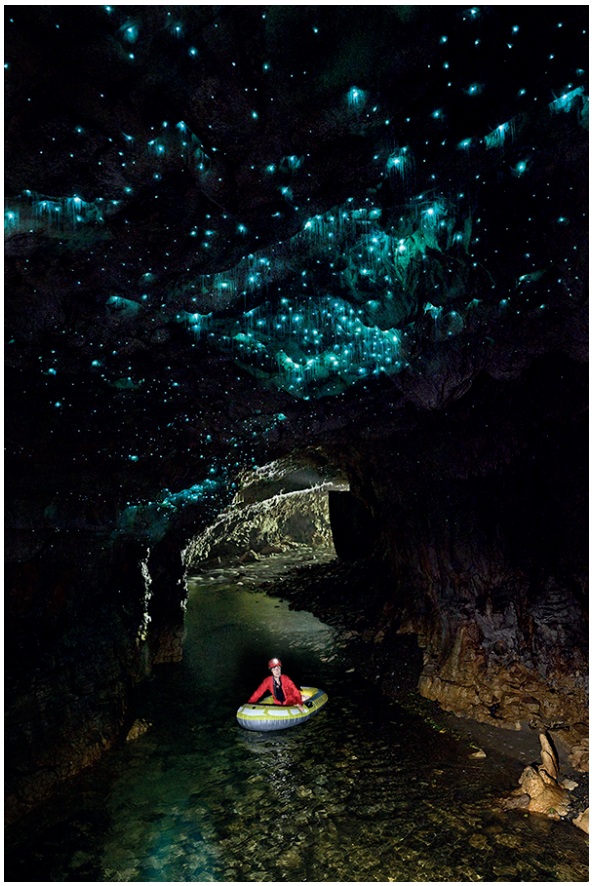

Photo 5: *Spellbound cave. The entrance passage with a large glowworm display over the river was an interesting subject. But by the time photographer, assistant and model were ready, many glowworms had extinguished their lights.*

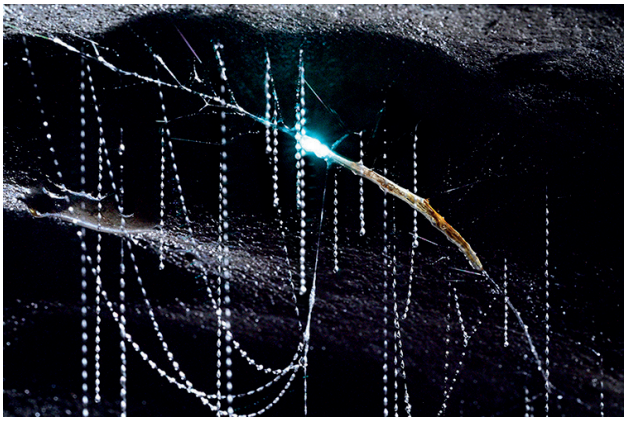

Photo 6: *Photo combining three superimposed shots: the first one to capture only the bright part of the glowworm, the second one with a flash lighting up the whole larva, and the third one with a flash backlighting the threads.*

4. Discussion

Photographic documentation of the subterranean world cannot be limited to frontal lighting, which despite being quick and easy to implement, has the disadvantage of making the subjects look flat. The use of several light sources is therefore advisable to enhance and better render them, without distorting them. This requires appropriate settings for each light source. But in some cases, it can be useful to take specific shots for each subject, possibly with exposure variations (bracketing). The final photo is then assembled in post-processing by superimposing the different shots. This allows the photographer to work calmly without the constraints of the shooting, and to harmoniously balance the final image which will reveal his strategy and what he really wants to emphasize. To make an analogy with cooking, at least in France, this means cooking each ingredient of a dish separately to better reveal its taste. And photographing glowworms is a perfect example of this, as they are so difficult to capture in their environment, mainly due to their sensitivity to light, noise and movement. Naturally, this entails particularly long and sometimes tedious photo sessions.

Photo 7: *The advantage of taking several shots is that you can set a specific exposure for each subject of the image (glowworms, model and rock). And above all, post processing makes it possible to enhance some of them and dull other ones.*

Acknowledgments

We would like to thank Phill Round and Kevin Jose, from the Auckland Speleological Group who got the permits to visit caves in the Waitomo region. They both were assistants for some of the pictures presented here.

Thank you to Peter Chandler, owner of Spellbound cave for allowing us to take pictures before the tourist tours.

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Documenting caves of Köýtendag (Turkmenistan)

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Abstract

After an initial reconnaissance in 2023, a scientific documentation expedition took place in the Köýtendag massif of Turkmenistan in April 2024. This massif is home to caves that were explored and studied by Russian cavers in the 1980s, but have since been almost completely forgotten. The 17-people multidisciplinary team had several objectives, including surveying known caves and a 3D photogrammetric rendering of one of them, studying the karstological context and cave fauna, and looking for new caves. But photographic documentation of the caves also had a special place, with a dedicated team ensuring that images were available to fully enhance the expedition.

Résumé

Après une première reconnaissance en 2023, une expédition de documentation scientifique s'est déroulée dans le massif du Köýtendag, au Turkménistan en avril 2024. Ce massif recèle des cavités qui ont été explorées et étudiées par les spéléologues russes dans les années 80, puis sont quasiment tombées dans l'oubli. L'équipe pluridisciplinaire de 17 personnes avait plusieurs objectifs, notamment la topographie des grottes connues et le rendu photogrammétrique 3D de l'une d'entre elles, l'étude du contexte karstologique et de la faune cavernicole ainsi que la recherche de nouvelles cavités. Mais la documentation photographique des cavités avait aussi une place privilégiée avec une équipe dédiée, ce qui a permis de disposer d'images pour pleinement valoriser l'expédition.

1. Introduction

The story began back in 2019, when some French cavers, (including Jean-Pierre Gruat, the project leader) decided to take a close look at the base of the great cliffs of the Köýtendag massif in Uzbekistan, which they had spotted on a map. Little is known about this massif, which is the final link in the Gissar Mountains. These begin in Tajikistan, and extend into the Baisun Tau massif, which includes the Chul Bair range (home to the Boy-Bulok and Vishnechsky caves) and the Hodja-Gur-Gur-Ata range (home to the Dark Star cave) in Uzbekistan. The aim of exploring the bottom of the cliff and looking for cave entrances proved impossible, as they couldn't get permission from the Uzbek military.

After searching for documentation on the massif, mainly from Russian sites, it turned out that various articles were written by a Russian geologist (Vladimir Maltsev, 1957-2014) and dealt with the Gap-Gotan cave system (Cupp-Coutun), which he studied in the 1980s and 1990s. The rest had been little explored since the fall of the USSR, as there were no Turkmen cavers to take over the initial studies, but everything confirmed the geographical, geological and karstological interest of the Köýtendag massif, which had been almost forgotten for about 30 years.

Therefore, a caving expedition to Köýtendag from the Turkmen side was planned in 2020. However, due to the Covid 19 pandemic, and the long administrative procedures required to get the necessary permits, this could only be achieved in 2023, with a reconnaissance trip and then in 2024, with a proper scientific expedition.

To get a visa for Turkmenistan requires a lot of planning and authorization: the massif lies on the border between Uzbekistan, Turkmenistan, and Afghanistan, and is classified as a national reserve. Morever, most of the caves are located in a military zone. Fortunately, the Turkmen ambassador to France, as well as the French ambassador to Turkmenistan actively supported our project. Thanks to them in 2023 and 2024, we finally got the invitation letter from the Turkmen Ministry of Foreign Affairs.

The 2024 team was composed of Philippe Audra, Lionel Barriquand, Jean-Marie Briffon, Gaël Cazes, Philippe Crochet, Jean-Philippe Grandcolas, Jozef Grego, Jean-Pierre Gruat, Annie Guiraud, Jean-Paul Héreil, Bernard Lips, Josiane Lips, Frédo Poggia, Alexandre Pont, Xavier Robert, and Jo De Waele.

2. Geographical and geological features of the Köýtendag

The geography and geology of the Köýtendag massif are described in greater detail in the article by Ph. Audra et al. (Speleogenesis of Gap-Gotan (Cupp-Coutunn) cave system, Köýtendag massif, Turkmenistan), included in the proceedings of the UIS 2025 Congress

The Köýtendag massif is the last western part of the Pamir-Alaï chain, which extends further east towards Tajikistan, Kyrgyzstan and Uzbekistan. The massif culminates at Aýrybaba (3139 m), the highest point in Turkmenistan. The massif is elongated in a north-south direction for around 60 km, with a width of 12 to 20 km. Its Turkmen slope, rising at a gradient of 20° to the summit, is cut by a multitude of canyons, more than 300 m deep and up to 700 m, making travel at level virtually impossible.

The karstified strata is made up of Upper Jurassic limestones, 400 m thick, with a massive reef facies with large corals, changing to a more marly and dolomitic facies at the top. In places, these limestones are slightly metamorphosed and silicified. This sedimentary series rests unconformably on the Precambrian metamorphic basement, which is composed of gneiss. The Köýtendag limestones are concordantly overlain by the 200 m-thick Gowurdak (or Gaurduck) evaporites, mainly

composed of gypsum (Kimmeridgian-Tithonian). The Köýtendag is an asymmetrical anticlinal dome, broken by major north-south faults, including the Chilghaz fault, which cuts the plateau into two “steps”.

3. The objectives of the expedition

Surveying was one of the main aspects of the expedition, employing up to ten people (Jean-Marie Briffon, Jean-Philippe Grandcolas, Jean--Pierre Gruat, Jean-Paul Héreil, Bernard Lips, Frédo Poggia, Alexandre Pont, Xavier Robert, Philippe Audra, Jo De Waele). Although maps of the main systems had already been made by Russian cavers in the 1980s, they were not available in detailed format (they were in paper version only, with neither profile view nor indication of depth). In addition, techniques have considerably evolved: a laser-aimed DistoX is now used for measuring and the data are collected by mobile phone (Topodroïd). Calculations and drawings are then made on computer using Therion or Topo Calc’R softwares. In the end, a great deal of work was carried out: fifteen caves were visited and some 19 km of passages were surveyed. All these maps provide a global view of the systems known to date and of the potential for future exploration.

In addition to the mapping work, Geophysicheskaya cave was the subject of **a 3D photogrammetric modeling operation**. The aim was to digitize all or part of the cave in order to accurately record its geometry, thus serving as a working basis for karstologists but also to offer an immersive vision of this exceptional cave to complement the photographs. This work was carried out by Gaël Cazes with a powerful LED projector and a pair of GoPro-type cameras. Over 50,000 shots covering more than 1.3 km of passages were taken to form the basis of the subsequent photogrammetric calculation. These images were then processed to generate a final 3D envelope. The result obtained have confirmed the feasibility of photogrammetry for large-scale digitization projects, offering a good alternative to lasergrammetry when the time available underground is a limiting factor.

Photo 1: *The Pink Chamber in Geophysikeskaya cave is partly covered with gypsum crusts. The stalagmites in the foreground are hollow.*

The team in charge with **karstology and hydrogeology** (Philippe Audra, Jo De Waele) worked on the collapse craters in gypsum and the speleogenesis of the caves.

The study of the underground fauna of the Köýtendag was started in 1963 by Russian teams. From 2013 to 2015, an extensive research program on the fauna of Turkmenistan was carried out.

Josiane Lips and Josef Grego, Slovakian mollusk specialist, made up the biologist team on the expedition. Terrestrial and aquatic fauna from eight caves, four former mines and a dozen springs were sampled. On the whole, the underground fauna was relatively poor, due to the fact that most of the caves are very dry. However, around 150 species of terrestrial invertebrates were recorded in the caves. It is already possible to say that many of the species collected are new to Turkmenistan, and several would be new to science. In addition, the study of the spring fauna has led to the identification of most of the species mentioned in the literature, but also to the collection of many new species. Some species that were very common in the 2023 expedition were absent in 2024, and conversely. This may reveal a seasonal variation in the cave fauna.

Relations between karst and mammals in the Köýtendag were studied for the first time by Lionel Barriquand. Many caves proved interesting: bones were found in Mumiyskaya and Tush-Yuruk contains many traces of hyenas, porcupines, as well as many other mammals.

Looking for new caves was a major objective of our expedition, so the team focused their search on four main areas. On the plain at the north-western foot of the massif, the limestone disappears beneath a cover of gypsum. There, some dark spots which had been spotted on Google Earth turned out to be real cenotes. An inventory of them was made. These gypsum zones are home to classic karst features, as well as depressions up to 70 m in diameter resulting from the collapse of vast chambers. Caves known to the Russian teams were found and mapped, but there were few discoveries. A second focus was the exploration of the many canyons that descend from the summit ridge some of which are dozens of kilometers long. In places, the walls featured dark spots that looked like cave entrances, but most of the time, they turned out to be simply “bubbles” with no lead. Apparently, in that area, few canyons intersect with former systems.

Another search area was at the south-western end of the massif, in the military area, in the canyons around the known caves. There, Russian teams had listed some twenty caves less than 500 m long. They remained untraceable and the park rangers didn’t seem to know about them

Finally, the last objective was to find high altitude entrances. The exploration team hiked up to an altitude of about 2,400 m, and reached an antecima. On the Russian map, a cave was marked. Using binoculars, they could spot entrances further up the mountain. Unfortunately, the team did not have time to reach it.

Photo 2: *Giant gypsum chandelier in Geophysikeskaya. Backlight is necessary to enhance the translucence of the chandeliers.*

Photo 3: *Hashim-Oyuk cave. "The Prison" is a five-meter-deep, two-meter-wide hollow gypsum formation.*

4. Photographic documentation of the caves

Bibliographic research had revealed photos dating back to Russian explorations over 40 years ago made by V. Malstev, and some more recent ones taken by Rémy Wenger during a short expedition in the 1990s. The Geophysicheskaya (Gulschirin cave) had been partly documented under another name for conservation purposes. As a matter of fact, this exceptional cave remained practically untouched thanks to its late discovery (1986), whereas the other caves of the area were severely damaged by gypsum and onyx mining.

Cupp-Coutunn-Promeszhutochnaya is the main cave system of the massif with a development of about 50 km. But it's mainly Geophysikeskaya (Gulschirin), and Hashim-Oyuk to a lesser extent, which have the most spectacular gypsum crystallizations of a scale and beauty comparable to those of Lechuguilla Cave in the USA. All these gypsum decorations can crystallize thanks to the very dry atmosphere of the caves. Chandeliers are formed of massive, transparent gypsum crystals, hanging from the ceilings. Other crystallizations are formed by fibers that grow from the base, like blades of grass. Crosses are made up of several fibers that bend or even curl as they develop, looking like flowers. Needles are found by thousands on the ground of some passages. The countless hollow stalagmites can be several meters high and often turn into columns as they reach the ceiling.

We therefore faced a major challenge: we had many exceptional subjects to cover, and we needed to document the entire Geophysikeskaya cave. Knowing that time in the country and the daily hours were limited, we devoted our time exclusively to photography, and concentrated our efforts on the two most interesting caves. A total of thirteen days were devoted to photography, with eight trips to Geophysicheskaya (Gulschirin), but there the possibilities for beautiful images are endless, three to Hashim-Oyuk, one to Promezhutochnaya and one to Kaptarhana, with an average of around ten shots per trip.

The main objective was of course to illustrate with lighting that emphasized the natural beauty of the subjects. Photographs were taken only with electronic flash units of varying power (Yongnuo 560III, Godox AD300 and Godox AD600). Given the whiteness of the gypsum-covered rooms, it was necessary to avoid direct lighting, which would have overexposed the shot, and to play with reflections. We were often assisted by members of other teams (mainly Jean-Pierre Gruat, Claire Falgayrac and Jean-Marie Briffon), so that we were able to work in groups of three or four, which is an optimal configuration.

Photo 4: *The White Chamber in Geophysikeskaya is entirely covered in gypsum.*

Photo 5: *The Flat Chamber in Geophysikeskaya features more "classical" stalactites except for this yellow cluster in the middle of a grey ceiling.*

Photo 6: *Red passages in Geophysikeskaya. The dark red color of the walls is due to the pyrite in the rock.*

5. Discussion

In the months that followed, the photos were used to illustrate various publications: articles in three caving magazines such as Spelunca (France), NSS News (USA), and Speleologia (Italy) and in the French magazine Terre Sauvage for the general public. A bilingual brochure richly illustrated was also published. Some twenty photos were exhibited at the Institut Français du Turkménistan. We also made a slide show showing the underground landscapes of Köýtendag.

This widespread communication based on the impact of the images has aroused the interest of film producers who consider making a documentary about this region of Turkmenistan.

The photographs were donated to the Turkmen authorities, who will be able to use them to support an application for UNESCO classification, a long-standing project that has not yet been completed. We hope they will also be able to motivate them to provide future expeditions with the necessary authorizations to search for new caves, and to encourage them to protect the caves.

For a photographer, being part of an expedition is an opportunity to cover unusual, even extraordinary subjects. It's always an experience we approach with the idea that we might not be able to repeat it in the future. It can be unique. What's more, it's limited in time. Going on an expedition generally represents a big investment in terms of availability and energy, but also financially.

In this context, the photographer is required to achieve a satisfactory result. It is out of question to be stuck because of damages or breakdowns of the photo equipment, so everything is doubled, camera, lenses, chargers, memory cards, cables, etc. We have to bring back images that best illustrate the discoveries and the team's work. Photos are the ideal complement to the final report. But the quality of the images must also enhance the value of the expedition; this can make it easier to find sponsors and obtain permits. For an expedition, a dedicated photographer or filmmaker is definitely a plus.

Photographic documentation is an essential part of an expedition, unfortunately all too often neglected, as it enables the expedition to be promoted, particularly for communication purposes (reports, articles, sponsorship requests). Moreover, in the case of this expedition, this aspect was put forward to get permits from the local authorities, who were very receptive to the idea, seeing it as a way of highlighting the richness of their heritage.

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O Cadastro Nacional de Informações Espeleológicas: Um Instrumento para Gestão e Conservação do Patrimônio Espeleológico Brasileiro

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Resumo

O Cadastro Nacional de Informações Espeleológicas (CANIE) é uma ferramenta essencial para a gestão e conservação do patrimônio espeleológico brasileiro, reconhecido como um dos mais relevantes mundialmente. Instituído pelo Conselho Nacional de Meio Ambiente (CONAMA) por meio da Resolução nº 347/2004, o CANIE tem como objetivo centralizar informações sobre cavidades naturais subterrâneas, auxiliando no licenciamento ambiental, na conservação da biodiversidade e no monitoramento desses ambientes. Desenvolvido pelo Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio) com suporte técnico do CECAV, o CANIE integra o Sistema Nacional de Informação do Meio Ambiente. Desde sua primeira versão em 2014, o sistema consolidou-se incorporando dados de diferentes fontes, como pesquisas científicas, levantamentos técnicos e processos de licenciamento ambiental. Em 2024, foi lançada uma versão modernizada, com interface aprimorada e novas funcionalidades. Atualmente, o CANIE armazena informações abrangentes sobre as cavernas, incluindo localização, características geológicas, biológicas, sociais e dados sobre áreas de entorno. Além de identificar áreas prioritárias para conservação e recuperação, o sistema promove o acompanhamento da evolução do conhecimento espeleológico. Sua contínua atualização e integração de dados fortalecem a pesquisa científica, contribuindo para a preservação sustentável das cavernas brasileiras.

Abstract

The National Registry of Speleological Information: A Tool for Managing and Conserving Brazil's Speleological Heritage - The National Registry of Speleological Information (CANIE) is an essential tool for managing and conserving Brazil's speleological heritage, recognized as one of the most significant in the world. Established by the National Environmental Council (CONAMA) through Resolution No. 347/2004, CANIE aims to centralize information on natural subterranean cavities, supporting environmental licensing, biodiversity conservation, and monitoring of these environments. Developed by the Chico Mendes Institute for Biodiversity Conservation (ICMBio) with technical support from CECAV, CANIE is part of the National Environmental Information System. Since its initial version in 2014, the system has consolidated its role by incorporating data from various sources, such as scientific research, technical surveys, and environmental licensing processes. In 2024, a modernized version was launched, featuring an improved interface and new functionalities. Currently, CANIE stores comprehensive information about caves, including their location, geological, biological, and social characteristics, as well as data on surrounding areas. Beyond identifying priority areas for conservation and recovery, the system enables the monitoring of the evolution of speleological knowledge. Its continuous updates and data integration strengthen scientific research, contributing to the sustainable preservation of Brazil's caves.

1. Introdução

As cavidades naturais subterrâneas existentes no território brasileiro compõem o Patrimônio Espeleológico Nacional (CONAMA, 2004), considerado um dos mais expressivos no cenário mundial. Até janeiro de 2025, o Cadastro Nacional de Informações Espeleológicas (CANIE) registrava 28.422 cavernas (CANIE, 2025), consolidando-se como a principal ferramenta de gestão e monitoramento dessas formações no país.

Com o objetivo de estabelecer procedimentos e parâmetros para orientar o licenciamento ambiental de atividades efetiva e potencialmente impactantes às cavernas ou à sua área de influência, assim como o processo de gestão ambiental e de biodiversidade, o Conselho Nacional de Meio Ambiente (CONAMA), por meio da Resolução nº 347/2004, instituiu o CANIE (CRUZ & PILÓ, 2019).

Desenvolvido pelo Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio), com o suporte técnico do Centro Nacional de Pesquisa e Conservação de Cavernas (ICMBio/CECAV), o CANIE integra o Sistema Nacional de Informação do Meio Ambiente e tem como missão congregar as informações espeleológicas existentes, incluindo aquelas dispersas em diferentes fontes de informação. O Cadastro constitui um valioso instrumento de referência para a busca de dados e informações atualizadas sobre o Patrimônio Espeleológico Brasileiro.

A primeira versão do CANIE foi elaborada e disponibilizada pelo CECAV em 2014, a partir da integração de dados da antiga Base de Dados Geoespacializados das Cavernas do Brasil (Base CECAV). Essa base foi constituída por levantamentos de campo do CECAV, estudos submetidos ao Centro, bibliografia especializada e dados de iniciativas como o Cadastro Nacional de Cavernas do Brasil (CNC) da Sociedade

Brasileira de Espeleologia (SBE) e o CODEX da Redespeleo Brasil (OLIVEIRA GALVÃO, 2014).

Na época, o cadastro foi desenvolvido em parceria com a Coordenação de Tecnologia da Informação (CTI/CADM) do IBAMA, seguindo os parâmetros estabelecidos pelo Governo Federal a adoção de linguagens e softwares livres: *PostgreSQL* e *PHP* (CECAV, 2018).

Em junho de 2024, o ICMBio lançou uma versão modernizada do CANIE, com uma *interface* mais intuitiva e acessível, além de novas funcionalidades que facilitaram o acesso e a análise de dados. Essa atualização incluiu a modernização da infraestrutura tecnológica do sistema, reforçando sua capacidade de processamento e análise integrada.

Atualmente, o CANIE é alimentado continuamente com dados provenientes de diversas fontes, como pesquisas científicas, explorações conduzidas por grupos espeleológicos, levantamentos técnicos e informações obrigatoriamente fornecidas nos processos de licenciamento ambiental, conforme disposto no Decreto nº 10.935/2022. O sistema armazena dados abrangentes sobre as cavidades naturais subterrâneas, que incluem, entre outros, aqueles relacionados à localização, características hidrológicas, aspectos biológicos e áreas protegidas. Também contempla informações essenciais para garantir o cumprimento da legislação espeleológica vigente, em especial aqueles contidos nas Instruções Normativas nº 2/2009 e nº 2/2017 do Ministério do Meio Ambiente e Mudança do Clima (MMA).

Além disso, o CANIE desempenha um papel crucial na gestão do patrimônio espeleológico, fornecendo informações detalhadas que possibilitam a identificação de áreas prioritárias para conservação, monitoramento e recuperação de ecossistemas subterrâneos. Sua atualização constante também permite o acompanhamento e disponibilização da evolução do conhecimento sobre os ambientes subterrâneos, um fator essencial para a avaliação de impactos ambientais e o planejamento de ações de mitigação eficazes. Por meio da integração de dados e do apoio contínuo de diversas instituições, o CANIE contribui para o fortalecimento da pesquisa científica e do conhecimento sobre a biodiversidade subterrânea, além de promover a sustentabilidade e a preservação das cavernas para as futuras gerações.

2. Materiais e Métodos

Credita-se ao naturalista alemão Sigismund Ernst Richard Krone o primeiro levantamento sistemático de cavernas no Brasil. No final do século XIX, Krone descreveu 41 cavidades no Vale do Rio Ribeira, no sul de São Paulo (Lino, 2001), sendo este considerado o primeiro cadastro de cavernas do país (MARTINELLI; GERIBELLO, 2015).

Em 1969, foi fundada a Sociedade Brasileira de Espeleologia (SBE), que assumiu a responsabilidade estatutária de manter um acervo centralizado sobre as cavernas brasileiras. No ano seguinte, Pierre Martin publicou uma relação das maiores cavernas do Brasil. Em 1971, a SBE adotou um sistema de numeração das cavidades baseado na ordem cronológica de descoberta, precedido pela sigla do estado correspondente. Desde então, a SBE passou a publicar periodicamente uma lista de cavernas. Após o XXV Congresso Brasileiro de Espeleologia, realizado em Vinhedo/SP em 1999, o cadastro passou a ser divulgado via internet e foi denominado Cadastro Nacional de Cavernas do Brasil (CNC) (RODRIGUES 2001).

Em 2004, o CECAV criou sua base de dados de localização de cavernas, alimentada por informações de outras bases, estudos espeleológicos, material bibliográfico e levantamentos de campo realizados por técnicos e analistas ambientais. A partir de 2005, o CECAV começou a disponibilizar, em seu site, parte dessa base de dados, contemplando informações validadas ou provenientes de fontes confiáveis, citadas por mais de uma fonte ou com geoespacialização compatível com as descrições disponíveis (OLIVEIRA-GALVÃO 2014).

A base de Dados Geoespacializados de Cavernas do Brasil do Cecav é o passo inicial para atender à Resolução CONAMA nº 347/2004, que em seu Art. 1º instituiu o Cadastro Nacional de Informações Espeleológicas (CONAMA, 2004).

A partir do EspeleoInfo, um cadastro de cavernas desenvolvido pela Base do CECAV de Minas Gerais, que teve sua concepção baseada na Base Cave, sistema de informações espeleológicas desenvolvido pela Companhia de Recursos Minerais (CPRM), o CANIE começou a ser desenvolvido (CRUZ, 2008).

Contudo, somente em 2007, durante o IX Encontro Técnico do CECAV, realizado em Brasília/DF, foram definidos os critérios para a caracterização de uma caverna e as feições a serem observadas. O evento contou com a participação de diversas áreas do conhecimento relacionadas à espeleologia, representadas pelo corpo técnico do CECAV, seus consultores e pesquisadores convidados. Ficou estabelecida a metodologia para a caracterização de cavidades naturais subterrâneas e os dados necessários para esse processo, resultando na criação da Ficha de Caracterização de Caverna do CECAV, que serviria como base para o CANIE (CRUZ, 2008).

Inicialmente, o cadastro foi desenvolvido utilizando banco de dados Oracle e linguagem *PHP*. No entanto, devido a atualizações no módulo de segurança da informação do IBAMA, foi necessário alterar a *framework* utilizada, o que comprometeu temporariamente o desenvolvimento do CANIE. Posteriormente, sob a gestão do Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio), o banco de dados foi migrado para *PostgreSQL*. Todo o sistema foi desenvolvido com base em softwares livres, seguindo os parâmetros estabelecidos pelo Governo Federal. O desenvolvimento ocorreu em seis etapas, conduzidas pela fábrica de software CTIS, sob a supervisão da Coordenação-Geral de Tecnologia da Informação (ICMBio/COTEC) e com orientação técnica do CECAV.

O Cadastro Nacional de Informações Espeleológicas (CANIE) foi oficialmente lançado durante a 111ª Reunião Ordinária do Conselho Nacional do Meio Ambiente (CONAMA), em 4 de setembro de 2013 (CONAMA, 2013), com o registro inicial de 9.530 cavernas (CECAV, 2019). No entanto, após atualizações e correções, o sistema passou a operar plenamente no início de 2014, quando a Base de Dados Geoespacializados das Cavernas do Brasil, então contendo 11.504 registros, foi definitivamente migrada para o CANIE (CANIE, 2025). Em 2019, o cadastro ultrapassou a marca de 20.000 cavernas registradas (CECAV, 2019).

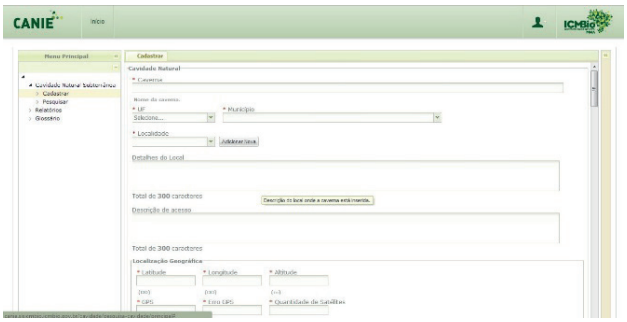

Figura 1: *Tela de cadastro da primeira versão do CANIE.*

Em 2020, foi iniciada a modernização do CANIE, com o objetivo de atualizar sua infraestrutura tecnológica e implementar novas funcionalidades. Basicamente, a nova versão foi desenvolvida utilizando as tecnologias: *Php7.4* e *Laravel 10* para o "*back-end*", *Vue.Js 2* e *Vuetify 2* para o "*front-end*", e a utilização do banco de dados *PostgreSQL10*. Além disso, foram utilizados outros recursos, tais como o *Anychart* para geração de gráficos e mapas, e a biblioteca *gasparesganga/php-shapefile* para geração de dados de mapa do tipo shapefile.

A nova versão, lançada em maio de 2024, apresentou uma *interface* mais amigável e moderna, além de funcionalidades como a realização de

pesquisas com filtros cruzados, produção de relatórios com cruzamento de dados e exportação para planilhas eletrônicas e arquivos geoespaciais (*shapefiles*). O sistema também passou a incorporar dados relacionados à Instrução Normativa nº 2/2017 do Ministério do Meio Ambiente e Mudança do Clima (MMA), complementando os dados anteriormente limitados à *IN* nº 2/2009/*MMA*.

O CANIE mantém perfis de acesso específicos para Usuário Externo, Órgão Licenciador e Administrador, refletindo as competências legais e as necessidades de gestão e controle. A otimização de desempenho do sistema foi um dos principais focos da modernização, garantindo maior agilidade e eficiência na navegação e na consulta aos dados. Outra melhoria significativa é a identificação automática do município e da UF com base nas coordenadas geográficas das cavernas, aumentando a precisão e confiabilidade dos dados. A modernização também trouxe uma funcionalidade inovadora: o cadastramento em bloco de cavernas, permitindo o *upload* de planilhas eletrônicas com até 300 cavernas por planilha, o que torna o processo de inserção de dados mais rápido e eficiente, especialmente para projetos que envolvem grandes volumes de informações.

O CANIE adota um processo de validação rigoroso para a localização das cavernas, com três níveis distintos de precisão. O Nível 1 é utilizado quando a caverna é inserida no sistema, com a verificação automática das coordenadas dentro da unidade da federação e do município. No Nível 2, as coordenadas foram coletadas ou conferidas *in loco*, de acordo com os procedimentos metodológicos definidos na "Rotina de procedimentos associados à coleta de dados relativos à localização de cavidades naturais subterrâneas", disponível no site do CECAV. Por fim, o Nível 3 é atribuído às cavernas cujas coordenadas se referem à caverna de Nível 2, devidamente topografada, com mapa inserido e disponibilizado no Cadastro.

O CANIE possui uma estrutura de informações organizada em cinco grupos temáticos: Dados Gerais, Área de Entorno, Seção Morfológica, Aspectos Sociais e Instruções Normativas, que refletem a abrangência e a diversidade dos dados necessários para a caracterização das cavernas brasileiras. Com um total de aproximadamente 190 campos, essa divisão tem como objetivo facilitar o preenchimento e a consulta das informações, além de garantir a padronização e a conformidade com os requisitos legais e técnicos.

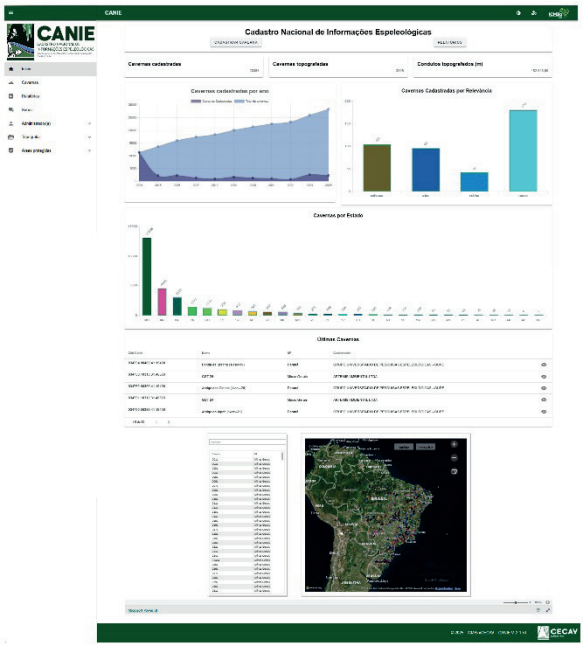

Figura 2: *Tela de cadastro do CANIE, versão 2.*

3. Resultados

A modernização do Cadastro Nacional de Informações Espeleológicas, concluída em 2024, resultou em uma *interface* aprimorada e maior eficiência no processo de consulta e visualização dos dados. O sistema agora possibilita realizar pesquisas com filtros cruzados, a produção de relatórios com cruzamento de dados e a exportação dos dados para planilhas e arquivos geoespaciais (*shapefiles*), permitindo a integração com outras plataformas e a edição em programas especializados.

Em janeiro de 2025, o número de cavernas registradas no sistema atingiu 28.422 (CANIE, 2025), representando um aumento substancial em relação aos 11.504 registros de 2014. Esse crescimento reflete o esforço contínuo para a ampliação e atualização do banco de dados. A modernização também trouxe a implementação de mapas interativos, permitindo que os usuários visualizem as cavernas e suas características diretamente no sistema, o que facilita a análise espacial.

Uma das melhorias significativas foi a otimização do processo de validação dos dados. O Nível 1, agora automático, verifica as coordenadas geográficas da entrada principal das cavernas, identificando automaticamente o município e a unidade da federação (UF) correspondentes, o que aumenta a precisão e a confiabilidade dos dados. Além disso, o sistema continua a permitir a validação de dados mais detalhados com os Níveis 2 e 3, para cavidades cujas coordenadas foram conferidas ou topografadas.

Uma inovação importante implementada na nova versão do CANIE é a possibilidade de cadastramento em bloco de cavernas por meio do *upload* de planilhas eletrônicas, o que torna o processo de inserção de dados mais ágil, especialmente para projetos ou estudos que envolvem grandes quantidades de informações. Esta atualização é uma melhoria significativa na gestão de dados espeleológicos, permitindo maior praticidade e rapidez no cadastramento. A eficiência desse novo recurso pode ser observada na quantidade de cavernas cadastradas: em todo o ano de 2024, foram registradas 2.667 cavernas, enquanto, somente no primeiro mês de 2025, já foram inseridas 2.376 (CANIE, 2025).

A contribuição do CANIE para o licenciamento ambiental também se intensificou com a modernização. Com a maior precisão nas coordenadas geográficas das cavernas e a possibilidade de cruzamento de dados, o sistema tem se mostrado essencial para a definição da área de influência das cavernas, ajudando na avaliação de impactos ambientais de novos empreendimentos e atividades. As informações detalhadas e geoespacialmente localizadas contribuem para a elaboração de relatórios técnicos, imprescindíveis nos processos de licenciamento ambiental e monitoramento de áreas de risco, com base nas normas ambientais vigentes.

Além disso, o CANIE desempenha um papel estratégico pois os empreendimentos que possam impactar cavernas são obrigados a inserir informações espeleológicas no sistema durante o licenciamento, conforme Instrução Normativa nº 2/2017/MMA. Essa obrigatoriedade assegura que os órgãos ambientais competentes tenham acesso a dados atualizados e confiáveis, permitindo a avaliação criteriosa dos impactos e a adoção de medidas de mitigação necessárias para a conservação do patrimônio espeleológico.

Para a ciência, o CANIE é uma fonte valiosa de informações que subsidiam pesquisas nas áreas de biologia, geologia, arqueologia, paleontologia e hidrologia. Ele permite que pesquisadores acessem dados detalhados sobre as cavernas e suas características, facilitando a elaboração de estudos mais abrangentes e aprofundados.

Já para os grupos de espeleologia, o sistema é um instrumento

essencial de consulta e registro. Ele oferece informações confiáveis que auxiliam no planejamento de expedições, na ampliação do conhecimento sobre novas cavidades e na promoção de uma exploração mais segura e sustentável.

Em 27 de outubro de 2022, o CANIE passou a integrar a Infraestrutura Nacional de Dados Espaciais (INDE) (INDE, 2022), ampliando a visibilidade dos dados sobre cavernas e fortalecendo a base de informações para a tomada de decisões em políticas públicas e planejamento ambiental.

Esses avanços, aliados a uma maior integração com plataformas governamentais e à crescente base de dados, têm contribuído significativamente para a gestão, monitoramento e conservação do patrimônio espeleológico brasileiro, e são fundamentais no processo de licenciamento ambiental e proteção do meio ambiente.

Os dados disponíveis no CANIE indicam que Minas Gerais é o estado com o maior número de cavernas cadastradas, totalizando 13.067, o que representa aproximadamente 46% do total. Em seguida, destacam-se os estados do Pará (4.448 cavernas), Bahia (2.919), Rio Grande do Norte (1.373) e Goiás (1.143). Juntos representam 81% das cavernas conhecidas no Brasil. O sistema também registra um total de 453.596,54 metros de condutos de cavernas já topografados, demonstrando o avanço no mapeamento espeleológico e a importância da documentação detalhada dessas formações subterrâneas (CANIE, 2025).

Esses dados refletem a importância de manter o cadastro constantemente atualizado, garantindo informações precisas e abrangentes sobre o patrimônio espeleológico brasileiro. A alimentação contínua do sistema contribui para a gestão e conservação das cavernas, além de subsidiar pesquisas científicas e tomadas de decisão em políticas ambientais.

As melhorias na versão de 2024 do CANIE também impactam positivamente no licenciamento ambiental, permitindo uma avaliação mais detalhada e precisa das cavernas e sua área de influência. A atualização tecnológica do sistema, somada à capacidade de integrar dados de diferentes fontes e ao uso de mapas interativos, contribui para uma análise ambiental mais eficaz e para o cumprimento das normas legais e ambientais vigentes.

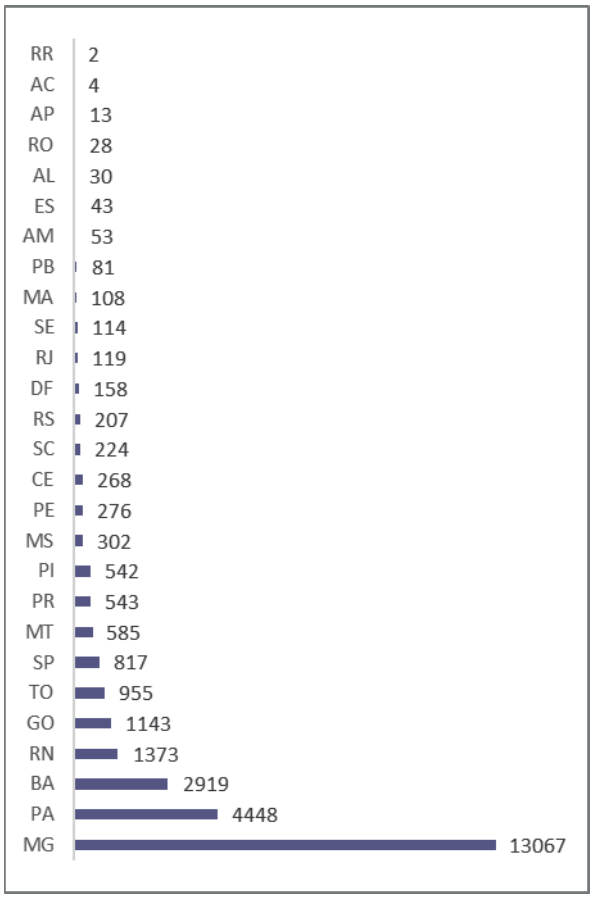

Figura 3: *Gráfico com a quantidade de cavernas por Unidade da Federação (CANIE, 2025).*

4. Discussão

O Cadastro Nacional de Informações Espeleológicas (CANIE) é uma ferramenta de suma importantes para a gestão e conservação do patrimônio espeleológico brasileiro. Disponível à sociedade a 22 anos, ele vem para atender à necessidade de reunir e organizar informações sobre cavernas em um sistema centralizado. Essa iniciativa partiu de uma articulação entre a legislação ambiental vigente e a atuação da comunidade espeleológica brasileira em parceria com o Centro Nacional de Pesquisa e Conservação de Cavernas (ICMBio/CECAV), órgão que, ao longo das décadas, se consolidou como referência na proteção e gestão das cavernas brasileiras.

CANIE desempenha um papel estratégico como repositório de dados sobre as cavernas do Brasil, consolidando informações essenciais para subsidiar pesquisas científicas, planejamentos de conservação e tomadas de decisão no âmbito do licenciamento ambiental e das políticas públicas. A gestão do sistema envolve esforços contínuos para assegurar que os dados sejam confiáveis, abrangentes e acessíveis, refletindo a diversidade e a relevância do patrimônio espeleológico nacional.

Entre os desafios enfrentados está a constante atualização das informações cadastradas, que frequentemente chegam de fontes diversas, como grupos espeleológicos, pesquisadores, órgãos públicos e da iniciativa privada. A implementação de processos de validação e a integração de dados robustos são ações prioritárias que fortalecem a credibilidade e a funcionalidade do cadastro.

A inclusão de novos registros e a geração de relatórios têm sido um destaque. O sistema, que já conta com dezenas de milhares de cavernas catalogadas, reflete não apenas a riqueza natural do Brasil, mas também o comprometimento em garantir que esse patrimônio seja protegido de forma eficiente e responsável.

Uma das grandes conquistas do CANIE tem sido o incentivo à colaboração entre diferentes atores. Parcerias estratégicas com universidades, organizações da sociedade civil e grupos espeleológicos têm contribuído significativamente para a ampliação da base de dados. Essas colaborações não apenas enriquecem o cadastro, mas também reforçam a importância do trabalho conjunto em prol da conservação.

Embora o investimento direto em tecnologia e capacitação ainda seja uma meta a ser alcançada, avanços como a modernização da *interface* e o aprimoramento das funcionalidades do sistema já são perceptíveis. Tais melhorias têm facilitado o acesso e o uso das informações por gestores, pesquisadores e demais interessados, contribuindo para que o CANIE se torne cada vez mais eficiente e confiável.

Com mais de duas décadas de existência, o CANIE se firmou como um dos principais instrumentos para a gestão do patrimônio espeleológico brasileiro. Ele não apenas organiza informações, mas também fomenta o conhecimento e a conscientização sobre a importância das cavernas para a biodiversidade, a cultura e a ciência. O aprimoramento contínuo do sistema e o fortalecimento das redes de colaboração são fundamentais para garantir que o CANIE continue a desempenhar seu papel estratégico, consolidando o Brasil como referência global na conservação do patrimônio espeleológico.

5. Conclusão

A modernização do Cadastro Nacional de Informações Espeleológicas (CANIE) foi um avanço crucial para a gestão do patrimônio espeleológico brasileiro, refletindo a busca por maior eficiência, precisão e acessibilidade. A nova versão do sistema, lançada em 2024, não só melhorou a infraestrutura tecnológica e a *interface* de usuário, mas também implementou funcionalidades que facilitam a pesquisa, a geração de relatórios e a integração com dados geoespaciais.

A implementação dos níveis de validação da localização das cavernas contribuiu para uma maior precisão e confiabilidade dos dados, fortalecendo o papel do CANIE no apoio ao licenciamento ambiental e à conservação das cavernas. Além disso, a incorporação dos dados relativos à Instrução Normativa nº 2/2017 amplia as informações disponíveis, atendendo às necessidades de regulamentação e preservação do patrimônio natural subterrâneo.

O CANIE, com quase de 28.500 cavernas cadastradas, se consolidou como uma ferramenta essencial para a gestão ambiental e a conservação espeleológica no Brasil. Espera-se que o sistema continue a evoluir, com a inclusão de novas cavernas e dados complementares, ampliando a base de conhecimento e contribuindo para a preservação sustentável das cavernas brasileiras. A contínua atualização e aprimoramento do sistema são fundamentais para manter a relevância e a eficácia do CANIE como uma ferramenta de gestão ambiental e conservação.

Agradecimentos

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The exploration and mapping of the Whigpistle Cave System, Edmonson County, Kentucky, USA

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Abstract

The Whigpistle Cave System is more than 69 kilometers long and is located in central Kentucky, USA. Exploration and mapping began in July, 1977 by employees of the National Park Service who were exploring caves in the region to better understand the karst hydrology and recharge of nearby Mammoth Cave. Up until May, 1983 they mapped approximately 32 kilometers of mostly lower-level, large passages with numerous streams. Several other groups have explored the cave since that time. In the early 1990s, the James Cave Project discovered Jackpot Cave. They mapped six kilometers. In April, 1996, Jon Jaspar and Alan Glennon found Martin Ridge Cave and within months had surveyed 11 kilometers and found connections to both Whigpistle Cave and Jackpot Cave, integrating the greater cave system. The current exploration and survey project was founded in July 2005. Since that time, 20 kilometers have been added to the cave with extensions across all three sections. Recently the rate of passage discovery has increased. Larger expeditions lasting two weeks take place in summer and fall. Other survey work takes place throughout the year when local cavers have the opportunity to visit the cave. The project is slowly shifting from long day trips to more camping, due to the long travel times to reach objectives.

1. Introduction

The Whigpistle Cave System is more than 69 kilometers long (13th longest in the USA and 49th longest on Earth at the time of writing) and is located near Mammoth Cave, the world's longest in central Kentucky, USA. The name of the cave is a play on the local name, whistle pigs, for a large, burrow-dwelling rodent in reference to the sounds these animals make. The cave was hydrologically connected to Mammoth Cave by dye tracing in the early 1980s with a positive trace between Hawkins River in Mammoth and Red River in Whigpistle, but no physical connection by a person has occurred. QUINLAN (1990) The cave contains what is likely the largest cave room in Kentucky known as the Big Womb with dimensions of 200 meters long, 40 meters wide and an average ceiling height of 13 meters.

Whigpistle is formed in Mississippian age limestones 100 m thick and is frequently overlain by Pennsylvanian sandstone cap rocks. The cave has formed through a complex interplay of primary base-level streams with allogenic recharge from the vast sinkhole plain to the west, south and east, and smaller tributary streams that provide autogenic recharge in the immediate vicinity of the system. The cave, and its five entrances, are on private land and maintaining good relationships with the landowners has been an ongoing challenge for cavers working in the area.

2. Materials and methods

The methods used for the mapping and exploration of the Whigpistle Cave System have evolved and changed with the changes in cave mapping technology through the decades that the cave has been under exploration and with the different groups that have mapped the cave up to the present time. The Whigpistle Cave (Splash) Entrance was first found in 1976 by Rick Schwartz. KERR (1981) The original explorers in the late 1970s, who worked for the National Park Service, employed analog instruments. They used foresights and backsights to ensure the accuracy of their survey work. Their sketches and drawings of the cave were produced at a large size and small scale that varied with the survey teams, but which showed many details of the interior of the cave passageways. Unfortunately, cave passage drawings were not oriented to north and frequently were oriented to include as much cave passage as possible on a given page. These first teams produced plan and cross section views, but not profiles of the cave passages. This has resulted in confusion and difficulties for the cartographers working to draft maps of the caves in the current era. These first teams used wetsuits to explore the cave and were not deterred by small passages and passage constrictions. However, these teams employed no vertical work or ropes and did only very limited passage modifications or enlargements to continue exploration. As a result, pits were not dropped, climbs were not undertaken and passages that became too tight to follow were not pursued further despite sometimes strong airflow. Don Coons produced a pencil draft of much of what had been surveyed in the cave.

The second group to work in the cave, the James Cavers, had explored caves in the area for decades BISHOP (2020). They explored the Jackpot section of Whigpistle, but their cartographer did not supply data and cave map sketches to the teams of cavers that currently work in the cave. This section of the cave has had to be remapped with the data and surveys being recreated in a time consuming and repetitive process. The James cavers did employ passage-enlargement techniques to follow prevalent winds through sections of this part of the cave. In some cases,

blasting and digging went on for multiple days before larger passages were accessed. These cavers were very skilled in rope work and used vertical techniques and wetsuits to explore passages. The James Cavers produced a map of the Jackpot section of the cave.

The work to replace the surveys from the James cavers was undertaken by the fourth and current group working to map and document the cave. These teams used analog instruments with back sights, plan, profile and cross section views and produced sketches oriented to north, improving upon the work of the first teams in the caves.

The third group to work in the cave in the 1990s, led by Alan Glennon and John Jasper, largely used the same methodology as the first group with analog instruments, foresights and backsights and sketches that included plan and cross section views. These cavers did some digging in the cave to access passages, including at the Martin Ridge Entrance, but did not use explosives in any way to enlarge passage constrictions. GLENNON (2001) Jon Jasper produced a map of the Martin Ridge section of the cave.

The fourth group has been exploring Whigpistle for 20 years. The Whigpistle Cave Project began in 2005 initially focusing on the re-survey of the Jackpot Cave section for a local landowner. Since then, the group has worked in all sections of the cave to further exploration of this vast system. Exploration has accelerated in recent years with good landowner relations, frequent trips and focused expeditions. Following the cave's air flow no matter where it goes, has paid off with kilometers of cave passage discoveries. (Fig. 1) The group employs whatever techniques are needed to explore the cave. This includes wetsuits for wet passages, ropework to descend pits and bolting to complete climbs. Micro-shaving techniques have been helpful in multiple locations. This targeted use of tiny explosive charges to remove small areas of bedrock is safe, fast and effective with a minimal amount of equipment.

Survey techniques for the project have changed over time. Analog instruments have been replaced with digital survey tools including the Disto X2 and Bric 4 and 5 popular with cave surveyors in the US. These tools allow for much faster and more accurate survey data collection. Some of the sketchers have also employed digital sketching on tablets or small computers. However, the wet and muddy conditions of the cave can make this a challenging endeavor.

Figure 1: *Cavers with the Whigpistle Cave Project map Coons Avenue, named for one of the first explorers of the cave. This passage was found using rock micro shaving to follow strong airflow. A belly-crawl 300 meters long and named Wacky Tacky way for its sticky mud also had to be negotiated to reach this much larger passage. Photo by Niles Lathrop.*

3. Results

Exploration and mapping began in July, 1977 by employees of the National Park Service (the agency that administers Mammoth Cave National Park) who were exploring caves in the region in a successful attempt to better understand the karst hydrology and recharge of Mammoth Cave. Up until May, 1983 they mapped approximately 32 kilometers of mostly lower-level, large trunk passages with numerous streams. In the early 1990s, to the east, cavers with the James Cave Project followed strong airflow to find Jackpot Cave with multiple large, upper-level passages including one, the Celestial Borehole, richly festooned with gypsum speleothems. They mapped six kilometers. In April, 1996, Jon Jasper and Alan Glennon, students at Western Kentucky University, found Martin Ridge Cave and within months had surveyed 11 kilometers and found connections to both Whigpistle and Jackpot Cave, integrating the greater cave system. The current exploration and survey project was founded in July 2005 after one of the local landowners asked cavers to make and provide a map of his cave. Since that time, 18 kilometers have been added to the cave with both small and large extensions across all three sections of the system. Landowner relations have improved due to the inclusion of active cavers who live above Whigpistle and whose neighbors own the cave entrances. Many of the discoveries have been in lower-level passages with strong airflow trending east and south. But large upper levels have also been found in Jackpot and Martin Ridge. Recently, with local cavers, members of the Green River Grotto and students from Western Kentucky University, the rate of passage discovery has increased. Larger expeditions lasting two weeks take place in summer and fall, the drier months of the year in central Kentucky. Other survey work takes place throughout the year when local cavers have the opportunity to visit the cave. The project is slowly shifting from long day trips to more camping, due to the long travel times to reach objectives. The project is also working in adjacent caves both inside of and outside of Mammoth Cave National Park in conjunction with the Cave Research Foundaion hoping to integrate and connect other caves into the ever-growing system.

Figure 3: *A caver with the Whigpistle Cave Project looks ahead into virgin, unexplored passage in the newly found Sgt. Peppers passage on the south margin of the cave. This kilometer-long passage was accessed by completing a short dig, donning wetsuits for a short, wet section and two micro-shaves of a bedrock protrusion. Many leads remain in this area. Cave camping will likely be pursued here in the future. Photo by Niles Lathrop.*

Recent discoveries have taken place in all three sections of the cave and have employed a variety of techniques to access new passages. In the Whigpistle section, cavers used micro-shaving techniques to make a connection between the alpha survey trunk passage and Quagmire Dome to the west in 2023, finding many leads and a lot of mud along the way. More than two kilometers have now been surveyed in this area including Heartbreak Creek and many leads remain, most trending to the south and at low levels.

Glennon and Jasper had noted a windy crawlway In Martin Ridge in 1996. Whigpistle cavers pushed this low and tight passage, named Velcro Crawl, with a floor of sharp chert in 2023 and 2024. The passage remains small and low and very uncomfortable, but breezy, for more than 200 meters. Finally, it opened up into large, parallel canyons trending east and away from the rest of the cave. More than a kilometer was surveyed here and multiple leads remain. Camping would be ideal in this area due to the challenging approach, but no good camping location has yet been found.

Following strong airflow, a single micro-shaving charge was used to remove a bedrock projection early in 2024 near the Splash Entrance, the primary entrance into the Whigpistle section. This led to the Wacky Tacky Way, 300 meters of low crawl with sticky mud and puddles of water. Eventually, this passage reached Coons Avenue and a complex of passageways that have been explored and mapped. Camping and vertical work has been employed here to facilitate additional exploration. Four kilometers have been mapped in this area and a connection to the cave's longest passage, Mexico Avenue completed. A few leads remain.

In the lowest section of Jackpot, down a series of four short rope drops, were leads not pushed by the James Cavers due an area of collapse that was unstable and periodic sumps that blocked passageways. Four hundred meters has been surveyed here when the passage was not sumped. Multiple leads remain and the Whigpistle team may siphon water from the sump pool in the future.

Early in 2024, at the end of the Celestial Borehole in Jackpot, Whigpistle caver Will Strehl felt strong airflow along one wall of the passage. Micro-shaving was used to remove a small area of flowstone to access more than a kilometer of survey including one of the largest trunk passages in the Mammoth Cave region now named Wonderland. Teams camped in this area to facilitate exploration.

The most recent discovery, in December, 2024, was a southwest trending trunk passage with nearly a kilometer of survey so far. This area was named Sgt. Peppers (fig. 3). To reach the new passage, Whigpistle cavers first had to complete a short dig, don wetsuits for a single low wet spot and micro-shave a bedrock protrusion. Many leads remain in this area.

Also, of interest to the Whigpistle cavers are new entrances providing access to more areas of the cave. There is the potential for new entrances in several locations accessed by climbs from below and potentially rappels from above.

A great deal of work has recently gone into completing maps of the cave. Quadrangle maps are being produced and the cave will have about 100 of these in total when the work is done. Eighty have been completed or nearly completed so far. Also, a large format quadrangle map book has been planned for the project. These maps will combine several of the quadrangle maps each, with the passages color coded to denote the level of a given passage.

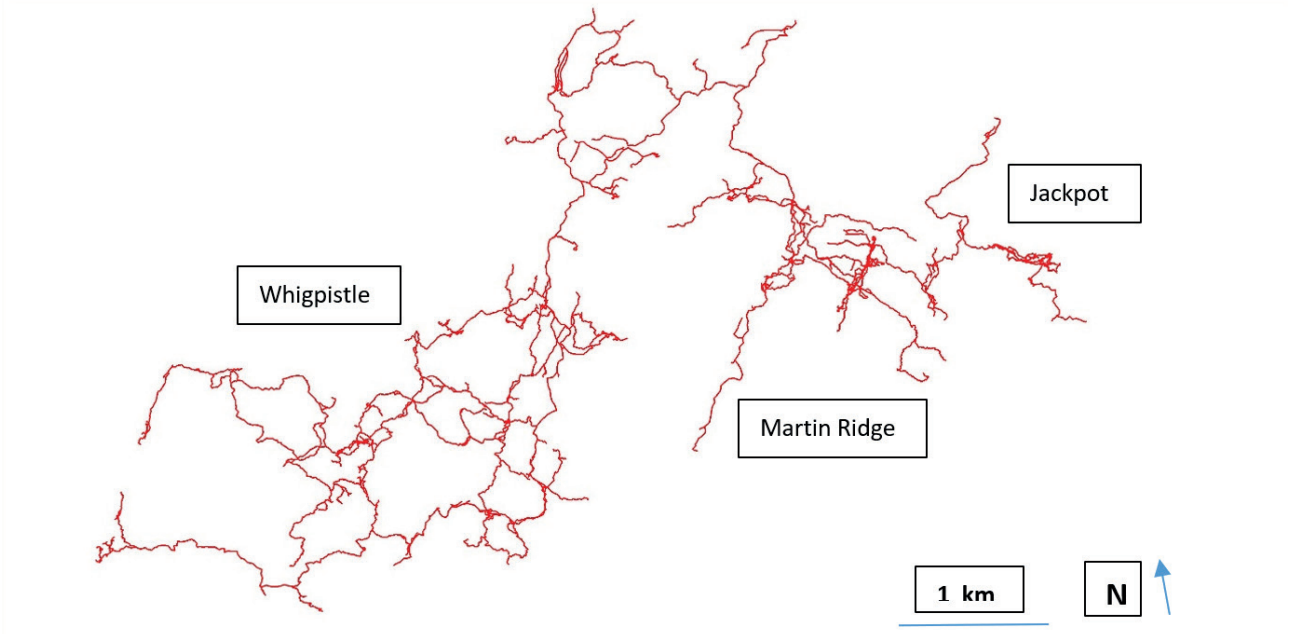

Figure 2: *Lineplot map of Whigpistle Cave.*

4. Discussion

The original exploration of the caves of the Mammoth Cave region began with Native Americans thousands of years ago. Through more than 100 years, the mapping and survey of the caves has continued. Whigpistle has now been explored for nearly 50 years, and there is so much more to do. Hundreds of leads remain. Most will not go far, but some, primarily those with airflow may continue for kilometers. The pace of discovery has recently accelerated generating not only more surveyed cave passage, but also more leads to add to the long list.

Project cavers will continue to push and survey these leads both inside the cave and in adjacent caves that might be connected. This work includes leads in all sections of the cave and in nearby caves such as Emelia River, Too Tight, Smith Valley and Martin in Mammoth Cave National Park and James and Coach caves on the historic Park Mammoth property.

The real prize is the possible connection to Mammoth Cave, which lies less than two kilometers away to the northeast but across a deep sinkhole valley. The recently discovered Wonderland section of Jackpot has bridged some of this gap and brought the two caves even closer together. Only time will tell when and if the connection can be made.

5. Conclusion

Cave projects grow, change and adapt as time goes by and this is certainly the case for the nearly 50 years of work that has gone into the exploration and mapping of this fantastic cave. Early work focused on horizontal passages and following the water. Later efforts involved advanced vertical work, digging, blasting and micro-shaving in small areas to access continuing cave passages.

Survey techniques have also changed with the times. Now survey data is created quickly and efficiently with digital tools and increasingly digital sketching and note taking on small computers. Whigpistle Cave will continue to grow and the cavers that work on the project will continue to adapt and change with the times incorporating new and innovative techniques as they become available.

Acknowledgments

We gratefully acknowledge and thank the dozens of hard-working cavers who have explored, mapped and enjoyed all three sections of Whigpistle Cave. The Quinlan cavers, the James Cavers, those that worked with Glennon and Jasper and now the Whigpistle Cave Project have all made many, many lasting contributions to understanding and exploring this amazing cave.

We also thank the landowners of the area who allow us access to the cave entrances and the passageways below their homes. Without their generosity our work in the cave could not take place.

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Novas explorações espeleológicas na gruta do Algar da Arroteia (Maciço Calcário Estremenho, PortugaL)

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Resumo

Localizada no Planalto de Santo António (Maciço Calcário Estremenho, Centro de Portugal), o Algar da Arroteia é uma cavidade cársica composta por três galerias principais subhorizontais, interligadas por condutas verticais. Descoberta na década de 1960 por membros da Sociedade Portuguesa de Espeleologia (SPE), a galeria mais profunda carateriza-se por uma circulação hídrica permanente. Explorações preliminares realizadas nas décadas de 1970 e 1980 pela SPE e pelo Núcleo de Espeleologia de Leiria (NEL) resultaram na documentação dos primeiros 1000 m. Contudo, foi apenas na última década, através de bombeamentos das águas em sifões, que se conseguiu avançar na exploração, alcançando 1364 m de desenvolvimento planimétrico e uma profundidade total de -88 m em relação à superfície topográfica. As novas campanhas exploratórias permitiram: (1) identificar uma evolução morfológica das galerias, passando de trajetos predominantemente retilíneos, com passagens angulares, para trajetos mais sinuosos; (2) elaborar uma topografia detalhada à escala 1:100 e com precisão 6D; (3) recolher dados para começar a delinear hipóteses interpretativas sobre a espeleogénese. No 10.º aniversário da retoma dos trabalhos de exploração destaca-se a importância da gruta do Algar da Arroteia para o entendimento da dinâmica hidrogeológica do maciço e da carsificação regional.

Abstract

Located in the Santo António Plateau (Estremadura Massif, Central Portugal), the Algar da Arroteia is a karstic cave composed of three main sub-horizontal galleries interconnected by vertical conduits. Discovered in the 1960s by Portuguese Speleological Society (SPE) members, the deeper gallery has a permanent water circulation. Preliminary explorations carried out in the 1970s and 1980s by SPE and the Leiria Speleology Group (NEL) documented the first 1000 m. However, pumping water from siphons made it possible to advance exploration in the past decade, reaching 1364 m of planimetric development and a total depth of -88 m relative to the surface. Subsequent exploratory campaigns allowed: (1) the identification of morphological evolution in the galleries, transitioning from predominantly straight paths, with angular passages, to more sinuous routes; (2) the production of a detailed topography at a 1:100-scale and with 6D accuracy; and (3) data collection to begin to outline interpretative hypotheses about speleogenesis. On the 10th anniversary of the resumption of exploration work, the importance of the Algar da Arroteia cave for understanding the massif's hydrogeological dynamic and regional karstification is highlighted.

1. Introdução

O Maciço Calcário Estremenho, situado na região centro de Portugal, representa o relevo carbonatado e carsificado de maior expressão morfológica no país, destacando-se pela sua relevância geológica e geomorfológica (MARTINS, 1949; AZEREDO, 1998, 2007; FERREIRA et al., 1988; CRISPIM, 1992, 1995; RODRIGUES, 2020; CARVALHO, 2018; e referências neles incluídas). Estruturado na dependência de uma espessa sucessão estratigráfica carbonatada essencialmente jurássica (AZEREDO, 1998, 2007; CRISPIM, 1992), e condicionado por uma estrutura geológica complexa com falhas, dobras e cavalgamentos (CARVALHO, 2018), o Maciço Calcário Estremenho apresenta-se com uma compartimentação interna em blocos morfo-estruturais abatidos e soerguidos: a Serra de Aire a Leste, a Serra dos Candeeiros a Oeste, o Planalto de Santo António no Centro e Sul e o Planalto de S. Mamede a Norte; entre estes relevos salientes na paisagem identificam-se a Depressão da Mendiga e os Poljes de Minde e Alvados (MARTINS, 1949; FERREIRA et al., 1988; CRISPIM, 1995; RODRIGUES, 2020). Embora os cursos de água superficiais sejam praticamente inexistentes no interior do maciço, a sua bordadura abriga diversas nascentes que alimentam rios de grande importância, como o Alviela, Almonda, Lena e Lis (Figura 1).

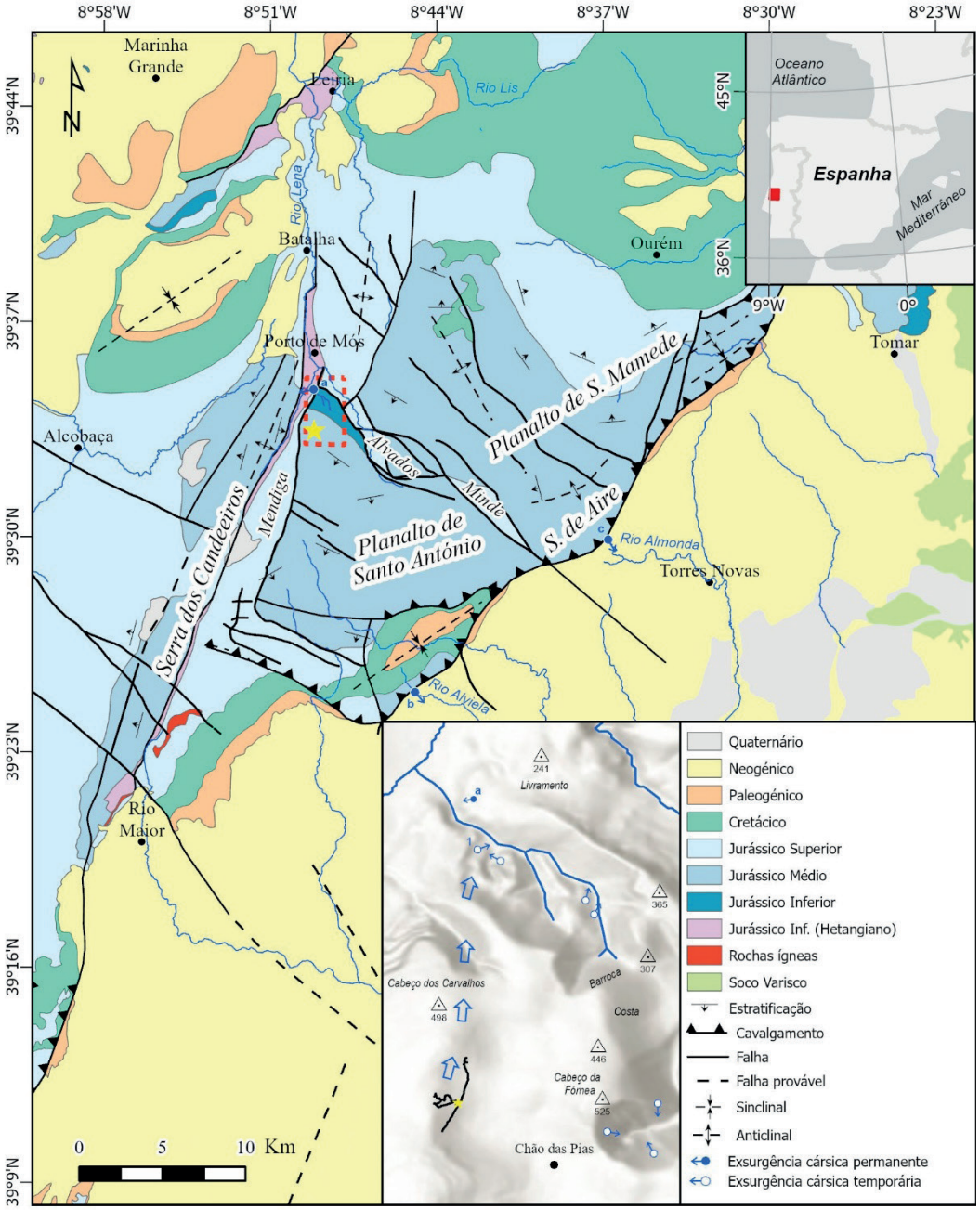

Figura 1: *Mapa de enquadramento geológico (simplificado) do Maciço Calcário Estremenho com indicação das principais unidades morfo-estruturais regionais (adaptado de Carvalho, 2018). A localização da entrada da gruta do Algar da Arroteia está identificada pela estrela amarela. As principais exsurgências cársicas do maciço são: (a) Olho de Água da Ribeira de Cima; (b) Olhos de Água do Alviela; e (c) Olho do Moinho da Fonte. No quadro inferior segue a localização em planta da gruta do Algar da Arroteia, assim como as principais exsurgências cársicas mais próximas e que caraterizam a bordadura do setor setentrional do Planalto de S. António, tais como a (1) Moinhola do Maneta; as setas azuis indicam a circulação hídrica subterrânea inferida (!) através de traçagens com corantes fluorescentes na década de 80 (THOMAS, 1985; CRISPIM, 2012).*

Em termos de geomorfologia cársica, o maciço é caraterizado pela presença de uma grande variedade de formas superficiais de pequena, média e grande dimensão, entre as quais se destacam lapiás, campos de lapiás, dolinas, uvalas, anfiteatros (fórnias ou *reculées*) e vales/canhões fluviocársicos com abrigos sob rocha ao longo das vertentes ("buracas"), bem como outras depressões abertas pela incisão fluvial, em algum caso parcialmente ou totalmente soterradas por uma cobertura siliciclástica pós-jurássica a configurar situações de paleocarso (FERREIRA et al., 1988; RODRIGUES, 2020). Ainda mais emblemática parece ser a paisagem cársica subterrânea onde cavidades naturais (lapas e algares), sistemas de cavidades e exsurgências, localizadas normalmente na bordadura do maciço, ditam a sua especificidade (FLEURY, 1925; MARTINS, 1949; THOMAS, 1985; CRISPIM, 1992; CANAIS & FERNANDES, 1999; REIS et al., 2023; e referências neles incluídas).

Entre as várias depressões alongadas de média dimensão que caraterizam os relevos salientes do Maciço Calcário Estremenho, e mais especificadamente na extremidade setentrional do próprio Planalto de Santo António, destaca-se a de Chão das Pias, com uma extensão a rondar os 1,5 km e cuja origem remonta, provavelmente, a dinâmicas de incisão fluvial, com sucessivos ou contemporâneos afeiçoamentos cársicos, aproveitando sistemas de fraturas preexistentes com orientação de N-S a NW-SE. Um conjunto de dolinas de abatimento, alongadas no sentido desta fraturação, caraterizam o fundo do vale (FERREIRA et al., 1988).

Na vertente ocidental da depressão de Chão das Pias, poucos

quilómetros a NO da aldeia homónima, na Freguesia de Serro Ventoso (Concelho de Porto de Mós), a 445 m de altitude, abre-se a entrada da gruta do Algar da Arroteia - ou Algar das Gralhas (coordenadas WGS84: N39º33´38.7´´, W8º49´06.1´´) (DIAS et al., 2019).

Localmente, a circulação das águas em profundidade é bastante diversificada, com trajetórias alternativas em direção a um conjunto de pequenas nascentes associadas à cabeceira do Rio Lena. De facto, traçagens com corantes fluorescentes demonstraram a existência de uma ligação hídrica subterrânea entre a gruta do Algar da Arroteia e a nascente da Moinhola do Maneta (Lena 4 em DIAS et al., 2019), um pouco a montante da principal nascente do Rio Lena (ou Olho de Água da Ribeira de Cima) (THOMAS, 1985; CRISPIM, 2012) (Figura 1).

A descoberta da gruta do Algar da Arroteia deu-se por elementos da Sociedade Portuguesa de Espeleologia (SPE) em meados da década de 60 (CRISPIM, 2012). As primeiras explorações surgem pela mão do Grupo de Espeleologia do Secretariado para a Juventude em 1972, com intuito puramente lúdico, permitindo a descoberta dos primeiros 300 m de poços e galerias (THOMAS, 1985). Posteriormente, com renovado interesse científico, diversos grupos de espeleologia, entre os quais se destaca o Núcleo de Espeleologia de Leiria (NEL), uniram esforços e, após conseguirem a passagem do sifão da Galeria do Rio, avançaram no sistema subterrâneo explorando mais 150 m adicionais de galerias (DIAS et al., 2019). As explorações foram interrompidas em meados da década de 1980 devido à impraticabilidade do sifão a jusante (S1). Apesar das tentativas de utilização de uma barreira de escoamento em cimento e tijolo, a recarga constante do sifão impossibilitou a retoma dos trabalhos de exploração (THOMAS, 1985). Tal obstáculo resultou num interregno de 35 anos durante o qual a extensão máxima da cavidade explorada permaneceu limitada aos 1000 m (DIAS et al., 2019).

Na celebração do 10º aniversário da retomada dos trabalhos de exploração na gruta do Algar da Arroteia, é objetivo deste trabalho apresentar os resultados das diversas campanhas de exploração realizadas entre 2015 e 2025. As novas explorações permitiram também a elaboração de uma topografia detalhada da cavidade, assim como a recolha de dados para começar a elaborar algumas hipóteses interpretativas acerca da sua espeleogénese.

2. Metodologias

Em 2015, o NEL decidiu retomar os trabalhos de exploração e cartografia da gruta do Algar da Arroteia considerando o reconhecido interesse científico. Numa fase inicial, o plano de trabalho concentrou-se na obtenção das permissões necessárias junto ao Instituto de Conservação da Natureza e das Florestas (ICNF), dado que a cavidade em estudo está localizada dentro dos limites do Parque Natural das Serras de Aire e Candeeiros (PNSAC). No desenvolvimento das campanhas espeleológicas foram utilizados os métodos de progressão em cavidade recomendados pela UIS – *Union Internationale de Spéléologie* (UIS, 2013).

Para a drenagem de dois sifões (S1 e S2 – ver a topografia da cavidade), foi implementada uma campanha de bombeamento artificial sistemática utilizando modernas bombas submersíveis do tipo "de furo". As bombas foram integradas a um sistema de boias e a um dispositivo eletromecânico (relé), permitindo o seu funcionamento alternado e prevenindo sobrecargas no sistema elétrico. As autorizações do ICNF, com renovação trimestral, permitiram, ainda em 2015, a instalação de 200 m de tubagens e fiações elétricas, assim como de novos 200 m de tubagens e uma 3ª bomba submersível em 2017. Retomou-se a albufeira artificial (barragem) criada nos anos 1980 (THOMAS, 1985), onde foi instalada a bomba principal, a aproximadamente -78 m abaixo da superfície topográfica. A sua função consistia na drenagem das descargas induzidas dos sifões, garantindo assim condições de segurança para a exploração da cavidade. As águas bombeadas foram reutilizadas para fins agrícolas e disponibilizadas à população, integrando a atividade espeleológica em estratégias de desenvolvimento sustentável.

As desobstruções requereram a aplicação de diversos métodos devido à considerável quantidade e extensão dos bloqueios encontrados. Na maioria dos casos utilizaram-se técnicas manuais, como martelo e escopro, especialmente para a remoção de concreções carbonatadas. Em situações específicas recorreram-se a explosivos de pequena dimensão, aplicando o método "mata-vacas" (LEMOS et al., 2002). Já em casos excecionais, que demandaram a remoção de volumes mais significativos de material, foram utilizadas pequenas quantidades de pólvora caseira de combustão lenta, detonadas remotamente por espeleólogos especializados em técnicas avançadas de desobstrução.

O levantamento topográfico foi realizado com recurso a sistemas digitais avançados utilizando o kit de melhoramento "DistoX", implementado nos medidores de distância Leica Disto A3Sub. Para o processamento e registo dos dados foi empregue o software PocketTopo, desenvolvido para PDAs, com ecrã resistivo (POCKETTOPO, 2020), permitindo a digitalização direta e eficiente das medições em campo. A calibração dos medidores de distância foi conduzida pela Associação de Estudos Subterrâneos e Defesa do Ambiente (AESDA) que aplicou uma metodologia própria (REGALA, 2015). Para assegurar a qualidade e a precisão do levantamento topográfico foi adotada a classificação padronizada pela UIS, conforme as diretrizes publicadas em 2012 (https://www.uisic.uis-speleo.org/wgsurmap.html - último acesso janeiro de 2025). Este sistema de classificação permitiu avaliar a precisão das medições em função de critérios técnicos rigorosos, garantindo a fiabilidade dos dados obtidos. O uso de equipamentos calibrados e softwares dedicados não só aumentou a precisão das medições, como também otimizou o tempo de levantamento em campo, facilitando a integração dos dados em sistemas de informação geográfica (SIG) para análises geomorfológicas posteriores e representação espacial tridimensional da cavidade. Este nível de precisão foi essencial para a exploração segura e para o estudo científico da gruta.

3. Descrição dos resultados

Em 2015, após a conclusão da drenagem do S1, foi possível avançar 30 m na cavidade, totalizando aproximadamente 500 m de área reexplorada. No ano seguinte (2016), os objetivos focaram-se na: (a) reexploração da galeria mais superficial; e (b) continuação da exploração do sifão S1. A contínua progressão numa das galerias mais profundas, caraterizada pela presença de um curso de água subterrâneo permanente, exigiu a realização de trabalhos avançados de desobstrução, incluindo o uso de explosivos, o que possibilitou a descoberta da batizada Galeria do Tiago (Figura 2).

Figura 2: *Na imagem superior, entrada da gruta do Algar da Arroteia durante uma das campanhas exploratórias (fotografia de Marco Dias). Na imagem inferior, descoberta da Galeria do Tiago em 2016 (fotografia de António Fael).*

Paralelamente aos esforços exploratórios foram iniciadas atividades de cartografia que, ao final do período considerado (2015-2024), resultaram numa topografia detalhada da cavidade, incluindo planta e perfis, em escala 1:100 e com precisão de 6D. A cobertura total atingiu 1364 m de extensão planimétrica e uma profundidade de -88 m em relação à superfície topográfica (Figura 3).

Em 2017, aproveitando um ano hidrológico extremamente seco, continuou-se a explorar a Galeria do Tiago, bem como se iniciou a progressão na Galeria Fóssil da Esquerda através de um poço com uma vertical de -8 m (Figura 3). A exploração da Galeria do Tiago possibilitou a descoberta da Passagem da Concertina, com intensa recarga hídrica que muito provavelmente foi induzida por forçamento hidráulico em situações de grande escoamento, e a da Galeria dos Açores, cujo fundo possuía uma grande quantidade de depósitos detríticos finos (pelitos) indicando uma zona de retenção prolongada das águas. A exploração permitiu, ainda, identificar uma conexão entre o S2 e o S1. Para além das descobertas associadas à rentabilização do tempo para progredir em cavidade, os anos de 2018 e 2019 permitiram desbravar o Meandro das Tormentas e identificar um outro acesso à cavidade através da Galeria do Vento (Figura 3), cuja conexão pode estar associada a uma dolina de colapso. A descoberta desta nova conexão revelou-nos a Sala da Boa Esperança, caraterizada por águas limpas e transparentes, sendo que é na Galeria do Rio que atualmente corre um curso de água permanente.

Os anos de 2020, 2021 e 2022 marcaram períodos de paragem das explorações devido às restrições impostas pela situação pandémica mundial (COVID-19), possibilitando aperfeiçoamentos, no gabinete, da topografia até então realizada.

Em 2023 as explorações foram retomadas com a continuidade da drenagem dos níveis inferiores, o que possibilitou a passagem pelo S2 e o avanço na cavidade. A drenagem completa do S2 resultou no escoamento do Sifão da Sala da Boa Esperança, evidenciando a conexão entre ambos.

Já em 2024 os esforços concentraram-se na elaboração da topografia da cavidade e compreensão da sua configuração do ponto de vista morfológico e genético. Uma leitura preliminar evidência a presença de galerias com trajetos essencialmente retilíneos, com passagens angulares, para depois passar a trajetos mais sinuosos, conforme as direções da fraturação ou mesmo a inclinação das camadas carbonatadas do Jurássico Médio.

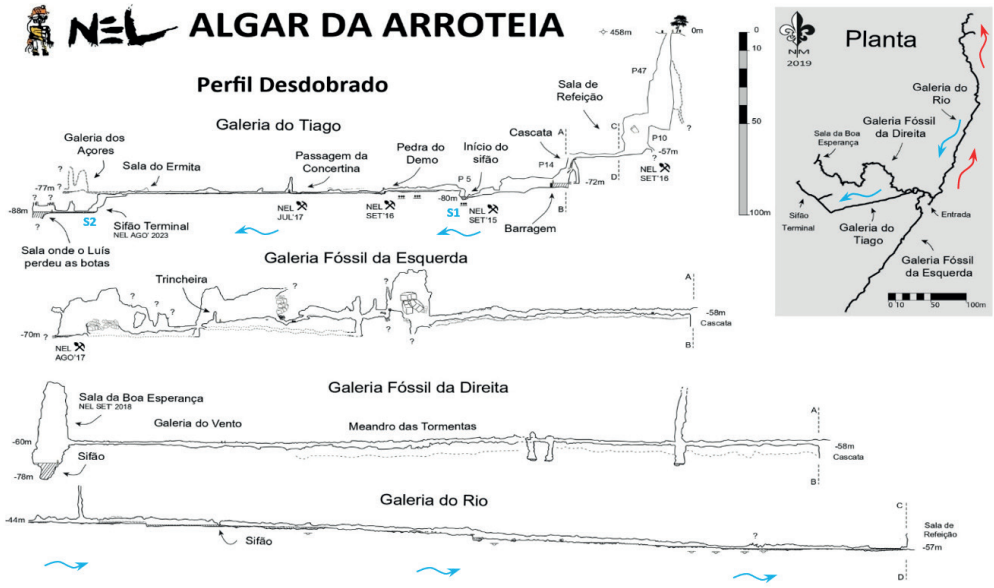

Figura 3: *Planta e perfis longitudinais da gruta do Algar da Arroteia. S1 e S2 (identificados a azul) são os sifões intervencionados. As setas azuis representam a direção do escoamento hídrico subterrâneo permanente da cavidade. As setas azuis em traços descontínuos identificam o escoamento das galerias mais superficiais em períodos de grande precipitação. Junto a planta da cavidade (canto superior direito) está indicado o escoamento das águas subterrâneas inferido pelas traçagens com corantes fluorescentes na década de 80 (setas vermelhas) e o escoamento verificado nas campanhas exploratórias do NEL (setas azuis).*

4. Considerações finais

A presença de um curso de água subterrâneo permanente na gruta do Algar da Arroteia torna esta cavidade um elemento essencial para o entendimento das dinâmicas hidrogeológicas do Maciço Calcário Estremenho, no Centro de Portugal. Além disso, a gruta desempenha um papel crucial na compreensão dos processos de carsificação, oferecendo uma oportunidade única para o estudo da evolução geomorfológica regional.

As atividades espeleológicas realizadas ao longo dos últimos 10 anos enfrentaram desafios significativos, marcados por avanços e recuos. Entre as conquistas, destacam-se a exploração e o mapeamento de 1364 m de extensão planimétrica da gruta, com um desnível total de -88 m em relação à superfície topográfica. Contudo, essas realizações exigiram consideráveis investimentos financeiros e esforços humanos, refletindo a complexidade e a demanda técnica envolvidas em projetos deste porte.

Os resultados alcançados ao longo da última década indicam um grande potencial para a continuidade das explorações espeleológicas e das investigações científicas, especialmente no que diz respeito ao entendimento da evolução genética (espeleogénese) da gruta do Algar da Arroteia. A possibilidade de desenvolver uma cartografia geomorfológica subterrânea de detalhe poderá ser fundamental para compreender e hierarquizar as formas e os depósitos encontrados (morfo-sequências), contribuindo para um quadro mais abrangente sobre a história geológica e geomorfológica da região.

Finalmente, na celebração dos 10 anos da retomada da exploração considera-se que a gruta do Algar da Arroteia ainda guarda muitas informações cruciais para o entendimento da hidrogeologia local e regional. Assim, acredita-se que a cavidade desempenhará um papel central nas futuras investigações, consolidando-se como uma referência para o estudo dos sistemas cársicos do Maciço Calcário Estremenho e de Portugal.

Agradecimentos

O conjunto das explorações e campanhas espeleológicas sofreram o apoio contínuo da Junta de Freguesia de Serro Ventoso e da Câmara Municipal de Porto de Mós. Agradecemos ao Parque Nacional das Serras de Aire e Candeeiros (PNSAC) e ao Instituto de Conservação da Natureza e das Florestas (ICNF) pelo suporte metodológico e burocrático. No desenvolvimento das atividades espeleológicas estiveram envolvidas um conjunto de associações espeleológicas nacionais (AESDA, ECTV, GEM e SAGA) e internacionais (Speleoklub Warszawski). Finalmente um agradecimento especial ao espeleólogo do NEL César Cordeiro, ao espeleólogo do NEL e presidente da Junta de Freguesia de Serro Ventoso Carlos Cordeiro e ao Tiago Carreira pelo inestimável apoio material e logístico fundamental para o sucesso da exploração.

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Assessment of a low-cost solution for cave mapping: a comparative analysis

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Abstract

This research compares two techniques for 3D cave mapping: point clouds from an iPhone's LiDAR sensor and a high-resolution 3D survey using a FARO Focus laser scanner to evaluate the strengths and limitations of the iPhone's portable, low-cost solution. Both methods were applied to the same areas of Agios Georgios, a show cave in Kilkis, Greece. Herein, the 3D mapping of a chamber was scrutinized. All 40 FARO scans were merged into a single file, producing a high-density point cloud, which was then decimated to a 1 cm spatial resolution to match the iPhone-generated point cloud's resolution. This resulted in a point cloud with 1/25th of its original density to ease the dataset comparison. Data processing in CloudCompare revealed: (i) iPhone-generated point clouds require significant overlap for accurate registration; (ii) for small cave chambers, iPhone data is reasonably accurate, with 90.576% of points having a Cloud-to-Cloud distance ≤ 0.2232 m; and (iii) iPhone models cave morphology with a smoother texture due to AI-enhanced mesh representation.

1. Introduction

This paper presents a case study to assess the results of using as a scanning technique the Light Detection and Ranging (LiDAR) sensor built-in iPhone devices for 3D cave mapping (Table 1). The assessment is conducted by comparing the resulting point cloud to the point cloud generated by a high-resolution 3D topographic survey using a FARO Focus^{3D} laser scanner.

The LiDAR sensor built-in an iPhone is a low-cost and commercial method for generating 3D models and has rapidly has found its application in speleology studies. The sensor emits infrared laser pulses to measure distances to objects, creating a point cloud, and generates an accurate 3-dimensional map in real time. The sensor can typically measure distances up to about 5 m, but its effective range might vary depending on lighting conditions.

The FARO Focus3D emits an invisible laser beam, using phase shift technology where the distance of the objects is determined by measuring the phase difference between the emitted and received laser signals. The FARO scanner collects up to 976,000 points per second, recording XYZ coordinates of each measured point. The final 3D representation is an integration of the point cloud with the images captured by the built-in HDR camera for a colored point cloud.

Agios Georgios Cave (Fig. 1), located in Kilkis, Northern Greece, is a show cave that has attracted speleological research from an early stage (PETROCHEILOU, 1962; 1973) and serves as the case study for this research. Various investigations have highlighted its morphological (IFANDI et al., 2015; LAZARIDIS, 2017; KARAKOSTA et al., 2019), archaeological, paleoclimatic (DOTSIKA et al., 2010), and paleontological significance (TSOUKALA, 1992; BASSIAKOS & TSOUKALA, 1996).

Three distinct areas of the cave were selected for the comparison of point clouds generated using the iPhone and FARO Focus3D. They were chosen based on their morphological differences and spatial extents. The first area corresponds to the junction of two passages, while the second represents a chamber. The third area is a vertically extended section, resembling the passage that connects the two levels of the cave, where the stairs of the tourist route are located. Herein, the results of the area 2 are presented.

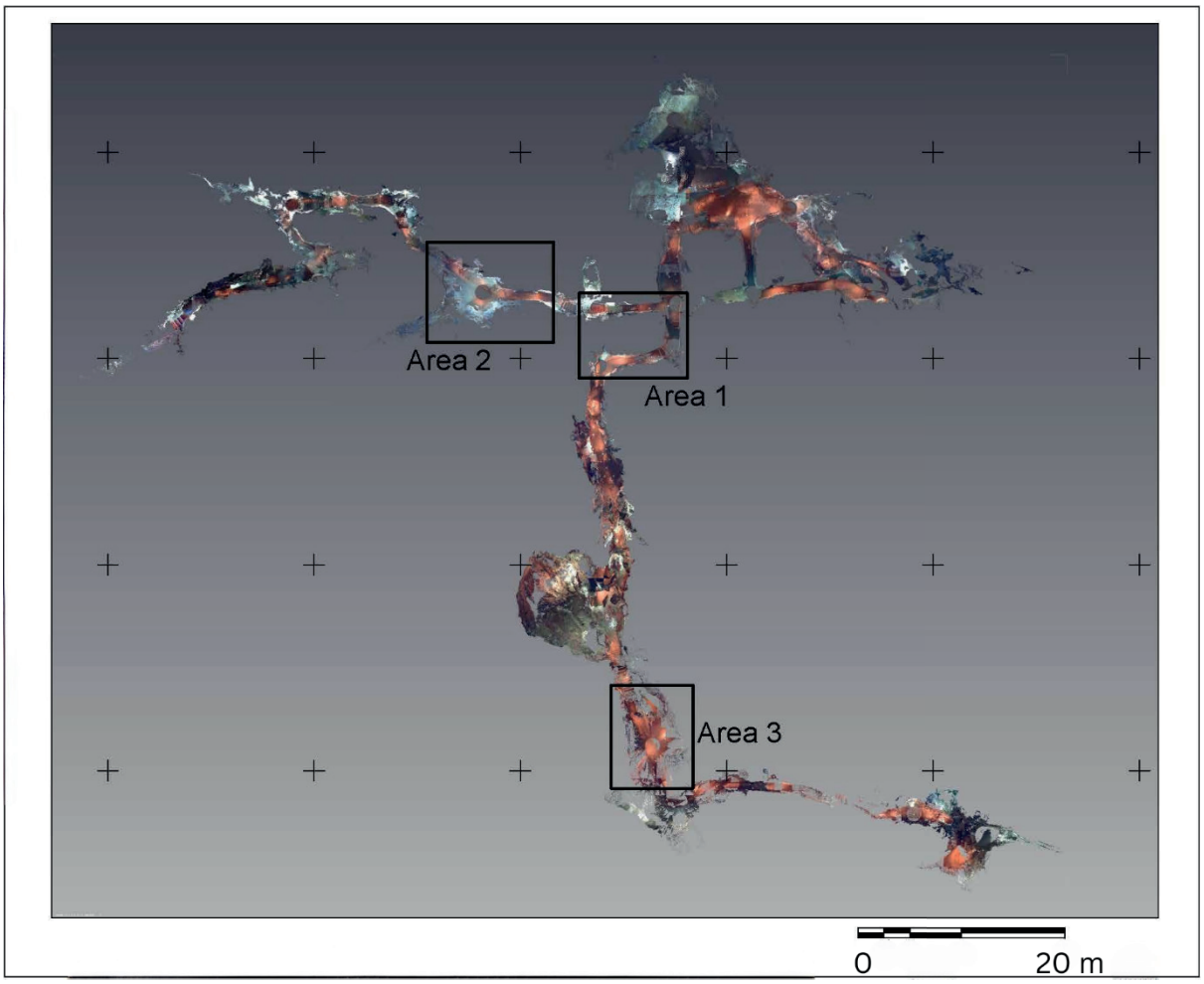

Figure 1: *Plan map of Agios Georgios Cave in Kilkis, generated from 40 high-precision scans using the FARO Focus3D laser scanner using software Pointools (CHRISTOGLOU et al., 2015). The colors in the map represent the mesh color of the generated 3D model.*

2. Methodology

Agios Georgios Cave was surveyed with a FARO focus laser scanner (CHRISTOGLOU et al., 2015). The point cloud from the FARO was reduced to a spatial resolution of 1 cm, and 40 scans were merged into a single file. This resulted in a point cloud with 1/25th of its original density to ease the dataset comparison. The initial step involved registering the point clouds using the SCENE software by FARO. This semi-automated process was executed by sequentially aligning pairs of consecutive point clouds, using spherical targets that have been placed on-site before-hand. This method ensured precise control over the registration process, reducing errors from the automated system. After the target-based registration, a cloud-to-cloud registration was used to refine the resulting point cloud, using the ICP algorithm. Accordingly, the three scans from the iPhone device using Polycam application were merged into a file. The Cloud-to--Cloud (C2C) Distance tool from the CloudCompare software was used to compare the "Area 2" point clouds from the different sources. In this study, the FARO's point cloud served as the baseline reference point cloud for comparison against the iPhone LiDAR-generated point cloud.

3. Results

Figure 2 is a comparison of the two point clouds. It reveals significant similarities. The overall morphology and size of the chamber is accurately captured by both methods, with no major differences. However, the cave outline generated by the iPhone appears noticeably smoother. These differences occur where the largest C2C distances were recorded (Fig. 3).

Figure 4 illustrates the absolute C2C distances between the two clouds. The majority of points have small distances, indicating strong alignment (blue areas). Green and yellow regions represent moderate differences. The small number of red points indicate significant differences. The red threshold line signifies that 90.576% of the points have a C2C distance of ≤0.2232 m. The maximum recorded distance between points is 0.929 m, with an average distance of 0.057 m.

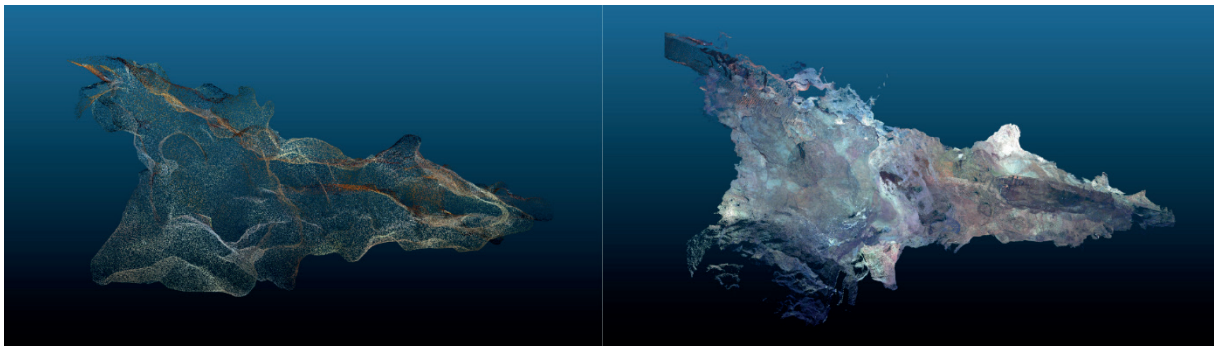

Figure 2: *Comparison of point clouds for Area 2 generated by the iPhone (left) and FARO Focus 3D (right).*

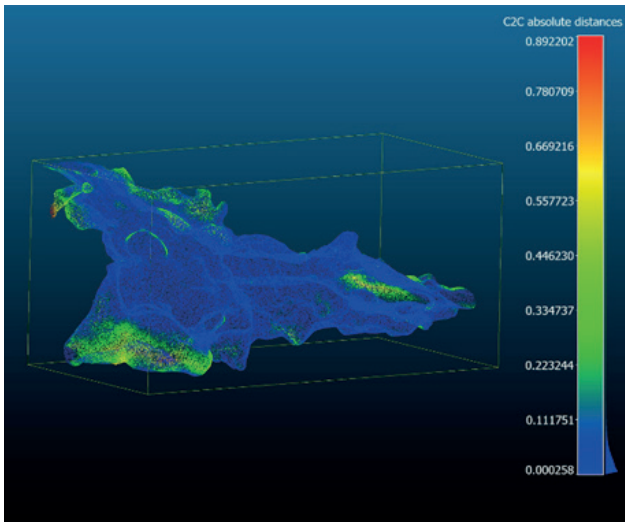

Figure 3: *Cloud-to-Cloud absolute distances between the reference point cloud generated by the FARO laser scanner and the point cloud generated by the iPhone LiDAR sensor, illustrating the spatial divergences between the two datasets. The color scale represents the absolute distances in meters, ranging from 0.000258 m (blue) to 0.892202 m (red), with intermediate values such as 0.223244 m (green) and 0.669216 m (yellow), providing a quantitative measure of the deviations.*

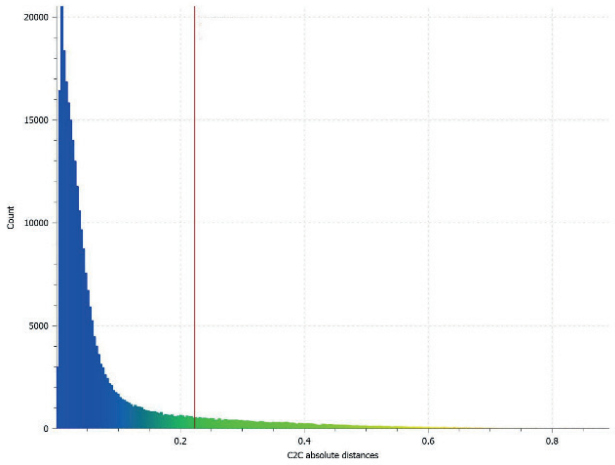

Figure 4: *Histogram illustrating the Cloud-to-Cloud absolute distances between the two point clouds: one generated using the iPhone LiDAR sensor and the other using the FARO laser scanner, for Cave Area 2. The red threshold indicates that 90.576% of points have Cloud-to-Cloud distance ≤0.2232 m.*

4. Concluding remarks

A comparative analysis was conducted between point clouds generated using an iPhone device, a low-cost solution for 3D cave mapping, and a FARO Focus3D laser scanner, a high-precision instrument for topographic surveys. The low average C2C distance of 0.0576 m indicates a generally strong alignment between the two datasets. The majority of points exhibit minimal deviations, confirming a high degree of correlation between the point clouds. However, in smaller recesses with insufficient lighting, gaps are present in the iPhone-generated point cloud. The Polycam application employs AI-based interpolation to fill these voids, resulting in a smoother texture and morphology in the final 3D model. The results showed that the mobile LiDAR system remains a practical tool for rapid 3D scanning and delivers satisfactory accuracy when applied in a chamber cave of within its approximate 5-m range.

Further research is required in areas of caves with diverse morphologies and spatial extents to comprehensively evaluate the capabilities of the iPhone LiDAR sensor in cave mapping. Additionally, an in-depth investigation is needed to identify the optimal methodology for its application, ensuring greater accuracy and reliability in 3D cave mapping using a low-cost device.

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Diseño de una aplicación Webgis para el trabajo espeleológico

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Abstract

DESIGN OF A WEBGIS APPLICATION FOR CAVING WORK. Geographic Information Systems are a very important tool for the integration of different disciplines, being ideal for the integration of interdisciplinary task in Speleology. In this work we explain how we are developing an application that allows us to simplify the registration of new cavities and deepen our knowledge of caves, and the technologies used that will allow us to improve it. The technological and economic resources we have are also considered to structure the application that allows it to be customized according to the work methodology of the Argentine Speleological Group (GEA).

Resumen

Los Sistemas de Información Geográficos son una herramienta muy importante para la integración de diferentes disciplinas, siendo ideal para la integración del quehacer interdisciplinario de la Espeleología. En este trabajo explicamos cómo estamos desarrollando una aplicación que nos permita simplificar el registro de nuevas cavidades y profundizar en el conocimiento de las cuevas, y las tecnologías utilizadas que nos permitirán mejorarla. También se consideran los recursos tecnológicos y económicos de que disponemos para estructurar la aplicación que permite personalizarla acorde a la metodología de trabajo del Grupo Espeleológico Argentino (GEA).

1. Introducción

En el trabajo de estudiar e investigar las cavernas intervienen diversas disciplinas de variadas áreas del conocimiento, produciendo y recolectando datos de diferentes características. A partir de esto surge la necesidad de crear una herramienta que permita integrar el trabajo interdisciplinario llevado a cabo en la espeleología. En los estudios previos y en el trabajo de campo que se realiza en cada exploración de cavidades naturales se recolecta una gran variedad de información, desde áreas de las ciencias sociales como la Antropología, Arqueología entre otras, así como desde las ciencias naturales como la Geología, la Biología, etc. y otras áreas como la Cartografía. Esta información en su conjunto plantea el desafío de su procesamiento, su integración y la referenciación de los datos no geográficos. Cuando hablamos de procesamiento nos referimos a la posibilidad de comprender los datos recolectados y analizarlos para brindar respuestas a los interrogantes que surgen en cada disciplina. La integración de los mismos a partir de su relación con el espacio nos permite elaborar nuevas ideas y conclusiones que no son posibles de abordar desde cada disciplina de manera aislada, en tanto la perspectiva interdisciplinaria posibilita profundizar en el estudio de las cavernas. Finalmente hay una parte de la información que resulta compleja de poder vincular a una ubicación geográfica, y esa dificultad también se espera superar con esta aplicación.

2. Materiales y métodos

A partir de la necesidad de tener una aplicación propia para cargar los datos tomados en campo y centralizar en un único lugar la información, facilitando su visualización, surgió la idea de crear una aplicación WebGIS. La aplicación se conformó con los datos de cuevas argentinas ya registradas en el Catastro Nacional de Cavidades Naturales (REDONTE, 2022). Con ella podremos exportar los nuevos registros en un formato apto para la incorporación del catastro, manteniendo un constante intercambio de datos que permita mantener actualizadas ambas plataformas.

Al tratarse de una aplicación de experiencia de usuario, de características predominantemente visuales, se diseñó primero la estructura básica: el backend como la base de datos, y luego la gráfica, pensando cómo se visualizan los datos respecto a su ubicación geográfica y el formato de los formularios de carga de datos.

Se empezó por desarrollar el sitio donde se guardan los datos geográficos, es decir, se desarrolló una parte del backend utilizando Django, por ser un framework de desarrollo web en Python que facilita la creación de aplicaciones robustas y seguras. Y además se utilizó la extensión GeoDjango añadiendo herramientas para manejar datos espaciales. La base de datos se desarrolló con PostgreSQL (sistema de gestión de bases de datos relacional de código abierto), y al trabajar con datos geográficos se utilizó la extensión PostGIS ya que agrega soporte para datos espaciales (coordenadas, geometrías, análisis geoespacial). Este diseño permite almacenar y gestionar datos geográficos como puntos, líneas y polígonos, y realizar consultas espaciales avanzadas (por ejemplo, encontrar lugares cercanos o calcular áreas). Finalmente junto con la herramienta Django se desarrolló el procesamiento de los datos espaciales en el backend.

Una vez resuelta esta conexión, se comenzó a trabajar con el mapa para su visualización utilizando Leafleat.js, ya que es una biblioteca de JavaScript para mapas que permite ver datos geoespaciales en el navegador. Por lo que lo utilizamos para la visualización de cartografías de fondo, capas de datos espaciales y permite interactuar con los mapas (zoom, clics, marcadores, etc.).

En la siguiente etapa se analizó la información que se necesita cargar en una campaña, a partir de esto se diseñaron los formularios. Con esta elaboración se abordó el desarrollo del backend y frontend,

intentando que resulte amigable para el usuario, ya que al integrarse permiten visualizar los datos cargados en el mapa. Se decidió utilizar Vue.js (Frontend) ya que es un framework de JavaScript que facilita la creación de interfaces de usuario interactivas y dinámicas. En nuestro caso nos permitió construir una interfaz web amigable e intuitiva, mejorar la experiencia del usuario con mapas interactivos y conectarse con la API del backend que creamos para mostrar datos geoespaciales. El uso de Leaflet nos facilitó generar una visualización fluida de los datos.

La tercera sección en la que se continuó trabajando es la gestión de usuarios, ya que lo requeriría al ser pensada como una aplicación exclusiva para los miembros de una asociación. Se generó una jerarquía para determinar un administrador que diera de alta los usuarios y esto se desarrolló con VUE.js y con Django con lo cual permite gestionar usuarios, permisos y autenticación.

La estructura de la aplicación se pensó segmentada para facilitar la actualización o desarrollo de cada sección, permitiendo que sea escalable en el tiempo y facilitando su mantenimiento.

3. Resultados

La herramienta desarrollada es una aplicación WebGIS que optimiza la gestión y el procesamiento de la información obtenida en el trabajo de campo y en la estructuración de la información bibliográfica o recolectada en campañas anteriores. Dicha herramienta permite cargar y editar los datos que se van obteniendo en las diferentes áreas de estudio, y almacenarlas en un único lugar, otorgando acceso a los miembros de la institución que lo utilicen para la elaboración de análisis e informes que permitan ampliar el conocimiento sobre las cavernas.

Es una herramienta de uso restringido para los miembros de la institución que se dediquen a la investigación de las cuevas. Para resguardar la información y que sea más seguro su acceso, cuenta con administradores a los cuales se les deberá solicitar las credenciales necesarias para acceso a la plataforma.

La aplicación se encuentra estructurada en tres sectores, un mapa interactivo, una sección de visualización y edición de la información, y por último un formulario de carga de datos, compuesto por diferentes campos.

En el mapa interactivo podemos visualizar cada uno de los datos sobre un mapa base de nuestra preferencia, en la parte inferior derecha se puede observar un pequeño panel con información general de todos los datos cargados, permitiendo que al ubicar el cursor sobre uno de los datos en la parte superior derecha podamos ver el nombre y tipo de la cavidad (Fig. 2).

En la sección de las fichas podemos observar el listado completo de todas las cavidades cargadas y un buscador que permite filtrar la información. Al seleccionar cada dato se puede obtener la información detallada de dicha cavidad (Fig. 1).

Finalmente, la sección de carga de datos cuenta con tres paneles en los cuales se encuentran distribuidos los diferentes campos que nos interesan cargar de cada cavidad.

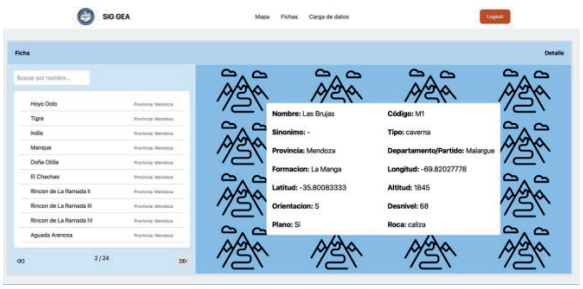

Figura 1: Sección de Fichas.

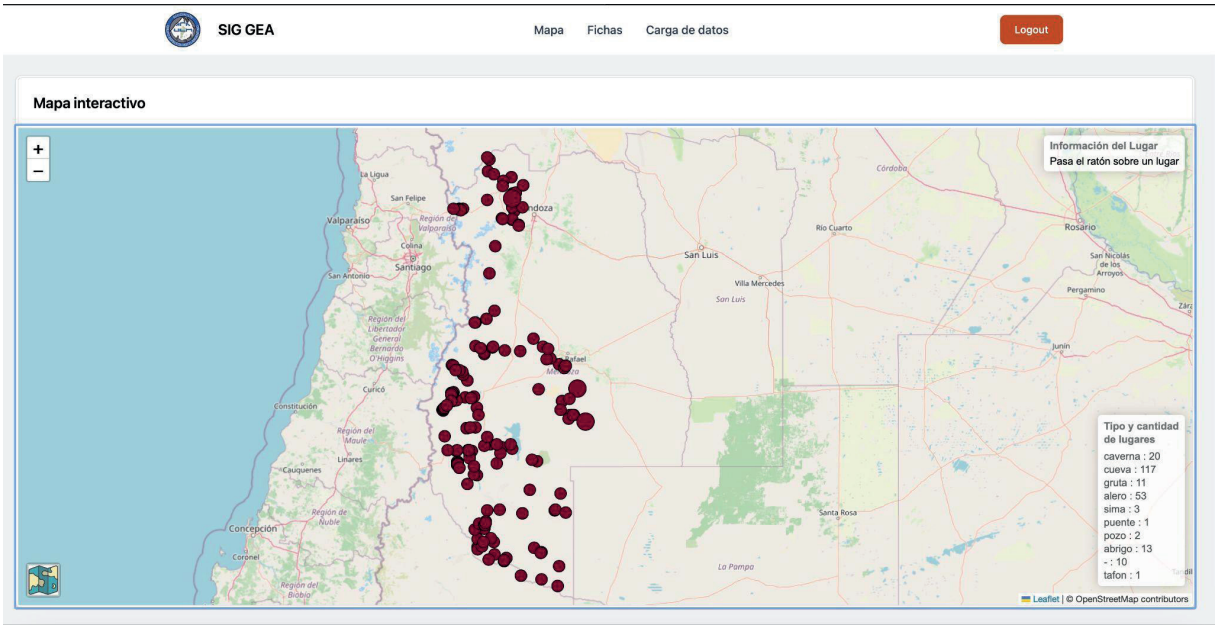

Figura 2: Sección Mapa interactivo.

4. Conclusiones

Vemos en el SIG una herramienta integradora para trabajar con información geográfica, siendo un sistema ideal en el nucleamiento del trabajo de diferentes disciplinas, en tanto herramienta polivalente. Al trabajar con información de distinta naturaleza, en esta aplicación se

busca unir y coordinar esos datos bajo un único punto de vista conceptual, ya que la herramienta establece las características de las relaciones existentes, y ya no dependen únicamente del ámbito de aplicación, brindando una mayor coordinación entre los diferentes profesionales. Además la utilización de esta herramienta posibilita integrar la información en un punto de vista teórico y encuadrarla en un marco común de trabajo. Esto se hace posible al vincular y relacionar la información a su localización espacial, permitiendo su análisis desde una concepción geográfica (OLAYA, 2014).

Pensando al SIG como una puerta de entrada a la información geográfica es que posibilita la colaboración de diferentes personas, siendo una pieza fundamental para la integración a nivel humano y profesional, por lo que vemos que permite dar un primer paso para pasar del trabajo interdisciplinario en la espeleología, a un trabajo transdisciplinario.

Al ser una aplicación con conexión por internet facilita trabajar en el campo pudiendo realizar los registros desde la misma aplicación sin necesidad de realizar una transcripción, minimizando ese tipo de errores. La aplicación está pensada para que no sea necesario contar con equipos informáticos sofisticados, siendo una herramienta accesible para grupos como nuestra asociación donde los recursos son escasos.

Vemos en esta herramienta la posibilidad de incorporar el trabajo de más profesionales en el estudio y la conservación de las cavidades naturales.

Agradecimientos

Agradecemos a Gabriel Redonte y Mariana Paparas por su colaboración en este proyecto, aportando otras perspectivas.

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Humpleu cave, Romania: 23 years of (waiting for) remapping: done!

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Abstract

Humpleu Cave, the 2nd longest cave of Romania, is scientifically very important. However, due to various reasons, the map was never completed, nor was there a longitudinal section. This is why we were asked to remap the cave. Because of variable weather, but mostly because of administrative problems, the remapping took longer that initially thought. However, in summer 2024 the remapping could be completed. The paper details the remapping process and shows the most important scientific findings that await research.

Résumé

Humpleu Cave, Roumanie: 23 ans d'(attente pour) retopographier: c'est fini! La grotte de Humpleu est la 2e en longueur de Roumanie, et elle est d'importance majeure pour la science. A cause de différentes raisons, le plan n'était jamais complet, et il n'y avait pas de coupe longitudinale. C'est pour cela qu'on était demandé de retopographier la grotte. A cause de la météo variable, mais surtout lié à des problèmes administratifs, la topographie prenait plus de temps que prévu. Finalement, en été 2024, elle a pu être terminée. La présentation détaille le processus de retopo et montre les résultats scientifiques les plus importants qui devront être étudié en détail.

1. Introduction

Humpleu Cave was discovered in 1984. Very quickly, it became clear that it was a big discovery, not only in length, but also with regard to the volume of the passages. For that reason, a «speleological run» began, and various clubs worked in that cave. Due to that, and due to the rather competing instead of collaborating mindset of that time, the various maps were mostly unpublished, and finally many of them got lost. Moreover, since Humpleu is a mostly horizontal cave, no longitudinal section was made. Only later on, when a shaft series was connected to the cave, the neighbouring parts of that shaft got a projected section.

Scientific research quite soon showed that the cave is important. The Speleological Institute «Emil Racovita» from Cluj was interested to conduct further research, but without good maps and longitudinal section, it was very difficult to proceed. This is why we were asked to remap at least the entrance parts of the cave. When this was done, we saw that it would be worth to remap the whole cave, in order to have a good dataset.

2. Humpleu Cave

Humpleu Cave is in the Apuseni mountains (Fig. 1). The entrance leads to the «Entrance room», which despite its size (40 m large, 12 m high) is actually a passage and not a room. From this passage and also further into the cave, smaller lateral passages split off. Half an hour from the entrance, a climb downward permits to reach a river, and after some climbing passages, this river can be followed almost horizontally for about 5 km. Here and there, lateral passages go off, but only one larger side passage was found. Above the river, the fossil parts of the cave continue, and sometimes connect back to the river. In some parts, the ceiling almost reaches the water level, forming semisumps that may close in humid weather conditions. Its end is a sump that was dived to no avail. Fir needles and other organic stuff proves that the sump is probably very close to a ponor at the surface.

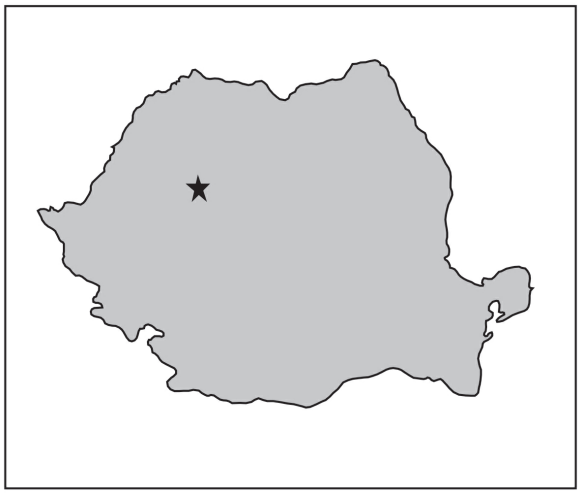

Figure 1: *Location of Humpleu Cave in Romania*

3. The remapping project

The remapping was done in an international collaboration. To remap a huge and long cave in the normal 1:500 scale would take several decades of work by very dedicated cavers. So, we decided to remap the cave in the scale 1:1000. This has the advantage that more than one room can be shown on one plan sheet, and the time used for drawing inside the cave is reduced to an acceptable amount.

The cave was remapped conventionally with tape, compass and clinometer. A plan view, a longitudinal section and cross-sections are taken. Caves belonging to the same hydrogeological system were also remapped and integrated into the general overview of the area. The data was introduced into Toporobot. Remapping was done during cave camps of 6 to 10 days duration. If possible, several groups were formed per day, some of them remapping, others equipping shaft passages or climbing chimneys in order to make mapping more effective. The largest international teams were active 2006-2008, when up to 50 participants were present. The organization of these camps are described in HAEUSELMANN (2009) After that time, knowing that we had to cross the semisumps to continue, we deliberally reduced the number of participants: it would be no fun to have someone flown in from Portugal, and on the spot he is told that the weather is too bad to do something...

During the remapping, the PNA (Parcul natural Apuseni) was founded. While a natural park usually is greeted by the cavers, its administration gradually made it more and more difficult to continue the work, and finally, 2017, we were told that no one has any access any more... Letters to the ministry, and to everyone else that could be involved, did not help. Then, surprisingly, during the ICS 2022, an SMS informed that the cave is open again! All necessary forms were filled.... but then the weather was not good to enter. 2023 we were told that we need a scientific project to finish the remapping, so this year was used to write that project. In the end, due to fortuitous coincidences (NO problem with administration, good weather, and good people), the remapping project was finally finished.

4. The results?

Humpleu Cave, originally indicated as having 40 km in length, was reduced to a bit more than 34 km... Indeed, some shafts in the big rooms in the end were not mapped. They are within cave sediment, thus very difficult to rig, and end blind anyway. Their total length is estimated to maybe 300 m. Since we also discovered new passages that were never mapped, we know that the formerly indicated 40 km are wishful thinking.

On the positive side, all 34 km are well mapped with map, longitudinal sections, and cross-sections. The map view of the cave is shown in Fig. 2, if possible, the original-size cave map (and longitudinal section) will be presented in the maps section of this congress.

Anyway, Humpleu Cave might be currently the largest cave worldwide that was entirely remapped.

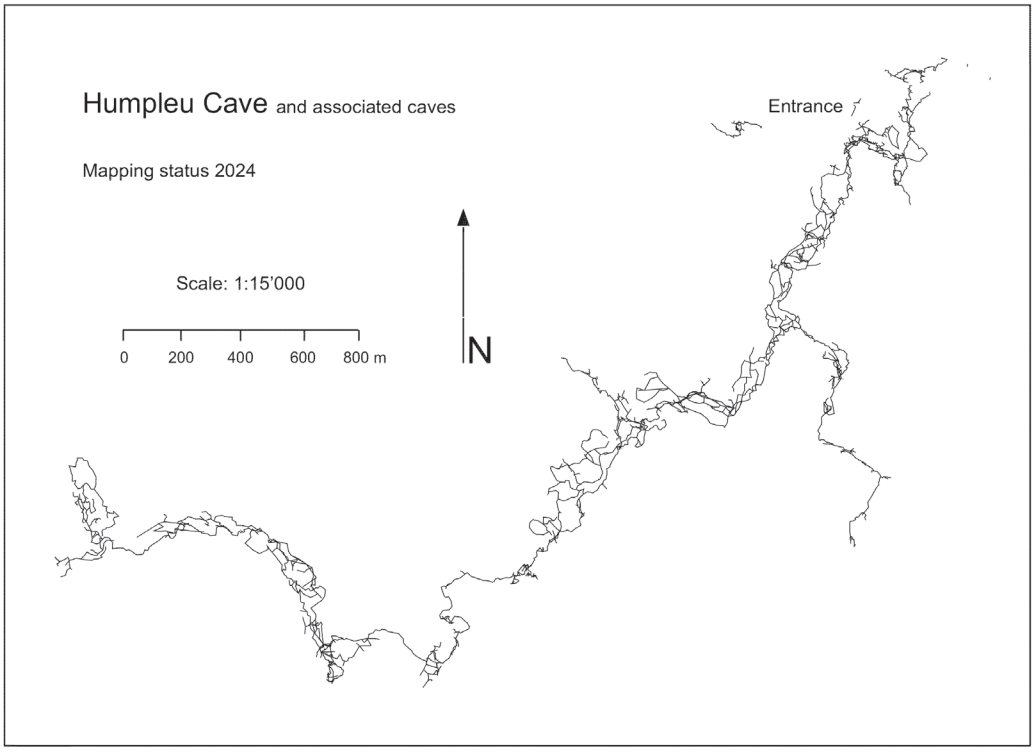

Figure 2: *The map of Humpleu Cave as seen today.*

5. Preliminary scientific results... and the future?

Despite the fact that Humpleu was, and continues to be, very interesting for science of various topics (past presence of bats, biocorrosion, paragenetic genesis, sediment deposition, (phosphate) minerals, landscape evolution, ...), the main focus of the project was the remapping, and scientific observations were not made regularly. The main reason is that if science begins, the effort is going there, and mapping is less interesting. Nevertheless, during the last 23 years, we discovered several findings:

The geode with the mega-scalenohedrons is in fact accidentally cut

by the cave, there is no genetic relationship. But analysis of greenish, whitish, and rose-colored clay proved that there are many phosphate minerals, that attest to the past presence of bats and completely transformed guano heaps. Further into the cave, rooms which are full of bat bones still attest to their past presence; but here and there, bats in decomposition show that sometimes, the cave is still visited.

Whereas the original idea on speleogenesis focussed on a gargantuan river flowing through the large passages, a MSc thesis (SOIT 2009) showed that there are fluvial notches containing pebbles along the walls of the large passages, and thus a mostly paragenetic genesis. The presently valid hypothesis is that most, if not all, large passages are result of paragenetic filling of an (initially small) meandering canyon that filled up with sediment, which in a later stage was emptied again for the most part (HAEUSELMANN 2013).

However, a difference in pebble size and composition between the passages in the rear part of the cave might point to still another, but complementary, hypothesis: that there were ponors in the valley to the southwest of the cave (Valea Ponorului), and springs downstream in the same valley, before the waters were captured by the present cave due to faster valley incision of Valea Firii in the northeast (Fig. 3). This is still very hypothetical... and needs a lot of work!

The future?

The remapping is done, hurrah! But as always, during the remapping, some passages were found that are not yet mapped. These passages shall be mapped in the years to come, and will be integrated into the final map when done.

In the coming years, the maps, pictures, and scientific works shall be compiled into a cave monography. This monography will not be complete, since many science has still to be done, but it shall serve as a good starting (continuing) point for further research.

In the coming years, scientific work will focus on speleogenesis and also dating of the speleogenetic events. We presume that Humpleu cave might be a very important cave to highlight the landscape evolution of this part of the Apuseni Mountains.

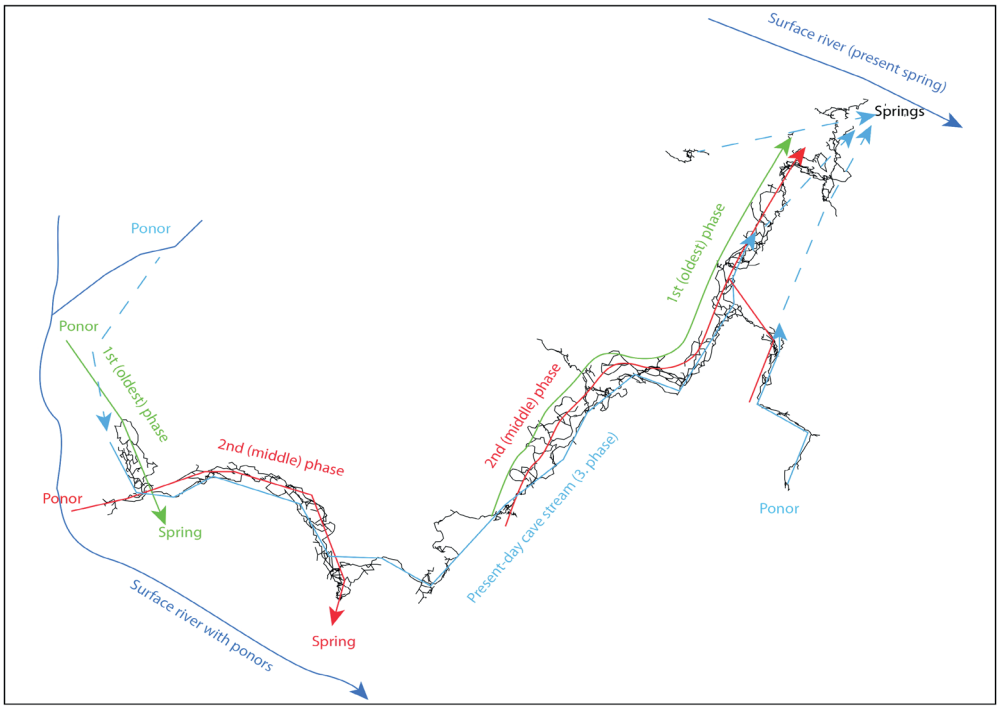

Figure 3: *The (very speculative!) hypothesis that the cave might be a merging of two or three different caves. This hypothesis is based on differences in sediment composition and size in the parts of the cave. The 1st and 2nd phase of both caves are not necessarily of the same age.*

Acknowledgments

The first, and largest, thanks go to the many, many cavers all over the world, who, with their benevolent work, made it possible to remap the cave.

A smaller acknowledgement goes to the administration of the Apuseni natural park, who allowed the work, but rendered it cumbersome and painful. We hope that the good results will improve relationships, and that future scientific works will be rewarding for everyone.

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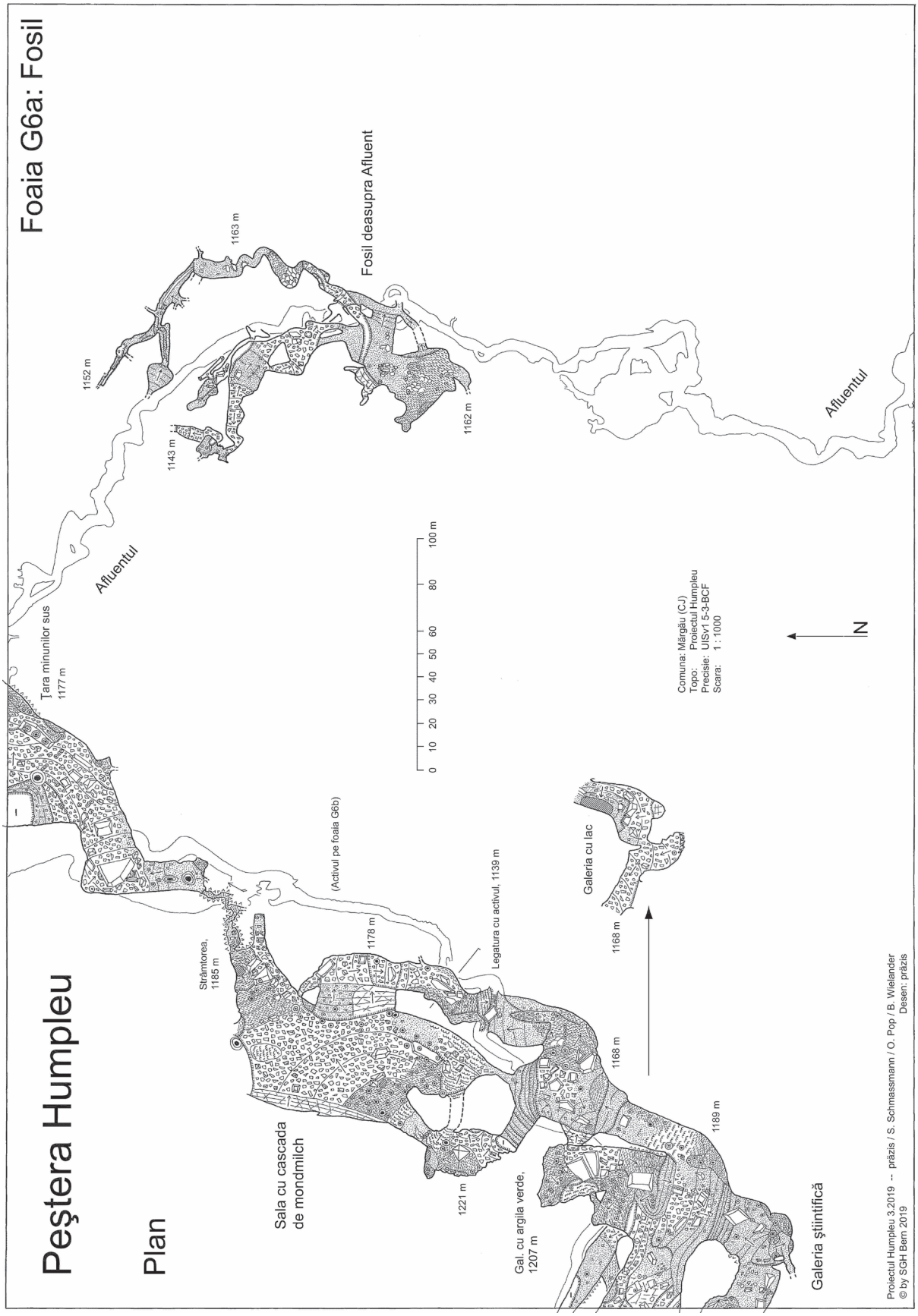
Figures 4 and 5 (next pages): *A sheet of the plan view and the longitudinal sections of Humpleu Cave.*


Foaia G6a: Fosil
Peştera Humpleu
Plan
Ţara minunilor sus
1177 m
Afluentul
1152 m
1163 m
Fosil deasupra Afluent
1143 m
1162 m
Afluentul
0 10 20 30 40 50 60 80 100 m
Comuna: Mărgău (CJ)
Topo: Proiectul Humpleu
Precisie: UISv1 5-3-BCF
Scara: 1 : 1000
N
Strâmtorea,
1185 m
(Activul pe foaia G6b)
1178 m
Legatura cu activul, 1139 m
Galeria cu lac
1168 m
Sala cu cascada
de mondmilch
1221 m
Gal. cu argila verde,
1207 m
1168 m
1189 m
Galeria ştiintifică
Proiectul Humpleu 3.2019 -- prăzis / S. Schmassmann / O. Pop / B. Wielander
Desen: prăzis
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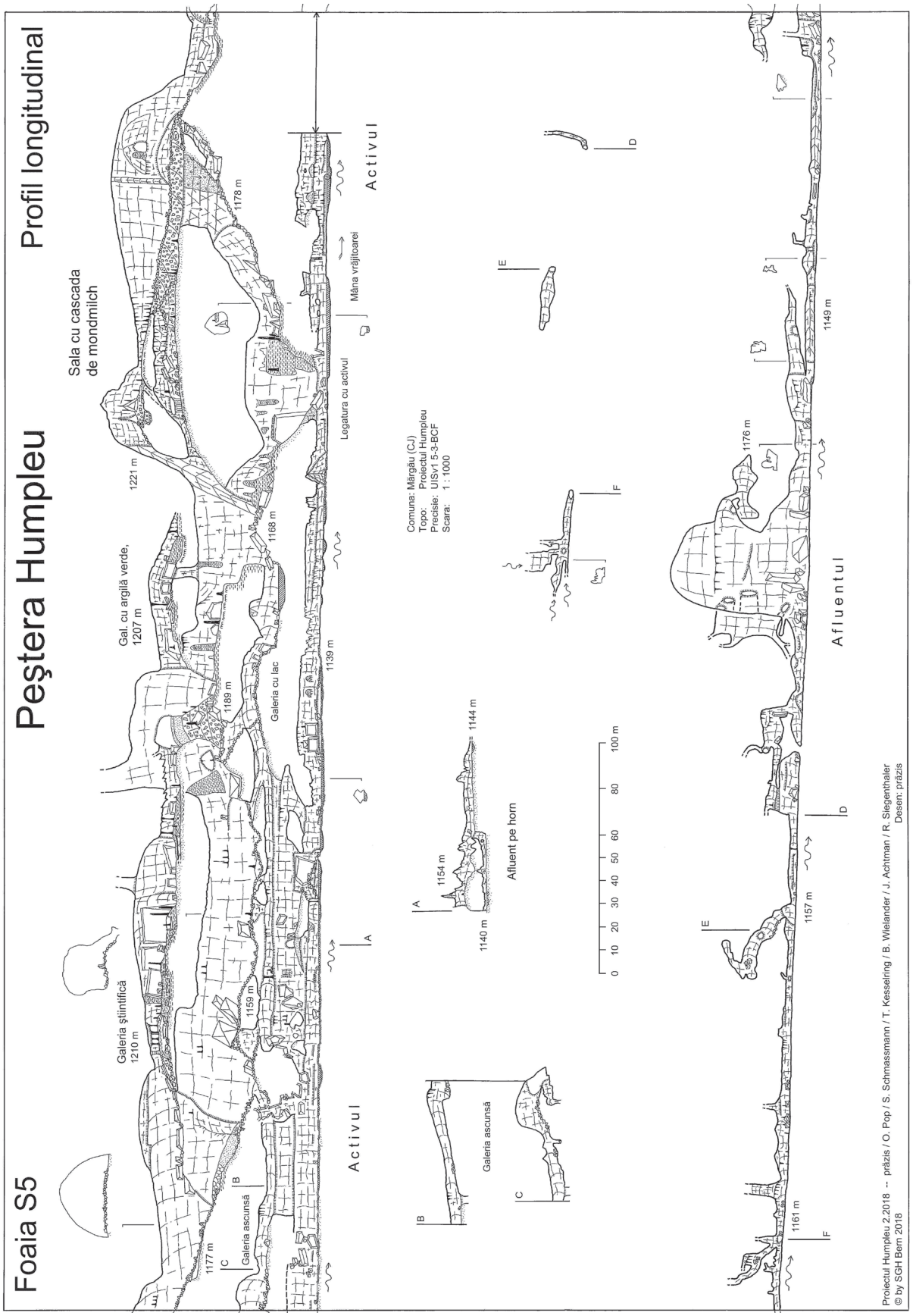
Foaia S5
Peştera Humpleu
Profil longitudinal
Sala cu cascada de mondmilch
Galeria ştiinţifică 1210 m
Gal. cu argilă verde, 1207 m
Galeria ascunsă
Galeria cu lac
Legatura cu activul
Mâna vrăjitoarei
Activul
Afluent pe horn
Afluentul
Comuna: Mărgău (CJ)
Topo: Proiectul Humpleu
Precisie: UISv1 5-3-BCF
Scara: 1 : 1000
0 10 20 30 40 50 60 80 100 m
Proiectul Humpleu 2.2018 – prăzis / O. Pop / S. Schmassmann / T. Kesselring / B. Wielander / J. Achtman / R. Siegenthaler
© by SGH Bern 2018
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Speleogenetic Insights from La Joya Cave: A Topographic Comparison using Disto-X and 3D LiDAR SLAM

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(3) Grupo Espeleológico Tlayolotl. Ex-Hacienda de San Juan Bautista S/N. Taxco el Viejo, Guerrero, México.

Abstract

The Joya cave is located in the northern part of the Guerrero state (southern sector of Mexico). This region is dominated by limestone and dolomite rocks from the Morelos Formation of Aptian-Albian age, situated in a foreland orogenic wedge area composed of a significant series of folds and thrusts formed between 93 and 43 Ma, followed by a series of strike-slips and normal faults active during 40, 23, and 16 Ma. This configuration assists the fissure volcanism accompanied by hydrothermal activity and the emplacement of ore deposits.

It is currently known that La Cueva la Joya develops in an area where all these elements combine, creating a highly complex 3D configuration that directly affects its morphology. However, the geological-structural topography with Disto-X elaborated in 2018, does not allow a clear view of the morphological characteristics needed to decipher its speleogenetic history.

This paper presents the results of a high-resolution 3D LiDAR SLAM scanning of the first section of La Cueva la Joya and compares it with the morphological interpretation and speleogenetic phases based on a topographic map made with Disto-X. The data obtained in this study show that it is an active cave, meaning it is still undergoing geological processes, with the development of a meandering canyon formed in at least three progressive phases, as epiphreatic conduits were identified in the upper part, followed by keyhole shaped structures and an epiphreatic conduit at the base. A paragenetic phase that overlaps the second conduit formation event was also identified.

Our study demonstrates the potential of high-resolution LiDAR SLAM scanning technology to revolutionize the field of karst geology. By generating more accurate and reliable evolutionary models, we are paving the way for a deeper understanding of speleogenetic processes in karst areas, inspiring future research and exploration in this fascinating field.

Resumen

La cueva La Joya se encuentra en la parte norte del estado de Guerrero (sector sur de México). Esta región está dominada por rocas calizas y dolomías de la Formación Morelos, de edad Aptiano-Albiano, ubicada en una zona de cuña orogénica de antepaís compuesta por una significativa serie de pliegues y cabalgaduras formadas entre 93 y 43 Ma, seguidas por una serie de fallas laterales y normales activas durante 40, 23 y 16 Ma. Esta configuración favorece el vulcanismo fisural acompañado de actividad hidrotermal.

Actualmente se sabe que la Cueva La Joya se desarrolla en una zona donde todos estos elementos se combinan, creando una configuración 3D altamente compleja que afecta directamente su morfología. Sin embargo, la topografía geológico-estructural con Disto-X realizada en 2018, no permite una visión clara de las características morfológicas necesarias para descifrar su historia espeleogenética.

Este artículo presenta los resultados de un escaneo 3D LiDAR SLAM de alta resolución de la primera sección de la Cueva La Joya y lo compara con la interpretación morfológica y las fases espeleogenéticas basadas en un mapa topográfico realizado con Disto-X. Los datos obtenidos en este estudio muestran que es una cueva activa, lo que significa que aún está experimentando procesos geológicos, con el desarrollo de un cañón meándrico formado en al menos tres fases progresivas, ya que se identificaron conductos epifreáticos en la parte superior, seguidos de estructuras en forma de cerradura y un conducto epifreático en la base. También se identificó una fase paragenética que se superpone al segundo evento de formación del conducto.

Nuestro estudio demuestra el potencial de la tecnología de escaneo LiDAR SLAM de alta resolución para revolucionar el campo de la geología kárstica. Al generar modelos evolutivos más precisos y confiables para una comprensión más profunda de los procesos espeleogenéticos en áreas kársticas, inspirando futuras investigaciones y exploraciones en este fascinante campo.

1. Introducción

La Joya Cave is one of the best-known sites by Mexican speleologists. It is located in the northern sector of the state of Guerrero, in southern Mexico (Figure 1). Its first topography was carried out by José Montiel and his team, Asociación Base Draco, in 1983, who reported a drop of

-234 m and a length of 3400 m. For more than 30 years it has been a training site for speleologists in south-central Mexico, due to its characteristics in its development, ranging from vertical drops, unclimbing and narrow passages, with a large number of morphologies. Subsequently, HERNANDEZ-VERGARA R. (2012) with the Grupo Espeleológico Tlayolotl (GET) retake this work and carry out a regional geological study where he integrates La Cueva de la Joya as part of the Zacatecolotla-Las Granadas karst system with a hydrological drop of 363 m.

In 2018, the members of the GET with support of the Grupo Unión de Rescate e Investigación de Oquedades Naturales (URION) carried out the La Joya Speleogenetic Project, which aimed to explore new galleries and perform geological-structural mapping studies to determine the morphology and speleogenetic phases.

The main result was a map of plan, profile and cross sections, made with Disto-X, at a scale of 1:200, which shows the primary morphologies of the cave grade 5-6, with an accuracy of between 1% and 2% according to the Mapping Grades proposed by the UIS (HÄUSELMANN, 2011). However, many of the geomorphological characteristics of the cave cannot be determined because the Disto-X tripod technique does not allow the detection of 3D variations in the conduit. Likewise, it does not allow for the observation of the morphologies of modified passages that would allow a clear description of its speleogenetic history.

This work proposes the use of the most advanced technology through the use of a LiDAR SLAM scanner, which allows an error of + 1cm and provides a detail of each passage, thus allowing comprehensive review of the geomorphological features and their modifications over time to establish a more accurate history of cave formation.

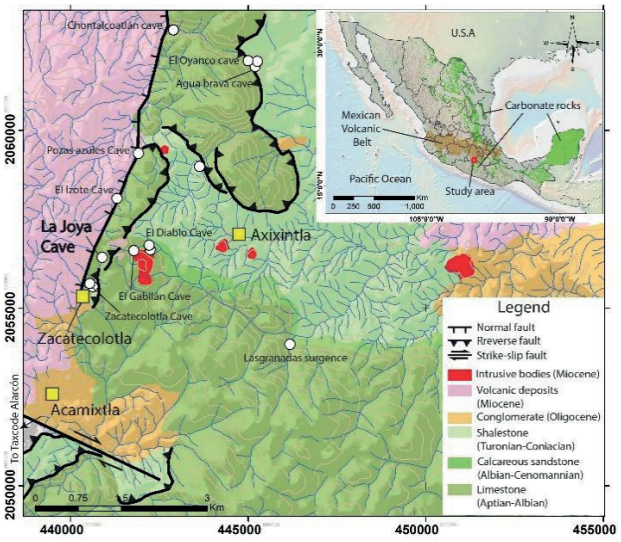

Figure 1: *a) carbonate rocks of Mexico, b) geological map of the study area modified by HERNANDEZ-VERGARA, 2013.*

2. Materials and Methods

This work was carried out in three main phases. The first phase focused on the geological-structural survey of the interior, presented as a geological profile. Measurements were focused on bedding, fractures, faults, and veins, using a Brunton compass with an azimuthal bearing and the right-hand rule technique for support.

The topography of La Joya cave was surveyed using a Leica Disto-X laser distance meter with a 100-meter range, equipped with trigonometric correction. This was mounted on a 1-meter-high tripod (emitter) and a second 1-meter-high tripod with a 10 cm diameter plastic plate as the laser spot (receiver). The starting point was established outdoors with the aid of a Garmin GPS Map 65s, which has an accuracy from 3 meters. For the cave's passage, the configuration measured distance, azimuth, inclination, left, right, up, and down at intervals of every 10 meters along the length. The plan map, profile, and cross sections were sketched in-situ on millimetric paper. The final map was edited using Adobe Illustrator.

The 3D scanning was performed using Emesent ST-X 2023 Light Detection and Ranging (LiDAR) scanner, which contains a Terrestrial Laser Scanner (TLS) which contains a Movile Laser Scanner (MLS) emitting around two million laser points per second (1,920,000 points/sec) with 3 returns. The cave was divided into seventeen sections, each scanned in a closed-loop to optimize the configuration of each zone. Each section was merged using Simultaneous Localization and Mapping (SLAM), a software with complex algorithms designed to analyze unknown environments, allowing for accurate stitching of each scan with an accuracy of +1 cm. Finally, the data obtained from both maps were analyzed using the classification systems proposed by FORD AND WILLIAMS (2007), PALMER (2007), and KLIMCHOUCK et al. (2000).

3. Results

La Joya Cave is part of a series of caves that developed along the trace of a NE-SW normal fault, generating a lateral contact between the volcanic rocks of the Tilzapotla Formation and the limestone rocks of the Morelos Formation (Figure 1). However, its development is oriented NW-SE and corresponds to strike-slip faults that intersect perpendicularly to this normal fault.

From the entrance to the Las Cortinas pit, the cave features wide galleries formed following stratification planes that dip to the NW and constitute a series of closed folds, which are affected by a series of lateral faults oriented NW-SE. This area contains debris of volcanic rocks up to 2 meters in size (Figures 2a and b).

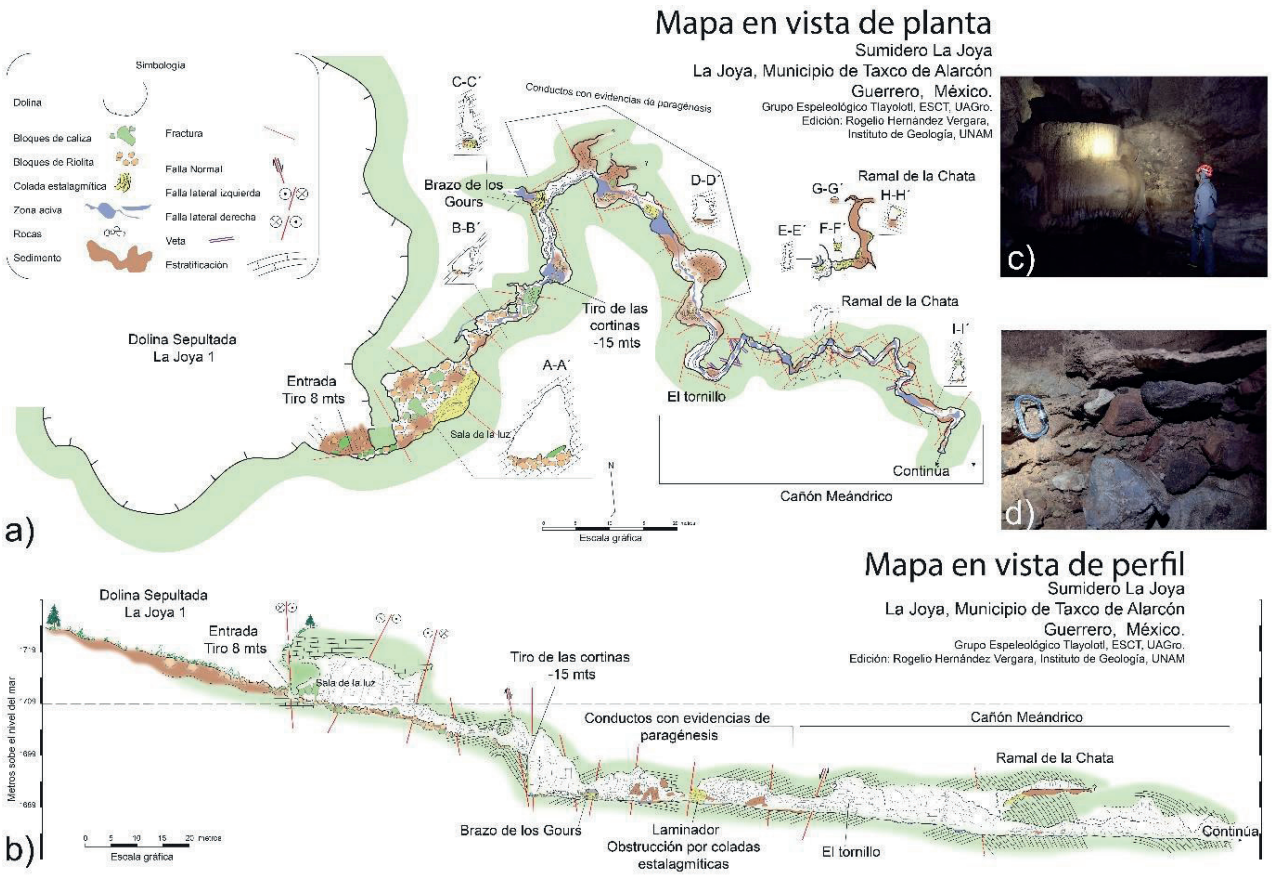

Figure 2: *Geological and structural map of La Joya Cave scale 1:200. a) plan view, b) profile view, c) volcanic sediments soported by flowstone calcite obstructing the main conduict before the D-D´ cross-section. d) zoom of volcanic semients.*

The second section of the cave begins at the base of the Las Cortinas pit, is formed by a normal fault oriented E-W, to the Tornillo area, consisting of wide galleries at the base and sub-vertical ceilings. In this zone the volcanic sediment fill of up to 3 meters in high was observed, causing a noticeable paragenetic phase (Figures 2c and d).

From the Tornillo area to the final sector of the mapped section, the cave develops in a network of NW-SE, NE-SW, and N-S oriented faults, forming epiphreatic conduits in the shape of a shallow canyon. This configuration remains consistent throughout the cave until the end at a depth of 234 meters and a length of 3000 meters.

3.1. Comparison of the Disto-X topography and 3D LiDAR Slam Scaning

A geological-structural topography was conducted using a laser distance meter, resulting in a map with a plan view, profile, and 9 cross sections (Figures 2a and b).

The study determined that the La Joya cave has two main conduits: the first at the upper part up to the Las Cortinas shaft, and the second, developing into a single gallery with a paragenetic phase. One of the main challenges of cave mapping using this technique is the description of the upper levels since only one point is obtained to describe the ceiling or upper part. However, the Chata branch, discovered in 2018 by rock climbing, can be see in the profile, revealing an upper epiphreatic level with fine sediments and speleothems. Nevertheless, the level of precision of this mapping shows variations of up to 5 meters on the plan map and an margin of error of up to 2%.

Futhermore, the result of the 3D scanning using LiDAR technology with SLAM stiching showed a margin of +1 cm. In adition, it offered a greather level of detail in both lower and upper conduits, allowing a much clearer understanding of the evolutionary phases of the cave (Figures 3a and b).

3.2. Evolution phases of La Joya Cave

Phase 1 (Level 1 epiphreatic conduit)

It was determined that from the base of the Las Cortinas shaft to the final section, the cave presents a very homogeneous configuration.

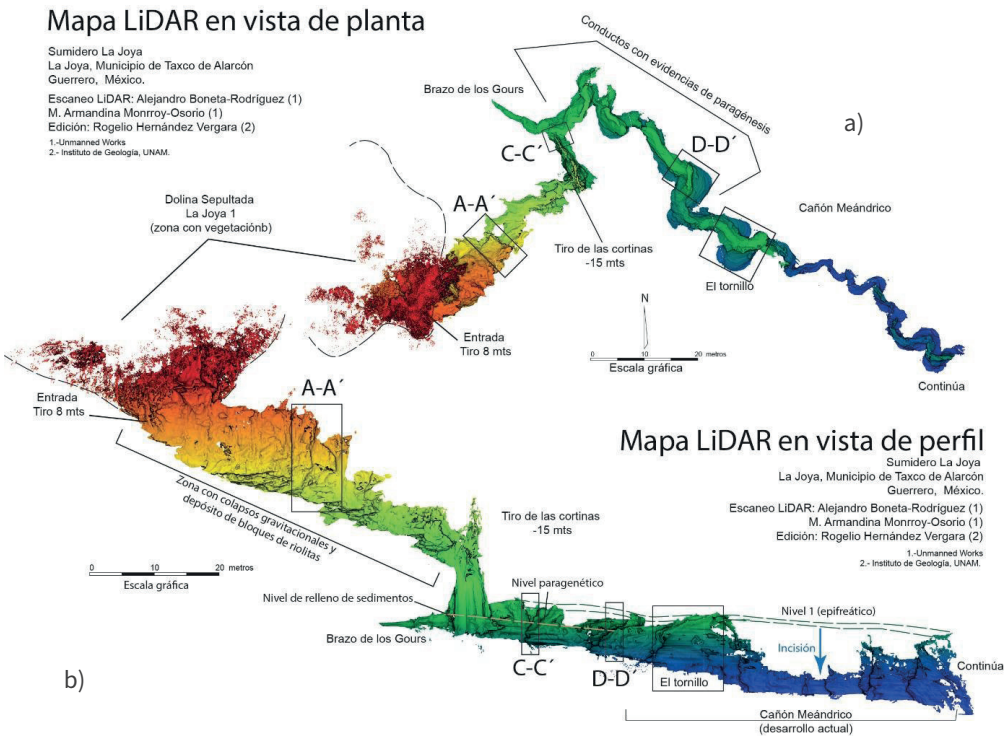

Figure 3: *3D LiDAR scanner of la Joya cave merged by SLAM tecnology.*

Phase 2 (Paragenesis)

From the cave's entrance to its end, volcanic-origin sediments are evident, with enter the cave through surface water currents. However, from sections A-A' to the Tornillo area, sediment layers are adhering to the walls, reaching up to 3 meters in height. These sediment layers are still visible, as flowstone, gours, and stalagmites were deposited over them. Another effect of this obstruction was generating a paragenetic phase characterized by forming pendant structures associated with pressurized water flows (Figure 4).

However, the 3D LiDAR scan clearly shows that this entire section presents an upper level with a semicircular shape, ranging from 1 to 2.5 meters in wide with a straight development, presenting a 3° dip towards the SE (Figures 3). Therefore, this is interpreted as Level 1 in the formation of the cave of epiphreatic origin.

Phase 3 Meanderin Canyon

Currently, La Joya cave is active, receiving around 0.5 m^3 of water during the torrential rainy seasons. This increase in water flow is reflected in the development of a meandering canyon, which originates from the incision of up to 20 meters of the upper level.

In Figure 5, the area known as the Tornillo is divided into four segments and clearly shows Level 1 (epiphreatic in yellow), which is almost straight and later presents incision with strong sinuosity, forming a meandering canyon similar to a meanderkarren.

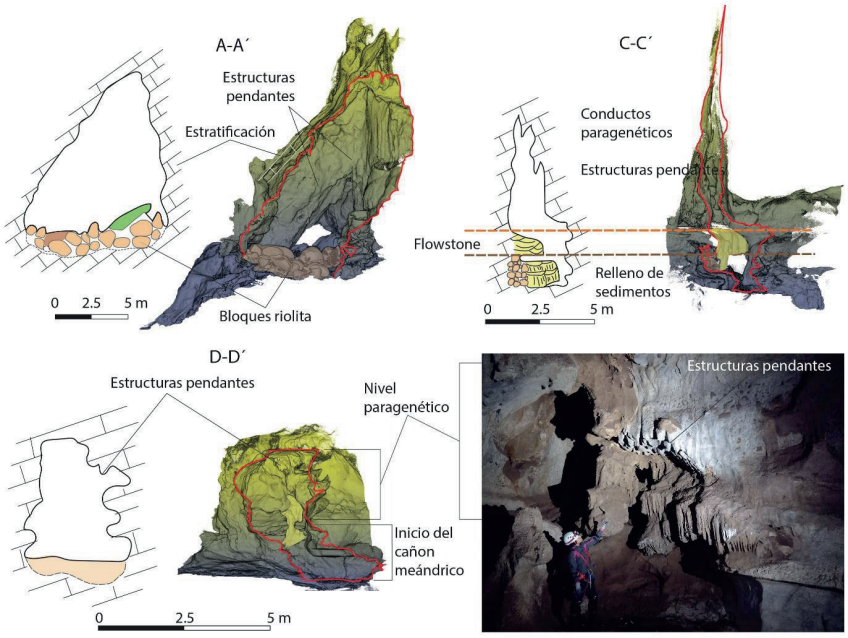

Figure 4: *Comparison between cross-sections elaborated by Disto-X and freehand drawing with the 3D LiDAR scan.*

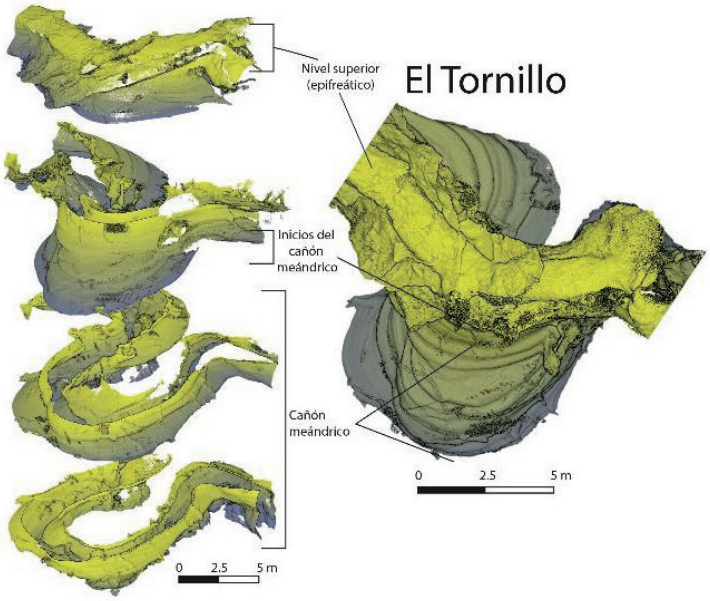

Figure 5: *Evolutive phases of El Tornillo section elaborated by 3D LiDAR scan.*

4. Conclusions

The use of cutting-edge technology in studies related to speleogenesis and karst evolution is a very useful tool when describing the geomorphology of the conduits. The implementation of the 3D LiDAR scanner with SLAM technology allowed us to determine that the paragenetic phase not only affected the lower level of the cave, but it was also possible to determine that, starting 50 meters before the Las Cortinas shaft, there was an almost total obstruction of the cave. This indicates that there was a mass removal process on the surface, which introduced a considerable amount of volcanic rocks into the La Joya cave.

Furthermore, the use of this technology confirmed that the Chata branch corresponds to Level 1 of the cave, with a small straight epiphreatic conduit, which was later modified by a paragenetic phase associated with entry of sediment, followed by erosion that lead to the incision and development of a meandering canyon.

Acknowledgments

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Planimetric trilateration cave topography

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Abstract

This paper presents the planimetric trilateration method for mapping cave topography, particularly focusing on Brazilian caves that often exhibit magnetic anomalies due to iron ore deposits and other lithologies. Conventional mapping techniques, such as the use of compasses and theodolites, are hindered by these anomalies, leading to significant measurement errors. The introduction of laser distance meters with integrated clinometers may offer an accurate and efficient enough mapping process. This study aims to illustrate the planimetric trilateration methodology, discuss various data collection techniques, present the equations for coordinate calculations, analyze expected intrinsic errors, and compare these errors with those obtained from conventional cave topography methods. Field tests conducted in Fogão Cave ("Gruta do Fogão") in Ouro Preto, Minas Gerais, reveal the efficacy of this approach in challenging environments, paving the way for improved mapping practices in speleology.

Résumé

Cet article présente la méthode de trilatération planimétrique pour la cartographie de la topographie des cavernes, en se concentrant particulièrement sur les cavernes brésiliennes qui présentent souvent des anomalies magnétiques dues à des dépôts de minerai de fer et à d'autres lithologies. Les techniques de cartographie conventionnelles, telles que l'utilisation de boussoles et de théodolites, sont entravées par ces anomalies, entraînant des erreurs de mesure significatives. L'introduction de télémètres laser avec clinomètres intégrés offre un processus de cartographie assez précis et efficace. Cette étude vise à illustrer la méthodologie de trilatération planimétrique, à discuter des différentes techniques de collecte de données, à présenter les équations pour les calculs de coordonnées, à analyser les erreurs intrinsèques attendues et à comparer ces erreurs avec celles obtenues par des méthodes conventionnelles de topographie des cavernes. Des tests sur le terrain effectués dans la Grotte do Fogão ("Gruta do Fogão") à Ouro Preto, Minas Gerais, révèlent l'efficacité de cette approche dans des environnements difficiles, ouvrant la voie à des pratiques de cartographie améliorées en spéléologie.

Resumen

Este artículo presenta el método de trilateración planimétrica para la cartografía de la topografía de cuevas, centrándose particularmente en las cuevas brasileñas que a menudo exhiben anomalías magnéticas debido a depósitos de mineral de hierro y otras litologías. Las técnicas de mapeo convencionales, como el uso de brújulas y teodolitos, se ven obstaculizadas por estas anomalías, lo que conduce a errores significativos en las mediciones. La introducción de medidores láser de distancia con clinómetros integrados ofrece un proceso de mapeo suficientemente preciso y eficiente. Este estudio tiene como objetivo ilustrar la metodología de trilateración planimétrica, discutir varias técnicas de recolección de datos, presentar las ecuaciones para los cálculos de coordenadas, analizar los errores intrínsecos esperados y comparar estos errores con los obtenidos a partir de métodos convencionales de topografía de cuevas. Las pruebas de campo realizadas en la Cueva de Fogão ("Gruta do Fogão") en Ouro Preto, Minas Gerais, revelan la eficacia de este enfoque en entornos desafiantes, allanando el camino para mejorar las prácticas de mapeo en espeleología..

1. Introduction

Brazil has a large number of caves, primarily occurring in carbonate, siliciclastic, and ferruginous rocks, in decreasing order (ICMBIO, 2023). Particularly in the latter lithotype, caves are sparsely distributed across the territory, with the Iron Quadrangle standing out as a significant region. In these rocks, which contain iron ore and other magnetic minerals, speleological surveying is subject to magnetic anomalies

(CRUZ & PILÓ, 2019).

To survey these caves with minimal errors, it is essential to utilize methods that do not rely on compasses. Even with careful positioning of survey stations to minimize magnetic interference, the compass measurement error can reach more than 20 degrees. Conventional theodolite mapping faces challenges due to the cumbersome operation of large, heavy equipment, as well as high costs and lengthy procedures. Previous attempts to connect stations with strings and measure angles with protractors have been made, but this method has its own difficulties, especially when the lines of sight are not close to horizontal.

The introduction of laser distance meters in the 2000s, including those with integrated clinometers at relatively low costs, enables topographic surveys through trilateration. This method allows for the determination of coordinates by simply measuring the sides of a triangle from two known vertices to find a third vertex successively. However, the main disadvantages of this method include the lack of publicly developed methodologies and applications that can collect and process data quickly and accurately, as well as the unknown intrinsic errors associated with this methodology.

The primary objectives of this work are to illustrate the planimetric trilateration method, discuss possible data collection methodologies, present the coordinate calculation equations, evaluate expected intrinsic errors, and make a synthetic comparison of these errors with those obtained through conventional cave topography.

In order to test this methodologies Fogão Cave ("Gruta do Fogão" or "Stove Cave"), in Ouro Preto municipality, Minas Gerais State, Brazil, was chosen, due to its proximity to SEE, to that it has been already mapped twice in order to allow comparisons and to its appropriate morphology. This test has been carried out together with other new methodologies described in another paper. It is an approximately 100m cave in dolomitic marble of 2.4 Ga Gandarela Formatcion, possibly the oldest carbonatic host rocks to bear caves.

2. Materials and methods

Traditional topographic methods applicable to caves can be divided into three categories: Traverse, Triangulation, and Trilateration (Figure 1).

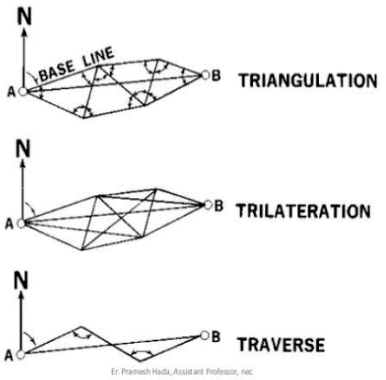

Figure 1: Traditional Cave Topography Methods.

The **Traverse Method** requires equipment that measures horizontal angles (typically a compass), vertical angles (clinometer), and the distances between stations (measured with a tape).

The **Triangulation Method** involves measuring horizontal angles between conveniently selected triangles, generally using a compass, and employing a clinometer to determine elevation differences between stations.

Planimetric Trilateration can be categorized into two types: three--dimensional (or spherical) trilateration and planimetric trilateration. The three-dimensional trilateration method involves measuring only the distances between selected triangle stations. It is similar to the way GPS and other GNSS devices calculates positioning, but this method will not be the focus of this study.

Planimetric trilateration utilizes a clinometer to measure vertical angles and the distances between the triangle stations for calculating horizontal coordinates. Figure 2 illustrates a typical planimetric trilateration mesh.

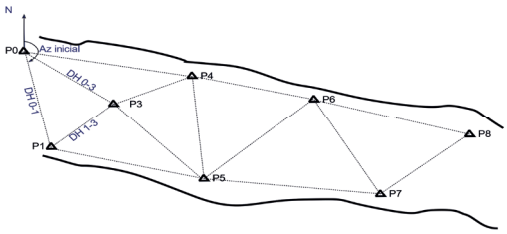

Figure 2: Exemplary Planimetric Trilateration Mesh.

From two stations with known coordinates (P0 and P1, as shown in Figure 2), the distances between these stations are measured to calculate the position of the desired station. This point can be graphically obtained by plotting the known coordinate stations on graph paper in the appropriate scale, drawing circles with a compass based on the horizontal distances, and identifying the intersection points. The two circles will intersect at two points, and the sketch allows for easy identification of the correct point.

To facilitate the calculation of station coordinates and analyze the intrinsic errors of the planimetric trilateration method, a calculation spreadsheet has been programmed based on the concepts presented in this section.

The **Horizontal Distance (DH)** can be calculated from the Inclined **Distance Read (DIL)** and the angle of inclination **(Alpha C)** between two stations (Figure 3) using the formula:

DH = DIL * cos (AlphaC)

The elevation of the station to be determined can also be calculated from the inclination reading (Alpha C) and the distance between the stations (Figure 3).

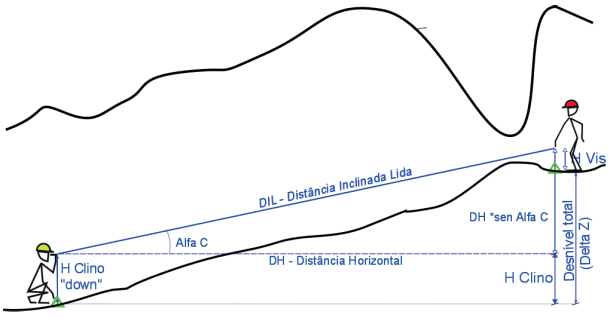

Figure 3: Calculation of Horizontal Distance (DH) and Elevation Difference (Delta Z) Between Two Stations (From SEE, 2024).

Using the **Inclined Distance Read (DIL)**, the **Inclination (Alpha C)**, the height of the clinometer at the base station **(H Clino)**, and the height of the Target Station **(H Vis)**, the Total Elevation Difference **(Delta Z)** between the Base Station (which has a known elevation) and the Target Station can be calculated with the following equation:

Delta Z = DIL * sen AlfaC + H Clino - H Vis

The elevation of the Target Station is computed by adding the known

elevation of the Base Station to the calculated elevation difference. Since the planimetric trilateration method (and all methods using triangles for coordinate calculations) requires two known stations to determine the coordinates of a new station, we will have two calculated elevation values. These values should ideally match; however, due to instrumentation and station positioning errors, they will likely differ within an expected error range. The elevgnssation of the new station is established by averaging the two calculated values.

The analytical calculation of planimetric coordinates (X and Y) is performed by solving the intersection problem of two circles (Figure 4).

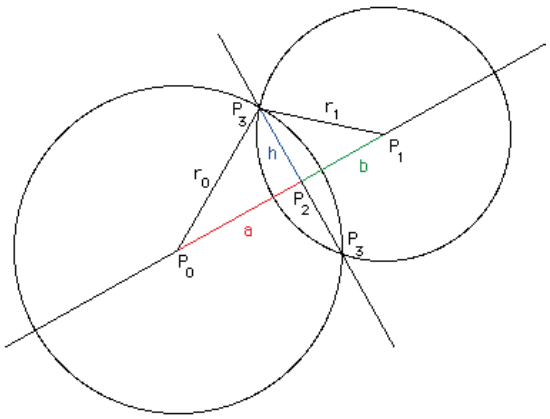

Figure 4: *Intersection of Two Circles and Graphical Elements for its Analytical Solution (BOURKE, 1997). Calculation of the coordinates of Point P3 based on one circle centered at P0 with radius r0 and another circle with radius r1 centered at P1. P2, a, b, and h.*

There are multiple methods to solve this case, and we have chosen the method presented by BOURKE (1997) for its simplicity and elegance. Please refer to the citation for further details.

In order to deal with such calculations, a spreadsheet was developed to calculate Azimuth from sights and the resulting data so the results could be readily processed by TOPGRU 2024, that can deal with sights with different heights in the stations.

TOPGRU is a free public educational speleotopographic software , developed since the 1980s by Marcelo Taylor de Lima, for SEE - Sociedade Excursionista e Espeleológica, Ouro Preto, Brazil, founded in 1937(LIMA, 1987, LIMA & SOUSA, 2022, SEE, 2024).). Its latest 2024 version includes the slightly modified “ADJUST” subroutine, originally developed and turn free code by Bob Thrun, as part of the “C-Map” application code s, based on method described by the SCHMIDT and SHELLENG (1970).

To carry out the tests, the combination of two regular topographical courses in the same stations were used using BRIC5 survey tool, not considering its Azimuths readings. This allowed a comparison between the trilateration method and a regular survey. BRIC5 is a speleotopographical survey tool produced by Kris Fausnight and John Fioroni in the USA.

The choice of the tests location took into account several factors: proximity and easiness to access, previous map of conventional topography and is physical characteristics. Gruta do Fogão is a cave that has a map lenght of 97 meters. Its shape is characterized as a branched linear formation, featuring irregular cuts, generally about 3 m high and 8 m wide. The cave contains fine and clayey sediment and the presence of an underground watercourse (OLIVEIRA & TIMO, 2005). It is located in Ouro Preto, the site of SEE. Its host rock is a dolomitic marble of Gandarela Formation. It was supposed to be a non-magnetic environment, to allow an effective comparison in-between conventional topography methods to this trilateration one.

It is located at the southern part of the São Francisco craton province houses the Iron Quadrangle (Quadrilátero Ferrífero), a preserved Paleoproterozoic orogenic belt affected by the collision and amalgamation of cratonic terrains during the Transamazonian orogeny (~2.1 Ga) (Alkmin & Marshak, 1998). The QF is characterized by large folds, thrust faults, and shear zones.

The stratigraphy of the QF (Figure 5) consists, from the base to the top, of a Meso to Neoarchaean TTG basement, followed by the greenstone belt sequence of the Rio das Velhas Supergroup. This sequence is discordantly overlain by the metasedimentary units of the Minas Supergroup and the Itacolomi Group (Heilbron, 2017; Alkmim and Teixeira; Lana et al., 2013). The Paleoproterozoic Minas Supergroup is subdivided into five groups and eight formations, comprising a succession of continental and marine rocks deposited in a passive margin environment. At the base of the Minas Supergroup are the Tamanduá and Caraça Groups, followed by the Itabira and Piracicaba Groups, with the Sabará Group at the top of the sequence (Figure 5).

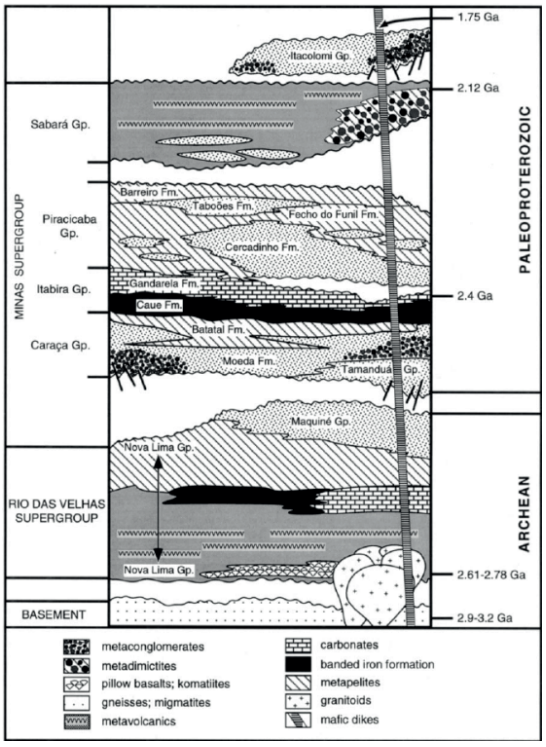

Figure 5: *Statigraphic column of Iron Quadrangle (“Quadrilátero Ferrífero) (from ALKMIN & MARSHAK, 1998).*

3. Results

On October 14, 2024, members of the SEE convened at the Escola de Minas to test this methodology, among others described in another paper.

When carrying out the initial protocols for “Gruta do Fogão” mapping it was detected tha the non-magnetic characteristics of the cave were not completely true. Preliminary results in field showed that an average of 1.7° in azimuth readings from sight and backsight procedures were present. Later office processing gave the average result of approximately 2.2° with a maximum of 4.2° and standard deviation of 1.1°.

Nevertheless, the TOPGRU 2024 2D analysis for closed polygonals of the combined conventional topography results achieved an average of about 0.35% with a maximum of 1.14% for 2D in 30 segments, backsight included. This relatively low figures allowed us to consider the

conventional topography good enough to be a basis of better quality to evaluate the goodness of the trilateration topography method.

To test the method, the same topographical stations of the conventional topography were used. Although all the conventional topography used sights and backsights, for the trilateration method only the distance and inclination figures of the sights were used, to simulate an actual survey. In trilateration, in most caves it should be very difficult to make backsights in some situations.

One GNSS point (commonly referred as "GPS point") nearby the entrance of the cave was stablished by a regular Samsung Galaxy S20 smartphone using HandyGPS app, taking the base coordinates as an average of 118 measurements, after approximately 10 minutes of stabilization. A second fixed point (F1) was determined by the conventional topography. From there the subsequent points were determined by a conjugation of the azimuth calculated from the specific spreadsheet prepared for this methodology and regular TOPGRU 2024 processing. A total of 6 stations were calculated this way (Figure 6)

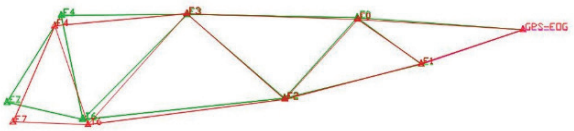

Figure 6: *Comparison between regular topographic survey (green) to trilateration methodology (red).*

The maximum accuracy of trilateration and triangulation methods are achieved using equilaterals planimetric triangles. In an actual cave, it is almost impossible to get that. So, whenever possible, the survey was carried out trying to have no internal planimetric angles over 90° nor under 30°. Only in one triangle (GPS-F1-F0) was not possible to follow that rule, but the good quality of the result allowed us to consider it valid.

A comparison between the coordinates of conventional and trilateration methods gave an error average of around 2.2%. Nevertheless, it ranged from about 0.4% up to almost 4%. (Figure 7).

Station	3D Error (%)	2D Error (%)
F0	1.68%	1.63%
F2	0.96%	1.25%
F3	0.35%	0.37%
F4	2.59%	2.89%
T6	3.88%	3.37%
F7	3.82%	3.93%
Average of Errors	2.21%	2.24%
Minimum Error	0.35%	0.37%
Maximum Error	3.88%	3.93%
Standard Deviation	1.34%	1.25%

Figure 7: *Errors of Trilateration Methodology compared to Conventional. Station: Represents the different stations being analyzed. 3D Error (%): The percentage of three-dimensional. 2D Error (%): The percentage of planimetric error.*

4. Discussion

The trilateration methodology exhibits promise to mapping caves that are sufficiently spacious and not excessively steep. Our findings indicate a noteworthy correlation with conventional topography methods, affirming the validity of this approach. However, the substantial error in the determination of station F1 may be attributed to the acute internal angle of the triangle, influenced by local physical constraints. As the survey progressed beyond station F4, a significant decrease in precision was observed, raising questions about whether this decline stems from inherent limitations of the trilateration method or inaccuracies in the conventional topography, particularly considering the pronounced magnetic interference noted within Fogão Cave.

Despite these challenges, the errors encountered during our tests align with mapping survey Grade 4, or even 5, as per UIS and BCRA standards, which is acceptable for many smaller magnetic caves found in Brazil's iron formations. While triangulation can be conducted using relatively inexpensive laser distance meters with built-in inclinometers, the initial determination of the first station's coordinates still necessitates the use of a magnetic compass, which may be more expensive.

In terms of efficiency, the time required to complete surveys using trilateration can be compared equally to conventional methods. However, the current methodology's reliance on field-calculated stations suggests that it is better suited for hand sketching rather than real-time applications. The new topographic base can be readily drawn in field by identifying the intersection points of two circles, representing the horizontal distances between known base stations, using a drawing compass and a ruler.

The spreadsheet developed for this methodology, while functional, presents usability challenges, particularly when considering multiple sights for each station. Future developments should focus on integrating the Planimetric Trilateration equations directly into the TOPGRU software, streamlining the process for users and enhancing overall efficiency.

5. Conclusion

In conclusion, the planimetric trilateration method represents a viable alternative for mapping cave topography, particularly in environments characterized by magnetic anomalies. Our study demonstrates that while this methodology is not without its limitations, it provides comparable accuracy to conventional topographic methods. The ability to efficiently determine coordinates through trilateration serves as a valuable tool for speleologists, particularly in challenging cave environments.

Future work will focus on refining this methodology and integrating it into existing topographic software, such as TOPGRU, to enhance its applicability and ease of use. Continued exploration of this technique will ultimately contribute to improved mapping practices within the field of cave topography, facilitating better understanding and conservation of these unique subterranean environments.

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Methodologies for hand-sketched speleological topography: integrating post-processed BRIC5 data with TOPGRU

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Abstract

This study presents methodologies for hand-sketched speleological topography, specifically integrating post-processed BRIC5 data with TOPGRU software. Two main methodologies, SPF and PPQ were developed and tested in the Fogão Cave (“Gruta do Fogão”) in Ouro Preto, Brazil. SPF is designed for high-detail environments, employing a team of an Instrumentalist, Notetaker, and Sketcher to ensure accuracy and efficiency. PPQ streamlines data collection by allowing a novice Notetaker to gather information without a dedicated sketcher, focusing on significant features noted by the Instrumentalist. Both methodologies effectively produced high-quality topographical maps, with closure errors of 1.1% for SPF and 1.5% for PPQ, even in the presence of moderated magnetic interference. The total survey time was approximately two hours, demonstrating competitive speed for detailed mapping. The integration of BRIC5 data with TOPGRU not only enhanced data processing efficiency but also minimized manual entry errors, laying the groundwork for future advancements in speleological mapping techniques.

Résumé

Cette étude présente des méthodologies pour la topographie spéléologique dessinée à la main, intégrant spécifiquement les données BRIC5 post-traitées avec le logiciel TOPGRU. Deux méthodologies principales, SPF et PPQ, ont été développées et testées dans la Grotte du Fogão (“Gruta do Fogão”) à Ouro Preto, au Brésil. SPF est conçu pour les environnements très détaillés, employant une équipe composée d’un instrumentiste, d’un preneur de notes et d’un dessinateur pour garantir la précision et l’efficacité. PPQ rationalise la collecte de données en permettant à un preneur de notes novice de recueillir des informations sans dessinateur dédié, en se concentrant sur les caractéristiques importantes notées par l’instrumentiste. Les deux méthodologies ont produit efficacement des cartes topographiques de haute qualité, avec des erreurs de fermeture de 1,1 % pour SPF et de 1,5 % pour PPQ, même en présence d’interférences magnétiques modérées. La durée totale de l’enquête a été d’environ deux heures, démontrant une vitesse compétitive pour une cartographie détaillée. L’intégration des données BRIC5 avec TOPGRU a non seulement amélioré l’efficacité du traitement des données, mais a également minimisé les erreurs de saisie manuelle, jetant les bases des avancées futures dans les techniques de cartographie spéléologique.

Resumen

Este estudio presenta metodologías para la topografía espeleológica dibujada a mano, específicamente integrando datos BRIC5 posprocesados con el software TOPGRU. Se desarrollaron y probaron dos metodologías principales, SPF y PPQ, en la Cueva de Fogão (“Gruta do Fogão”) en Ouro Preto, Brasil. SPF está diseñada para entornos de alto nivel de detalle, y emplea un equipo de un instrumentista, un anotador y un dibujante para garantizar la precisión y la eficiencia. PPQ agiliza la recopilación de datos al permitir que un anotador novato recopile información sin un dibujante dedicado, centrándose en las características significativas observadas por el instrumentista. Ambas metodologías produjeron mapas topográficos de alta calidad de manera efectiva, con errores de cierre del 1,1% para SPF y del 1,5% para PPQ, incluso en presencia de interferencia magnética moderada. El tiempo total de estudio fue de aproximadamente dos horas, lo que demuestra una velocidad competitiva para el mapeo detallado. La integración de los datos BRIC5 con TOPGRU no solo mejoró la eficiencia del procesamiento de datos, sino que también minimizó los errores de ingreso manual, sentando las bases para futuros avances en las técnicas de mapeo espeleológico.

1. Introduction

TOPGRU is a free public educational speleotopographic software, developed since the 1980s by Marcelo Taylor de Lima, for SEE - Sociedade Excursionista e Espeleológica, Ouro Preto, Brazil, founded in 1937 (LIMA, 1987, LIMA & SOUSA, 2022, SEE, 2024). Its latest 2024 version includes the slightly modified "ADJUST" subroutine, originally developed and turn free code by Bob Thrun, as part of the "C-Map" application code, based on the method described by the SCHMIDT and SHELLENG (1970).

BRIC5 is a speleotopographical survey tool produced by Kris Fausnight in the USA and sold worldwide by John Fioroni. Among all of its high-end charactheristics, the registered data collected during surveys can be exported as CSV file, that can be read in TOPGRU 2024 version. The methodologies described in these papers should work with BRIC4 devices with the latest firmware updates too.

This conjunction allowed the development of new field and office speleo topographical methodologies, described in this paper. These methodologies were developed with the aim to use it in hand sketched high detailed (scales of 1:200 or bigger) high precision (BCRA and UIS grades 6) surveys.

In order to test these new methodologies Fogão Cave ("Gruta do Fogão" or "Stove Cave"), in Ouro Preto municipality, Minas Gerais State, Brazil, (Figure 1) was chosen, due to its proximity to SEE and that has been already mapped twice, in order to allow comparations. It is an approximately 100m cave in dolomitic marble of 2.4 Ga Gandarela Formatcion, possibly the oldest carbonatic host rocks to bear caves (Figures 2 and 3).

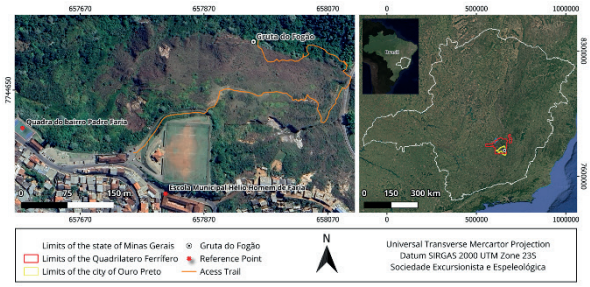

Figure 1: *Site location at Ouro Preto, Minas Gerais, Brazil.*

Figure 2: *Entrance and General view of Fogão Cave. Photo by Marcelo Taylor.*

Figure 3: *Detail of iron rich layers in the dolomitic marble of Fogão Cave. Photo by Beatriz Pires.*

2. Materials and methods

Three new methodologies have been selected to be developed and tested.

Methodology 1: SPF ("Só para fortes")

This methodology involves a team consisting of an experienced Instrumentalist and Notetaker, along with a Sketcher, responsible for creating plans, profiles, and sections. Both sights and backsights were taken to the main statios to improve quality. The Notetaker take notes of the BRIC5 reference number of the best sight of at least three shots and writes down Azimuth, Horizontal Distance and Vertical Distance (a feature BRIC5 provide) to allow precise sketching. Then sequentialy takes splays for the cave contours wall, only the first and last BRICR reference number being written down. The same splays procedure is used for extended profile and cross sections at each station. The sketcher translates the measured stations into conventional plans and profiles, with the possibility of assistance from the Instrumentalist. Later in office, BRIC5 data is processed in TOPGRU allowing a precise definition of the contours of the cave. Data recording utilizes a spreadsheet consistent with traditional methodologies, ensuring reliable data processing.

Methodology 2: PPQ ("Pois é, pra quê?")

This methodology eliminates the need for a dedicated sketcher, focusing on streamlined data collection. It includes only an Instrumentalist and a Notetaker. No lateral readings or annotations for horizontal distances, azimuths, or vertical heights are made; all details are recorded through splay sighting sequences, with the Instrumentalist employing various categories of "types" to denote significant features. Data processing occurs later in the office using spreadsheets, allowing map drawing from the numerous categorized splays taken, a process notably fast with BRIC5. This methodology is particularly useful in simpler cave systems where extensive detailing may not be necessary at the time of measurement.

Methodology 3: TLT ("Trilateraoquê?")

This methodology is tailored for caves with strong magnetic influences where traditional compass use is impractical. It utilizes two known coordinate stations (one GPS-based and one reliable for compass readings) to calculate a third station and continues this process as needed. Data collection focuses on inclined distance and angle measurements, using devices like a clinometer and a laser rangefinder. This methodology is scope of another paper, so we will not deal with it here.

The choice of the test location took into account several factors: proximity and easiness to access, previous maps of conventional topography and its physical characteristics. Fogão Cave shows a map lenght of 97 meters (Figure 4), and its shape is characterized as a branched linear

formation, featuring irregular cuts, generally about 3 m high and 8 m wide. The cave contains fine and clayey sediment and the presence of an underground watercourse (OLIVEIRA & TIMO, 2005). Fogão Cave host rock is a dolomitic marble of Gandarela Formation (Figures 2 and 3).

Therefore, Fogão Cave is inserted in the region of the Iron Quadrangle (Quadrilátero Ferrífero), a preserved Paleoproterozoic orogenic belt affected by the collision and amalgamation of cratonic terrains during the Transamazonian orogeny (~2.1 Ga) (ALKMIN & MARSHAK, 1998). More specifically, within the Dom Bosco syncline, which houses Paleoproterozoic sediments of the Minas Supergroup. This sequence includes the Itabira Group, which is divided in Cauê Formation, composed mainly of itabirites (metamorphic Banded Iron Formation), and subsidiary by hematitic phyllites, dolomitic phyllites and marbles, overlain by Gandarela Formation (DORR, 1958), composed by metamorphic carbonate rocks, mainly dolomitic marbles and subsidiary calcitic marbles, phyllites and lens of banded iron formations (ROSIÈRE & CHEMALE JR, 2000). However, this division is not distinct, as dolomites and itabirites occur intercalated both vertically and laterally, with abrupt contacts between lithologies (PIRES, 1995).

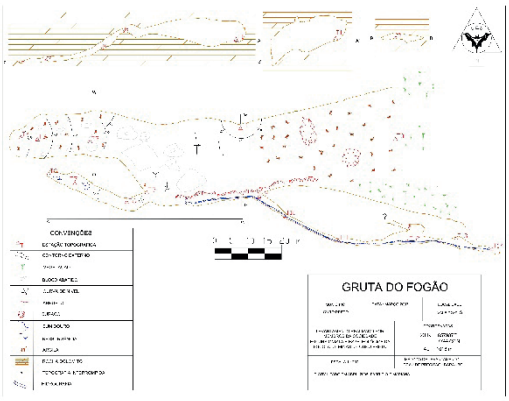

Figure 4: *One of the previous maps of Fogão Cave (OLIVEIRA & TIMO, 2005).*

BABINSKI et al. (1995) dated stromatolitic carbonates of the Gandarela Formation, obtaining an age of 2419 ± 19 Ma using the Pb-Pb method. It is likely that these are possibly the oldest carbonatic host rocks to bear caves

3. Results

On October 14, 2024, members of the SEE convened at the Escola de Minas to test the selected methodologies. The Vale do Ojô, specifically the Gruta do Fogão, was selected for field testing due to its accessibility and prior mapping efforts.

The fieldwork was carried out on October 15. Before entering the cave, thorough checks were conducted to ensure all participants were equipped with the necessary Personal Protective Equipment (PPE) and that all equipment was accounted for using a checklist.

The team proceeded with the full calibration process for the two BRIC5 devices. The results of the calibration were critically analyzed, with one team achieving a precision error of 0.12° for both azimuth and inclination and other of 0.21° for azimuth and 0.15° for inclination and considered as good.

Two teams were formed to implement the proposed methodologies. Before commencing the topography survey, the teams cleared the measurement histories of the BRIC-5 devices and initiated a Loop Test to evaluate the accuracy of their readings. Team 01 (SPF) achieved a closure error of 1.1%.and Team 2 (PPQ) a closure error of 1.5%. These values were considered above the usual loop error found in previous closures with BRIC5 devices, typically 0.1 to 0.2%. To investigate the high errors, both teams were instructed to take three sights and backsights to evaluate magnetic interference. The average of these measurements was high, of 1.7°, probably due to ferromagnetic layers in the host rock and in sediments in the cave (Figure 3), so all stations sights had been made with correspondent backsight. Later office processing gave an average result of approximately 2.2° with a maximum of 4.2° and standard deviation of 1.1° in about 25 measurements.

Data collection protocols were carefully followed (Figure 5):

- Each base point was marked with labeled stakes for reference.
- Measurements included at least three conventional readings and three counter-readings for each base and writing the BRIC5 reference number of the most averaged one. In methodology SPF the Note taker also wrote the Azimuth, Inclination and Horizontal Distance, to help the sketching in field, although these data are not typed in office. For PPQ only the BRIC5 reference numbers were typed.
- The Notetaker positioned the target behind the stake to facilitate accurate readings, ensuring the instrumentalist could illuminate the target with their headlamp.
- Observations and data were meticulously recorded, with the Notetaker annotating the first and last codes provided by the BRIC5 for detailed plan, cross section and extended profile respectively (Figure 6). It was emphasized to the teams to avoid tangential measurements to cave walls, ceiling and floor, as much as possible.
- The sketcher of SPF Methodology has been provided with laser disto meters to make it easier to draw the details in field. They were told by the Notet of the main azimuth, inclinations and distance between stations too.

Figure 5: *Detail of survey procedure. Stations labeled in vertical sticks and reflective patch used as target. Photos by Beatriz Pires.*

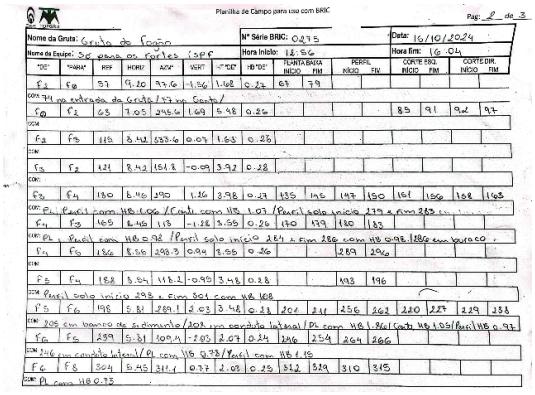

Figure 6: *One of the field sheets registered during the tests, SPF method. Notice that splays are taken and registered sequentially to allow easy processing.*

On October 16, participants reconvened to discuss and process the gathered speleotopographical data. The data was downloaded from BRIC5 devices and demonstrated how to fill out the new developed spreadsheets for processing with the TopGru 2024 program. Only BRIC5 reference numbers were typed, what avoid the annoying digitations of Azimuth, Inclination and Distance, also minimizing errors. The auto filling capacities of the spreadsheet allowed to type the huge number of splays taken easily (Figure 7).

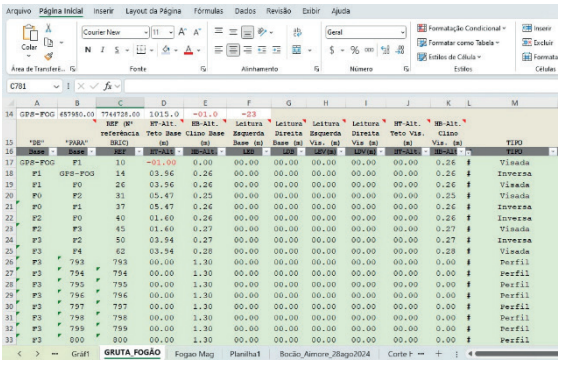

Figure 7: *Example of TOPGRU PPQ spreadsheet of Fogão Cave. Notice the types of measurement in (last row).*

Afterwords the data were processed by TOPGRU 2024, generating the basis to draw the cave map .

In SPF method a total of 242 sights were surveyed: 22 for main stations and for 220 splays: 88 splays to detail plan view, 67 to extended profile and 65 for cross sections.

PPQ survey method has been carried out with 763 sights, 27 to main stations, and 736 splays: 216 to plan view walls (Figure 8), 96 for extended profile, 324 for cross sections and 100 for 14 different types of internal detail.

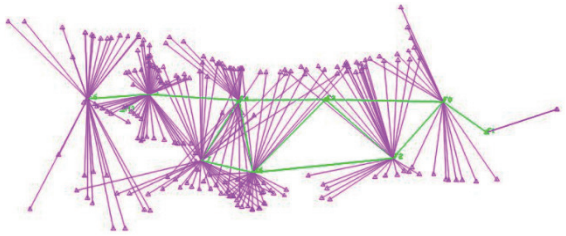

Figure 8: *TOPGRU dxf output of PPQ method main stations (green) and walls contour splays (magenta).*

The TOPGRU 2024 2D analysis for closed polygonals results achieved an average of 0.30% with a maximum of 0.57% for SPF method. 3D results were even better, with 0.04% average and 0.46% maximum over 19 segments, including backsights. For PPQ method an average of 0.39%, maximum of 1.14% for 2D and 0.24% average and maximum of 0.66% for 3D in 25 segments.

The total time of survey, including instructing the team, in site equipment calibration and magnetic interference evaluation was about 6 hours. The survey for both methods took about 2 hours to complete, with the two teams working at the same time, on from the entrance to the end and the other from the end to the entrance. With a trained team, it is expected to achieve a similar speed to conventional topography.

The office processing time was like a regular one, mainly because the learning curve of the new spreadsheet to be processed. Since no Azimuth, Inclination and Distances had to be typed, it is expected that this processing time will be substantially faster than the conventional. One of the maps outputs (SPF method) can be seen in Figure 9.

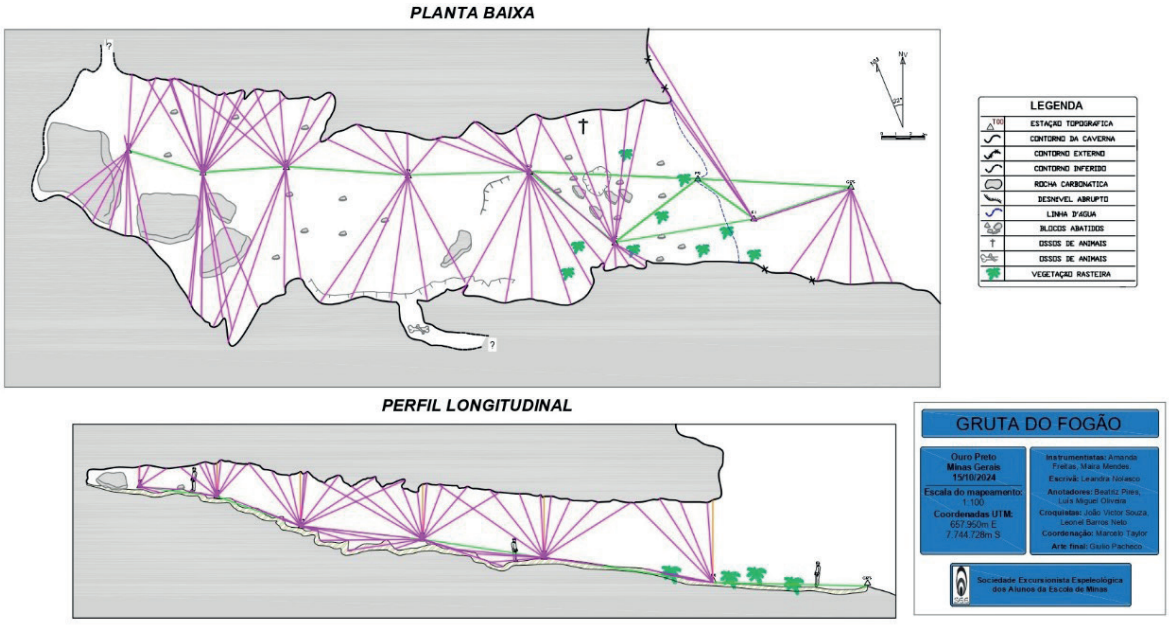

Figure 9: *Synthetic Fogão Cave map, SPF method. Centerline and splays kept to better visualization of the method.*

4. Discussion

The methodologies developed for hand-sketching speleological topography, namely SPF, PPQ, and TLT, exhibited distinct strengths and applicability tailored to various cave environments. The possibility of introducing numerous splays and details data to the topography meant a great increase in the quality of the final maps.

The challenges encountered, especially concerning magnetic interference, underscore the necessity for meticulous planning and execution in caves with complex geological features.

Methodology 1: SPF was particularly effective ig environments requiring high detail. This methodology is much more detailed in provi-

ding topographical information, while it is very similar in and sketching work and time.

Methodology 2: PPQ presented a streamlined approach that allowed for flexibility and efficiency in data collection, making it particularly suitable for simpler cave systems. By eliminating the need for a dedicated sketcher, the methodology allowed the team to concentrate on detailing the environment, while ensuring thorough documentation through flags and sighting sequences. The substantial total of 763 sights collected indicates a thorough data-gathering process, facilitated by the easiness of acquiring data with BRIC 5. In this test phase the separation of the details was still achieved by separating different sets of data in the spreadsheet. Future encoding in Topgru can split the different types in one layer each, allowing the process to be straight forward. The average closure error of 0.39% for 2D analysis and 0.24% for 3D results demonstrates that this methodology can yield high-quality results, even with moderate magnetic interference.

The results obtained from the Gruta do Fogão survey indicate that both SPF and PPQ methodologies are viable, SPF being very similar to other survey methodologies and PPQ advancing through a “Total Station” approach.

The successful integration of BRIC5 data with TOPGRU software further enhances the potential for accurate and detailed speleological mapping. This integration allows for efficient data processing, significantly reducing human error in data entry.

5. Conclusion

The methodologies presented in this study for hand-sketching speleological topography, specifically SPF and PPQ, represent significant advancements in the field of cave surveying. The successful application of these methodologies during the Gruta do Fogão survey has illustrated their effectiveness in producing high-quality topographical maps, even in the presence of magnetic interference.

Methodology 1: SPF demonstrated its strength in environments demanding high detail and precision. The results obtained, including closure errors comparable to established standards, confirm that SPF remains a reliable choice for detailed mapping. The total survey time of approximately two hours reflects a competitive speed, particularly when considering the detailed nature of the data collected.

Methodology 2: PPQ, on the other hand, showcased its adaptability and efficiency, making it particularly suitable for simpler cave environments. By streamlining the data collection process and allowing for greater flexibility without the need for a dedicated sketcher, this methodology has the potential to significantly improve field surveying practices. The substantial number of sights collected—763 in total—demonstrates the methodology’s ability to gather data rapidly while maintaining quality.

The survey for both methods took about two hours to complete,

The integration of BRIC5 data with TOPGRU software has further improved the mapping process, enhancing efficiency and accuracy in data handling. With the ability to minimize manual data entry errors, the methodologies presented here lay a solid foundation for future advancements in speleological mapping techniques.

In conclusion, the methodologies developed in this study not only improve the quality and efficiency of cave mapping but also may enhance the speed of the detailed surveying process. As these techniques are refined and adapted for various contexts, they will undoubtedly contribute to improving the overall practices in cave survey work. Future research should focus on expanding the application of these methodologies in different cave systems, ensuring their continued relevance and evolution in the field.

6. Acknowledgments

We gratefully thank Paulo Eduardo Santos Lima for guiding us to Fogão Cave and discussing speleotopographical issues. To Tiago Vilaça Bastos of “Prospecto Ambiental” for providing one of the comparative maps of this paper. To all SEE members, from the present or the past that helped to improve speleotopographical mapping techniques. To all TOPGRU group participants that always helped to “make it better and easier”.

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Mapeamento de cavidades hospedadas por rochas ferríferas e/ou ferruginosas com uso de sensor LiDAR. O caso da Cavidade do Manso

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Resumo

Em função do recente interesse surgido em relação às cavidades ferríferas e/ou ferruginosas no Brasil, muito recurso técnico e científico vem sendo empenhado no estudo destas cavernas. No caso da topografia de cavidades, devido às dificuldades impostas pela natureza magnética dos itabiritos, jaspelitos, metadiamictitos ferruginosos e coberturas diversas, novos dispositivos e métodos de trabalho vem sendo empregados rotineiramente com a intenção de produzir documentos mais precisos. Uma destas ferramentas é o sensor LiDAR, mais comumente conhecido como laser scanner. Essa ferramenta foi utilizada para a execução do levantamento topográfico da Cavidade do Manso, sete anos após esta caverna ter sido mapeada a partir dos métodos de topografia convencionais. Como resultado, observou-se um significativo ganho no tempo de execução, uma maior precisão cartográfica e uma maior acurácia morfológica – tanto em planta baixa quanto nos perfis e seções. Já quando observados os atributos espeleométricos, destacam-se: a área total (m^2), com uma diferença de valores na casa de 6,5%, e o volume (m^3) com 10,9%, valores estes que não podem ser desprezados dada a importância destes atributos em processos como o de análise de relevância espeleológica.

Abstract

Iron ore cave survey using LiDAR sensor. The case of Manso's cave. Despite the recent interest in iron ore caves, in Brazil, a great deal of technical and scientific resources have been devoted to study these caves. In the case of cave survey, due to the difficulties imposed by the magnetic nature of iron ore, new devices and work methods have been routinely employed with the intention of producing more accurate maps. One of these tools, is the LiDAR, more commonly known as laser scanner. This tool was used to perform the survey of the Manso's Cave, seven years after this cave had been mapped using conventional survey methods and tools. As a result, a significant gain in execution time, greater cartographic precision and greater morphological accuracy were observed – both in cave area and in profiles and sections. When observing the speleometric attributes, the following stand out: the total area (m^2), with a difference in values around 6.5%, and the volume (m^3) with 10.9%. It is important to highlight that such differences in value can be decisive in classifying a cave as of maximum relevance, in light of the brazilian environmental laws.

1. Introdução

Cavidades hospedadas por rochas ferríferas, como os itabiritos e jaspilitos, e ferruginosas, como as cangas e o ferricrete são formas cujos estudos são bastante recentes, quando comparadas a cavernas inseridas no carste tradicional. No Brasil, de acordo com Piló & Auler (2005), é provável que a primeira menção a cavernas em minério de ferro seja devida do francês Noel Aimé Pissis que em 1842, descreveu cavidades e estalactites relacionadas aos itabiritos da Unidade Espeleológica do Quadrilátero Ferrífero (Oliveira, Olivito & Rodrigues-Silva, 2011) região centro-sul do estado de Minas Gerais. Todavia, é com a atuação sistemática dos geólogos da *United States Geological Survey* (USGS), também no Quadrilátero Ferrífero, e que passamos a ter descrições e estudos mais detalhados sobre cavidades desta natureza, com destaque para Guild (1957) e Simmons (1963), que trazem alguns pormenores relacionados ao litotipos destas cavernas e até sobre os processos espeleogenéticos envolvidos.

Com o advento da Constituição da República Federativa do Brasil de 1988, que em seu Art. 20, Inciso X, traz como bens da união "*as cavidades naturais subterrâneas e os sítios arqueológicos e pré-históricos*", e o subsequente fortalecimento da legislação espeleológica brasileira, os estudos espeleológicos integraram de forma mais sistemática os processos de licenciamento ambiental – o que passou a fomentar o desenvolvimento técnico-científico dos métodos e ferramentas frequentemente utilizados na elaboração de estudos espeleológicos, inclusive **da topografia de cavernas.**

Desde o início dos anos 2000, cavernas ferríferas e/ou ferruginosas foram extensamente mapeadas no Brasil com o objetivo de suprir a demanda dos processos de licenciamento ambiental, o que resultou em um acervo cartográfico significativo. Porém, a maior parte deste trabalho, foi conduzida com o uso de instrumentos que apresentam alta susceptibilidade ao magnetismo da rocha encaixante, necessitando assim do emprego de adaptações e correções durante o levantamento de campo que por vezes podem resultar em erros graves no produto final.

Nos últimos anos, a utilização de bússola, clinômetro e trena vem sendo substituída pelas "ferramentas híbridas", equipamentos que utilizam de magnetômetros, acelerômetros e microprocessadores capazes de coletar o azimute, a inclinação e a distância de uma visada com apenas um toque – e transferir essas informações, via bluetooth, para um *tablet* ou *smartphone*. Contudo, tanto a Disto X2 quanto a BRIC5 estão sujeitas a interferência magnética, necessitando assim de técnicas de correção ao longo do trabalho.

Frente a tais desafios, outros equipamentos como teodolito e até mesmo estação total foram utilizados em levantamentos topográficos de forma isolada, porém, sem resultados significativos. Tais ferramentas são comumente utilizadas em mapeamentos de abrigos, no contexto da arqueologia, mas suas dimensões, peso e operação são fatores limitadores para a espeleologia.

Neste cenário, onde a busca de alternativas para a execução de bons mapas espeleotopográficos é fundamental para subsidiar estudos mais robustos, surge a alternativa da utilização do LiDAR – ou como é mais conhecido, laser scanner.

A tecnologia do sensor LiDAR (*Light Detection and Ranging*) tem como princípio de funcionamento a emissão de pulsos de laser para modelar uma determinada superfície a partir de distâncias. Estes pulsos partem de um emissor que compõe o equipamento, atingem uma determinada superfície e são capturados por um receptor. O tempo de retorno desse pulso ao receptor é usado para calcular a distância entre o equipamento e o objeto – permitindo assim a construção de um modelo tridimensional da superfície escaneada. Este equipamento tem como limitações principais o seu elevado custo, sua virtual fragilidade física e a incapacidade de coletar informações de anteparos translúcidos, como a água. Porém, é capaz de realizar uma modelagem da superfície muito precisa, é de fácil operação e reduz o tempo de exposição da equipe ao ambiente subterrâneo – minimizando inclusive eventuais impactos negativos causados pela circulação de pessoas na cavidade.

Com o objetivo de estabelecer parâmetros comparativos entre os resultados alcançados pela topografia convencional e o mapeamento com uso do LiDAR – em cavidades hospedadas por rochas ferríferas e/ou ferruginosas – é trazido aqui o caso da Cavidade do Manso, que foi mapeada utilizando os dois métodos.

A Caverna da Fazenda do Manso ou Cavidade do Manso (código CANIE 020544.07392.31.46107), está localizada no distrito de Lavras Novas, município de Ouro Preto, região centro-sul do estado de Minas Gerais, Brasil (Fig. 1). Localmente, insere-se no topo de uma vertente cuja entrada principal esta relacionada a uma feição doliniforme. Desenvolve-se no contato do Itabirito (Supergrupo Estrada Real, Grupo Sabará, Formação Saramenha) com a Canga Detrítica, sobreposta devido a sua idade e filiação genética ao Itabirito.

Além dos parâmetros espeleométricos da Cavidade do Manso, serão apresentados também os dois mapas topográficos da caverna para fins de comparação morfológica.

2. Materiais e métodos

A Cavidade do Manso foi mapeada pela primeira vez no ano de 2015. Este levantamento contou com o emprego de técnicas de topografia já consagradas, que utilizam de bússola de visada, clinômetro e trena a laser para a coleta dos dados topográficos. De forma específica, foram utilizados na ocasião: (i) trena a *laser Leica Disto D3a* para medir a distância de um ponto ao outro; (ii) bússola e clinômetro *Suunto Tandem* 360PC/360R Zona 3 (adequada para topografia de cavidades e balanceada para Zona Sul Equatorial) para medir a graduação do azimute em relação ao norte magnético e a graduação da inclinação em relação ao plano horizontal de um ponto ao outro; e (iii) uma planilha de anotação dos dados coletados.

Com o objetivo de minimizar o impacto da interferência magnética na bússola, foi empregado um método de correção, in loco, que pode ser denominado como "método de correção pela visada de ré". O princípio deste método é apresentado na figura a seguir (Fig. 2).

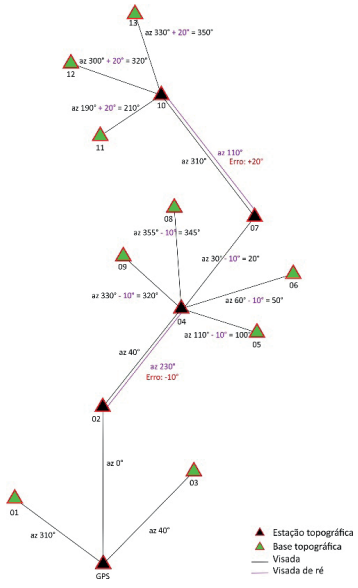

Figura 2: *Aplicação do método de correção pela "visada de ré".*

Embasado nas medidas coletadas e devidamente anotadas em planilha, é elaborado o croqui de campo. Nesta representação gráfica da cavidade, constam as bases topográficas, os contornos das galerias e salões, suas características morfológicas e feições significativas, tais como estruturas geológicas, hidrologia, sedimentos clásticos e/ou químicos e orgânicos, assim como a localização de vestígios paleontológicos, artefatos arqueológicos, interferências antrópicas recentes, entre outros detalhes. Neste momento, utiliza-se papel milimetrado, régua graduada e transferidor 360º a fim de compor um desenho em escala (1:100 cm). Por fim, foi tomada junto a entrada da cavidade, a sua localização geográfica, obtida a partir do uso de um GPS de navegação GPS MAP *Garmin 64 S*.

Após a coleta dos dados de campo, já em gabinete, utilizando o *software Compass 5.0*[1], foram gerados arquivos vetoriais (.dxf) das medidas realizadas em campo (chamadas de linhas de trena) e que ao serem importados no *software ZWCAD*[2] *2020*, sobrepostos aos croquis de campo, serviram de base para a digitalização do mapa da caverna (Fig. 3).

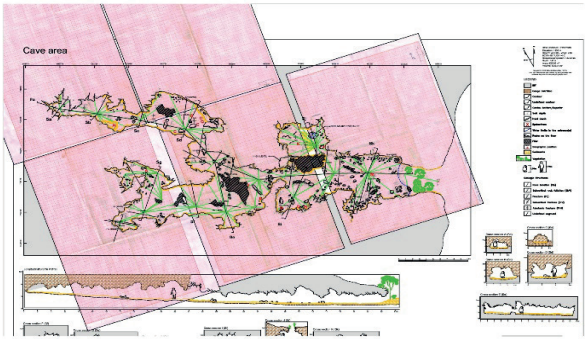

Figura 3: *Processo de elaboração do mapa topográfico da Cavidade do Manso em ferramenta CAD.*

Em 2022, a Cavidade do Manso foi remapeada, desta vez com a utilização do laser scanner ZEB GO, da GeoSLAM. O ZEB GO permite uma coleta de até 43.000 pontos por segundo a um alcance de até 30

metros com uma acurácia variável de até 3 cm. Sua operação parte de uma triangulação estabelecida por coordenadas geográficas na entrada da cavidade. Para a coleta destas coordenadas, utilizou-se um receptor GNSS RTK CHCNAV i73, do fabricante CHCNAV. Este equipamento é capaz de coletar coordenadas geográficas com uma precisão milimétrica, operando em 1408 canais, a partir das tecnologias GPS, GLONASS, Galileo, BeiDou, QZSS, PPP e SBAS. Após o registro das informações geográficas, iniciou-se o levantamento topográfico - percorrendo toda a extensão da cavidade com o laser scanner, preferencialmente na posição vertical.

Após o término do processo de escaneamento, os dados são processados pelo software GeoSlam Hub, que permite a exportação da nuvem de pontos em formatos mais acessíveis, como o (.las) ou (.laz). O tratamento da nuvem de pontos foi realizado no software Riscan PRO 2.0, da fabricante RIEGL, onde foi possível produzir modelagens (Fig 4), contornos no eixo horizontal, seções e perfis no eixo vertical e curvas de nível com equidistância centimétrica.

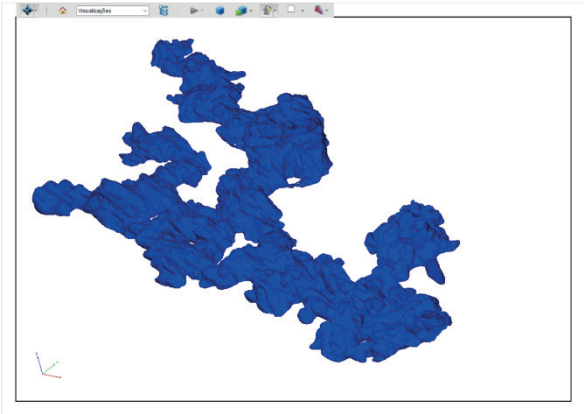

Figura 4: *Modelagem obtida a partir da nuvem de pontos da caverna.*

Espeleometria

A exceção do volume da cavidade, todos os demais atributos espeleométricos, em ambos os levantamentos, foram obtidos a partir de métodos já consagrados na literatura, trazidos de forma bastante didática por Rubbioli e Moura (2005). A projeção horizontal (m), foi obtida a partir da aplicação do princípio da descontinuidade. O desnível total do piso (m) foi avaliado com base em perfis longitudinais, que tomam como referência as cotas mais elevadas e mais rebaixadas do piso da caverna. A área (m^2), foi definida tomando como referência os contornos da planta baixa, subtraída, posteriormente, do valor da área (m^2) de massas rochosas, como pilares.

No caso do mapeamento tradicional, o volume (m^3) foi obtido a partir da multiplicação da área (m^2) final da cavidade pela média de sua altura (m). A média da altura da caverna é conferida pelos perfis e seções definidos pelo topógrafo ao executar o trabalho de campo. Isso significa que tanto a qualidade quanto a quantidade dos perfis e cortes transversais definidos para uma caverna são fundamentais para um valor de volume (m^3) final mais fidedigno à realidade daquele ambiente subterrâneo.

Já a modelagem traz de forma automatizada, via software, o valor do volume (m^3) da cavidade. Basta que a análise considere os mesmos princípios observados pela topografia tradicional, como o fechamento do modelo no ponto zero da caverna.

3. Resultados

Ambas as iniciativas de mapeamento da Cavidade do Manso resultaram na elaboração de mapas topográficos da cavidade, considerando tanto a planta baixa quanto perfis e seções. O mapa topográfico da Cavidade do Manso executado a partir do emprego de técnicas convencionais, foi finalizado em 2015 e graduado, conforme os critérios propostos pela British Cave Research Associaton (BCRA), como 4D (Fig. 5).

Já o mapeamento conduzido com o uso do laser scanner, foi classificado como BCRA XD (Fig. 6). É importante destacar que não há uma graduação específica que considere levantamentos topográficos executados com uso de sensor LiDAR – e por isso – adotou-se a graduação mais precisa prevista pela BCRA, que considera a utilização de equipamentos de topografia de alta precisão, como teodolito e estação total.

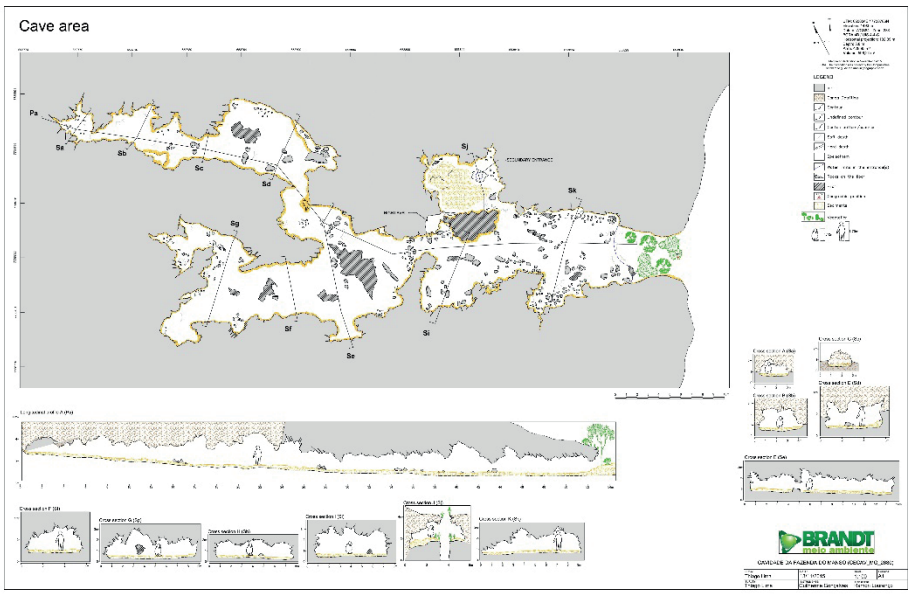

Figura 5: *Mapa topográfico da Cavidade do Manso, executado com o uso de métodos tradicionais de topografia subterrânea.*

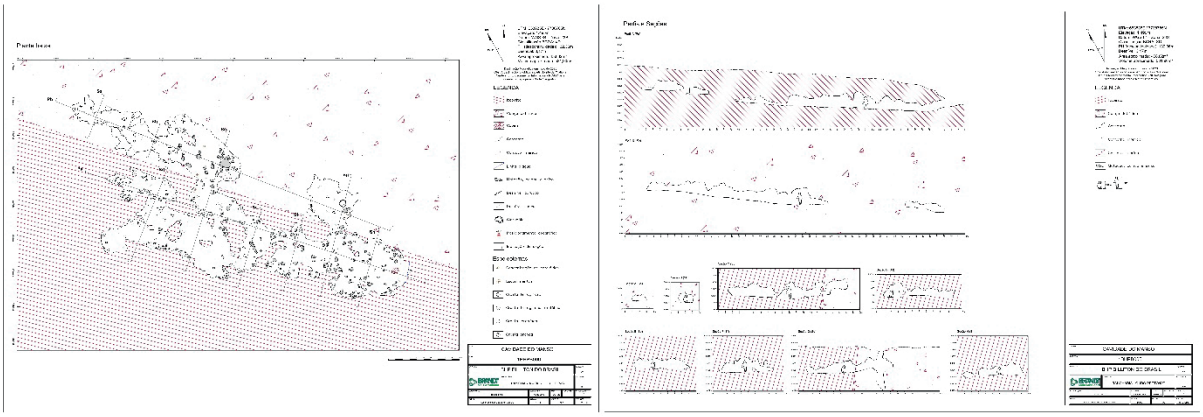

Figura 6: *Planta baixa, perfis e seções da Cavidade do Manso, elaborada com o uso de sensor LiDAR.*

4. Discussão

Do ponto de vista prático, o mapeamento da Cavidade do Manso com o uso do GeoSLAM ZEB GO trouxe agilidade, acurácia morfológica e uma maior confiabilidade para os dados espeleométricos. Quando comparado ao mapeamento tradicional, o tempo gasto para realização do trabalho de campo, com uso do ZEB GO, foi reduzido em 80% (Fig. 7). A nuvem de pontos final da caverna atingiu um total de 7.794.342 pontos, o que significa que para cada metro quadrado, tem-se uma densidade de 16.988 pontos.

Cavidade do Manso		
Atributos	**Mapeamento Convencional**	**LiDAR**
Data	04 a 06/11/2015	17/08/2022
Tempo de execução (horas)	20	4
Quantidade de pontos	N/A	7.794.342
Quantidade de bases topográficas	166	N/A
Distância total de visadas (metros)	661	N/A
Projeção horizontal (m)	132,39	132,36
Desnível total do piso (m)	3,80	3,17
Área em planta baixa (m²)	428,95	458,82
Volume (m³)	596,24	531,9

Figura 7: *Comparação de atributos relacionados ao método do mapeamento.*

Quando comparada a localização geográfica, a orientação em relação ao norte magnético e também a morfologia – nota-se que, apesar da localização da entrada da caverna apresentar uma boa similaridade entre os métodos, sua orientação em relação ao norte magnético apresenta distorções no método convencional. Isso certamente está relacionado a interferência magnética imposta pelo substrato rochoso à bússola, comprovando que o método de correção adotado durante o mapeamento convencional minimiza mas não elimina possíveis erros ocasionados por este fenômeno. O uso de receptores GPS com tecnologias distintas também é um fator a se destacar, já que existe uma diferença significativa de precisão entre um GPS de navegação e um GPS RTK. Finalmente, o padrão morfológico reticulado da Cavidade do Manso está bem expresso em ambos os resultados (Fig. 8), pois o método de irradiação de visadas a partir de uma estação topográfica fixa permite a coleta de um número expressivo de visadas que tem como principal objetivo adicionar precisão ao croqui elaborado em campo, sendo este o mais recomendado em levantamentos topográficos que necessitam de uma representação morfológica mais precisa.

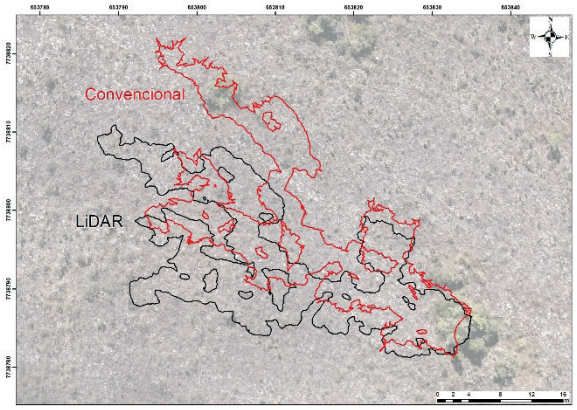

Figura 8: *Comparação dos contornos em planta baixa. Mapeamento convencional X LiDAR.*

Ao analisar os atributos espeleométricos obtidos para a Cavidade do Manso, percebe-se que tanto para a projeção horizontal (m) quanto para o desnível do piso (m) a diferença entre os resultados alcançados é desprezível (Fig. 9). Portanto, para estes dois atributos, o método topográfico convencional foi assertivo quando consideramos o grau de precisão buscado por este mapeamento. Já para a área em planta (m²) e para o volume (m³), há uma variação de 6,5% e 10,9%, respectivamente – valores estes bem aceitáveis frente ao grau de acurácia proposto pelos dois métodos.

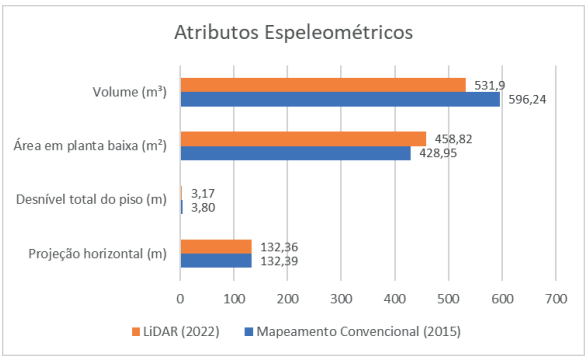

Figura 9: *Atributos espeleométricos da Cavidade do Manso, obtidos pelo mapeamento convencional e também pelo mapeamento com o uso de LiDAR.*

5. Conclusão

Diante dos dados trazidos por este trabalho, í possível afirmar que há sim um ganho significativo na utilização de sensores LiDAR no mapeamento de cavidades hospedadas por rochas ferríferas e/ou ferruginosas. O tempo de execução, a acurácia, e o fato de que estes equipamentos não estão susceptíveis ao magnetismo imposto pelo substrato rochoso fazem destes sensores uma boa alternativa para a topografia destas cavernas. Porém, seu elevado custo ainda é um fator limitador para a popularização da ferramenta na espeleologia. No caso da Cavidade do Manso, houve também um ganho significativo quando observamos seu prolongamento em relação ao norte magnético e também em sua representação morfológica. Alguns dos resultados obtidos por este estudo comparativo, foram aplicados por Brandt (2024) no estudo de relevância da Cavidade do Manso, classificando esta como de máxima relevância também por apresentar dimensões notáveis em extensão, área e volume em uma amostra regional que contou com um total de 980 cavidades com desenvolvimento linear superior a cinco metros – todas elas localizadas no Quadrilátero Ferrífero. Tal argumento justifica a relevância de um levantamento topográfico preciso, e a busca por novos métodos e técnicas que contribuam para a elaboração de bons mapas de cavernas.

Agradecimentos

Agradeço a Brandt Meio Ambiente e ao seu time de espeleologia pelo apoio constante na elaboração deste estudo e a BHP Billiton, na figura do Sr. Eduardo Pereira, pela cordial cessão dos dados trazidos por este trabalho.

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Caves and Karst Databases at the French Caving Federation (FFS)

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Abstract

We describe the bases developed by the database commission of the French Speleology Federation (FFS), starting with its central module, the Karsteau cave database. It offers a long-term storage environment, a rich information structure compatible with the KarstLink vocabulary, a cartographic interface, advanced search functions, and a decentralized organi-zation for data administration and validation, as close as possible to the field cavers and researchers. The satellite modules, to date, include a bio-speleological base, a database of observations of pollution of karst environments, and a database of physical measurements from our physical data sensors. We briefly describe the projects currently under development: a mobile application, usable on smartphones or tablets to use and enter information directly in the field; and a module dedicated to studies of karst waters, integrating one or more specialized bases, and analysis and visualization applications, aimed at very long-term studies. Karsteau and its current modules will be demonstrated on our stand at the congress.

Résumé

Caves and Karst Databases at the French Caving Federation (FFS). Nous décrivons les bases développées par la commission bases de données de la Fédération Française de Spéléologie, en commençant par son module central, la base de données de cavités Karsteau. Celle-ci offre un environnement de stockage pérenne, une structure d'informations riche et compatible avec le vocabulaire KarstLink, une interface cartographique, des fonctions de recherche poussées, et une organisation décentralisée d'administration et de validation des données, au plus près des spéléologues et des chercheurs de terrain. Les modules satellites, à ce jour, incluent une base bio-spéléologique, une base d'observations de pollutions des milieux karstiques, et une base de mesures physiques de nos enregistreurs de données physiques. Nous décrivons succinctement les projets en cours de développement : une application mobile, utilisable sur smartphone ou tablette pour utiliser et saisir des informations directement sur le terrain ; et un module dédié aux études des eaux karstiques, intégrant une ou des bases spécialisées, et les applications d'analyse et de visualisation, visant des études sur le très long terme. Karsteau et ses modules actuels feront l'objet d'une démonstration sur notre stand au congrès.

1. Introduction

Digital data exchanges are becoming an increasingly important element in the world of caving. This is why our federation has chosen to create a full-fledged commission: "Database Commission". Heir to a long history of databases managed in a rather dispersed manner, the commission's missions are:

- To provide tools for managing caving data in order to ensure their sustainability, protection and sharing, in compliance with the wishes of contributors and federal ethics.
- To provide training and support for clubs and committees wishing to manage caving data.
- To set up exchange protocols between the various commissions (scientific, documentation, bibliography, etc.) and other FFS structures.
- To strengthen relations with organizations outside the FFS involved in the management of karst data.
- The federation develops its own tools in collaboration with its institutional partners.

Karsteau. This is the official reference database of the Federation for managing cave data. But there are other cave databases in France and among our partners, our goal is not to impose a single base, but to network these bases and encourage data exchanges, while respecting the specific operation of each base.

In the same vein, we are developing specific bases, for other types of information, designed in a modular way to ensure the management, dissemination and inter-operability of data:

The Karsteau Biospel module is designed to centralize and structure the biological data collected in caving, during all phases of the study and identification by experts.

POK (the Karst Open Portal) is a central tool for the collection, analysis and dissemination of environmental data, dedicated to monitoring pollution in the karst world.

The Physical Measurements module is dedicated to storing time series from all types of sensors (e.g. temperature, CO2, flow, conductivity, radon, etc.), to reflect the temporal variability of karst systems, and to allow short and long term monitoring and analysis of these data.

In this article, we will describe Karsteau and its current modules, and we will outline the directions of its planned evolutions.

2. Karsteau: https://www.karsteau.org/karsteau/

This is our main database, bringing together central information on cavities, a cartographic interface, and decentralized data entry, management (and validation) functions. Created in the 1980s in Aquitaine, it has gradually been extended to other French and Spanish regions, then becoming the official database of the FFS in 2022. It is available in English, French, Spanish and Basque.

Growing rapidly today, it covers 65 French departments, but also regions in Spain, Bosnia, Cuba, and Georgia. To date, more than 1,150 users have opened an account and the database contains 25,000 cavities. The data is managed and verified in a decentralized manner, as close to the field as possible, currently by 36 local or national administrators. The information access policy is defined at the level of each territory. In many cases, some of the cavities are accessible without restriction, the vast majority are accessible to all federated cavers, as well as to our partners. Some cavities, or some information, are only accessible with specific conditions, for security or preservation reasons.

A cartographic interface and a very complete set of search criteria are available to users.

Access rights: the management of access rights in Karsteau is based on several levels in order to ensure a balance between accessibility, security and collaboration. These rights are defined according to the role and responsibilities of each user:

A **Simple visitor** has restricted access to public information. A **Reader** (with a registered account) has access to consultation of all the data of a region, a geographical sector, or the entire database. An **Editor** has the possibility to modify and add data in a given sector. A **Collaborative Group** defines a shared workspace allowing members of the group to interact on common projects. Finally, an administrator manages users and rights within a region, a group, or the entire database.

This hierarchy of rights guarantees a secure and structured framework for accessing and managing information.

The **import and export** of data in Karsteau is based on rigorous protocols aimed at ensuring the consistency and reliability of the information. Thanks to automated validation tools and strict control processes, data exchanges are carried out smoothly and securely.

Before any integration, the data is subjected to a series of tests to avoid errors and inconsistencies: Verification of the existence of sectors and geographical areas, and the correspondence of coordinates with the sector and area indicated. Verification of the consistency of the associated municipality; verification of the correct classification of data (UIS typology) according to their nature. Thanks to these protocols, Karsteau guarantees the integrity of information, facilitates the exploitation of exports and ensures effective interoperability with other databases.

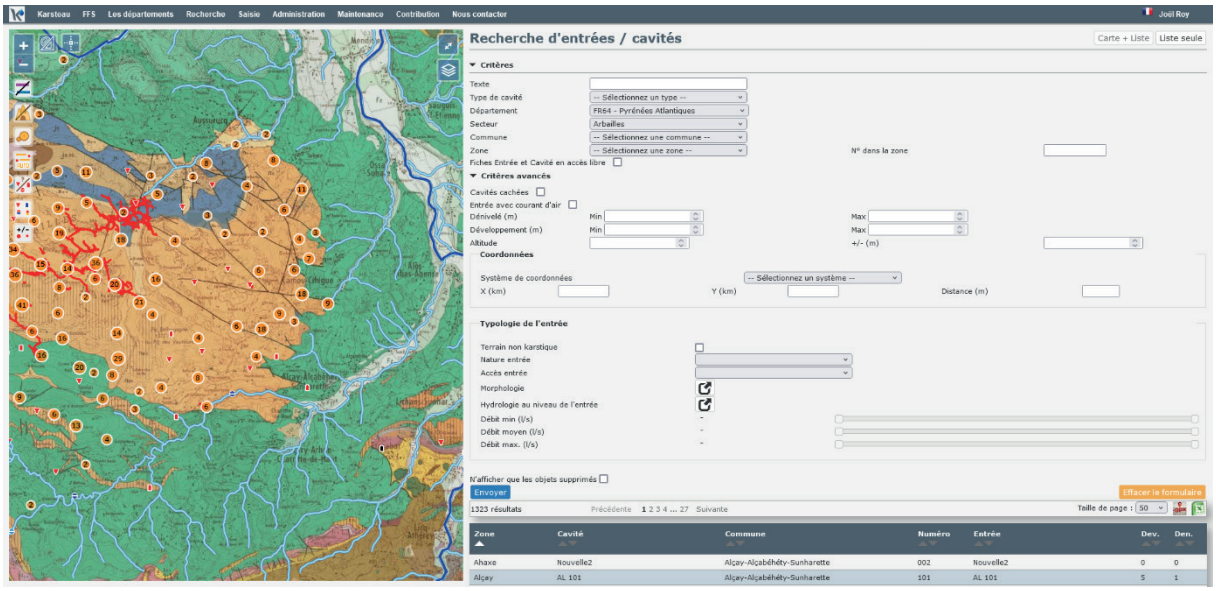

Figure 1: *Présentation cartographique, et formulaire de recherche dans Karsteau.*

3. Biological Module

The Karsteau bio module is designed for the management and exchange of data related to biodiversity in karst environments. Designed in collaboration with the FFS Biospeleological Study Group, it allows the structuring and sharing of information concerning the fauna and flora encountered during speleological explorations. This module facilitates the recording of biological observations, such as the presence of endemic, threatened or rare species, as well as information on their habitat and distribution. It allows precise monitoring of material batches made up of observations / photos / information relating to a harvest in a given Station. The determinations and exchanges make it possible to indicate the messages exchanged and the species that have been determined by a specialist.

Figure 2: *Trichaphaenops obesus (Photo : Josiane Lips).*

4. Pok-Speleo: Participatory inventory of pollution of karst sites

Pollution in karst environments is a critical issue for our federation, given the vulnerability of these environments to chemical, biological and physical contamination. The environmental monitoring tool, pok--speleo.fr, is already in itself an alert action towards elected officials, local authorities, competent bodies and populations. However, for this approach to be successful, the dissemination of this alert must be as wide as possible, and that cavers, clubs and committees take ownership of this inventory. Then, beyond a general communication of the tool, targeted information can be carried out on certain reports to pre-identified actors in order to alert them and resolve a potentially dangerous situation more effectively.

Figure 3: *Screen-shot of the Pok interface in the Pyrenean region.*

5. Mesures Physiques

Based on the proposals made on the KarstLink website [1], and the proposals made during the UIS 2022 congress [2], we have built a database specific to sensors that record series (potentially very long) of physical measurements. Speleologists are familiar with reefnets for pressure and water height measurements in our underground rivers. But our database, based on the KarstLink S2 vocabulary, can manage any type of time series, with its metadata (location, sensor type, physical quantities, time steps and intervals, precision, etc.). For modularity reasons, this measurement database is independent of the cavity databases, and the locations can refer to cavities stored in any database responding to Karstlink queries, for example Karsteau or Grottocenter. The measurements, on the other hand, are not stored individually in the database, but in the form of much more compact files, in text or CSV format, as produced by the sensor software; only the structure of the files is specified in the metadata. In passing, we propose a redesign and extensions of the KarstLink specifications to include new use cases and improve compatibility with other platforms.

Once the series are stored, they must be able to be used. Any external application will be able to access them through KarstLink-type requests. For example, we could ask to import all the CO2 and Radon measurement files, taken within a 50 km perimeter around Bordeaux, between 2020 and 2024... The client application will then be in charge of decoding, analyzing, and/or visualizing all of this data. Beyond the classic uses of data backup and analysis, the federation is developing a more specific use case within the framework of the OFSEC project, of observing all the physical parameters of a small number of “witness” sites, over a long period. These observations produce a large volume of data, which must be saved in a sustainable manner, to conduct scientific studies in 20 or 30 years. This will be a “zero point” for long-term studies of the evolution of cavities, canyons, siphons with climate change.

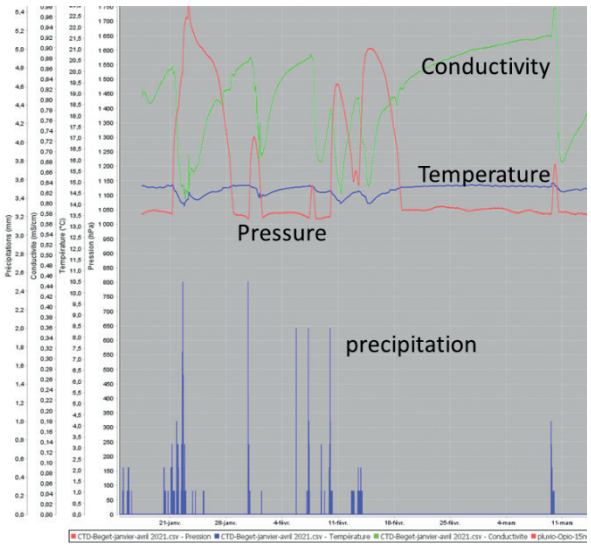

Figure 4: *Visualization of data series.*

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6. Conclusion and future plans

The tools developed by the FFS constitute a coherent set of databases addressing various facets of karst, from the caves themselves (entrances, speleometrics, topographies, docu-mentation, etc.), their biological and physical studies, their pollution. All these databases are managed, fed, validated, by the local structures of the federation, and accessible to all its members and partners.

We will conclude by mentioning two projects currently under study:

Field module for Karsteau – "Prospector" (under develop-ment).

The objective is to develop a mobile application or an interface optimized for the use of Karsteau in the field. This tool will allow speleologists, hydrologists and other users to: Collect data in the field; consult existing information; update data in real time via their smartphone.

The application can be used even without a connection in areas without a network. A buffer will preload the exploration area, and the data will be updated automatically as soon as a connection is available again.

Hydraulic module for the observation of underground karst networks (under design).

We will develop a module for the collection, analysis and monitoring of hydraulic data from underground karst groundwater systems, intended for speleologists as well as professionals and researchers.

This database will collect data relating to groundwater, levels, flow rates, multi-parameter probes, tracing, precipitation, etc. It will be supplemented by analysis and visualization applications, interactive graphs and dashboards, and alert systems.

Built as an extension of Karsteau and its physical measurement module, it will allow exchanges following the KarstLink standards, will allow secure sharing of data between researchers, managers and federations, as well as long-term monitoring to identify trends, anomalies, and developments related to climate change.

Acknowledgments

We warmly thank the federation for its support, the development teams of Karsteau, POK, the Setanso company for the Bio module, the semantics experts and their students for the prototype of the Physical Measurements module, the scientific commission of the FFS for their collaboration and their feedback.

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Devil´s Cave: Beauties and Secrets of São Paulo's Most Famous Cave

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Abstract

The Caverna do Diabo State Park, created in 2008, covers over 40,000 hectares and spans the municipalities of Barra do Turvo, Cajati, Eldorado, and Iporanga, attracting many visitors year-round. Its main attraction, the Caverna do Diabo, has over 8,000 meters of development, of which 800 meters are open to the public. Due to its historical, scenic, educational, social, and environmental significance, it is considered one of the most important caves in Brazil. In 2024, with the support of the Forest Foundation of the State of São Paulo and the Union of Paulista Speleologists, expeditions began to create images for the publication of a book, aimed at serving as a support material for guides and tourists. This project aims to present and share the in-situ experiences encountered during the systematic photographic survey of the cave's iconic chambers, highlighting the techniques used and the logistical challenges overcome to achieve an "state-of-the-art" quality standard. By revealing the beauty and secrets of São Paulo's most famous cave, this project becomes a powerful tool for raising awareness and valuing the preservation of Brazil's speleological heritage.

Resumo

O Parque Estadual da Caverna do Diabo, criado em 2008, ocupa uma área de mais de 40.000 hectares e abrange os municípios de Barra do Turvo, Cajati, Eldorado e Iporanga, sendo uma das maiores atrações turísticas da região. Seu principal atrativo, a Caverna do Diabo, possui mais de 8.000 metros de desenvolvimento, dos quais 800 metros estão abertos ao público. Por sua relevância histórica, cênica, educativa, social e ambiental, a caverna é considerada uma das mais importantes do Brasil. Em 2024, com o apoio da Fundação Florestal do Estado de São Paulo e da União Paulista de Espeleólogos, iniciaram-se as incursões para a elaboração de imagens que servirão como base para a publicação de um livro. O objetivo desse projeto é criar um material de apoio para guias turísticos e visitantes, proporcionando um registro técnico e visual das belezas subterrâneas. Este trabalho busca apresentar e divulgar as experiências vividas durante o levantamento fotográfico sistemático de salões icônicos da caverna, destacando as técnicas utilizadas e as dificuldades logísticas superadas para alcançar um padrão de qualidade "estado da arte". Ao revelar os segredos e encantos da caverna mais famosa de São Paulo, o projeto se torna uma ferramenta poderosa para a conscientização e valorização da preservação do patrimônio espeleológico brasileiro.

Resumen

El Parque Estatal de la Cueva del Diablo, ubicado en São Paulo, es un tesoro natural que combina belleza escénica con importancia histórica y científica. Creado en 2008, el parque ocupa una vasta área y está situado entre los municipios de Barra do Turvo, Cajati, Eldorado e Iporanga. La Cueva del Diablo, con sus impresionantes 8.000 metros de extensión, se destaca como la principal atracción del parque, con 800 metros abiertos al público para su visita. Este proyecto de levantamiento fotográfico, iniciado en 2024, es una iniciativa fantástica para registrar las bellezas subterráneas de la cueva, proporcionando un material valioso tanto para el público general como para los profesionales del área de espeleología. La colaboración con la Fundación Forestal del Estado de São Paulo y la Unión Paulista de Espeleólogos es esencial para garantizar que las imágenes capturadas cumplan con un estándar técnico elevado, ayudando en la divulgación y valorización de este patrimonio natural.

El desarrollo del libro, con el registro de las experiencias vividas durante las incursiones y la superación de las dificultades logísticas para alcanzar el "estado del arte" en la fotografía espeleológica, tiene un gran potencial educativo. No solo ofrecerá un contenido valioso para turistas y espeleólogos, sino que también contribuirá a la concientización sobre la importancia de la preservación de las cavernas y otros ambientes naturales. La Cueva del Diablo, con su ecosistema único, es un claro ejemplo de cómo el turismo y la conservación ambiental pueden ir de la mano, siempre que haya un esfuerzo continuo de estudio, valorización y educación sobre la preservación de los patrimonios naturales.

1. Introduction

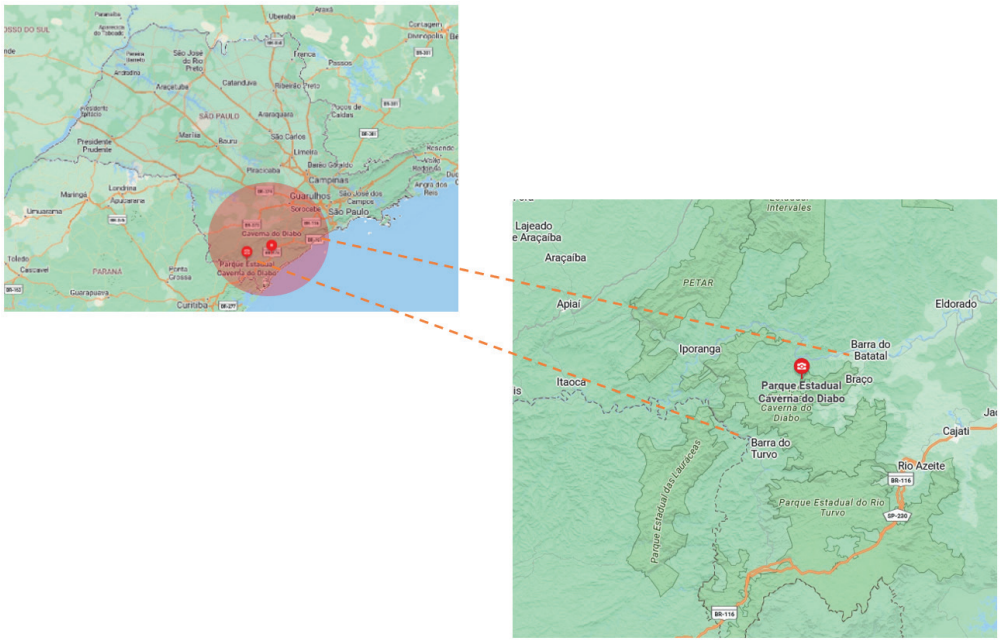
a. Context and Justification

Photobooks about caves in Brazil generally do not focus on a single cave, exploring it individually to allow for a detailed and in-depth understanding of its scenic beauty, geological and biological importance, exploration challenges, as well as its historical and anthropological aspects. Therefore, the production of the book "*Caverna do Diabo: Beauties and Secrets of São Paulo's Most Famous Cave*" is justified by the originality of the work and the relevance of publicizing this important Brazilian speleological heritage. The book, which is both contemplative and informative in nature, will provide content of interest to casual visitors as well as guides and speleologists, who will find educational material and support for their activities.

b. The Caverna do Diabo State Park, SP

Protected Areas (PAs) are territorial and marine spaces with natural and/or cultural attributes of special relevance for the conservation, preservation, and sustainable use of their resources, playing a crucial role in maintaining biological diversity. Created in 2008, the park is part of the Jacupiranga Conservation Mosaic, along with 13 other units. It spans over 40,000 hectares across the municipalities of Barra do Turvo, Cajati, Eldorado, and Iporanga. The park's main attraction is the Caverna do Diabo, one of the largest caves in the state, with more than 8,000 meters of extension. The park also features trails and waterfalls, offering visitors moments of leisure, adventure, and relaxation..

The Caverna do Diabo State Park was originally part of the older Jacupiranga State Park, created in 1969. It was divided in 2008, resulting in the creation of the Rio Turvo and Lagamar de Cananeia parks, along with other units, forming the Jacupiranga Conservation Mosaic. The Caverna do Diabo has been publicly known since 1891. The park sees significant visitation at the national level, with nearly 34,000 people either visiting for the first time or returning annually to explore the cave and its various attractions.



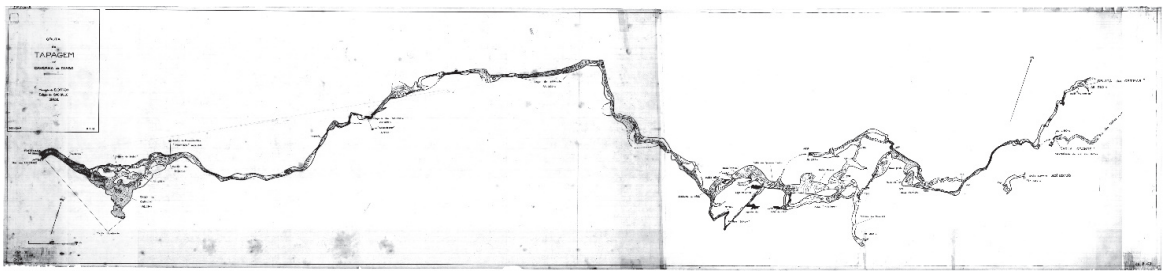
Maps 1 and 2: *Location of conservation mosaics in southern São Paulo State. (source: @2023 tomtom).*

c. The Caverna do Diabo

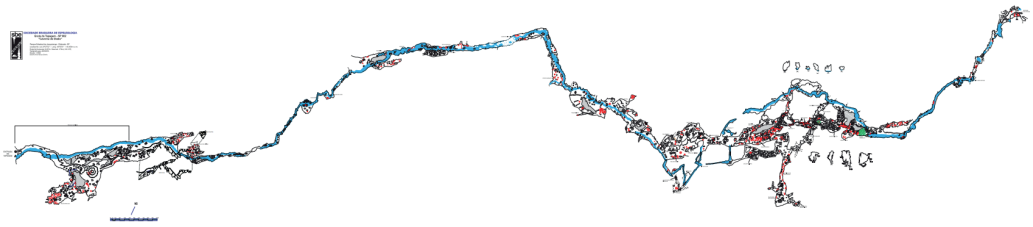
Since the 19th century, the Caverna do Diabo was known to local residents, who referred to it as Gruta da Tapagem. The first exploration was carried out by agronomist Lourenço Granato in 1901. Since then, the site has drawn the attention of explorers and speleological groups. The first documented systematic exploration is attributed to Colonel Rodolpho Pettená. Later, the Aranhas and Clube Alpino Paulista groups, in 1964, conducted the first topographic survey, with a notable contribution from Michel Le Bret. In the same year, they made the first crossing between what was then called Gruta da Tapagem and the Ostras resurgence, a significant achievement in the speleological field at the time.

In 1967, the SEE (Excursionist and Speleological Society) from Ouro Preto (MG) conducted biospeleological and geological studies, producing a new topography and establishing the cave as the largest in Brazil at that time, with a length of 2,850 meters. In the 1990s, the SBE (Brazilian Speleological Society) initiated the ProCad (Caverna do Diabo Project), aiming to promote the integration of groups and produce a new map of the cave. In the 2000s, systematic studies and surveys were carried out to create the Management Plan, which is still in effect.

With more than 8,760 meters of horizontal projection and a 175-meter known vertical drop, according to the latest mapping, the Caverna do Diabo is the longest cave in São Paulo State. It is also notable for the quantity and variety of speleothems and the volume of some of its chambers. The river gallery, extensive and interspersed with waterfalls and swimming sections, presents a unique challenge due to both the volume of water and the low temperatures.



Map 3: *Map of the Caverna do Diabo, SP - 1964 (source: Clube Alpino Paulista).*



Map 4: *Map of the Caverna do Diabo, SP (source: Brazilian Speleological Society).*

2. Materials and Methods

The photographic documentation of caves has been constantly evolving, keeping pace with technological advancements in both image capture and lighting, as well as post-processing. With the improvement of sensors and lenses, it is now possible to document large chambers and intricate details of speleothems with greater accuracy, revealing forms and nuances that were previously hidden.

For image capture, a Nikon D800 camera was used, equipped with two wide-angle lenses: an AF-S Nikkor 14-24mm f/2.8G ED and an AF-S Nikkor 24-70mm f/2.8G ED, both with a maximum aperture of f/2.8, as well as a Nikkor macro 1:1 lens, also with an aperture of f/2.8, for close--up details. These lenses were chosen for their ability to capture both expansive underground scenes and intricate details with high definition.

The lighting system consisted of three Godox V860 II (N) flashes, with a guide number of 197, one Godox AD200 flash, with a guide number of 60, one Godox AD360 flash, with a guide number of 80, and one Godox AD600 flash, with a guide number of 87. All flashes were remotely triggered using Godox X-Pro 2 radio transmitters, allowing precise control of the lighting during photographic sessions in challenging environments with difficult access and lighting conditions.

Post-processing of the images was carried out using Adobe Photoshop, where color corrections, exposure adjustments, and compositional techniques were applied to optimize the visibility of speleological details.

3. Results

The photographic documentation revealed a high level of detail and clarity in the cave formations, with the use of advanced equipment allowing for the capture of previously hidden features. The combination of the Nikon D800 camera and the selected lenses provided sharp and accurate representations of both wide chambers and intricate speleothems.

The lighting system, composed of multiple Godox flashes, was effective in ensuring even and controlled illumination throughout the caves, overcoming the challenges posed by the low-light environment. The remote triggering system allowed for precise control of the light distribution, enhancing the visual clarity of the cave structures.

Post-processing in Adobe Photoshop enabled further enhancement of the images, adjusting for exposure discrepancies and fine-tuning color balance to highlight the nuances of the formations. The final images show the caves in a level of detail that is both scientifically valuable and visually striking.

4. Conclusions

The Caverna do Diabo, with its immense speleological and historical significance, is one of Brazil's greatest natural treasures. The photographic documentation project carried out in this study not only reveals the grandeur of its chambers and the diversity of its speleothems, but also showcases the technical and logistical challenges overcome to capture high-quality images. The resulting images, enhanced through advanced capture and

processing techniques, will serve as a valuable resource for educating visitors, guides, and researchers, as well as raising awareness about the preservation of speleological heritage. Thus, the project contributes to the appreciation and protection of Caverna do Diabo and other similar natural sites.

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Use of a cell-phone based 3D scanning app and 3D printing as resources for speleology in Bahia, Brazil

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Abstract

As 3D scanning technologies become more portable and accessible, they present as a promising alternative for any speleologist to perform cave representations. We tested the use of the Polycam smartphone application to represent caves and shelters in three locations in the municipality of São Desidério (BA, Brazil). The digitization of shelters with cave paintings, in well-lit outdoor contexts, was successful. Narrower conduits and smaller caves also had good results, when compared to the available maps. However, more distant walls and higher ceilings, over 5 m away, were not able to be detected, in a capture mode dependent on the device's LiDAR sensor. Even so, the results that were possible to obtain, associated with 3D printing, can generate educational applications, and improve traditional mapping.

Resumo

Utilização de um aplicativo de escaneamento tridimensional para celular e impressão 3D como recursos para a Espeleologia na Bahia, Brasil. Conforme as tecnologias para escaneamento tridimensional se tornam mais portáveis e acessíveis, elas se apresentam como uma alternativa promissora para qualquer espeleólogo executar representações de cavernas. Testamos o uso do aplicativo para smartphone Polycam para representar cavernas e abrigos em três localidades do município de São Desidério (BA). A digitalização de abrigos com pinturas rupestres, em contextos exteriores e bem iluminados, foram bem sucedidos. Condutos mais estreitos e cavernas menores também tiveram bons resultados, quando compados aos mapas disponíveis. Entretanto, paredes mais distantes e tetos mais altos, acima de 5m de distância, não foram capazes de ser detectados, em um modo de captura dependente do sensor LiDAR do aparelho. Ainda assim, os resultados que foram possíveis de obter, associados a impressão 3D, podem gerar aplicações didáticas, e aprimorar mapeamentos tradicionais.

Résumé

Utilisation d'une application de numérisation tridimensionnelle pour téléphones portables et d'impression 3D comme ressources pour la spéléologie à Bahia, au Brésil. À mesure que les technologies de numérisation 3D deviennent plus portables et abordables, elles présentent une alternative prometteuse pour tout spéléologue souhaitant réaliser des représentations de grottes. Nous avons testé l'utilisation de l'application pour smartphone Polycam pour représenter des grottes et des abris dans trois endroits de la municipalité de São Desidério (BA, Brésil). La numérisation d'abris avec des peintures rupestres, dans des contextes extérieurs et bien éclairés, a été un succès. Les conduits plus étroits et les grottes plus petites ont également donné de bons résultats par rapport aux cartes disponibles. Cependant, les murs plus éloignés et les plafonds plus hauts, à plus de 5 m de distance, n'ont pas pu être détectés, dans un mode de capture dépendant du capteur LiDAR de l'appareil. Cependant, les résultats qu'il a été possible d'obtenir, associés à l'impression 3D, peuvent générer des applications pédagogiques et améliorer les cartographies traditionnelles.

1. Introduction

Cave mapping is a fundamental activity in Speleology, not only allowing us to better understand a cavity in terms of its dimensions and morphology, but also serving as a basis for various related works. Topographic techniques using compasses, clinometers, tape measures and sketches have become traditional, serving the majority of cases, although difficulties arise in their use, from situations in abysses or flooded caves, to the mapping of cavities in ferruginous rocks, where compasses could prove useless.

The advent of three-dimensional digital scanning technologies would soon prove to be an interesting alternative for cavers to represent caves, although such equipment was initially unusual, expensive, bulky and sensitive to the environmental conditions found underground, as well as being in many cases inaccurate in relation to irregular terrain or low light. However, the development of technologies and the popularization of 3D scanning have produced increasingly cheaper, portable and accessible alternatives for the general population, including the speleological community and their related areas of expertise (see TSAKIRI et al., 2007; RÜTHER et al., 2009; LERMA et al., 2010; CHANDELIER & ROCHE, 2014; GALLAY et al., 2015; IDREES & PRADHAN, 2016; DE WAELE et at., 2018; Triantafyllou et al., 2019; PFEIFFER et al., 2022; KHOMCHAN & TADSUDA, 2024).

To test a mobile-based scanning tool available for smartphones and explore its potential in Speleology, we attempted to scan shelters and passages in three locations in the municipality of São Desidério, in the western Brazilian state of Bahia. From the data collected, we also 3D printed selected areas for educational purposes.

2. Materials and methods

The municipality of São Desidério has a karst landscape developed in Neoproterozoic carbonate rocks, with hundreds of recognized cavities (see Rubbioli et al., 2019). Searching for caves and easily accessible areas, with different situations to test a three-dimensional scanning, we chose three previously known locations in this municipality, Tapuias' Hill, Lagoa Azul Municipal Park and the village of Beleza.

São Desidério can be accessed from the capital of Bahia, Salvador, via BR-242, or via BR-020 if departing from Brasília (DF), and then accessing BA-463. From the urban center of São Desidério, to reach the sites in Tapuias' Hill and the Lagoa Azul Park, access is via BR-135, which in this section is characterized by na unpaved road, generally in good conditions. The areas are located 5 and 16 km, respectively, from the municipal headquarters. The village of Beleza is accessed via an unpaved local road, and is located 18 km from the center of São Desidério.

At Morro dos Tapuias, two features would be the target of scanning: a shelter with cave paintings and engravings on blocks, in a well-lit area, and a cave, the Gruta Morro dos Tapuias. With a total length of 417 m and a 31 m vertical range, the initial portion of this cavity has two entrances joining in a relatively wide chamber, with a main linear passage extending almost 90 m to WSW, with a width of more than 5 m and slightly trapezoidal sections. After about 30 m in this passage, it connects to another, almost parallel and smaller, to the south, presenting abundant concentrations of guano on the floor. Aphotic zones can be observed in the final passages of the cave, which are also narrower.

In Lagoa Azul Park, we selected two caves that are part of the tourist itinerary for this location: Grutinha da Onça and Gruta do Catão. The first is a small cave, about 25 m long and 7 m in depth, in an U-shaped passage in plan view. The second is a larger cave, a highlight of the park, with 160 m of length in a linear conduit in NE-SW direction, that basically crosses a massif from one side to the other. A river runs along the cave, in a passage that is usually over 50 m wide, with a ceiling at elevations of around 10 m, except at the entrances, where much higher heights can be reached. Because the cave basically develops like a tunnel with wide entrances, it has few aphotic regions, but the luminosity can be quite reduced at its midpoint.

In the last location, the village of Beleza, we have an archaeological site (Seu Camé) with cave paintings in shelters and a cave, the Grutão da Beleza, a cavity that develops to the south of a large sheltered area, divided into two passages to the east, on different levels. The smaller, upper passage is often referred by visitors as a separate cave, the "Grutinha" da Beleza (the "small grotto"), with a length of around 40 m. The larger, lower passage develops for around 130 m, wider than 15 m in most of its length.

We searched for maps of all selected caves to compare with the scanning results, but we could not find a previous map for Grutinha da Onça. The Bambuí Speleological Research Group kindly provided maps of Gruta Morro dos Tapuias and Gruta do Catão. We used a map of Grutão da Beleza prepared by the extinct Morcegos do Cerrado EspeleoGrupo (MorCEg), currently owned by the Federal University of Western Bahia (UFOB). Maps of the archaeological sites of Seu Camé were available from LEÃO (2019).

The application used to obtain the three-dimensional data was Polycam, version 4.0.10, on an iPhone 14 Pro Max. This app was used in its free trial version, with some limitations when compared to the paid version. We tested the acquisition modes based on photogrammetry and the camera's LiDAR sensor (available on modern iOS devices, from the iPhone 12 Pro onwards).

The scanning was performed using random walks, always performed by the same person, seeking coverage of the main elements, especially on the floor and walls up to a height of 1 m, to allow at least comparison with the floor plans of the pre-existing mappings. The application informs the user if he is traveling through areas too quickly, and in the acquisition mode by the LiDAR sensor, if it has already collected data from a particular area. In the case of areas with low natural light, an LED light source for video recordings was held next to the phone, to illuminate the area captured by in front of the camera.

In Grutinha da Onça, Gruta do Catão and Gruta Morro dos Tapuias, measurements of the main speleometry data were taken, with a survey team reduced to one instrument reader, one lead tape person and one spreadsheet/sketcher, using a tape measure and Brunton geological pocket transit, allowing the speed of traditional data acquisition to be compared with the scanning.

For three-dimensional printing, the files were saved in GLB format and edited in the softwares 3D Builder version 20.0.4.0 from Microsoft Corporation (part of the Windows accessories) and Blender version 4.3.2, an open source software.

The files were printed on Creality 3D printers, Ender 5, Ender 7 or CR-10 Smart models. The prints made so far used PLA filament, which has temperature limitations. The files were sliced for printing in the UltiMaker Cura program version 5.8.1, using standard quality with 0.2mm layers, with a 4% quarter cubic filling.

3. Results

The scanning was carried out over three field days, one in each pre-selected area. At Tapuias' Hill, the scanning of the rock painting wall went smoothly, using only natural lighting. However, the scanning in the cave had problems. In the initial portions, the high ceiling was often too far away for the phone's LiDAR sensors to capture (above 5 meters); therefore, we focused on scanning only the floor and walls, up to about 1 m in heights. In addition, the volume of data during the scanning of the entrance hall led to a crash in the application, which did not generate a model (only confirmed after the field). We separated the main passage and its parallel passage into two other independent scanning stages, so as to not overload the camera's processing, but we anticipated difficulties in joining these sections accurately later.

In Lagoa Azul Park, we scanned Grutinha da Onça in a single step (Figure 1). However, in Gruta do Catão, whose floors were very homogeneous and often poorly lit (even with LED lighting), the app had difficulties again, failing to capture the model. In all previous cases, we had always used the LiDAR sensor capture mode, but we decided to test the photogrammetry capture mode, since we already knew that the sensor would not be able to capture details at the ceiling distances that Gruta do Catão presented, especially on the amphitheater-shaped wall that developed above the cave entrance. None of the attempts with the photogrammetry mode were successful, resulting in major failures in the application's attempts to identify the superposition of surfaces correctly.

Finally, in the village of Beleza, the scanning of the shelter at the archaeological site was once again successful (Figure 2). It was also possible to capture the upper passage, the "Grutinha" da Beleza, but

once again the attempt to scan the larger passages interrupted the processing and failed to acquire the scans.

In cases where the acquisition was successful, after waiting for the data to be processed, it is still possible to observe the results in the field. However, the entire acquisition consumes a lot of energy from the phone's battery, and in some situations, we leave the processing for a later time, already outside the locations.

In the generated models, the limitations of the application can be seen in many details, even in slightly larger columns. A wooden staircase in the descending passage of Grutinha da Onça came out incomplete, and the application also had difficulty in reconstructing tree trunks and undergrowth. Obviously, speleothems and smaller blocks are poorly represented in relief, and the superimposition of colored photos on the digital models only helps a little in the identification of such features.

Still, the scan represented well the general morphology of the narrower passages, that allowed to approach walls less than 3 m away. This also enable the printing of passages of the Gruta Morro dos Tapuias and "Grutinha" da Beleza. Figure 3 shows the comparison between the scan of the latter, the 3D printing of the passage section and the plan view obtained by traditional mapping with BCRA 4C accuracy.

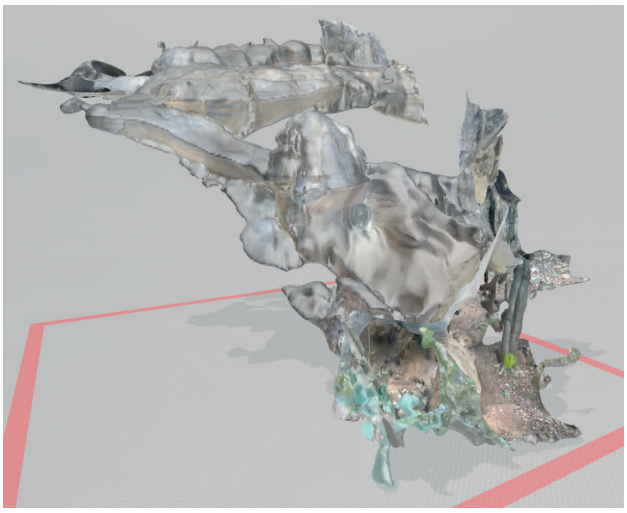

Figure 1: *Three-dimensional model for the Grutinha da Onça, in the Lagoa Azul Municipal Park, in near lateral (longitudinal) view.*

Figure 2 *Three-dimensional model for the shelter with cave paintings at Seu Camé's archaeological site, in the village of Beleza.*

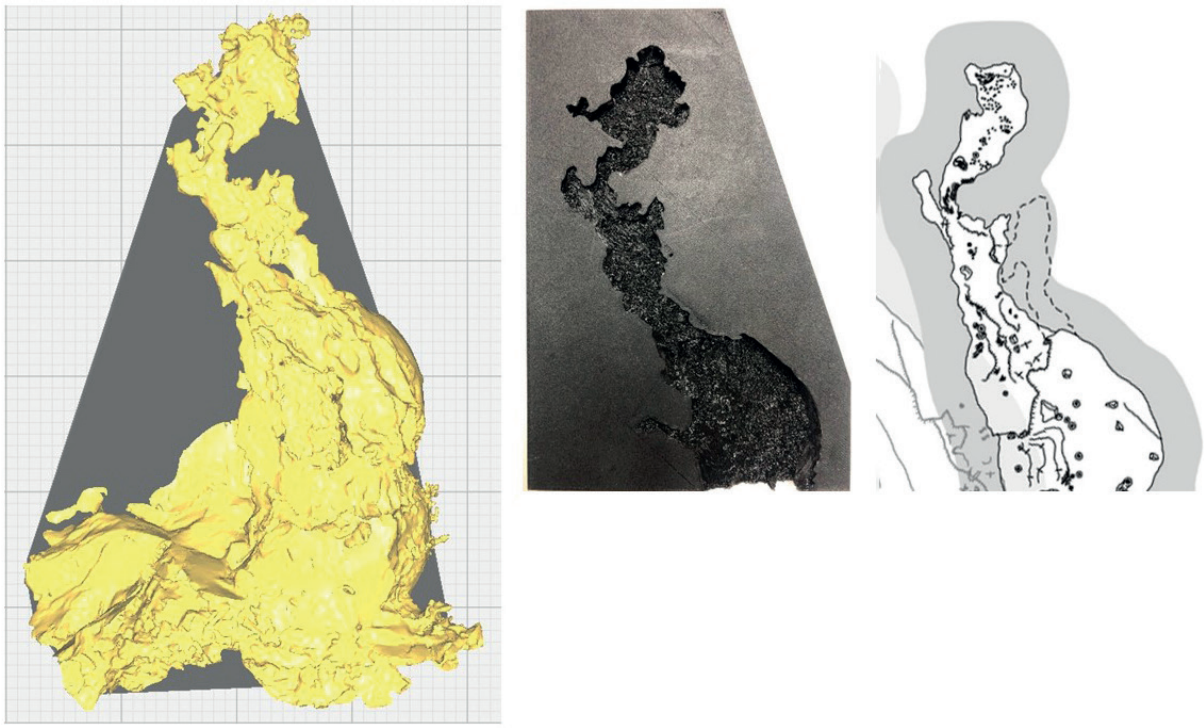

Figure 3: *Comparison between the three-dimensional scan of the "Grutinha" da Beleza, three-dimensional print of a subhorizontal section at a scale of 1:200 and the corresponding part of the floor plan of the MorCEg's cave map.*

4. Discussion

The level of detail, coverage and accuracy was considerably better in the external shelters than in the caves, but even if the results are not excellent, they can fulfill several roles. Still, the results for narrower passages and smaller cavities seem quite satisfactory, when compared to the available maps, and may even help in improving them.

Three-dimensional scanning allowed the visualization and appreciation of features that could go unnoticed in traditional mapping. In Grutinha da Onça, for example, a dome-like configuration is noticeable in its descending passage, in addition to different levels of vadose stabilization.

The problems with scanning larger passages are not related to lighting issues, since the entrance to the Catão and Morro dos Tapuias caves are well lit. This is partly a limitation of the LiDAR sensor itself, but it could at least be compensated for by photogrammetry capture. Even so, this also yielded unacceptable results. The application may not have the same processing capacity for irregular and natural environments as it would have for urban spaces and artificial interiors, but the photogrammetric reconstruction was probably hampered by the impossibility of going around the walls, an issue that is an obstacle for most cave scenarios, and by the limited number of photographs that the free version tested allowed.

In addition to the distance to the walls being a limiting factor for the type of conduit that can be acquired, a lack of contrast in poorly lit and homogeneous scenarios also appears to have been the case. This was observed on the floors of both the Gruta do Catão and the Grutão da Beleza.

It is important to keep in mind that this type of scanning requires a person to walk across a large area of the cave floor, increasing trampling of the substrate and potentially putting at risk delicate features that cavers would normally avoid approaching. We advocate prioritizing the conservation of the cave and its mineral, biological, paleontological, and archaeological aspects, among others. It is better to fill a scanning gap virtually in post-processing than to sacrifice some aspect of the actual cave.

Problems with this type of scanning can also include maintaining a relatively slow pace for the acquisition to be effective, but it was still as fast as the surveying of the measurements, in a reduced surveying team. Since the team was not being slowed by sketching, it is easy to point out that the scanning, even at its slow pace, was faster than traditional mapping.

Nowadays, digital devices, particularly smartphones, are almost ubiquitous, and together with the possibility of uploading digital model data to the Internet, it is possible to view the 3D files almost anywhere. Even so, printed models can be used as an alternative when digital files are impractical. Of particular importance is accessibility for people with disabilities, such as blindness and low vision. Using software, it is possible to cut the model and explain concepts such as linear development and longitudinal and transversal sections, as a tool for teaching cave mapping. The typical layering of filament prints at lower resolutions can be used to advantage, to show the concept of contour lines.

5. Conclusion

Despite the limitations of the cave scanning tested here with Polycam, the promise of increasingly affordable technology may seem to indicate the end of traditional cave mapping in the near future. But we do not think that is the case yet. At the moment, this application still seems to be intended to complement and even improve the maps already made, and not to replace them entirely.

The potential of using 3D printing for models in pedagogical alternatives has only been superficially explored. The models can even be produced commercially, to complement kits for Geomorphology classes and science fairs. The popularization and availability of data like this, aided by the internet, can help promote not only the caves of a certain region, but Speleology as a whole.

Acknowledgments

We gratefully thank Robson Soares BRASILEIRO for the help during our field expeditions, the Tourism Secretary of the Municipality of São Desidério for facilitating access to the Lagoa Azul Municipal Park, and the Quitanda Lab, in the person of Kleymilson do Nascimento SOUZA, for access to the 3D printing facilities.

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Recent speleological exploration in Xiaonanhai karst area, Shaanxi Province, China

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Abstract

In total, 8,624 m of new cave spaces were discovered and documented during the Shaanxi 2023 and 2024 expeditions in Central China. 1,530 m of new spaces were discovered in the Tianxingyan Cave, bringing its length to 14,347 m. In the Boniukeng Cave, 1,620 m were discovered to reach a new length of 4,319 m and a depth of 488 m. The interconnection of the two caves has not been found yet. The Boniukeng Cave, in particular, with its dozens of vertical steps and horizontal traverses, water passages and a considerable total length, is undoubtedly an extreme cave whose further exploration will be conditioned by setting up an underground bivouac and a redesign of a number of anchoring sites to make passage better accessible and safer. A significant progress was achieved also in the Heiwodong Cave, where 2,398 m of new passages were explored and mapped, so the cave is now 3,631 m long and 419 m deep. Also a new cave named Taipingdong was documented and mapped and it is now 1,246 m long and 254 m deep. Exploration started also in several new abysses and caves, where first hundreds of meters was discovered.

1. Introduction - Shaanxi project

Between 2016 and 2019, six expeditions were held under the common name of "Shaanxi Project". The aim of this Czech-Chinese speleological project is the exploration and documentation of karst areas in Shaanxi Province (Central China). The project is organized by Czech Speleological Society and the Geological Institute of the Czech Academy of Sciences in cooperation with the Institute of Karst Geology of the Chinese Academy of Geological Sciences, and in a very valuable support from the Shaanxi Geological Survey. The main interest of this project is focused on the Xiaonanhai area (Nanzheng County south of Hanzhong). This area consists mainly of a north to northeast sloping limestone plateau Daya Mountain. To the north and east, the plateau is bordered by a wild mountainous karst landscape with deep valleys and canyons. There are dozens of tiankengs, sinkholes and chasms. The history of exploration in this area, as well as more detailed information on the geological background and - above all - the speleological results (until 2022) and the scientific potential of the whole area are presented by Filippi et al. (2022). The purpose of the here presented brief contribution is to report on the new results of the 2023 and 2024 expeditions, organized after 4-year gap occurred by Covid 19 global pandemic.

Otherwise, ongoing results, including cave maps, are presented annually in the magazine Speleofórum (see e.g., Motyčka and Filippi 2024).

2. Tianxingyan and Boniukeng caves

More than 19 caves have been discovered and explored in the Xiaonanhai area but two of them are the most important on Daya Plateau - the Tianxingyan (Sky Star) and Boniukeng caves. During the Shaanxi 2023 expedition, a new progress has been made in the Tianxingyan Cave where 1,530 m of new spaces was discovered and in the Boniukeng Cave where 1,620 m of new spaces discovered. (Fig.1) Unfortunately, the interconnection of these two caves has not been found yet. Final parts of the Tianxingyan Cave are represented by a siphon at the end of the Streaky Hall (Fig. 3) and by an inaccessibly narrow passage at the end of the Final Corridor. Final parts of the Boniukeng Cave are represented by a huge rock collapse called the Big Collapse and two drain corridors (the Missing Siphon and an unnamed passage trending to north-east). Reaching the final parts of both caves is very time-consuming. In almost 15 km long Tianxingyan Cave, one first have to surpass steps with rope techniques, then long free climbing and wading in a difficult terrain and also cross twice the flooded sections. With an elevation of almost 500 m, the Boniukeng Cave is a very difficult cave overall, with many pitches, waterfalls, and pools at the bottoms of high corridors. Future exploration in both these caves will be very difficult, and a second bivouac needs to be built in the Tianxingyan Cave and bivouac is already needed also in the Boniukeng Cave.

Figure 1: *Large and nicely colored Streaky Hall – space above the Final Siphon, Tianxingyan Cave, Shaanxi Province, China. Photo by M. Filippi.*

Figure 2: *The Final Siphon in the Streaky Hall, Tianxingyan Cave, Shaanxi, China. Photo by J. Sirotek.*

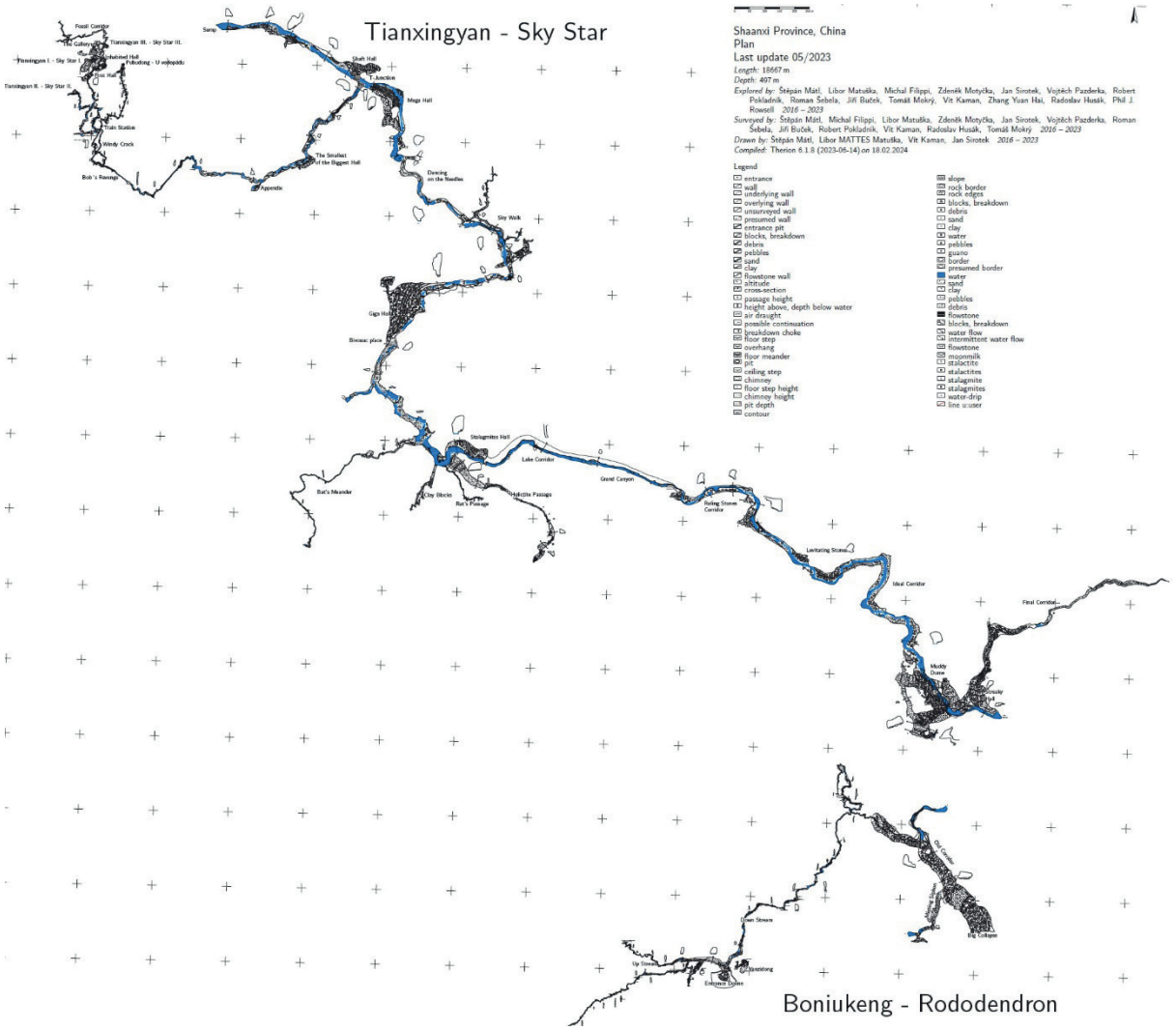

Figure 3: *Maps of the Tianxingyan and Boniukeng caves – their mutual position, Shaanxi Province, China.*

3. Heiwodong Cave

Heiwodong Cave was discovered in 2018, reaching a length of 1,233 m and a depth of -168 m. Due to other priorities, exploration was stopped until 2023, when only 130 m was discovered due to high water levels. Progress in the Heiwodong Cave was significant only in 2024, when The Well shaft was descended and large horizontal passages were discovered (Fig. 4).

4. Scientific value

During all expeditions, interesting geological phenomena are documented - mainly speleothems and also cave sediments. Most classical forms of speleothems are various

flowstones, draperies, soda straws, coralloids, helictites or cave pearls (see example on figure 7). The speleothems are usually concentrated to fossil levels of cave passages. Vast majority of speleothems are formed by calcite, but locally gypsum is common mostly growing from fine sediments on cave bottoms. Much less common are fine crystalline crusts of whitish to yellowish calcite together with whitish to pale-blue ball-like aggregates of celestite (SrSO4).

In total, 2,398 m of new passages, shafts and cave halls were discovered. After reaching the last accessible point, the cave is now 3,631 m long and -419 m deep (Fig. 5). Several new caves and abysses were discovered on the Daya Plateau. The Taipingdong (1,246 m long and -254 m deep), the Huoshigou (592 m long and -149 m deep) are the longest caves and the continuation is still promising (Fig. 6.)

These are formed along networks of fractures and on rock edges in two cave halls at the end of the Helictite Passage in the Tianxingyan Cave. Manganese and/or iron oxyhydroxides covering both clasts and speleothems are locally common in some caves. Especially in some parts of the Tianxingyan Cave, clay and silt sediments (i.e. “mud deposits”) represent a very interesting phenomena. Water action gives rise to formations like dripholes with conulites (i.e. cone-shaped deposits lining the walls of the holes/mud funnels), ripple marks, “mud speleothems” formed due to splashing and down-flowing water, etc.

In addition to mineralogy, the entrances of the caves are particularly interesting for their paleontological potential. The cave entrances and deep valleys with steep walls served as traps for animals. The most interesting find was made in a small fossil corridor near the entrance to Tianxingyan Cave.

Along with other bones of several animals, well-preserved teeth of the prehistoric elephant Stegodon orientalis were

found here (Filippi et al. 2022). With targeted research, further finds are likely to be found here and in other caves.

Figure 4: *Huge corridor in the Heiwodong Cave, Shaanxi Province, China. Photo by R. Husák.*

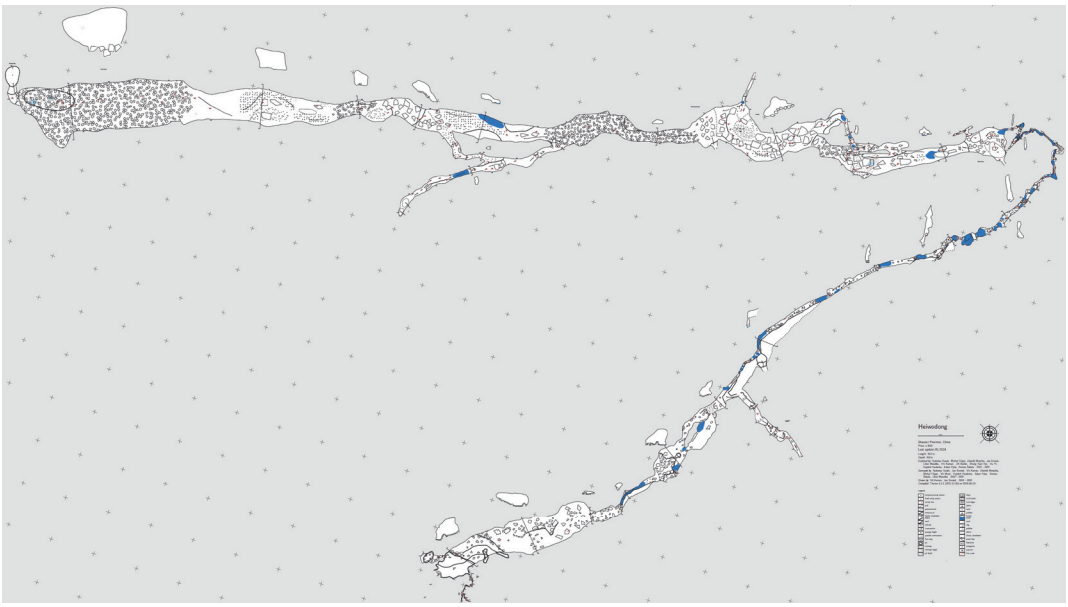

Figure 5: *The map of the Heiwodong Cave, Shaanxi Province, China.*

Figure 6: *Entrance part of the Taipingdong Cave, Shaanxi Province, China. Photo by R. Husák.*

Figure 7: *Over 0,5 m high and over 4 m wide sinter formation on the bottom of the Hall of Three Rivers in the Heiwodong Cave, Shaanxi Province, China. Photo by M. Filippi.*

5. Conclusion and future perspectives

A total of 8,624 m of new cave space was discovered and documented during the Shaanxi 2023 and 2024 expeditions. 1,530 m of new space was discovered in Tianxingyan Cave, making this cave now 14,347 m long and remaining the longest cave in the area. In Boniukeng Cave, 1,620 m was discovered and the cave reaches a new length of 4,319 m and a depth of -488 m, which means it is the deepest cave in the area. In Heiwodong Cave, 2,398 m of new passages was discovered, explored and mapped, so the cave is now 3,631 m long and -419 m deep. The Heiwodong Cave is the longest cave, situated outside the Daya Plateau. In total, 39,150 m of cave passages was discovered during eight Shaanxi expeditions organized between 2016 and 2024.

Exploration and research in the Xiaonanhai karst area near Hanzhong (Nanzheng County) will continue. Based on Hong et al. (2019), this area is now the northernmost occurrence of large karst features in China and provides a high potential for the significant speleological and scientific discoveries. The Xiaonanhai karst area represents a mature cave system that reflects the orogenic history of the area. Main direction of groundwater drainage is facing towards the West to the Guanyin Temple, Baishuidong and Longwangmiaodong resurgences. The caves here may extend for tens of kilometres and numerous large underground chambers and deep shafts are expected. However, as we can see in the caves, and also based on surface morphology, the eastern and north eastern parts of the area are affected by significant tectonic features, which causes large damage of underground spaces and make further progress difficult.

Acknowledgments

We wish to thank our colleagues from the Institute of Karst Geology of the Chinese Academy of Sciences and mainly to colleagues from the Shaanxi Institute of Geological Survey for their great support and cooperation. Of course, all other the members of the expedition (Jan Sirotek, Libor Matuška, Vojtěch Pazderka, Štěpán Mátl, Radek Husák, Adam Pyka, Vít Kaman, Vít Musil) also deserve thanks for their great work. The exploration of the karst is also carried out with the support of the Institute of Geology of the CAS (RVO 67985831).

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Tham Lô, Khammouane, Laos: exploration and characteristics

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Abstract

Tham Lô is a fossil cave with large passages and it is located high on the slopes of a polje. It shows two altimetric levels, that are each subhorizontal though they are separated by a 80 m deep slope with small pits. Mapping was started by the author in 2001 and it continued during several other exploration campaigns in Khammouane, up to almost a 8 km long development. There is a variety of speleothems, made up of calcite (flowstones, stalagmites, rimstones, bidirectional stalactite assemblages, capillary tubiforms…) and of a combination of mondmilch masses, crusts and bowls associated with gypsum crusts, also isolated gypsum flowers. Especially striking are "soft" flowstones and rimstones into which walking leaves footprints.

Résumé

Tham Lô au Khammouane, Laos : exploration et caractéristiques. Après sa découverte par des villageois, Tham Lô a été commencée de topographier en 2001 et, pour notre part, nous y sommes allés jusqu'en 2014. Cette grotte fossile de gros calibre est perchée bien au-dessus du poljé de ban Vieng, dont les versants la recoupent. Outre ses dimensions, elle est caractérisée par des spéléothèmes originaux, de calcite avec coulées, gours, rims, stalagmites subhorizontales, stalactites bidirectionnelles, tubes capillaires, et de mondmilch associé à du gypse, en masses, croûtes ou amas subsphériques. Il y a aussi des gours et coulées « mous » dans lequel le pied s'enfonce, etc. La grotte comporte deux niveaux altimétriques séparés par un plan incliné avec de petits puits totalisant un dénivelé de 80 m, avec un développement de type subhorizontal pour chacun d'eux. Les galeries principales suivent peu ou prou la direction des couches et les galeries transverses leur pendage.

1. Introduction

Tham Lô is a major fossil cave in the karst of Khammouane, Central Laos. It is located 35 km to the Northeast of Thakhek, the province head city.

Figure 1: Location of Tham Lô, 35 km to the NE of Thakhek.

It was spotted in 2001, during our 8th exploration campaign of this karst, out of the some thirty we performed there. This cave is lying in a hill which is part of a wide limestone massif, on the edge of a branch of the polje of Ban Vieng (Fig. 1). We learnt of it thanks to Ban Vieng and Ban Louang villagers, who had investigated a part of it one or two years before. Previously, it was hidden by virgin forest in the polje. Villagers claimed they had penetrated several hundred metres inside. Indeed, we asked them if they knew some cave that we were still unaware of and after more than a week, they informed us of their discovery.

This is how we started the exploration and topography simultaneously.

This paper presents the successive campaigns and the related discoveries. It must be said that during each campaign, we did not explore entirely a single cave but, instead, we were mapping parts of several. This is perhaps not the usual way, but our purpose was to understand the karst in the whole and what we were learning in a cave could be applied to another.

2. Successive investigations

In 2001, we learnt of the cave at the end of our campaign. First, the author went to the entrance with villagers who were carrying weapons, mainly guns, riffle and crossbows in order to deter any attack from some bandits in the forest. It was not as safe as nowadays. In 1997 to 1999, we were not allowed to go to the polje of Ban Vieng, because "we could have been mistaken for Americans". Was it the true reason? The question is still raised.

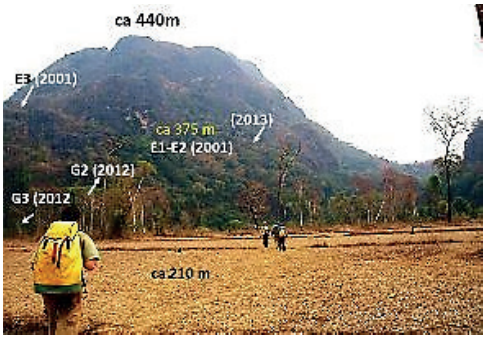

Figure 2: Location of the cave in the landscape (CM).

Figure 3: *The E1 entrance: the main passage is intersected by the hill slope, at a place with a reverse fault and associate folding. Note the high tree in the passage (CM).*

The author mapped the cave along the northern branch, from twin entrances E1 and E2 to a third entrance at the end of the cave. A several tens of metres deep pit, a blind smaller side branch and a narrow constriction of the otherwise large passage are present. Rims were discovered by the author downward of the main entrance, in a narrower part of the passage (Fig. 4). He also observed 1 m long subhorizontal stalagmites (or wallmites?) high along a wall in the other branch of the cave (Fig. 5), hence not accessible.

Figure 4: *Rims on the calcite floor around calcified boulders (CM).*

The southern branch is covered with boulders at the beginning. A hole in the ceiling makes up a fourth entrance. Going eastward (see cave map in Section 3), there are spectacular, though classical, calcite flowstones, rimstone dams and stalagmites. The side branch leads to an undescended shaft. See Section 4 below for the teams.

In 2002, the main passage was continued through a large chamber full of large boulders and often occupied by fog. The author noticed there the existence of rims cutting through these boulders. Beyond, the passage continues and different speleothems appear, with abundant moonmilk spread either as crusts with gypsum and as bowls (Fig. 6).

The main passage splits horizontally with a large left branch, unmapped, said by a participant having no continuation, and a narrower one (South Passage), which is cut through by oblique perpendicular galleries sloping to the North. There at the branching spot, starts also the way down to the lower level of the cave: a slope with a short shaft at each end

Figure 5: *Subhorizontal stalagmites pointing toward cave entrance, due to preferential evaporation therefore calcite deposition toward the light of Entrance E1. The tips are covered with some vegetation (CM).*

Figure 6: *Moonmilk and gypsum crusts and bowls (CM).*

The South Passage is significantly narrower. It shows vertical and also subhorizontal stalactites in opposite directions which indicate changes in cave wind. Moonmilk is almost absent.

Shaft 2, discovered in 2001, was estimated by two participants as being 200 m deep, which was virtually impossible, owing to regional context.

In 2004 (CREI bull n° 13, p. 61), two teams were made. A team mapped 600 to 700 m of passages in the lower level, but the map was kept secret by the mapper. Another team with a lot of ropes went downto the bottom of Shaft 3, which does not exceed much more than 40 m depth. The given explanation was that the feeling of great depth estimated in 2002 was due to sound reduction by moonmilk at the shaft bottom.

The author decided to investigate the so-called terminated large passage to the left. Indeed, after an ascending step and a surface full of low rimstone dams, a large depression could be easily crossed through and beyond… the passage was continuing, with a lot of wind. In the rising sloping passage, small tubiform speleothems are present on a wall and on the calcite floor. They vary in inclination from horizontal to rising obliquely and can be hollow as soda straws, or display an external shape rugged to a variable degree. Many are rather fragile, because of their nature, also because of their location, which is partly on the cave floor. At the top of the rising passage, there is a side passage toward the West. A quick look into it showed us a large fallen stalagmite with many pieces of charcoal from torches (Fig. 7).

Figure 7: *Charcoal from burnt sticks used as torches in the cave (CM).*

Then the main passage goes down and the long slope is covered with very unusual flowstones and rimstones (Fig. 8). Their specificity is that they are soft.

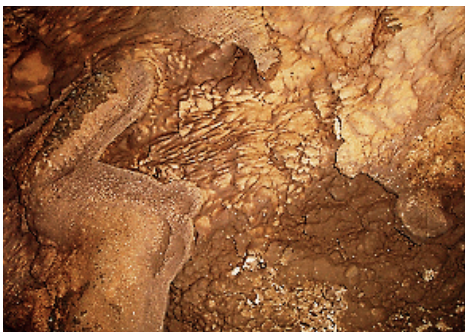

Figure 8: *Soft flowstones and rimstones (CM). L=1.5 m.*

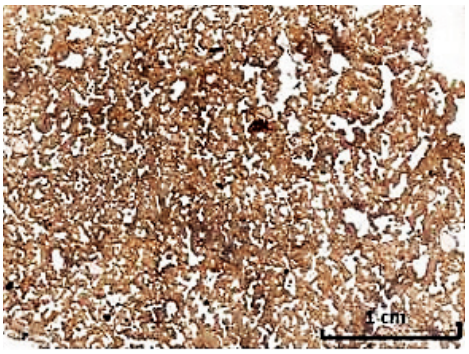

Figure 9: *Soft, highly porous, flowstone, natural light (CM).*

Walking on them may leave footprints in the sense that they are flattened. Indeed, they are highly porous (Fig. 9) and rarely show laminae (at least where we observed them), even though they can present rough bedding.

A sample was collected in 2004 and it was analysed in 2005 by X-RAY diffractometry: it contains 74 % of calcite, 17 % of quartz and 9 % of goethite, according to the interpreting technician. Certainly, more samples are needed.

Such deposits cannot be chemical only and must have a second cause of biological origin. Why they are specifically located at their place remains to be understood.

Near the bottom of the slope, human footprints are present on the floor (Fig. 10), as we discovered the day when we mapped the passage in 2004. They are not recent, as they are partly calcified, and at the same time may be not so old because calcitisation is developped to a limited amount. Footprints are present at several places but there is no obvious pathway between these locations. Possibly, they might be contemporaneous of the charcoal left at a moderate distance (Fig. 7).

Figure 10: *Calcified footprints in a dry rimstone pool (CM).*

This proves that men entered the cave at least up to this point and this probably long before villagers entered again at the turn of the third millenium.

At the very bottom of the slope, a transverse talweg leads water (at the rainy season) toward a hole in the cave wall. Beyond that, other rimstone dams are present, in the opposite direction but they do not show a very large porosity and are not soft.

The top slope is abruptly interrupted by a larger passage. Mapping was stopped at the bottom beyond the crest at the beginning of Giant Passage. On the crest proper, hollow stalagmites are present on the southern side of the passage (Fig. 11).

Figure 11: *Hollow stalagmite, naturally broken (CM).*

Hollow stalagmites have been observed by the author in several locations in Khammouane. In Tham Lô, X-RAY diffractometry performed in 2005 on 3 chips indicated a content of 97 to 99 % of calcite, the remaining fraction being interpreted by quartz by the technician. No aragonite was mentioned.

In 2005 (Mouret et al, 2005/ 2008), focus was directed at the continuation of the large, main, upper passage, starting at the bottom of the slope mentionned just above, beyond the hollow stalagmites. Mapping was performd by the author for the whole main Giant Passage. The large northern branch is covered with calcite flowstones and choked at the end also by calcite. The eastern branch has a silty/sandy floor followed by a talweg leading to a sinkhole on the northern side. Further away, the passage gets larger and it is covered with enormous boulders which complicate the extent.

Figure 12: *Gypsum flowers in the upper Giant Passage (CM).*

Then the passage goes down toward the South, before rising again in a narrower section with boulders, dry ground and gypsum flowers on floor and boulders (Fig. 12). After that, it greatly enlarges and displays again very large boulders. A possible choked passage may exist on its northern side. Further away, an upward calcite step leads to a subhorizontal

higher floor level with a calcite and dry silty floor. Shaft 3 cuts through the passage over the whole width of the passage, but the way continues beyond.

Closer to the entrance, on the southern side of the Giant Passage, two ascending side branches are present.

In 2006 (CREI Bull., n°15, 2006), JMO borrowed author's rope and with JFV went to Shaft 3. He descended it down to the bottom and followed around 100 m of new passage without mapping it. The author mapped a side branch leading to Shaft 4. It is a complex of narrower galleries, some ascending toward the South, the rest ending into Shaft 4.

At that date, far more than 7 km were mapped but for the lower level, we had to trust the lengths announced by the two mappers.

In 2007, the whole survey of upper level was confidently given by the author to JMO for he adds the lower level.

In 2013 and 2014, the author and friends went again into Tham Lô where he met a group of unknown westerners asking him who he was and why he was there. These people were moving in the cave with great disorder and unsecure behaviour. They said that we were not the cave explorers.

We precised the outside context of Tham Lô. At a similar elevation, to the East of it, remnants of a likely collapsed cave were pointed out.

Along hill slopes below entrances E1 and E2 to Tham Lô, two other caves were discovered: a cave choked by boulders after a few tens of metres, which is located at a lower elevation (Fig 2) and downdip of Entrance E1 to Tham Lô; it may be related to the lower level of the latter.

At the floor level of the polje, a sinking streamlet was mapped down to a sump. Condensation water was particularly abundant along the walls of the active passage.

A paper with a fake history of the cave exploration and fake bibliographic references was published in 2017 and for these reasons we are not going to cite it here.

3. Cave map

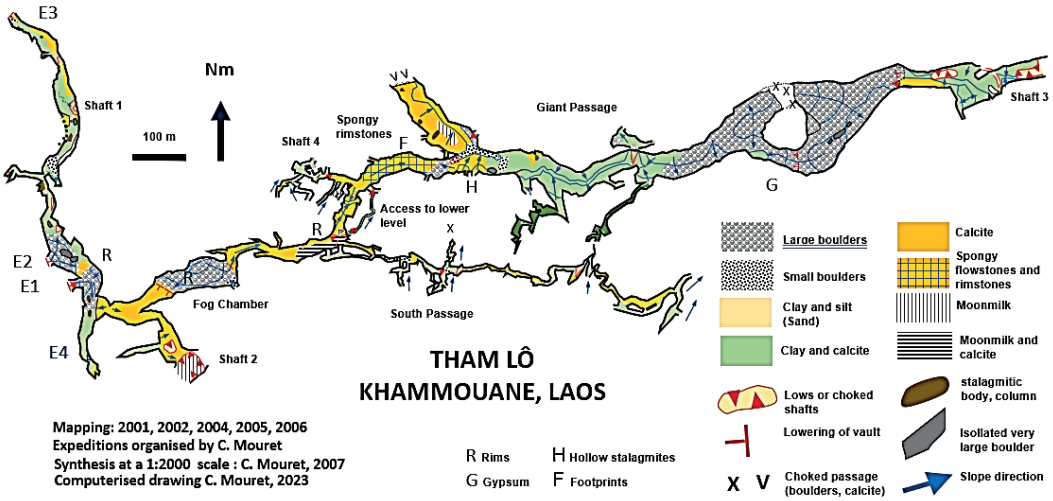

Figure 13: *Map of the upper level.*

The map of upper level (Fig. 13) was prepared by the author, based on his surveys and these by Xavier Noguès mainly (see next chapter) The upper level is overall subhorizontal though entrances E1 and E2 are in elevation. There is a succession of longitudinal ups and downs. Only transverse passages are sloping along the geological dip. Areas with boulders and others with calcite or mondmilch deposits do alternate. They are shown with distinct representations. Vertical shafts have a different origin of the oblique passage leading to the lower level.

4. Mappers and other participants

Topographers and "assistants": **2001: CM** (the author) with Jérôme Lordon (JL): northern branch; **Xavier Noguès (XN)** with Catherine Noiriel (CN): southern branch up to entrance to Fog Chamber. 1,2 km mapped. Spelunca n°84, 2001, p. 26; CREI Bull., 2001, n° 10, p.87. **2002: CM**, with JL and Emmanuel Guichard: South Passage; **XN** with CN, Jean-François Vacquié (JFV) and Jean-Michel Ostermann (JMO), Olivier Bonnet: southern branch to Shaft 3, Fog Chamber and parts of South Passage; **JMO** for the short way down to the lower level. Spelunca n° 92, 2002, p. 7 à 11; CREI Bull. 2002, n° 11, p. 56. **2004: CM**, Hélène Frume, Jacques Chambard: one team in the main gallery up to Giant Passage; Philippe Bence (PB), Florence Guillot (FG), JMO: in Shaft 2; **Charles Ghommhid** (CG), Pierre Sans and Helmut Steiner, all in the cave for the first time, and JFV (CREI Bull. 2004, p.61): survey in the lower level; **2005**: one team: **CM**, JFV, Bernard Giai-Checa, Hélène Frume, Jacques Chambard (Mouret, 2005), then a reduced team for branches: **BGC** mapper, JFV… **2006**: A team with **author** and Jacques Rolin on an interesting side passage leading to Shaft 4. One team to the provisional end of main passage at Shaft 3: JMO and JFV, no mapping; two teams in the lower level: **CG and FG** as mappers, with Maria Madrid, PB and HS. Far more than 7 km mapped at that date. **2013**: author together with JFV and Jacques Rolin. **2014**: author together with the same persons and Jean-Félix Vacquié.

5. Overview on Tham Lô

Tham Lô is one of the caves that we investigated, after others, in order to obtain a knowledge on the distribution of fossil passages vs elevation above base level.

It is a major fossil cave In Khammouane and both upper and lower levels are located high above the floor of Ban Vieng Polje. The end of the lower level toward the hill slope is said to show vegetal roots and is therefore close to the outside. Upper entrances E1, E2 and E4 are due to an incidental intersection of the cave by the hill slope. E1 and E2 are consequently bounded by large boulder flows. meanwhile E3 is an intersection of the passage by a talweg with a doline located higher than the floor of the polje.

Tham Lô, as a number of caves in Khammouane, shows oblique passages that follow the geological dip. The latter are perpendicular to main subhorizontal passages that follow to a variable degree the

direction of strata. Among other sloping caves, Tham Phiseua shows the largest difference in elevation: +475 m (MOURET et al, 2019), with an overall slope around 25 degrees. Such caves show subhorizontal passages which are cut through or ending against sloping passages. In Tham Lô, only cut through passages have been observed.

This pattern is present to a varying amount at the scale of Khammouane massif and its interpretation cannot be done cave per cave; as it must consider the entire massif at the same time, with respect to the regional geological history. it will be necessary to compare the relative elevations of subhorizontal passages in different caves, in order to check whether there is some similarity or not and how it can be explained.

We do not know the whole of Tham Lô and we base our interpretations on what was available to us during our explorations. Also, the meaning of northern branch between Entrances E1-E2 and E3 is not fully clear, as some tectonic complexity occurs in this area.

A large variety of speleothems is present in Tham Lô, as in some other caves in Khammouane. Besides the classical calcite deposits, i.e. flowstones, rimstones, columns, stalactites and stalagmites, helictites, there is a number of ascending warm air deposits, with rims around vents in flowstones and even in boulder piles (as in Fog Chamber, MOURET, 2010) and hollow stalagmites on incompletely consolidated sediments.

Deposits with a biogenic component are of two kinds: spongy flowstones and rimstones with a porosity that can reach up to 30 % and cannot correspond only to chemical deposition. The presence of goethite in their composition and the reddish-brown colour point out possible bacteria and/ or microalgae. In any case, there is either a dissolution of calcite or a deposition guided by dissolution of calcite or a deposition guided by microorganisms.

Moonmilk covers wide areas at several places with a different setting. One area with good ventilation is located around the triple junction of Giant Passage, South Passage and access to the lower level. There, moonmilk is usually formed of thick masses and also of bowls with a radial and concentric internal structure. It is commonly associated with gypsum crusts, but it may be lying beside calcite.

Moonmilk is present at the closed bottom of Shaft 2. In a side branch of the passage leading to Shaft 4, it is lying as relatively thin crust-like deposits; there, there is a specific lower limit which corresponds with the lower surface of fog, at least temporarily, Moonmilk is commonly associated with humid areas.

Another characteristic of Tham Lô is the wind throughout galleries. It even flows to the outside: cooler air is felt several tens of metres before reaching Entrance E1. Inside, it is especially felt near the saddle where starts the passage to Shaft 4. Oblique small stalagmites grow there facing the wind. In the main passage. Near E1, subhorizontal stalagmites grow toward the light, by evaporation at their

tip, where some vegetation grows. Such speleothems are logically fed by capillary water from rock wall. Their low angle slope is compatible with this origin. In South Passage, bidirectional subhorizontal stalactites indicate frequent changes of wind direction. Fog is a common as in a number of caves in Khammouane. Fog Chamber is seldom free of it, and visibility may be reduced to a few metres. Nevertheless, this is not at all a problem when we are moving in the cave and we do not need a guide line.

One just needs to be organised. In Tham Lô, we never got lost, because we always carry with us reflectors of light that we place at key points in order to secure the way back.

6. Conclusions

The exploration of Tham Lô has brought a lot of information on the cave and on the karst of Khammouane. Not only the geometric pattern and cave evolution are of interest, but also speleothems and cave winds.

Much remains to be done after our work, even though not all results were made available to us. It was important to make better known the exploration history.

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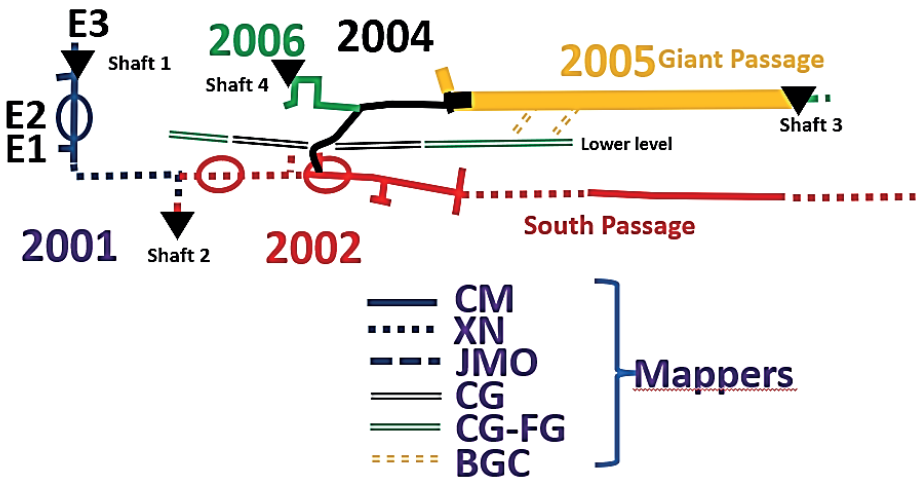

Annex 1: *Mappers. The colour corresponds to the year, the shape of the lines to the mappers (full names in Section 4). The combination of colours and lines indicates who mapped what and when.*

Projeto “Mar de Minas”: um recorte das ocorrências espeleológicas

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Resumo

Apesar de existirem diversas evidências geológicas que expressam as origens marítimas do estado de Minas Gerais, esse conhecimento é pouco difundido fora do meio acadêmico das geociências. Com o objetivo de divulgar e ampliar os conhecimentos sobre essa temática, foi iniciado o projeto de extensão “Mar de Minas: passado submerso”, criado pelo Centro Universitário de Belo Horizonte (UNIBH) e iniciado no segundo semestre de 2024. O presente trabalho representa um recorte da atual fase de documentação que o projeto “Mar de Minas” se encontra, dando ênfase às ocorrências espeleológicas mapeadas durante os levantamentos do projeto e exaltando a importância do reconhecimento desses patrimônios naturais. Ao final, também são destacadas as perspectivas para a continuidade desse projeto em 2025.

Abstract

“Mar de Minas” Project: a segment of speleological occurrences. Although there are several geological evidences that express the maritime origins of the state of Minas Gerais, this knowledge has little dissemination outside the academic environment of geosciences. In other to disclose and amplify this thematic’s knowledge, the extension project “Mar de Minas: Passado Submerso” was started, created by the University Center of Belo Horizonte (UNIBH) and started in the second half of 2024. The present work represents a segment of the current phase of documentation in which the “Mar de Minas” project is situated, emphasizing the speleological occurrences mapped during the project’s surveys and highlighting the importance of recognizing these natural heritage sites. In the conclusion, the perspectives for the continuation of this project in 2025 are also highlighted.

1. Introdução

O estado de Minas Gerais, conhecido por sua riqueza cultural, histórica e natural, possui uma característica surpreendente e pouco conhecida fora do meio geocientífico, isto porque já foi coberto por um mar que deixou evidências a olho nu. Apesar de estar localizado no interior do Brasil, distante do litoral, evidências geológicas indicam que grande parte do território mineiro já esteve submerso pelo mar (PIVETTA, 2014).

Nesse contexto, o Centro Universitário de Belo Horizonte (UNIBH), lançou, em 2024, o projeto de extensão intitulado “Mar de Minas: passado submerso”, cujo objetivo é disseminar o conhecimento da história geológica da região de Minas Gerais para diferentes grupos sociais, com ênfase na população em idade estudantil da Região Metropolitana de Belo Horizonte (RMBH), através do levantamento de evidências geológicas que corroborem com a hipótese de que a região já esteve submersa em seu passado. Esse levantamento está sendo realizado pelos alunos dos cursos de Geologia e Engenharia de Minas do UNIBH, que até o momento já cadastraram cerca de 30 pontos diferentes, distribuídos ao longo de locais como: Catas Altas, Diamantina, São José da Serra em Jaboticatubas, Ouro Preto, Pedreira Paraíso em Sete Lagoas, Ribeirão da Mata entre Santa Luzia e Lagoa Santa, Serra de São José entre São João del-Rei, Tiradentes, Santa Cruz de Minas, Coronel Xavier Chaves e Prados, e Serra dos Alves em Itabira.

Esse trabalho representa um recorte do projeto Mar de Minas e tem por objetivo apresentar as principais observações feitas durante o levantamento de dados em locais de ocorrência espeleológica visitados durante as atividades de campo.

2. Materiais e Métodos

A pesquisa vem sendo conduzida com o objetivo de identificar e documentar evidências geológicas, estratigráficas e paleontológicas que sustentem a hipótese de que, no Período Ediacarano, a região de Minas Gerais esteve submersa por um mar raso. Inicialmente, realizou-se um levantamento bibliográfico para direcionar a escolha dos locais mais promissores para a coleta dessas evidências.

Com base nesse levantamento, foram selecionadas três grutas iniciais como áreas de estudo: Gruta Rei do Mato, em Sete Lagoas; Gruta da Lapinha, localizada em Lagoa Santa; e Gruta do Maquiné, em Cordisburgo (Fig. 1).

Essas localidades foram escolhidas devido à presença de formações geológicas e fósseis associados a ambientes marinhos, como rochas

calcárias, estromatólitos colunares e marcas de água que são indicadores de antigos fundos marinhos.

As atividades de campo, em primeira etapa, ocorreram nos meses de dezembro de 2022, setembro e outubro de 2024, e consistiram no reconhecimento e descrição de aspectos geológicos das áreas selecionadas. O trabalho de campo envolveu a observação e descrição de rochas, fósseis e outros materiais geológicos relevantes. Para a análise dessas amostras, foram empregadas técnicas de identificação estratigráfica e paleontológica, incluindo a análise de fósseis ictiológicos, rochas calcárias, estratigrafias características e marcas de água.

A coleta de dados foi realizada de forma sistemática com uso GPS de mão para o registro das coordenadas geográficas, câmera/celular para registros fotográficos, bússola para descrição geométrica das camadas sedimentares observadas nos afloramentos e caderneta para registro das informações levantadas acerca das características físicas observadas e controle de amostras coletadas.

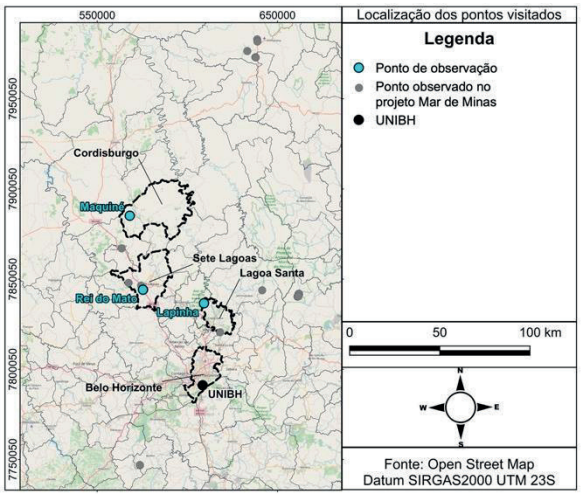

Figura 1: *Localização dos pontos visitados no projeto Mar de Minas, com destaque para as três grutas.*

3. Resultados

Na Gruta da Lapinha, além de espeleotemas e estratificações plano-paralelas (Grupo Bambuí), são observados fósseis marinhos, incluindo conchas, nas paredes calcárias, sugerindo a presença de ambientes marinhos no passado (Fig. 2).

Na Gruta do Maquiné, observa-se estratificações cruzadas que sugerem sucessões de eventos transgressivo-regressivos, da Formação Lagoa do Jacaré (Grupo Bambuí), relacionados com mudanças no nível do mar ao longo do tempo, implicando na alternância entre depósitos sedimentares marinhos e continentais (Fig. 3).

Na Gruta Rei do Mato observam-se rochas de aspecto misto entre calcário e arenito, com estratificações plano-paralelas e cruzadas e de coloração cinza (Fig. 4), do membro Lagoa Santa, da Formação Sete Lagoas (Grupo Bambuí). Ao entrar na gruta, também se observam Espeleotemas que ainda permanecem se desenvolvendo.

Figura 2: *Registros fotográficos da Gruta da Lapinha.*

Figura 3: *Registros fotográficos da Gruta do Maquiné.*

4. Discussão

A ideia principal do projeto Mar de Minas é fornecer evidências geológicas e paleontológicas robustas que corroborem a hipótese de que Minas Gerais já foi coberto por um mar raso há aproximadamente 550 milhões de anos, durante o Período Ediacarano.

As estratigrafias transgressivas e regressivas observadas nas três grutas, com intercalações de sedimentos arenosos, hora com mais calcáreo, hora com menos, seguem o padrão conhecido de variação no nível do mar. As transgressões indicam o avanço do mar sobre áreas continentais, com a formação de camadas de sedimentos marinhos sobre sedimentos continentais, ocorrendo quando o nível do mar sobe e inunda regiões antes emersas. As regressões, por outro lado, indicam o recuo do mar, resultando na deposição de sedimentos continentais, como arenitos e argilas, nas áreas anteriormente submersas.

O calcário, uma rocha sedimentar formada pela precipitação de carbonato de cálcio, é típico de ambientes marinhos rasos. Esse processo ocorre quando organismos marinhos, como corais e moluscos, acumulam suas conchas e esqueletos ou quando a água rica em cálcio evapora, formando depósitos de carbonato de cálcio. Nesse caso, nas três grutas foram observadas essas rochas relacionadas ao Grupo Bambuí. O Grupo Bambuí, presente em grande parte de Minas Gerais, é composto por rochas sedimentares e metassedimentares de origem marinha, como calcários, dolomitos e siltitos. Essas rochas foram formadas em ambientes marinhos rasos, como plataformas carbonáticas, e são encontradas em municípios como Sete Lagoas, Lagoa Santa, Januária e Diamantina. A presença de estratificações cruzadas, marcas de ondas e estromatólitos colunares reforça a ideia de um ambiente marinho raso e dinâmico (SEER et al. 2023).

Figura 4: *Registros fotográficos da Gruta Rei do Mato.*

5. Conclusão

A história geológica de Minas Gerais, com seu passado submerso, oferece uma oportunidade única para a educação científica, especialmente para alunos do ensino básico. A exploração de cavernas, grutas e afloramentos rochosos pode ser usada como ferramenta pedagógica para ensinar conceitos de geologia, paleontologia e estratigrafia de forma prática e envolvente.

A espeleologia, ciência que estuda cavernas, fornece conhecimento essencial para a preservação da história geológica e ambiental. As formações calcárias encontradas em Minas Gerais, como as grutas da Lapinha, Maquiné e Rei do Mato, são resultados da dissolução de rochas carbonáticas por água, formadas em ambientes marinhos. Essas cavernas são verdadeiros arquivos geológicos, pois guardam evidências do passado marinho do estado.

Com relação ao projeto Mar de Minas, o mesmo seguirá em desenvolvimento ao longo de 2025. Como objetivos previstos no projeto ainda constam: (i) o levantamento de mais evidências geológicas para corroborar com a hipótese da presença de um ambiente marinho; (ii) criação de material lúdico para o difusão desse conhecimento para alunos do ensino fundamental e médio de escolas na RMBH; (iii) criação de roteiro científico geológico com a temática sobre a evolução geológica da região de Minas Gerais, com vistas para o fortalecer a concepção de sustentabilidade geológica e cultural da história de formação da paisagem do estado.

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Time Travel: An Overview of the Main Caving Equipment from the 80s and 90s in Brazil and Its Technological Evolution

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Abstract

This paper provides a historical review of the main equipment used for caving practices between the 1980s and 1990s, in Brazil, and its technological evolution. Based on scientific works and field reports, the equipment was grouped into categories according to their uses and functions: for topography - such as compasses and clinometers, lighting - such as carbide lamps, and climatology - such as thermometers and psychrometers.

Resumo

O presente artigo faz uma revisão histórica dos principais equipamentos utilizados para a prática de espeleologia entre as décadas de 1980 e 1990, no Brasil, e sua evolução tecnológica. A partir de trabalhos científicos e relatos de campo, os equipamentos foram agrupados em categorias de acordo com seus usos e funções: para topografia - como bússolas e clinômetros, iluminação - como lanternas de carbureto e climatologia - como termômetros e psicrômetros.

1. Introduction

Caving, in its process of sporting and scientific evolution, has increasingly highlighted the importance of studying caves for the development of research. From the interest in caves linked to a science in Brazil, the Danish Peter Wilhelm Lund (1801-1880), in the mid-1835, produced the first scientific descriptions of caves using equipment that allowed a certain precision in the information recorded (FERNANDES & FARIA, 2024). A few decades later, the remarkable work of the German-Brazilian Richard Krone (1861-1917) described limestone caves in the Vale do Ribeira (MARTINS, 2023) and advocated for the use of topographic equipment in his research. Finally, the creation of the first speleological group in America, the *Sociedade Excursionista Speleologica* (currently SEE), starting in 1937, highlighted the need for recording and organizing data about caves and cavities - beyond describing their topographic, paleontological, climatic, geological, and biological characteristics. According to the editorial in volume 16 of the journal Espeleo-Tema - a newsletter that gathers scientific articles reunited by the *Sociedade Brasileira de Espeleologia* (SBE) - published in 1992, titled "Caving in the 80s," important compilations of data about caves in the country date back to that time.

> "If the development of the speleological science was important for the protection of the heritage, even more significant was the organization of the national speleological community and the strengthening of the Brazilian Society of Speleology. Noteworthy are the reorganization of the National Register of Natural Cavities and the publication of the Index of Data about the Caves of Brazil, as well as the systematic work of the Commission for Registration, Speleometry, and Speleological Provinces (ESPELEO-TEMA, 1992).

Often adapted from other activities, such as mining and extreme sports, the equipment used in speleological activities aimed to expand the horizons of data collection beyond what had been produced up to that time and to assist in building a database that could be consulted and expanded by future researchers. According to RUCHKYS et al. (2015):

> [...] In Brazil, most of the speleologists who began their activities before the 1990s went through the difficult task of improvising all the equipment: helmets, carbide lamps, ropes, climbing ascenders, not to mention footwear, backpacks, and clothing, among other things.

In this context, the survey conducted describes below the main equipment used for topography, lighting, and underground climatology in Brazil between the 1980s and 1990s.

2. Materials and methods

The historical rescue of records regarding the use of topography, lighting, and underground climatology equipment in speleological activities, which are the subjects of this article, involved the analysis of the first issues of *InformAtivo SBE*, a periodical of the *Sociedade Brasileira de Espeleologia* (SBE), digitized by Davidson Santos from the Seção de História da Espeleologia (SHE) of SBE, as well as papers published in the journal Espeleo-Tema, also from SBE, in addition to articles presented at the organization's congresses during the 1980s and 1990s. To contextualize the technological advancements, present in the current equipment used in Brazil, articles on the researched topics were gathered from Google Scholar using the Portuguese keywords "*topografia cavernas*" (11,500 results), "*temperatura cavernas*" (39,200 results), and "espeleoclima cavernas" (36 results).

3. Results and discussion

3.1. Underground Topography

The activity of mapping and surveying caves developed between the 1980s and 1990s in Brazil represents both a milestone for the improvement of data produced in the previous decades, using equipment that gained complexity and elevated levels of calibration and precision, in a period when the peak of analog instruments was established, before their evolution to digital technology.

It is important to remember that the degree of precision of a topographic survey - whether calculated by the polygonal method, by radiation, or by triangulation - determines the reliability of the map and results in a set with distinct levels of detail (SÁ, 2023).

In Brazil, the most used system to determine this in relation to the central line of the topography is the one by the British Cave Research Association (BCRA), which establishes seven degrees of precision and four classes for detailing lateral conduits (SÁ, 2023). In a text written for *InformAtivo SBE* nº one, from January 1985, the speleologist Sergio Beck points out the use of innovative equipment at the time for achieving a more precise survey of the Santana cave, conducted between July 1983 and November 1984. According to BECK (1985):

> The difference between this topography and the previous ones was both the use of more precise equipment (Suunto compass and clinometer) (Figure 1) and the subsequent processing of the data with a scientific calculator. In fact, instead of plotting the bases with a protractor and ruler as was done before, azimuth, inclination, and distance were transformed into three coordinates along the north, east, and vertical axes, starting from a zero point - the entrance of the cave.

Figure 1: *Suunto clinometer PM-5/360 PC, a milestone for the improvement of topography in the nineties in Brazil. Source: eBay.com.*

In a paper titled "Methodological Evolution in the Mapping of Toca da Boa Vista, Campo Formoso - Bahia," AULER et al. (1992) describe the details and workings of the American Brunton compass used in their fieldwork (Fig. 2).

> It consists of a metal box divided into a main body and a lid. A double-ended needle rotates over a fixed graduated disk inside which the clinometer is coupled. The lid has a mirror, essential for reading the azimuth. The Brunton compass is quite popular among geologists due to its robustness and ease of measuring the direction and dip of structures. It is a very precise instrument that has been used for a long time in underground surveying, although it is rapidly losing popularity to instruments that are easier and quicker to handle, such as those from the Suunto line.

Figure 2: *American Brunton compass, used in fieldworks in Brazil. Source: Personal archive FERNANDES A., 2025.*

PEREZ & TABERA (1987) and WARILD (1988), apud AULER et al. (1992), also describe the topofio and its utility.

> The topofio, a device developed by the French, is, in most models, a handcrafted distance measuring tool, consisting of a small diameter sewing thread spool, interconnected with some rollers and finally an odometer that records the length of thread extracted. All components fit into a small, quite sturdy plastic container. The topofio is primarily used among the French, being practical and quick for long sighting. Some models of the topofio have a compass and clinometer.

In addition to the Brunton model, AULER et al. (1992) also mention the Suunto compass, model KB 14/360RT, the clinometer of the same brand, model PM 360 PCT, and the open-type PVC measuring tape without a reel. The reviewed reports indicate that equipment such as compass, clinometer, measuring tape, and leveling instrument were the basis of topographic activity during the described period. FERNANDES et al. (2023) remind us that the product of this type of survey, now known as a conventional topographic map, contains the floor plan, cross-sections, longitudinal section, geographical location of the cave entrance, speleometric parameters (area, volume, horizontal projection, elevation difference, degree of accuracy, etc.), geological, biological, archaeological characteristics, etc.

According to FERNANDES et al. (2024), the technological development of the devices used conventionally, which have transitioned from analog to digital over the past twenty years, now enters a new chapter in their evolution, with new approaches: the digital laser measuring tape, laser scanning, and mapping through images (photogrammetry). Nowadays, there are devices available with the capability to create three-dimensional (3D) representations of caves with a high degree of precision and graphic quality. This mapping process generates an extremely accurate digital model through the analysis of a series of points arranged in three dimensions, often referred to as a "3D cloud" (FERNANDES et al., 2024).

The product of this type of survey, which represents for some authors the state-of-the-art, is presented as a high-resolution 3D model composed of the virtual visualization of the arrangement and shape of the cavities (FERNANDES et al., 2024).

Characteristic since the beginning of its history, the modernization of the equipment used in speleology practice first reaches related areas with greater investment interest,

such as mining. In the most recent articles describing innovative technologies related to topography, material generated in Brazil arises from the need to facilitate and expedite environmental licensing processes for the area and, given its high cost, is primarily led and employed in projects developed by large corporations.

Among the equipment mentioned in current scientific works are the Leica DistoX310 digital laser measuring tape (Fig. 3), which, according to FERNANDES et al. (2023), can fully replace the set of compass, clinometer, and measuring tape, allowing for the measurement of azimuth, inclination, and distance of the sights; the static laser scanner model Leica BLK360 and the portable laser scanner model Geoslam

ZEB REVO, which use rotating mirrors to generate laser pulses that can combine distance data and horizontal and vertical angles to produce three-dimensional coordinates (BUCKLEY et al., 2008); in addition to photogrammetry software for processing the information read by the scanners and reconstructing the three-dimensional space.

Figure 3: *Leica DistoX310 digital laser measuring tape. Source: Leica Geosystems.*

3.2. Lighting Equipment

Despite inheriting the knowledge acquired about light production in underground cavities from the mining industry, which gained a primary role in society after the Industrial Revolution, it was only throughout the 20th century that speleology, which was emerging as a science in the world, began to adapt equipment used in mining excavation for cave exploration. It took 56 years after the discovery of acetylene gas — a highly flammable substance whose combustion produces a very bright flame — by the British chemist Edmund Davy in 1836, for researchers Henri Moisan from France and Thomas Willson from Canada to stabilize it in the laboratory through a solidification process that resulted in the creation of calcium carbide. The "carbide stones," as they were commonly known, reacted upon contact with water, releasing controlled amounts of acetylene, sufficient to produce a consistent and lasting flame. This innovative production method created a commercially viable product that quickly became popular, extending beyond the mines and crossing borders. On a page dedicated to the history of carbide, the Virtual Museum of Speleologist Geraldo Gusso (MVEGG) describes the development of the lighting system, which would become one of the main ones used for speleological activities until its gradual replacement after the 1980s by portable electric lanterns.

> Thus, in the early years of the 20th century, carbide lamps flooded the stores, marking the beginning of a revolution in portable lanterns, which were used in industries, mines, railways, or domestic activities (MVEGG, n.d.).

In addition to portable lanterns, a piece of equipment composed of a reactor and a helmet with mixed lighting developed in fiberglass by Espeleogrupo Monte Sião (EGMS) and called SPELAION was mentioned in the *InformAtivo SBE* number 5, by Sergio BECK from CEU (*Centro Excursionista Universitário*), in the article 'New Lighting Option for Speleology,' and number 6, in 'Lighting for Speleology,' by José Ayrton LABEGALINI from EGMS, who described details of the technology that would become popular among cave explorers as one of the main models of helmet-mounted lanterns used in Brazil starting in the second half of the 1980s (Fig.4).

> [...] We inform that such reactor has excellent mechanical resistance, the resin used has a melting point of 125°, it ignites slowly when directly exposed to fire for a certain period, and in the latest test conducted in early October at the Jeremias Cave, the set operated for 10 hours, with a single load and one interruption to remove excess carbide dust.

As time went by, the weight of the set with reactor, water, powder, and carbide, combined with the emission of soot that was becoming an environmental problem regarding the preservation of caves, led to the development of other lantern technologies derived from electric light and powered by batteries - succeeded by the current LED models - which began to replace the old system and brought a new concept of practicality to speleologists (SOUZA, 2003).

Figure 4: *Petzl Explorer kit, consisting of an Ecrin Roc helmet, 1 Ariane carabiner, and a Duo flashlight. Source: Spelaion Brasil (Facebook), 2020.*

3.3. Underground Climatology

Another type of data collection, in addition to topographical, also had its importance mentioned in the researched records: the study of speleoclimate. According to LOBO (2010), the study of subterranean atmospheric systems was divided into three periods in Brazil: between the years 1960 and 1980, when only point measurements of temperature and relative humidity were taken; from the 1990s on, when the first systematic monitoring work of speleoclimate began; and the third period, at the turn of the century, which occurred with the increase of monitoring work focused on environmental conservation. In the article "The Importance of the Thermal Profile of Caves" published in InformAtivo SBE number 4, in 1985, Nelson da Silva CÉSAR Jr. recorded the importance of determining the thermal profile of caves at that time.

> From it, we can extract morphological, topoclimatic, mesoclimatic, and microclimatic data. According to the nomenclature proposed by Andrieaux. [...] We can compare, in some aspects, the thermal survey with a long topography. When we look at the thermal curve of a given cave, we can immediately say what type of cavity we are examining, even without looking at its map.

To conduct this type of measurement, as well as to determine the relative humidity of the air, the use of hygrometers (Fig. 5), psychrometers, and dry and wet bulb thermometers, all analog, was mentioned. In the "Espeleodica" column, published in InformAtivo SBE number 8 in 1986, Nelson da Silva CÉSAR Jr. describes that through the temperature difference between a dry bulb thermometer and a wet bulb thermometer, it is possible to measure the relative humidity of the air with a certain degree of accuracy without the need of a hygrometer. MOREIRA & TRAJANO (2010) report the use of an Assman psychrometer with an accuracy of 0.2 degrees, positioned 20 cm above the ground to

determine the topoclimate of the caves in Altamira and Itaituba, in a study conducted in Pará.

From the second period, starting in the 1990s, LOBO (2010) mentions the use of equipment such as thermohygrographs, evaporimeters, and barographs, in addition to the technological innovation arising from the use of automatic data loggers, currently used in conjunction with smartphones and specific software capable of generating detailed graphs and spreadsheets with the collected data. PIMENTEL & BERNARDI (2024) describe the equipment recently used for thermal monitoring of cavities in the Carajás National Forest in Pará.

> The temperature data collection was carried out using HOBO MX2201 and MX2203 model data loggers, with recordings at 10-minute intervals. [...] The connection and download of data from these data loggers were performed using a smartphone via Bluetooth and through the HOBOmobile software.

Figure 5: *Thermo-hygrometer Incoterm, frequently used by speleologists of Brazil in the nineties. Source: Personal archive FERNANDES A., 2025.*

4. Final Considerations

In an article written for the InformAtivo SBE, a publication of the Brazilian Speleology Society, in 1987, the Italian speleologist Giovanni Badino stated that "*a cave is not a structure in itself, but a form of the mountain or hill and the product of all its histories and as complex as these*," and emphasized that "*one should not think only of the cave, but of the whole mountain, with the cave inside*." Taking this thought into account for the rescue of a timeline of the equipment that has been used in the history of Brazilian speleology and its evolution over time, it is possible to analyze that a modern, digital, and compact piece of equipment used today may not only be a gadget that performs quick calculations, provides lighting in the blink of an eye, or records the peculiarities of the underground world of caves, but a product of all its previous versions, which may have contributed not only to the evolution of the speleological activity itself but also to the development of the explorer's own skills. Furthermore, recovering this history over time serves as an important record of the limitations for the development of this type of scientific activity during the period covered by the survey - between the 1980s and 1990s in Brazil - and of the achievements that were possible even while working in a challenging scenario, compared to what was already being developed worldwide. On the other hand, looking at the possibilities that technological advancement has allowed with the development, mainly, of topographic and temperature measurement equipment - which gained functionalities and had their capacity for precision and data recording expanded - opens a new dimension for the analysis and timely review of data collected in the past, from an enhanced technical perspective.

Our survey does not exhaust the research on all the equipment that was used in the practice of speleology between the 1980s and 1990s but seeks to contribute to the historical recovery by describing the main citations within the temporal scope, in content related to or linked to SBE. There is still room for this research to be expanded in the spatial, temporal and documentary spheres, or by increasing the diversity of equipment to be considered in the searches.

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Atualização e Validação de Dados Geoespaciais de Cavidades Naturais: Um Estudo de Caso em Rio Branco do Sul-PR

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Resumo

A qualidade posicional dos dados geoespaciais representa um dos principais requisitos para a gestão, controle e monitoramento das condições ambientais das cavidades naturais e seus entornos. A instituição, há vinte anos, do Cadastro Nacional de Informações Espeleológicas (CANIE) uniu nacionalmente os dados de múltiplas fontes, épocas e métodos de posicionamento. Os dados posicionais das cavidades ocorrentes no município de Rio Branco do Sul - PR, cadastrados no CANIE (2022), são uma amostra representativa de dados de cavidades mapeadas antes do uso disseminado da tecnologia Global Navigaton Satellite System (GNSS). Considerando os dados espeleológicos presentes no CANIE (2022), foi realizada a atualização e adequação do cadastro das informações espeleológicas do referido Município, com o uso de GNSS e implantação de marcos geodésicos em campo. Os dados obtidos, compatíveis com aplicação na escala 1:1000 do Padrão de Exatidão Cartográfica para Produtos Cartográficos Digitais (PEC-PCD), foram estruturados segundo os padrões da Infraestrutura de Dados Geoespaciais Brasileiros (INDE) e atualizados no CANIE e no Cadastro Nacional de Cavernas (CNC). A comparação entre os dados adquiridos com os dados do CANIE permite concluir que há a necessidade de validação em campo dos dados presentes no CANIE, especialmente os adquiridos sem o uso da tecnologia GNSS.

Abstract

The positional quality of geospatial data represents one of the main requirements for managing, controlling, and monitoring the environmental conditions of natural cavities and their surroundings. The establishment of the National Registry of Speleological Information (CANIE) twenty years ago brought together data from multiple sources, periods and positional methods nationwide. The positional data of cavities occurring in the municipality of Rio Branco do Sul - PR, registered in CANIE (2022), are a representative sample of data from cavities mapped before the widespread use of Global Navigation Satellite System (GNSS) technology. Considering the speleological data present in CANIE (2022), the registry of speleological information for this municipality was updated and refined using GNSS technology and the implementation of geodetic markers in the field. The data obtained, compliant with the 1:1000 scale standard defined by the Cartographic Accuracy Standard for Digital Cartographic Products (Padrão de Exatidão Cartográfica para Produtos Cartográficos Digitais – PEC-PCD), were structured according to the standards of the Brazilian Geospatial Data Infrastructure (Infraestrutura de Dados Geoespaciais Brasileiros – INDE) and updated in both CANIE and the National Cave Registry (Cadastro Nacional de Cavernas – CNC). The comparison between the newly acquired data and the existing CANIE data highlights the necessity of field validation for the data in CANIE, particularly those collected without the use of GNSS technology.

1. Introdução

O objetivo deste trabalho é apresentar os procedimentos metodológicos e os resultados do projeto intitulado “Atualização e adequação do cadastro das informações espeleológicas do município de Rio Branco do Sul - PR” referente ao Edital de Chamada Pública nº EDITAL SBE 01/2023 AMPLIANDO ROTAS – APOIO AO PATRIMÔNIO ESPELEOLÓGICO BRASILEIRO”, o qual revisou a localização das 47 cavidades localizadas no município de Rio Branco do Sul - PR (CANIE, 2022).

O Grupo de Estudos Espeleológicos do Paraná (GEEP-Açungui), principalmente nas décadas de 1980 e 1990, foi responsável pelo levantamento da maioria dos dados presentes no CANIE referentes à área estudada (FIGURA, 1), os quais possuem acurácia posicional, em sua maioria, condizente com as tecnologias anteriores ao uso do sistema GNSS. Desde a coleta até a integração dos dados no CANIE, a linhagem dos dados cadastrados pelo GEEP-Açungui pode ser descrita resumidamente na seguinte ordem: 1) emprego de cartas topográficas e fotografias aéreas para definir a posição das cavidades em campo; 2) Registro analógico dos dados geoespaciais; 3) Digitalização e transformações de sistemas projetivos, em especial de data (Córrego Alegre, SAD69 – primeira e segunda realização, SIRGAS 2000); 4) Manipulação em meio digital e 5) integração ao CNC e ao CANIE.

Considerando que a gestão do patrimônio espeleológico, especialmente após a publicação da resolução CONAMA nº 347 que definiu a área de influência de 250 m ao entorno da área ocupada por cavidades sem estudos prévios, é baseada na localização das cavidades, fica evidente a importância da componente espacial para a preservação do Patrimônio Espeleológico Brasileiro. Todavia, Ferreira (2019) baseado em dados do Tribunal de Contas da União TCU de 2014, observa que somente 8,7% dos dados de cavernas registradas no CANIE haviam sido validadas.

Compete ressaltar, também, a carência de estudos de cunho cartográfico com enfoque em métodos de locação e validação posicional de cavidades. Os estudos com abordagens espeleométricas, os problemas relacionados ao levantamento da topografia interna, métodos de cálculo de área, volume, projeção horizontal, desenvolvimento linear, caracterizações geotécnicas e, até mesmo, a modelagem preditiva para a ocorrência de cavidades, são problemas mais comumente abordados em estudos dedicados ao mapeamento de cavidades.

Diante deste cenário, a definição da posição inequívoca e a materialização de um referencial *in loco* para cada cavidade, a exemplo do realizado no presente trabalho, pode representar um procedimento metodológico para a validação posicional dos dados do CANIE, em especial dos dados adquiridos antes do uso da tecnologia GNSS.

Segundo o mapeamento geomorfológico do Estado do Paraná (MINEROPAR, 2006) os limites do município de Rio Branco do Sul estão contidos na unidade morfoestrutural Cinturão Orogênico do Atlântico, a qual pode ser subdividida em quatro unidades morfoesculturais representadas por planaltos dissecados com "nível de dissecação altos", drenadas pela bacia hidrográfica do rio Ribeira.

A evolução geológica, conforme Fiori (1994), inclui eventos tectônicos que fraturaram, falharam, metamorfizaram e dobraram os litotipos neoproterozoicos presentes nas formações do Grupo Açungui. Tal evolução, principalmente as deformações de caráter rúptil, possui forte influência na paisagem cárstica regional. As faixas metacalcárias que abrigam as cavidades abrangem 44% da área do município de Rio Branco do Sul e possuem rumo nordeste/sudoeste (BIGARELLA, 1953).

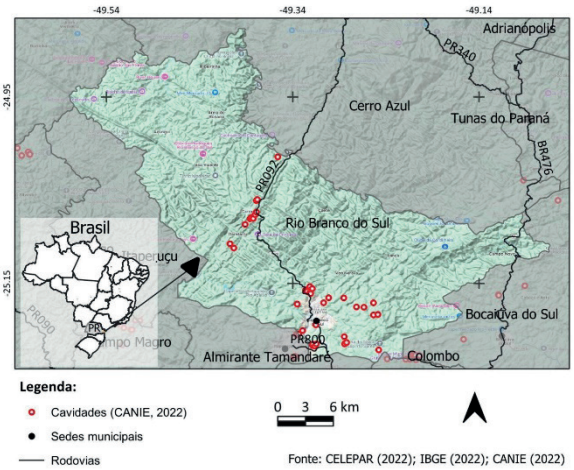

Figura 1: *Local do estudo com as cavidades segundo o CANIE (2022) identificadas.*

O clima tipo Cfb, segundo a classificação de Köppen, predomina em praticamente toda área estudada. A região é marcada por condições típicas de clima temperado e úmido (Mesotérmico), com verão ameno, chuvas bem distribuídas durante o ano, temperatura média do mês mais quente inferior a 22°C, precipitação de 1100 a 2000 mm anualmente, geadas em um período médio de ocorrência de dez a vinte e cinco dias por ano e sem períodos secos em uma estação específica.

2. Materiais e Métodos

Para a atualização e adequação do cadastro das informações espeleológicas do município de Rio Branco do Sul – PR, a base de dados do CANIE, ano de referência de 2022, foi utilizada como principal referencial de nomenclatura e de localização espacial das cavidades ocorrentes na área estudada. Além da base de dados do CANIE foram consideradas, secundariamente, os dados primários adquiridos e sistematizadas pelo Grupo de Estudos Espeleológicos do Paraná (GEEP-Açungui) desde a década de 1980.

Para auxiliar na localização das cavidades em campo foram analisadas as imagens de satélites disponibilizadas pelo Google Earth Pro (2024), considerando a série temporal entre os anos 1990 e 2020. A comparação de dados de imagens de satélite e os pontos de localização das cavidades permitiu a definição dos melhores acessos e orientação dos deslocamentos em campo. A integração de dados espaciais (imagens, linhas e pontos) foi realizada no software OruxMaps GP instalado em um smartphone e em um aparelho GNSS Garmin modelo GPSMAP 65s multi-band.

A implantação dos marcos geodésicos e a materialização da referência espacial para cada cavidade priorizou a proximidade em relação à entrada de cada cavidade e considerou dois fatores limitantes: 1) o multicaminhamento do sinal GNSS em função da interação com as superfícies, especialmente com o relevo e a vegetação - atenuado a partir do afastando do maciço rochoso da entrada da cavidade e da implantação do marco em áreas com vegetação menos densa (área de clareiras naturais ou abertas para o rastreio de dados GNSS) e 2) presença de solo para a penetração da haste metálica e fixação do marco geodésico (Figura 2) – teste de penetração com o "furão" (instrumento metálico para a perfuração do solo).

Para a implantação dos marcos geodésicos foram realizados rastreios de sinais de constelações GNSS (Global Navigation Satellite System) e definição das coordenadas referentes às suas respectivas posições em campo. Foi utilizado um receptor GNSS de dupla frequência (ArduSimple - RTK Calibrated) de nível centimétrico multibanda (L1, L2) com multifrequência e multiconstelação. A antena receptora, exceto em um caso (Gruta do Estilo), foi posicionada a 2 m (dois metros) de altura em relação a posição central da plaqueta metálica do marco geodésico (Figura 2). A única exceção, Gruta do Estilo, se deu por conta de a mesma estar posicionada em uma bancada desativada de mina e o único local possível de fixação do marco geodésico ter sido na entrada da cavidade, a qual tinha menos de 2 m (dois metros de altura).

A obtenção de dados GNSS em locais sem a cobertura de dados de telefonia móvel demandou tempos de rastreio de 40 minutos, intervalo de tempo que permitiu o registro de informações representativas para o pós-processamento. O pós-processamento de dados foi realizado no software Emlid Studio 1.7, o qual comparou os dados brutos registrados em campo (arquivos com cerca de 25 Mb obtidos a partir do rastreio de 40 minutos em campo) com os dados da estação de referência de funcionamento contínuo Curitiba (UFPR) e/ou Pinhas (PRPI) pertencentes à Rede Brasileira de Monitoramento Contínuo (RBMC).

Em locais com telefonia móvel foi utilizado o sistema NTRIP (Networked Transport of RTCM via Internet Protocol) para correção de dados em tempo real entre o receptor instalado sobre o marco geodésico e a Estação Curitiba-UFPR. Para otimizar as atividades de levantamento de dados, uma vez que a espera de 40 minutos de rastreio limitava o aproveitamento das etapas de campo, uma antena receptora de sinal de internet da empresa Starlink foi utilizada para permitir o uso do sistema NTRIP em locais sem cobertura de dados de telefonia móvel. Para cada marco geodésico implantado foi confeccionado um documento, denominado de "Monografia do ponto", para a descrição da localização e situação individual de cada marco.

Figura 2: *Sistema receptor instalado sobre o marco geodésico para a obtenção de dados de rastreio GNSS e definição das coordenadas (Latitude e Longitude) e altitude.*

Os dados adquiridos foram estruturados segundo as normas da Especificação Técnica para Aquisição de Dados Geoespaciais Vetoriais (ET-ADGV) versão 3.0, a qual considera "Gruta_Caverna" como classe pertencente à Categoria "Relevo" (REL), instanciável em todas as escalas. A primitiva geométrica ponto, conforme a tabela de aquisição de objetos da ET-ADGV, foi a primitiva geométrica de representação das cavidades. Para a estruturação dos dados em concordância com a ET-EDGV foi utilizado o Complemento DSG Tools, instalado no Software QGIS, e os dados espaciais e não-espaciais foram armazenados em banco de dados geoespaciais gerenciado pelo PostgreSQL/PostGIS.

3. Resultados

As atividades de campo permitiram localizar 42 cavidades no município de Rio Branco do Sul - PR, sendo 9 delas novos cadastros e 33 atualizações/adequações posicionais de cavidades já cadastradas no CANIE (2022). Verificou-se que algumas cavidades cadastradas nas décadas de 1980 e 1990 foram destruídas parcial ou integralmente pela mineração, corroborando relatos informais e os dados passados pela Prefeitura do Município (NASCIMENTO et al., 2024).

Com os dados posicionais obtidos a partir do processamento de dados de rastreio GNSS foi possível verificar consideráveis erros posicionais em relação aos dados cadastrados no CANIE (2022). A título de exemplo, pode-se citar o erro posicional de ~670 m verificado na Gruta da Piedade (possui um único acesso), a Gruta Itaretama que apresentou erro posicional de ~1462 m, a Gruta da Boa Vista II com ~772 m. Os menores erros posicionais observados foram de ~13 m, verificados na Gruta Taici II, e ~17 m identificado no Abismo do Deslize. O médio observado foi de ~171 m.

A figura 3 apresenta a posição das cavidades em relação aos dados posicionais do CANIE (2022) e os dados posicionais definidos em campo, bem como a divergência dos limites municipais entre o mapeamento do Governo do Estado do Paraná, de 2014 e os limites definidos pelo IBGE, de 2022, fato que motivou a inclusão de algumas cavidades anteriormente pertencentes ao município de Bocaiúva do Sul - PR no cadastro do município de Rio Branco do Sul - PR.

As figuras 4 e 5, com a informação "Marco Geodésico Implantado", tiveram seus dados posicionais corrigidos ou inseridos nas bases de dados do CANIE-CECAV e CNC-SBE.

4. Discussão

Embora no CANIE (2022) conste a ocorrência de 47 cavidades no município de Rio Branco do Sul (Figura 4), algumas delas já foram destruídas parcial ou totalmente pela atividade minerária, conforme relatos de moradores, empreendedores e informações da base de dados da Prefeitura do Município. Para além disso, foi observado que as cavidades "Gruta do Garrafão" e "Buraco da Araucária" não possuem "dimensões que permitam acesso a seres humanos", e não deveriam ter sido cadastradas como cavidades naturais nas bases do CANIE e do CNC (BRASIL, 2008). As 9 cavidades identificadas e cadastradas no Município, em apenas 12 meses de trabalhos na região, demonstram o alto potencial espeleológico regional.

É importante destacar que esses resultados sintetizados na Figura 3 podem ter origem em dois aspectos comuns no cadastro de cavidades, o primeiro relacionado às tecnologias empregadas nos mapeamentos realizados anteriormente ao uso de "aparelhos de GPS" (baseados em fotografias aéreas e cartas topográficas) e, o segundo, relacionado à possibilidade de diferentes cadastros considerarem distintas entradas das cavidades como referencial para definir as coordenadas cadastradas, fato menos provável visto que o método empregado se baseou nos dados já cadastrados na base do CANIE.

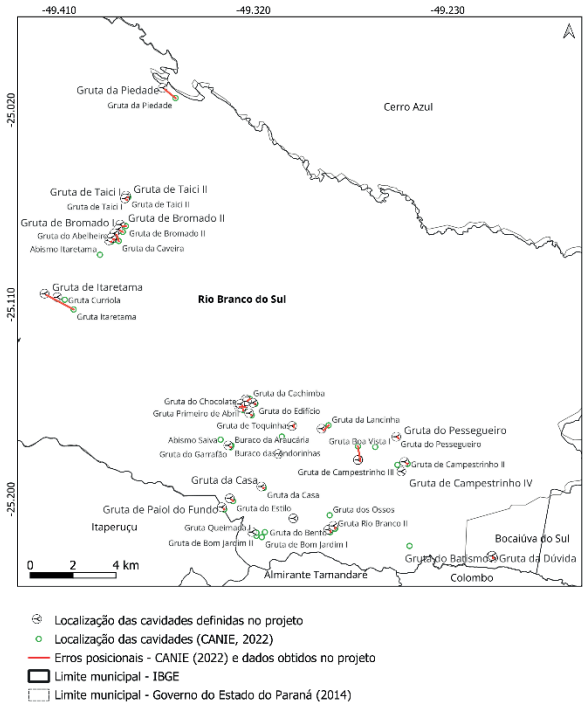

Figura 3: *Cavidades cadastradas no projeto em Rio Branco do Sul - PR.*

5. Conclusão

A avaliação, correção e compatibilização dos dados de localização das cavidades ocorrentes no município de Rio Branco do Sul - PR, tanto de cavidades descobertas durante os trabalhos de campo quanto as já cadastradas no CANIE, permitiu a atualização das informações referentes ao patrimônio espeleológico do referido município. Os métodos adotados, em espacial a implantação de marcos geodésicos na entrada das cavidades, representam a materialização de um referencial geoespacial inequívoco, útil para o uso do poder público, pesquisadores e demais agentes interessados no patrimônio espeleológico e cárstico regional.

A produção de dados acurados, compatíveis com a escala 1:1000, estruturados segundo os padrões de dados geoespaciais integráveis à INDE, ao CANIE e ao CNC, representa um avanço para as ações do poder público, especialmente para ações de fiscalização, definições de áreas de proteção e segurança jurídica, o que vai ao encontro aos objetivos do Programa Nacional de Conservação do Patrimônio Espeleológico (instituído pela Portaria MMA No 358, de 30 de setembro de 2009) - o ICMBio/CECAV.

Cavidades cadastradas no CANIE - Ano de referência 2022			
Número de registro	**caverna**	**Localidade**	**Situação da cavidade (2024) - Ampliando Rotas**
007907.00132.41.22206	Abismo de Bromado	Bromado	Marco Geodésico implantdado
007908.00133.41.22206	Abismo do Deslize	Bromado	Marco Geodésico implantdado
007940.00165.41.22206	Abismo do Erro	Bromado	Área particular não acessada (Relato de destruição)
007905.00130.41.22206	Abismo Itaretama	Bromado	Área particular não acessada
007931.00156.41.22206	Abismo Saiva	Saiva	Não localizada (relato de destruição)
028729.00199.41.22206	Buraco da Araucária	Saiva	Não deveria ter sido cadastrada (não se enquadra como cavidade)
028730.00200.41.22206	Buraco das Andorinhas	Saiva	Não deveria ter sido cadastrada (não se enquadra como cavidade)
007972.00196.41.22206	Caverna Campestrinho I (Gruta de Itacolombo)	Campestre	Marco Geodésico implantdado
007968.00193.41.22206	Gruta Boa Vista I	Boa Vista	Destruído pela mineração
007967.00192.41.22206	Gruta Boa Vista II	Boa Vista	Marco Geodésico implantdado
007974.00198.41.22206	Gruta Campina dos Pintos	Campina dos Pintos	Não localizada em campo
007903.00128.41.22206	Gruta Curriola	Itaretama	Área particular não acessada
007941.00166.41.22206	Gruta da Cachimba	Cachimba	Marco Geodésico implantdado
007952.00177.41.22206	Gruta da Casa	Zona Urbana	Marco Geodésico implantdado
007909.00134.41.22206	Gruta da Caveira	Bromado	Marco Geodésico implantdado
007961.00186.41.22206	Gruta da Lancinha	Lancinha	Marco Geodésico implantdado
007919.00144.41.22206	Gruta da Piedade	Piedade	Marco Geodésico implantdado
007957.00182.41.22206	Gruta da Toca	Zona Urbana	Marco Geodésico implantdado
007950.00175.41.22206	Gruta de Bom Jardim I	Bom Jardim	Não localizada (relato de destruição)
007948.00173.41.22206	Gruta de Bom Jardim II	Bom Jardim	Não localizada (relato de destruição)
007910.00135.41.22206	Gruta de Bromado I	Bromado	Marco Geodésico implantdado
007911.00136.41.22206	Gruta de Bromado II	Bromado	Marco Geodésico implantdado
007973.00197.41.22206	Gruta de Campestrinho II	Campestre	Não localizada (relato de destruição)
007970.00194.41.22206	Gruta de Campestrinho III	Campestre	Não localizada (relato de destruição)
007932.00157.41.22206	Gruta de Paiol do Fundo	Paiol do Fundo	Marco Geodésico implantdado
007971.00195.41.22206	Gruta de Pessegueiro	Pessegueiro	Marco Geodésico implantdado
007912.00137.41.22206	Gruta de Taici I	Bromado	Marco Geodésico implantdado

007913.00138.41.22206	Gruta de Taici II	Bromado	Marco Geodésico implantdado
007958.00183.41.22206	Gruta de Toquinhas	Toquinhas	Marco Geodésico implantdado
007906.00131.41.22206	Gruta do Abelheiro	Bromado	Marco Geodésico implantdado
007963.00188.41.22206	Gruta do Bento	Areias	Marco Geodésico implantdado
007935.00160.41.22206	Gruta do Chocolate	Cachimba	Marco Geodésico implantdado
007937.00162.41.22206	Gruta do Cotovelo	Cachimba	Marco Geodésico implantdado
007947.00172.41.22206	Gruta do Edifício	Cachimba	Marco Geodésico implantdado
007934.00159.41.22206	Gruta do Estilo	Paiol do Fundo	Marco Geodésico implantdado
028736.00201.41.22206	Gruta do Garrafão	Saiva	Não deveria ter sido cadastrada (não se enquadra como cavidade)
007938.00163.41.22206	Gruta do Pilãozinho	Cachimba	Marco Geodésico implantdado
007942.00167.41.22206	Gruta do Sapato	Cachimba	Marco Geodésico implantdado
007962.00187.41.22206	Gruta dos Ossos	Areias	Área particular não acessada (Relato de destruição)
007904.00129.41.22206	Gruta Itaretama	Itaretama	Marco Geodésico implantdado
028737.00202.41.22206	Gruta Ninho do Urubu	Saiva	Marco Geodésico implantdado
007936.00161.41.22206	Gruta Primeiro de Abril	Cachimba	Marco Geodésico implantdado
007944.00169.41.22206	Gruta Queimada I	Bom Jardim	Marco Geodésico implantdado
007949.00174.41.22206	Gruta Queimada II	Bom Jardim	Área particular não acessada (Relato de destruição)
007965.00190.41.22206	Gruta Rio Branco I	Areias	Marco Geodésico implantdado
007964.00189.41.22206	Gruta Rio Branco II	Areias	Não localizada (relato de destruição)
007956.00181.41.22206	Gruta Último Suspiro	Bom Jardim	Área particular não acessada (Relato de destruição)

Figura 4: *Cavidades cadastradas no CANIE (2022).*

Cavidades cadastradas no município de Rio Branco do Sul-PR - Edital Ampliando Rotas 2023/2024					
Código CANIE	**caverna**	**UF**	**Município**	**Localidade**	**Situação da cavidade (2024) - Ampliando Rotas**
031664.00312.41.22206	Gruta de Campestrinho IV	PR	Rio Branco do Sul	Campestre	Marco Geodésico implantdado
031665.00313.41.22206	Abismo sem Nome	PR	Rio Branco do Sul	Bromado	Marco Geodésico implantdado
031666.00314.41.22206	Boa Vista III	PR	Rio Branco do Sul	Boa Vista	Marco Geodésico implantdado
031667.00315.41.22206	Gruta do Treze	PR	Rio Branco do Sul	Paiol de Baixo	Marco Geodésico implantdado
031668.00316.41.22206	Gruta do Pinheiro	PR	Rio Branco do Sul	Cachimba	Marco Geodésico implantdado
031669.00317.41.22206	Toca do Ferrão	PR	Rio Branco do Sul	Cachimba	Marco Geodésico implantdado
031670.00318.41.22206	Gruta da Dúvida	PR	Rio Branco do Sul	Bacaetava	Marco Geodésico implantdado
031671.00319.41.22206	Fenda do Cristoph	PR	Rio Branco do Sul	Bacaetava	Marco Geodésico implantdado
031672.00320.41.22206	Gruta Norte	PR	Rio Branco do Sul	Bacaetava	Marco Geodésico implantdado
031673.00321.41.22206	Gruta dos Causos	PR	Rio Branco do Sul	Bacaetava	Marco Geodésico implantdado
031674.00322.41.22206	Gruta Olaria	PR	Rio Branco do Sul	Olaria	Marco Geodésico implantdado

Figura 5: *Cavidades cadastradas no projeto em Rio Branco do Sul-PR.*

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Unity is strength: "Speleoteca": the shared catalogue of italian speleological libraries

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Abstract

In 2007, the "Centro Italiano di Documentazione Speleologica – Biblioteca Franco Anelli" (CIDS) promoted the creation of "Speleoteca", a shared digital catalogue of Italian speleological libraries. Speleoteca is currently gathering 24 speleological libraries of clubs and associations, covering eleven regions from northern to southern Italy. The database is available online by an OPAC (Online Public Access Catalogue), which allows simple or advanced research of about 40'000 titles of monographs, serials, collections and articles. Each element is associated with authority files and subjects, which follow the Speleological Subject Classification (SSC) proposed by the Union Internationale de Speleologie (UIS). The project is constantly growing with the entrance of new libraries each year, and the collaboration with other institutions such as Grottocenter and Wikicaves.

1. Introduction

One of the fundamental aspects that characterized the speleological activity since its origin is documentation. The exploration of unknown territories in the world beneath our feet is followed (or should be followed) by the production of documents able to describe caves and caving such as: activity reports, topographic surveys, photographs, descriptions of caves, expeditions' reportage, etc.

Over the years, the complex and varied world of documentation related to caves and karst has found space between the pages of specialized magazines and bulletins, often self-produced and printed by the speleological associations themselves.

Publication of journals, monographs and thematic volumes have constantly characterized the editorial activity of speleologists and caving associations. All these documents represent a treasure of invaluable knowledge that can be used to study, understand and interrogate a karst area; plan activities in a new territory; know the "state of the art" of a specific place and who and what was done before.

If this is true, on the other hand speleological libraries are rarely perceived as «technical» places to find useful information and data. Even worse: speleological libraries are often «non-places», like dusty shelves or boxes full of books archived in a closet or the warehouse of a caving club. Despite being physically stored and conserved, without an interrogable and accessible catalogue these materials remain unknown to the public and the speleological community.

In an increasingly digital world, the frequentation of speleological libraries, albeit with some exceptions, is decidedly negligible. Despite this, they represent archives of texts that could be mostly rare, or unique, since their difficulty to be found in other institutions or public repositories. Thus, speleological libraries play a fundamental role in preserving, transmitting and making this heritage accessible.

2. The project

Aiming to fulfill these goals, on the far-sighted initiative of the "Centro Italiano di Documentazione Speleologica – Biblioteca Franco Anelli" of the "Società Speleologica Italiana" (SSI), the Speleoteca project was born in 2007. It is a digital catalogue, available online, which actually permits the consultation of around 40'000 titles of speleological publications. The catalogue is shared and populated by the activity of 24 speleological libraries spread across the Italian territory. The list of the libraries that collaborate to the project is summarized in Figure 1. Most of the libraries are currently active, whereas few of them have temporary stopped the cataloging activities.

Library Name	Speleological Association	City	Region
Biblioteca Gruppo Speleologico Cudinipuli	Gruppo Speleologico Cudinipuli	Cosenza	Calabria
Biblioteca Gruppo Speleo Alpinistico Vallo di Diano	Gruppo Speleo Alpinistico Vallo di Diano	Pertosa	Campania
Biblioteca Gruppo Speleologico "Natura Esplora"	Gruppo Speleologico "Natura Esplora"	Summonte	Campania
CDS - Biblioteca "F. Allocca"	Federazione Speleologica Campana	Corleto Monforte	Campania

Library Name	Speleological Association	City	Region
Biblioteca "Luigi Fantini"	Gruppo Speleologico Bolognese	Bologna	Emilia-Romagna
Biblioteca Gruppo Speleologico Ferrarese	Gruppo Speleologico Ferrarese	Ferrara	Emilia-Romagna
Biblioteca Gruppo Speleologico "G. Chierici"	GSP "G. Chierici" Reggio Emilia	Reggio Emilia	Emilia-Romagna
CIDS - Biblioteca "Franco Anelli"	Società Speleologica Italiana	Bologna	Emilia-Romagna
Biblioteca Commissione Grotte E. Boegan	Commissione Grotte E. Boegan	Trieste	Friuli-Venezia Giulia
Biblioteca Gruppo Triestino Speleologi	Gruppo Triestino Speleologi	Trieste	Friuli-Venezia Giulia
Biblioteca Società Adriatica di Speleologia	Società Adriatica di Speleologia	Trieste	Friuli-Venezia Giulia
Archivio Speleologico "A. Pastorelli"	n.d.	Sanremo	Liguria
Biblioteca Speleo Club Ribaldone	Speleo Club Ribaldone	Genova	Liguria
Biblioteca Gruppo Grotte Milano	Gruppo Grotte Milano	Milano	Lombardia
Biblioteca Gruppo Speleologico Piemontese	Gruppo Speleologico Piemontese	Torino	Piemonte
Biblioteca Gruppo Puglia Grotte	Gruppo Puglia Grotte	Castellana Grotte	Puglia
Biblioteca "Franco Todde"	Federazione Speleologica Sarda	Iglesias	Sardegna
Biblioteca Gruppo Ricerche Speleologiche "E.A. Martel" Carbonia	Gruppo Ricerche Speleologiche "E.A. Martel" Carbonia	Carbonia	Sardegna
Biblioteca Gruppo Speleologico Archeologico Apuano	Gruppo Speleologico Archeologico Apuano	Massa	Toscana
Biblioteca Gruppo Speleologico Pistoiese	Gruppo Speleologico CAI Pistoia	Pistoia	Toscana
Biblioteca Gruppo Grotte "Pipistrelli"	Gruppo Grotte "Pipistrelli" CAI Terni	Terni	Umbria
Biblioteca Gruppo Speleologico Perugia	Gruppo Speleologico CAI Perugia	Perugia	Umbria
Biblioteca "F. Dal Cin"	Gruppo Grotte Treviso	Treviso	Veneto
Biblioteca Gruppo Speleologico Padovano	Gruppo Speleologico CAI Padova	Padova	Veneto

Figure 1: *List of the libraries in the Speleoteca project, associated with their speleological association, city and region.*

Except one, all libraries are managed by speleological associations (e.g., clubs, groups, federations). Few libraries (4) have small heritage (< 1000 volumes). The majority (12) have medium-sized consistency (1000-5000 volumes). Seven libraries have up to around 10'000 volumes, and only one, the "Biblioteca Franco Anelli", has a larger heritage.

About half of the libraries participating in the project are currently equipped with a reading station, whereas some of them (10) still lack the complete collocation of the volumes on shelves, meaning that not all books are easily available for consultation.

Ten libraries (42% of the whole) permit loans both to the members of the association and the public, or to specific audience (e.g., researchers, academia, speleologists), while the majority (12) only to the associations' members. The remaining libraries do not provide loans.

The Speleoteca catalogue was originally deriving from the one of the CIDS "Biblioteca Franco Anelli", which actually comprises around 30'000 monographs and 1500 serials. In the early 2000s, the "Franco Anelli" library joined the national SBN catalogue ("Sistema Bibliotecario Nazionale"), following the international standards and procedures to catalog bibliographic materials. This prestigious acknowledgment permitted the library to gain visibility and join the online OPAC of the "Unified libraries of Bologna" (UBO).

In 2007 the entire catalogue, originally handled by Access software, has been transmigrated to a commercial software specifically developed for libraries, adopting the basic standard cataloging procedures of SBN: the Bookmarkweb.

This first online catalogue opened the possibility to be populated not only by a single library, but multiple collections. It was the birth of Speleoteca, with other three libraries joining the shared catalogue.

In 2020, the Bookmarkweb software was abandoned to transmigrate the Speleoteca catalogue to a new, more interactive and aesthetic software: ClavisNG by Comperio.

The new software permits a complete customization of the OPAC website (Figure 2) and guarantees a close dialogue with SBN. Furthermore, it allows the storage of digital files, book covers, and other documents. The entire Speleoteca OPAC is available both in Italian and English language.

Actually, 24 libraries have joined the project and over 30 specialized users have the access to the software, with different "levels" (and permits) of cataloging based on their experience.

The project aims to create a network of librarians that can share knowledge and give practical support each other. At least one or two meetings are organized each year to dialogue on eventual problems related to cataloging and software procedures, exchange experiences and plan future activities.

One of the objectives of the project is also to valorize the single libraries, coordinating education encounters, courses, events and promoting social media divulgation.

The valorization of Italian speleological libraries can be further enhanced with a programmatic plan to make them visible to the whole citizenship, for example by organizing events open to the public; stimulating the cooperation with public institutions, SBN and regional networks; digitalizing rare documents and archives, that can be made accessible online. It is worth mentioning that four Speleoteca's libraries own ancient volumes edited before 1830. These rare items and books, published prior to the modern organization of editorial print, are true masterpiece that should be better divulgated. All these activities, mostly conducted by volunteers, require huge amount of time and dedication.

In fact, the "sad" truth is that the 60% of the libraries count only on one (single) operator, while just 10 libraries on teams up to 2 or 3 volunteers. Therefore, the Speleoteca project aims to be not only a shared catalogue, but also an assembly of people where co-working and co-operation can reduce difficulties and limitations.

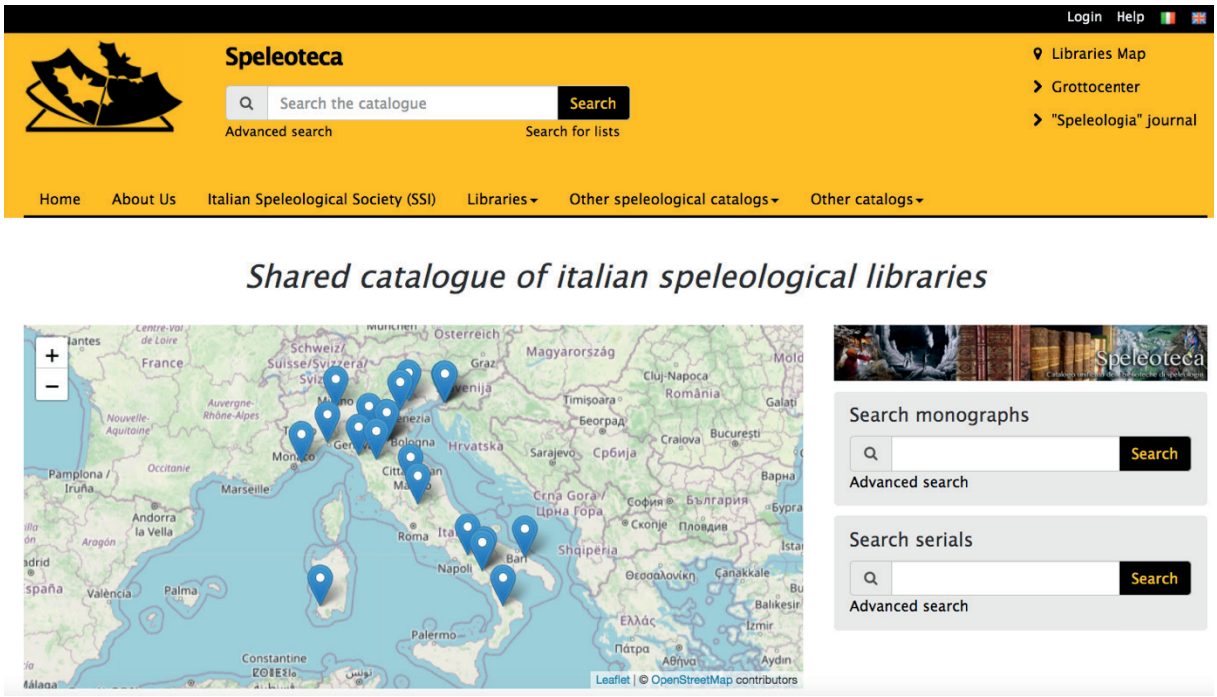

Figure 2: *Speleoteca's homepage. The OPAC can be navigated both in Italian or English language.*

3. Speleoteca, an Online Public Access Catalogue

The Speleoteca catalogue, managed with the ClavisNG software developed by the Italian company Comperio, can be accessed online on the website <https://speleoteca.biblioteche.it/>.

This shared catalogue allows team working among different librarians and guarantees a continuous exchange of knowledge, as well as conformity to the Italian bibliographic guidelines for catalographic description issued by the "Istituto Centrale per il Catalogo Unico" (ICCU) - Italian Ministry of Culture.

The main and fundamental advantage of a shared catalogue is that all the descriptive work performed by a librarian, can be 'used' and implemented by the other colleagues, without the need of producing a new catalog description ex-novo. Furthermore, the software dialogues with the SBN database, allowing the import of resources that already exist in the national catalogue.

The search options for the users are both "simple" and "advanced" modes, and can be filtered by classes based on the international Speleological Subject Classification (SSC), proposed by the UIS, authority files and qualifications (language, date of publication, country) (Figure 3).

Every resource in the database is distinguished by its bibliographic level into: monograph, serial, article (analytic), and collection. The search options can be limited to interrogate each specific bibliographic level.

Authority files involve: authors, arguments, entities, places, subjects, uniform titles. The authority control permits the users (and catalogers) to refer to unambiguous terms/subjects and make consultation easier.

Multiple access points, links and search keys are available to the users, as well as the possibility of saving their own searches and preferred items, logging as clients.

The libraries have also the possibility to store digital files, that can be made accessible or not to the public freely or under specific licenses (CreativeCommons or others). Also, if wanted, each library can implement its own loan system digitally.

Finally, the Speleoteca's OPAC can be customized choosing between different templates, layouts and sub-menu, and it is constantly updated. The homepage and the pages of specific libraries can host "digital shelves" to show thematic resources (for examples organized by latest arrivals, by subjects, authority files, collections or custom chosen) in dynamic slide-bars.

4. Conclusions and future perspectives

Despite being a powerful tool, it is important to underline that the Speleoteca catalogue, resulting from the migration of a rather simple database, has still numerous gaps: much information from old cataloging is incorrect, various fields are incomplete or require continuous retrieval information. Most important, many serial resources (bulletins, journals) still lack the entry of the single issues and analytical titles.

The necessary work requires the collaboration of various subjects and skills, that is why a shared catalogue is needed: working together to reduce everyone's work and to guarantee conformity to the international bibliographic standards, today a fundamental requirement for archives and thematic libraries.

Sadly, the situation highlighted in the previous chapters testify that much is still to be done to make speleological libraries attractive not only to the general public, but especially to the speleological community. This is the most important challenge to be faced in the next future.

The progressive (and inevitable) path to digitalization and web-based diffusion of cultural heritage (both of books and non-book materials) requires being constantly updated with the most recent guidelines and standardized procedures, especially to avoid waste of resources and time.

Over the years, the librarians participating in the Speleoteca project have developed a concept of «common work», not only perceived as the sum of individuals, but also as people acting animated by the same spirit.

In progressive growth, more and more speleological associations have joined the project, with the entry of 6 new libraries in the last two

years, and the planning of future collaborations with the UIS (Grotto-Center). The future will reserve continuous challenges and will require a continuous turnover to feed this project. In order to make speleological libraries known to the vast community of scientists, authorities and specialists (but also speleologists themselves!), it is essential to plan long-term actions in the spirit of conservation and divulgation.

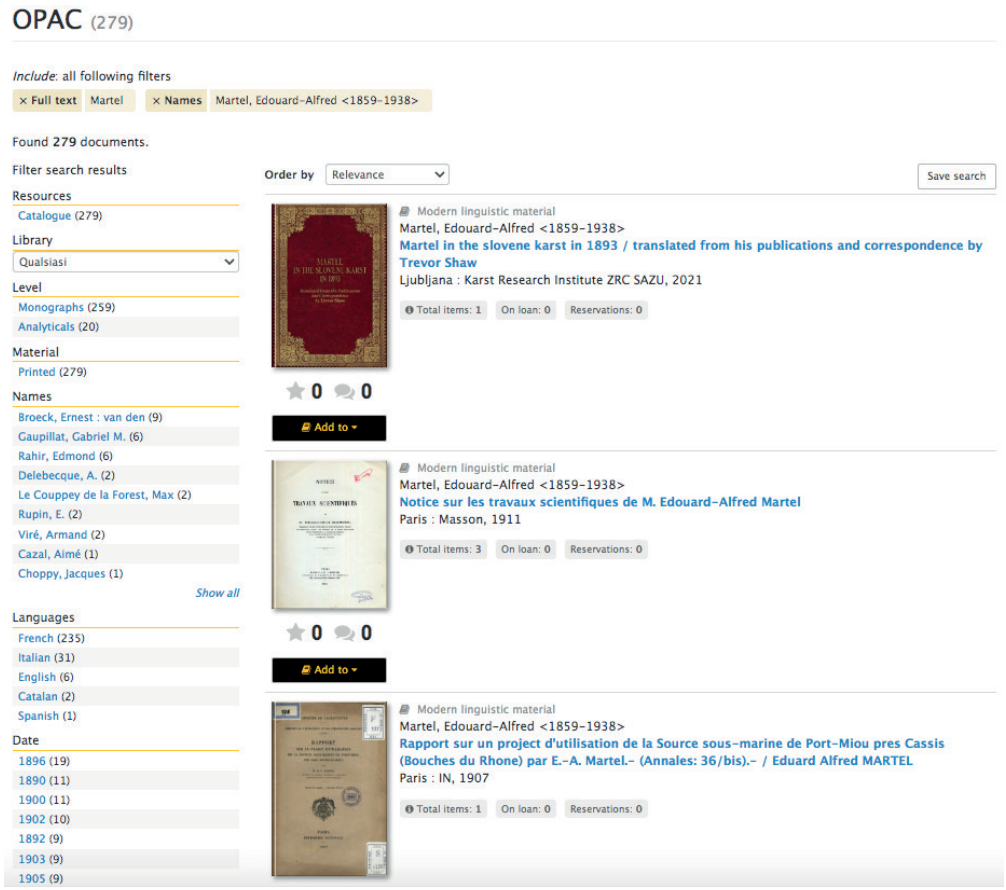

Figure 3: *Example of the search interface for the authority file (name): "Martel, Edouard-Alfred" in the Speleoteca's catalogue.*

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Image analysis and change detection from laser scans to characterise mobile sediments in caves

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Abstract

The distributed hydraulic properties of fluvio-karstic systems affect the spatial distribution and granulometry of clastic sediments in cave streams. Products of bedrock corrasion and plucking are entrained in the flow as bedload according to the balance of forces exerted overhead by the moving fluid, the basal-shear stress along the reach of the cave stream being function of channel gradient, sediment size and water depth. Laserscan surveys are increasingly used to reconstruct the detailed spatial distribution and granulometry of cave river deposits and evaluate their mobility. On the one hand, repeated surveys at different epochs allows for significant change to be detected spatially, proving sediment mobility, as well as quantified by providing a distance measure between volume integration. The cumulative grain-size distribution curve can be used to characterise the different riverbed facies and constrain the hydrodynamic properties of the cave stream. Here we investigate these fluvio-karst systems spanning several hundred metres each, in a cave system located in the Ardèche (Southern France). Using handheld LiDAR mobile mapper measurements, we acquire georeferenced pointclouds for two epochs to produce a detailed geomorphologic map of 40 m reach of the underground river Claysse. We also evaluate a blend of topographic indicators to produce a set of greyscale images suitable for automatic clast recognition and sizing, finding that the openness blend is best suited to automatic grain size extraction. We then adapt and leverage existing image-analysis workflows to extract the granulometry of the channel lag deposits and use the sediment size distributions to compute sediment entrainment thresholds in this cave, which range from 25-50 N m2.

1. Introduction

Sediment movement in cave conduits is mostly episodic and related to storm events (HERMAN et al., 2012). Past studies of cave stream reaches suggest that most of the bedload is mobilised by annually recurring flood events (DOGWILER & WICKS, 2004). Sediment fluxes in and out of cave river passages are modulated by climatological settings and therefore, in (seasonally) active karst conduits, they appear to be in a constant state of readjustment (HERMAN et al., 2012). From a physical perspective, it is stream competence, in the form of basal shear stresses exerted by the water flow on the pebbles which dictates which fraction of the sediments are entrained in the bedload and mobilised. The critical shear stress (τc) necessary to entrain particles is empirically derived from the Shields parameter, for fully turbulent flows (DINGMAN, 1984) and varies linearly with the median grain size (D_{50}), the density difference between clast and fluid, as well as the local acceleration due to gravity.

$$\tau_{c50} = \Theta_{crit}(\rho_s - \rho_w)gD_{50} \quad (1)$$

Others relate the critical shear stress directly to a grain size (namely the 90th percentile D90) with an empirical power-law fitted to cave sediment data (HERMAN et al., 2012):

$$\tau_{c90} = 0.341\ {D_{90}}^{1.021} \quad (2)$$

Both these estimates are used to characterise the flow conditions necessary to entrain clasts, given the geometry measured at the site. Standard values for parameters used in Eqs. 1 & and 2 are: θ_{crit} = 0.0044, ρ_s = 2600 kg m3, and ρ_w = 1000 kg m^3. High water stages, i.e., increasing water depth of the flows tends to mobilise larger sediment fractions. Conversely, decreasing maximum flood discharges under changing climatic conditions could lead to some fractions becoming immobile at present.

In geosciences, multitemporal LiDAR acquisitions are a well-known methodology to detect and quantify surface or volume changes and deformation. This approach is equally valid to investigate the issue of sediment mobility in karstic conduits in a quantitative manner by repeatedly acquiring the evolving sediment deposit geometries. Approaches to detect change between two epochs at the same outcrop fall in several categories, namely differencing Digital Elevation Models or computing 3D cloud-to-cloud distances e.g., with the M3C2 algorithm developed by LAGUE et al. (2013).

To better understand the competence of the caves stream at present, it is necessary to determine the grain size distributions in the river bed facies. To achieve this, known point counting methods (Wolman's) can be confronted to image analysis and automatic extraction of grain size in what is known as numerical sieving. While for surface rivers, the analysis of well-lit orthophotos has become a routine exercise, this is not the case for in-cave sedimentary deposits. The surface models acquired by lasergrammetry may lack useful colour information in the visible light spectrum. However, various strategies for highlighting topographic features may be employed to recreate a greyscale raster image which is directly usable in an image-segmentation workflow for numerical sieving. Specifically, one has to find a combination of topographic indicators which yield significantly different pixel values for the body of clasts and the interstices. Since bedload is often made up of somewhat rounded clasts, estimates of terrain convexity or concavity are well suited to this segmentation. The outlining of small topographic features has

gathered interest in the archaeological community (DONEUS, 2013), with measures such as local relief modelling or sky view factor calculations, local topographic dominance, etc. Yet others, like positive and negative topographic openness, used together also appear well suited to the segmentation of clasts and interstices from a topographic image (YOKOYAMA et al. 2002).

To test this approach, we use a study site in southern France where sediment mobility in karst conduits could be captured around a series of flood events. The open syncline of St André du Cruzières, Ardèche is heavily karstified. One perennial spring, Moulin de Pichegru, drains the 40 km2 watershed. The seasonally running river Claysse drains a non-karstic watershed before sinking at the Goule de Sauvas, representing the contact with carbonate lithologies. A total of 38 km of kartic conduits have been explored in the cave systems therein including 22 km in the Peyrejal - Sauvas - Cocalière system (ARNAUD, 2023). Allogenic recharge over Carboniferous to Triassic, non-karstic catchments (BERGER et al., 1988) injects a considerable amount of non-soluble bedload in the active branches of the system, namely Sauvas, Condamines, Cocalière and Peyrejal. Here we focus on a 40 m long reach of the Cocalière branch of this karstic system. The area is dominated by riffle and pool morphology (MONTGOMERY & BUFFINGTON, 1997) at altitudes ranging between 171 and 178 m above sea level a.sl. In normal conditions, the cave passage is completely dry, and the floor is almost entirely armoured by a sediment deposit comprising gravel to cobble grade lag bars corresponding to the river thalweg facies, as well as silty to sandy dunes corresponding to the less energetic slack-water facies deposited in the waning stage of a flood event (FARRANT & SMART, 2011). In dry conditions, the water table is confined to a lower cave level below this branch, and the water resurges at the Moulin de Pichegru directly.

Between 01/2024 and 06/2024, the cave passage filled with a seasonal stream on four occasions, remobilising sediments up to cobble-grade. We use a combined approach involving change detection from lasergrammetry and image analysis to quantitatively describe the flow conditions during high water stages of a flooding event in a karst conduit.

2. Materials and methods

We scanned a section of the Cocalière branch on two occasions, bracketing a flood event and quantify sediment balance using cloud-to-cloud distance using the M3C2 algorithm. Terrestrial or mobile LiDAR scanning is well suited to the fast acquisition of detailed point-clouds and it is a widespread tool for modelling and visualising cave geometry (JAILLET et al, 2014). Scenes acquired with mobile or tripod mounted scanners (Leica BLK2GO and Faro, respectively) were assembled by matching the two immobile portions of the point clouds, namely wall and flowstone surfaces. For this, the iterative closest point algorithm implemented in CloudCompare was used to find the rigid transformation matrix minimising the registration error (BESL & McKay., 1992). This transformation matrix was then applied to map one of the scenes onto the other. We then computed cloud-to-cloud distance measurements on the repeated scan scenes using CloudCompare's implementation of the M3C2 algorithm (LAGUE et al. 2013). The essence of the algorithm is to proceed point by point, and within a search radius (normal scale, Table 1) evaluating a normal vector i.e. the orientation of the tangent plane to the surface resolved by one point-cloud. Within a given neighbourhood cylinder (search scale, Table 1), nearby points of both source and target scenes are projected onto the normal vector and the distance between the two distributions' respective centres of mass is stored as the M3C2 distance (LAGUE et al. 2013). By providing a registration error between two scan epochs, an estimate of significant change at a confidence level of 95% is also computed. In the following, cloud 1 refers to the first scan epoch (pre-flooding), while cloud 2 refers to the second.

parameter	value / range
Registration error	0.014 m
Registration error enabled	True
normal scale	0.05 m
search scale	0.025 m
cloud 1 subsampling scale	0.01 m

Table 1: *presets for the M3C2 distance calculation.*

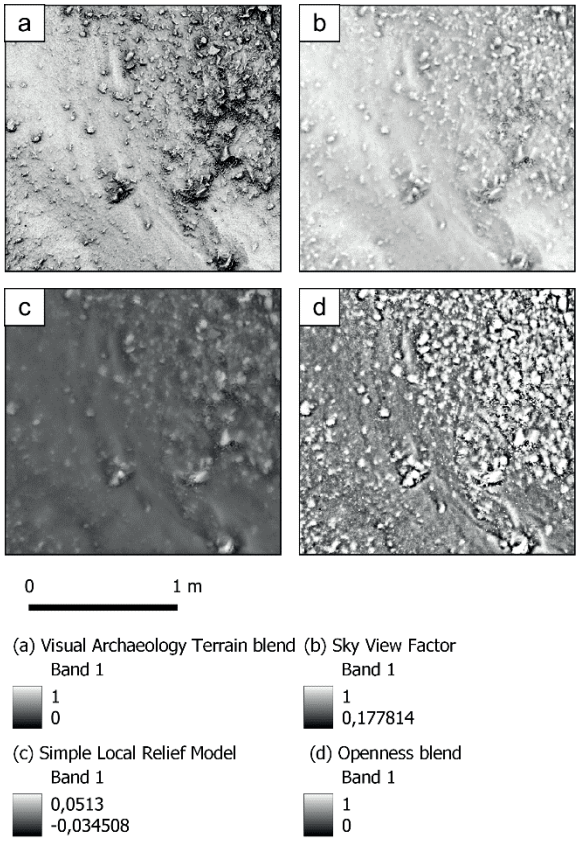

Figure 1: *Comparison of topographic visualisations (KOKALJ et al., 2016).*

We also carried out a grain size analysis on the sediment deposits within the cave using image analysis techniques, specifically using a blend of positive and negative openness (see definition below). Fig 1. Shows a set of other topographic indicators which are routinely used to pick out micro-relief elements from surrounding terrain. Of these, the openness blend has the following desirable properties for automatic segmentation: the inside of clasts has uniformly high pixel values, while interstices and low convexity terrain, like slopes made of sub-pixel, sandy clasts have uniformly low values. This ensures that the extraction algorithm has both few false positives and false negatives.

The openness topographic indicator is based on the calculation of the complementary zenithal or nadiral angle to the maximum elevation angle in a given radius surrounding a given pixel for positive and nega-

tive openness respectively YOKOYAMA et al. (2002). The computation is done within a moving kernel, looking in 8, 16 or 32 possible directions (DONEUS, 2013). The 1D equivalent is shown in Fig. 2. Here we use the implementation of this algorithm in the Relief Visualization Toolbox (RVT, KOKALJ et al., 2016).

In this work, we decided to compute a raster DEM of the cave floor at resolution of 0.5 cm / pixel. We then computed positive and negative openness and blended by alpha compositing yielding an 8-bit greyscale image using the presets detailed in Table 2 on the RVT.

parameter	value / range
Layer 1	positive openness
number of directions	32
noise removal	3 (high)
maximum radius (pixels)	10
linear normalisation	13° – 98°
opacity (%)	50
Layer 2	negative openness
number of directions	32
noise removal	3 (high)
maximum radius (pixels)	10
linear normalisation	68° – 98°
opacity (%)	100

Table 2: *presets for the openness blend used for automatic clast size extraction.*

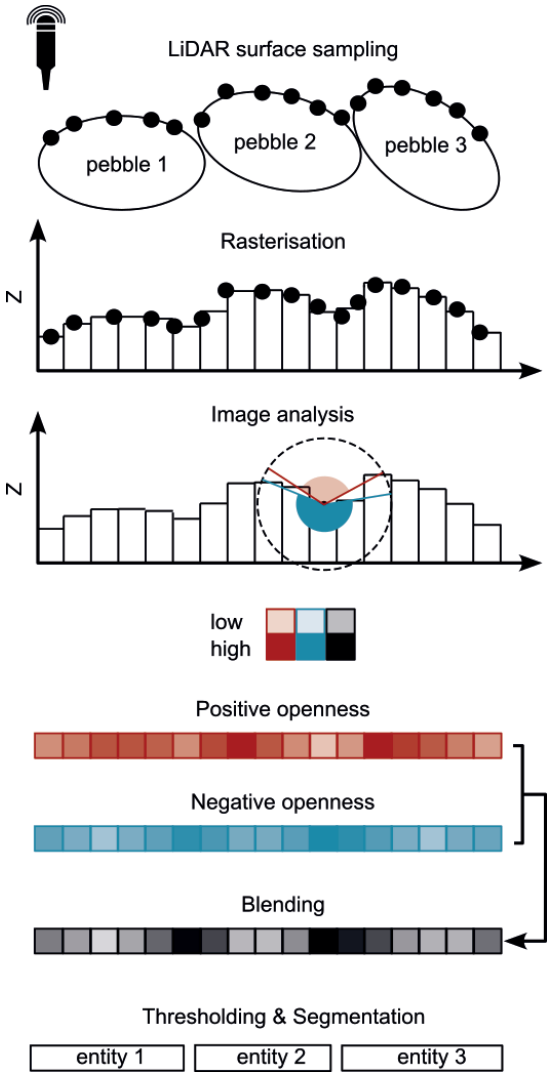

Figure 2: *Workflow for the automatic segmentation of pebbles from a Digital Elevation Model using the Topographic openness measures and image blending.*

To extract grain sizes from a greyscale image, we used the *open-cv* python library to first threshold the pixel values and identify foreground and background as the resulting Boolean array. The foreground patches are then uniquely categorised and each clast is represented by a contiguous pixel region.

The size of the regions is estimated by finding the best-fitting ellipse with area equal to that of the identified pixel region. The length of the semi-minor axis is then taken as the representative diameter of the clast found on the picture. The main assumption is that in a top-down view of imbricated sediments, the shortest axis (c) of a clast is hidden, while the medium – and representative - (b) and long (a) axes are visible. The cumulative distributions of semi-minor axes from the raster image remain areal counts, so we convert each grain size bin to volume fractions using standard χ-weighting (Eq. 3, STROM et al., 2010).

$$n_{ai} = \chi n_i = e^{\beta \ln(2)\overline{\Psi_i}} n_i \quad (3)$$

with $\overline{\Psi_i} = \frac{\Psi_i + \Psi_{i+1}}{2}$ and β = 2 as weighting parameter. For each generated image, N represents the total number of clasts identified. $\Psi_m = \log_2 D_m$ denotes the size for which the m-percentage of particles are finer. Using these distributions, a sorting coefficient can be calculated using:

$$\sigma = \Psi_{84} - \Psi_{16}$$

The greater the difference between the 16th and 84th percentiles of the grainsize distribution is, encapsulated by σ, the less sorted the sediment deposit.

3. Results

In the following case study, mainly horizontally oriented digital elevation models, the calculated positive (negative) M3C2 distances between cloud 1 and 2 (LAGUE et al., 2013) can be interpreted as elevation gains (losses), correlated with net deposition (removal) of sediment. Using the digital elevation model, the visual archaeology terrain blend was produced using the Relief Visualization Toolbox (KOKALJ et al., 2016). This image (shading on Fig 2.) reveals that the traces left by passing cavers (footprints on a gravel bank) were erased by the flooding event. Large tree trunks or branches lying in the middle of the passage were removed by the flooding event.

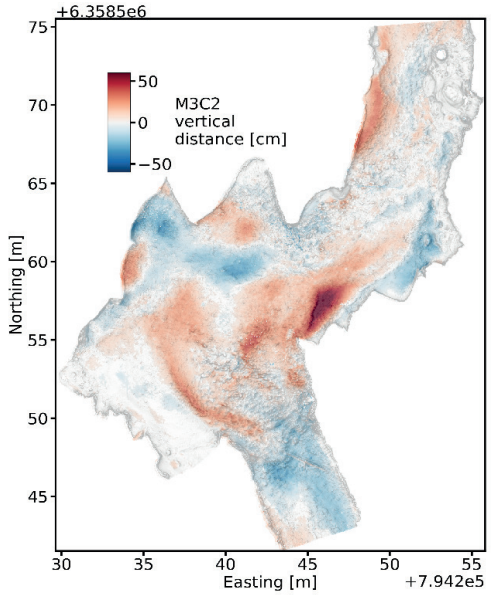

Figure 3: *positive (red) and negative (blue) cloud to cloud distance map according to the CloudCompare implementation of the M3C2 algorithm (LAGUE et al. 2013).*

On Fig. 3, the spatial distribution of positive and negative topographic change between the two scan epochs is clearly non-random. For instance, sediment deposition formed a gravel bar in the inside of the bends of the passage, where flow velocities were presumably lower than in the outer bends. Conversely, elevation loss and sediment removal occurred in the outer bends of the passage, as well as at the foot of a rise to the south of the passage. Assuming no significant change in sediment porosity, spatial integration of the M3C2 distance over the area allows a volumetric sediment balance estimate to be made. This corresponds to the signed-volume between the two surfaces. Specifically, significant change was detected over 73 % of the study area, yielding a net deposition of 6.4 m^3 over an area of 122 m^2.

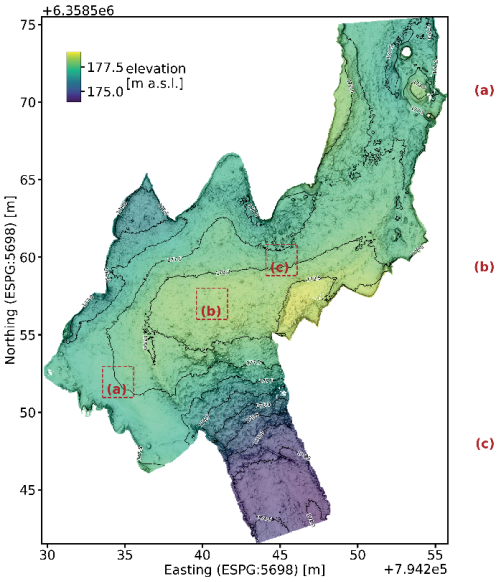

Figure 4: *Digital elevation model of the study area and insets corresponding to the different river facies (a) slackwater, (b) gravel bar, (c) thalweg.*

We present the results of different visualisation styles in Fig1, which corresponds to the inset (a) on Fig 2. The intermediate steps and results of automatic grain size extraction on the other two square regions, each covering 4 m^2 areas are given on Fig. 4.

Numerical sieving allows a quantitative comparison between the distribution percentiles for samples a, b and c, using a Bootstrap approach to detect whether the distributions are significantly different. Using the automated image segmentation, we find that slack water facies in (a) are characterised by large areas where sub-pixel sandy bars are free of any identified pebbles (Fig. 5). Channel facies (b) is defined by more sorted sediment, deposited at internal bends of the cave channel. Channel thalweg facies (c) is well defined by coarser cobble-grade sediment 35, but it is apparently less-well sorted than (b), indicating that the finer pebbles may not have been effectively winnowed out by the stream (FARRANT & SMART, 2011).

location	N	$\mathbf{D}_{50}$	$\mathbf{D}_{90}$	σ	τ_{c50} [Nm^{-2}]	τ_{c90} [Nm^{-2}]
(a)	311	38 ± 1	60 ± 1	0.96 ± 0.01	26.4 ± 0.2	21.1 ± 0.2
(b)	530	55 ± 1	109 ± 5	1.2 ± 0.05	37.8 ± 0.7	35 ± 2
(c)	446	62 ± 3	158 ± 9	1.6 ± 0.1	43 ± 2	53 ± 4

Table 3: *results from automated pebble counting and numerical sieving given as mean and standard deviation estimates of 2000 Bootstrap samples.*

The simple application of eqs. (1) and (2) to back-calculate the basal shear stresses yields some expected results (Table 3). For instance, the minimum basal shear stress necessary to have moved the 90th percentile of clasts in the coarsest and least sorted facies (c) corresponding to the river thalweg, is N m2.

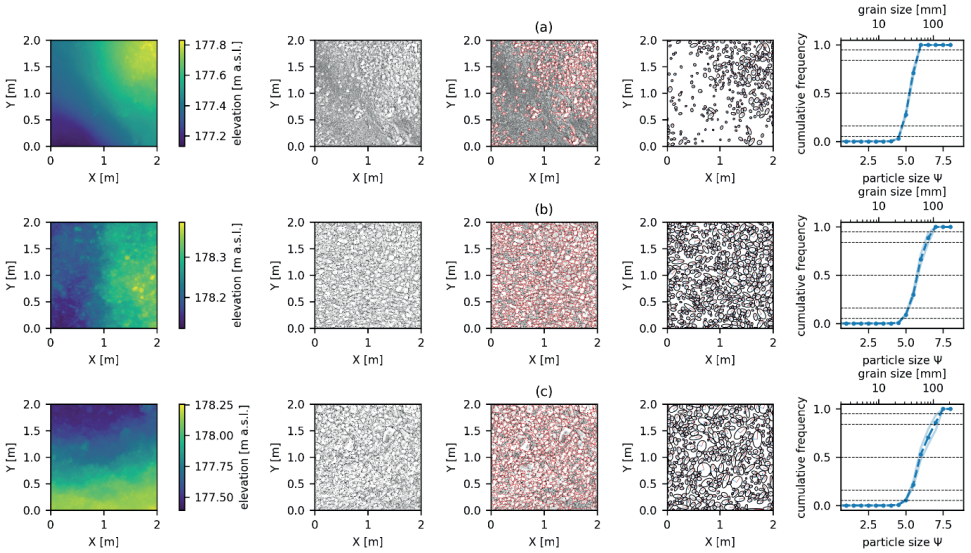

Figure 5: *Examples of the intermediate steps during automatic grain sizing from a digital elevation model.*

4. Discussion

The rationale behind the openness indicators was to emphasise micro-relief elements from the surrounding landscape and make them clearly distinguishable from the terrain. It is free of directional bias and its two variants allow the delineation of both convex pebble tops and concave interstices. Other prominent terrain analysis measures that achieve this purpose are the portion of visible sky or Sky View Factor (SVF), as well as Local Relief Modelling (LRF), which both have the advantage of being related to meaningful physical quantities. However here we discuss them in relation to their usefulness for producing easily segmented greyscale images. SVF uses zenith angles above the horizontal plane, so the general slope of the terrain is preserved in a SVF map, making it more intuitive to read and interpret, but a poorer choice for automatic segmentation (DONEUS, 2013). With openness, clasts lying on a tilted plane will have a similar signature to those lying on a horizontal plane. On the other hand, LRM involves removing general topography by subtracting a low-pass filter in iterative manners; it therefore provides a map of height differences between micro-features and local terrain. The visual comparison of all three measures in Fig. 1b, c & d respectively highlights the suitability of the openness blend in generating an easy-to-threshold image clasts irrespective of the general trends of the surrounding terrain, and irrespective of clast sizes. In contrast, the sky-view factor image generally has equally high values for flat, unobstructed terrain, as for the top of clasts, so there is a high risk of falsely identifying these large regions as clasts. The local relief model retains the height anomaly information, and larger clasts therefore show up as spots with high values, whereas smaller clasts lying almost flush with the surrounding surface are characterised by pixel values of zero.

The combination of grain size and analysis and significant topographic change also provides additional constraints on the hydrodynamic properties of the cave stream in flood conditions, with respect to the mobility of sediments in cave streams. At the Cocalière system, the stage of the underground Claysse river during sub-annually recurring floods is high enough to mobilise large cobbles, and therefore clearly allows the through-put of sediment derived from non-karstic catchments upstream of Goule de Sauvas, all the way to the surface at the Event de Cotepatière. The mean transit time of such sediments in their approximately 5 km underground course remains to be modelled.

5. Conclusion

The workflow presented here allows conclusive characterisation of sediment deposits whose clast sizes is chiefly made up of sizes above 1 cm. Clear differences in median size and sorting coefficients allow the various cave stream facies to be distinguished on the basis of a topographic model of the cave floor. Moreover, coupling this with a map of significant topographic change allows for the minimum stress exerted by the overlying fluid during a flood event which mobilised the sediment to be estimated. Since it is based on 2.5D visualisations however the image segmentation technique remains a 2.5D approach and further work should emphasise the automatic segmentation of individual clasts from the point cloud itself, which would allow 3D ellipsoids to be fitted to the sets of points representing each clast.

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Los relevamientos topográficos en el sistema cavernario Cuchillo Curá, Neuquén, Argentina

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Abstract

TOPOGRAPHIC SURVEYS IN THE CUCHILLO CURÁ CAVE SYSTEM, NEUQUÉN, ARGENTINA. The "Cuchillo Curá" Cave System is located in the province of Neuquén, Patagonia Argentina, and stands out for being the largest cave system in Argentina. It houses a great diversity of cave fauna and has concretions of great scenic beauty. The history of its topographical survey dates back to 1982 with the first works of the Argentine Speleological Group (GEA), sustained during a research project on the site that, except for some interruptions, extended for more than 40 years. In different annual campaigns, generally in the summer, about 50 members of GEA participated in these works and local speleologists collaborated. This work reviews the topographic and cartographic work throughout those years.

Resumen

El Sistema Cavernario de Cuchillo Curá se ubica en la provincia del Neuquén, Patagonia Argentina y se destaca por ser el sistema cavernario más extenso de Argentina, por albergar una gran diversidad de fauna cavernícola y tener concreciones de gran belleza escénica. La historia de su relevamiento topográfico se remonta a 1982 con los primeros trabajos del Grupo Espeleológico Argentino (GEA), sostenidos durante un proyecto de investigación en el sitio que, salvo algunas interrupciones, se extendió por más de 40 años. En distintas campañas anuales, generalmente de verano, participaron de estos trabajos unos 50 miembros de GEA y colaboraron espeleólogos locales. En este trabajo se reseña la labor topográfica y cartográfica a lo largo de esos años.

1. Introducción

El sistema de cavernas Cuchillo Curá se ubica en las estribaciones del cordón homónimo, en el Departamento Picunches, en el centro oeste de la Provincia del Neuquén (Fig. 1). Se localiza a unos 13 km al Sur de la localidad de Las Lajas, a una altitud media de 910 metros sobre el nivel del mar. Se encuentra resguardado en el Área Natural Protegida Cuchillo Curá (ANPCC) creada en 2003 (decreto provincial Nº 161).

El sistema cavernario se desarrolla con un rumbo general este – oeste en rocas carbonáticas de edad mezosoica y se encuentra conformado por cuatro cavidades: la cueva de los Cabritos, cuya entrada se encuentra bloqueada por depósitos de dunas desde el año 2001; las cavernas del Gendarme y del Templo, que se comunican por galerías; y la caverna del Arenal (ARDITO et al., 2022).

Figura 1: *Cartografía de la de Los Cabritos. GEA, 1986.*

2. Metodología

Los trabajos formaron parte de un proyecto de investigación en el sitio y comenzaron con las exploraciones de 1982, continuándose año a año hasta 1992, cuando se vieron interrumpidos por la existencia de explotaciones mineras en proximidad de las cuevas. Esto obligó a enfocar los estudios en verificar los impactos antrópicos, tarea que concluyó en 1998 y fundamentó la protección legal del sitio en 2003, retomándose los relevamientos topográficos en 2012, 2018, 2020 y 2022.

El instrumental utilizado para los relevamientos topográficos realizados entre 1982 y 2018 fueron una brújula taquimétrica con trípode, cinta métrica y mira de nivelación centimetrada. Dicho relevamiento fue realizado dentro de los estándares de precisión 6D propuestos por la Unión Internacional de Espeleología. A partir de 2020 se empleó un distanciómetro láser Disto X para completar el relevamiento de las cavernas (Fig. 2) (CATINARI et al., 2023). Los relevamientos se efectuaron a traves de poligonales y radiaciones, calculándose el desarrollo de las cavernas por el método «map lenght».

Figura 2: *Tareas topográficas. Medición Brújula Taquimétrica y con láser Disto X (GEA, 2020).*

3. Resultados

La caverna de mayor desarrollo es la caverna del Templo (Fig. 5) que tiene 1.931,50 m que sumados a los 1.691,18 m de desarrollo de la caverna del Gendarme (Fig. 3) forman el actual sistema cavernario Gendarme - Templo de 3.622,68 m, la cavidad más extensa registrada en Argentina. La caverna del Arenal (Fig. 6) presenta un desarrollo de 1.299,50 m y la menos extensa es la cueva de los Cabritos (Fig. 4) con 83,10 m de desarrollo. En su totalidad el Sistema Cavernario Cuchillo Curá posee a la fecha un desarrollo de 5005,28 m. Además se pudo calcular el desnivel de cada una respecto a la boca de acceso con el nivel más profundo de cada cavidad, la caverna del Gendarme presenta el mayor desnivel de 17,99 m (CATINARI et al., 2022).

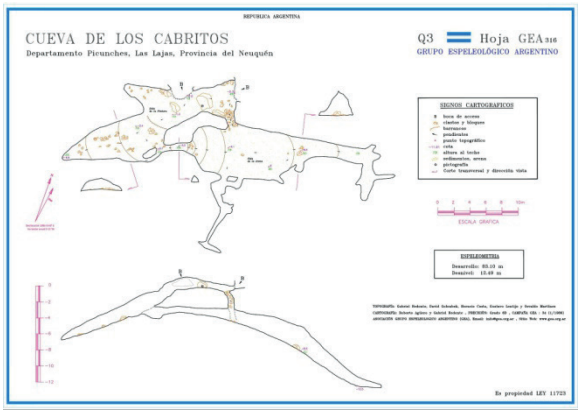

Figura 3: *La cueva de Los Cabritos fue relevada en 1986 y su cartografía publicada en el mismo año a escala 1:100. Digitalizada en 2022.*

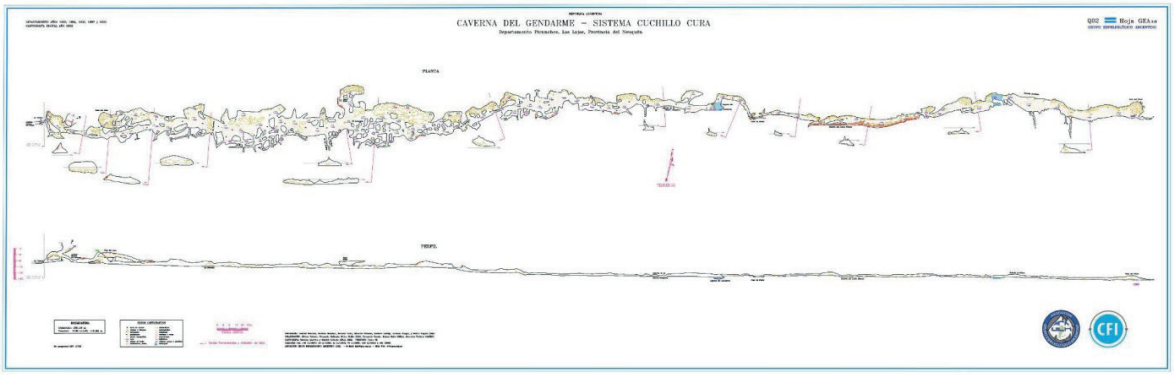

Figura 4: *La topografía de GEA en Cuchillo Curá se inició en la caverna del Gendarme en 1982, continuó en los años 1983, 1984, 1986, 1987 y 2020, publicándose en este último año la cartografía a escala 1:500. En 2022 se digitalizó (CATINARI et al., 2022).*

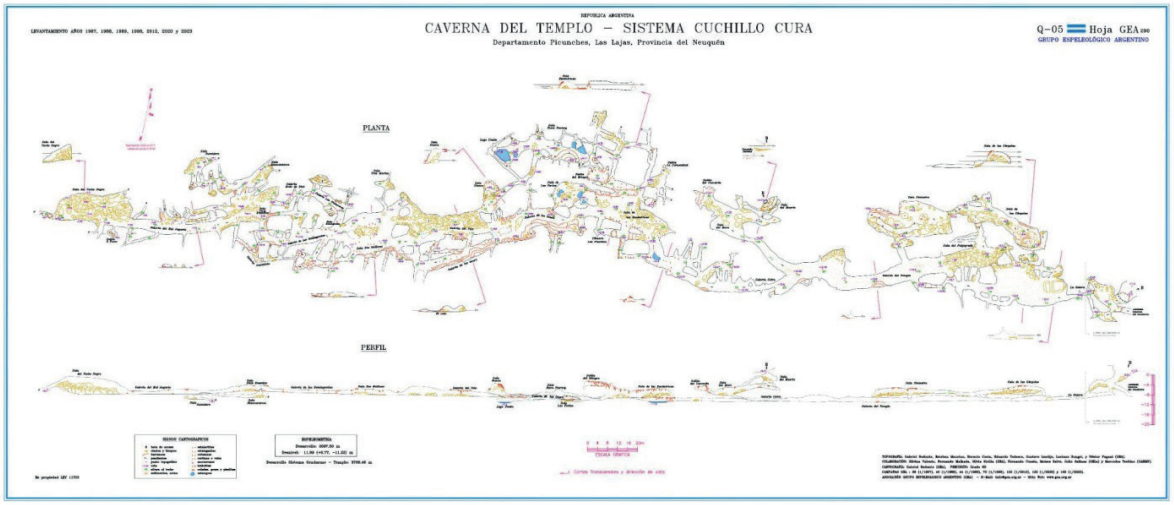

Figura 5: *La caverna del Templo se relevó en 1987, 1988, 1989, 1998, 2012 y 2020. En 2023 se relevaron nuevas galerías y se actualizó la cartografía digital.*

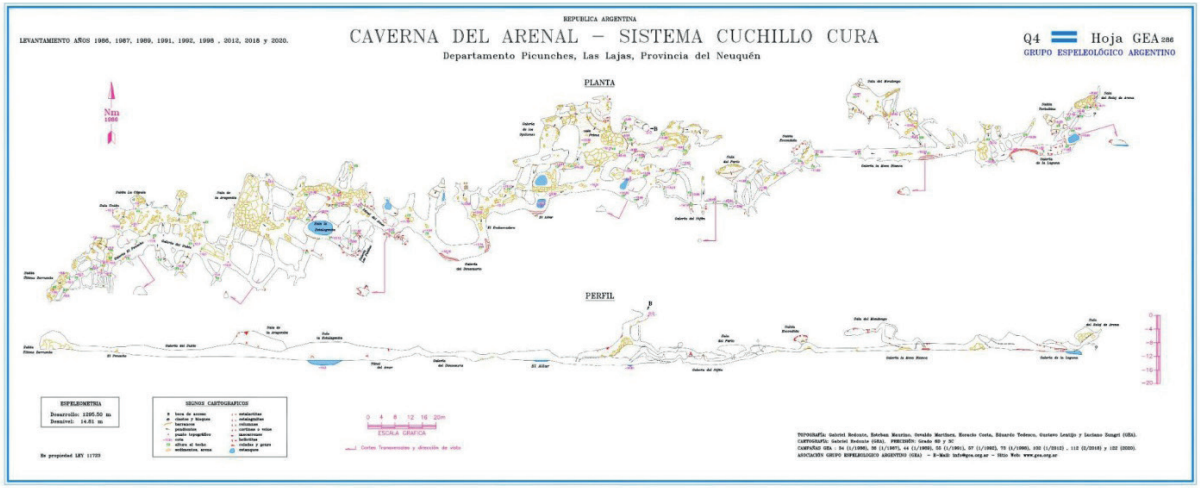

Figura 6: *El relevamiento topográfico de la caverna del Arenal se realizó en 1986, 1987, 1989, 1991, 1992, 1998, 2012, 2018 y 2020. En 2022 se digitalizó la cartografía en formato vectorial.*

4. Conclusión

El relevamiento topográfico y la posterior confección de las cartografías de las cavidades, sumado a la topografía de superficie, fue una herramienta fundamental para la elaboración de estrategias y para proponer a las autoridades gubernamentales medidas que resguarden este patrimonio espeleológico. Dichos documentos constituyeron la base para la creación del ANPCC en 2003. Esta cartografía brindó el soporte para el estudio de las cavidades desde otras disciplinas, materializado en 2022 en los proyectos "Lineamientos estratégicos para la construcción de un plan de manejo del área natural protegida Cuchillo Curá (Dpto Picunches), provincia de Neuquén" y "Estudios Espeleológicos de Base en el Sistema Cavernario Cuchillo Curá, provincia de Neuquén". El trabajo topográfico sostenido ha posibilitado contar con cartografía de las cuevas y del carso superficial, herramientas insustituibles para gestionar su protección como Área Natural Protegida y los estudios actualmente en curso para su manejo y conservación.

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Infocav, an online registry of argentine caves

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Abstract

This work describes the characteristics of the InfoCav program for the online management of the National Registry of Natural Cavities, administered by the Unión Argentina de Espeleología (UAE), the national federation, through a Cadastre Commission. This tool provides remote access to a database and images of Argentine caves, allowing users to register and edit information. This allows a permanent online update among all the federated groups of Argentina collaboratively. In addition, a version for smartphones is under development and the main features, screenings, and benefits are described. This app will be available for installation on the Play Store in 2025.

Resumen

INFOCAV, UN CATASTRO EN LÍNEA DE CAVIDADES ARGENTINAS. En este trabajo se describen las características del programa InfoCav para la gestión en línea del Registro Nacional de Cavidades Naturales, administrado por la Unión Argentina de Espeleología (UAE), la federación nacional, mediante una Comisión de Catastro. Esta herramienta permite acceder de forma remota a una base de datos e imágenes de cuevas argentinas, registrarlas y editarlas. Esto hace posible una actualización en línea permanente entre todos los grupos federados de Argentina de manera colaborativa. Además, se encuentra en desarrollo una versión para smartphones. Se describen sus principales características, visualizaciones y beneficios. Esta aplicación estará disponible para su instalación en Play Store en 2025.

1. Introduction

The National Natural Cavity Registry is a collective registry of Argentine speleologists whose history dates to 1988 with the first lists and analogical records. This registry is managed by a commission with the support of the national federation: the Unión Argentina de Espeleología (UAE). Argentina is a large country, yet speleology is not very developed and there are few active groups of speleologists. They all cooperate with the registry and need to access the data and maps quickly and remotely. For this reason, a data management system was designed to have access online. Unlike Grottocenter, InfoCav is a restricted access database managed by a federation. Each federated group has a representative who has their access key and can share it with their group. In addition, this federation establishes cooperation agreements between government authorities and research & development institutions. When an agency or researcher needs information, they must require it and specify the use. This decision is taken because Argentina does not have national legislation to preserve caves and because Argentina does not have national legislation to preserve caves and karsts. Therefore, making public the cavern data indiscriminately could facilitate irresponsible use of them.

This cadastre of caves currently contains some 2,300 registered cavities of various types such as caverns, caves, rock shelters, pits, natural bridges, etc., with different developments, depths, and types of lithologies.

2. InfoCav features

InfoCav was developed during the COVID-19 pandemic with the cooperation of the consulting firm Centzon. After several tests, it was launched in 2021 (Redonte G., 2022). This computer tool is a geographic information management system that allows storing text, hypertext, and images. It shows a 3D map with views of the georeferenced caves (Figs. 1 and 2) and a report of the main characteristics of each cave, its environmental status, the cave map, photos, bibliography, and links to websites (Fig. 3). From the database it is possible to search for caves or make lists by province, region, name, cadastral code and other attributes such as type of rock, development, depth, altitude, etc.

Access can be set as an administrator, user, or guest for a limited time. In administrator mode, it allows you to make a periodic backup of the database in TXT, JPG and PNG. In other access modes, it only allows you to make searches,

view screens, make lists, and download a report in PDF format.

The system was developed using PHP and stores cadastral information in a MySQL database. Digital maps are rendered using the ArcGIS program.

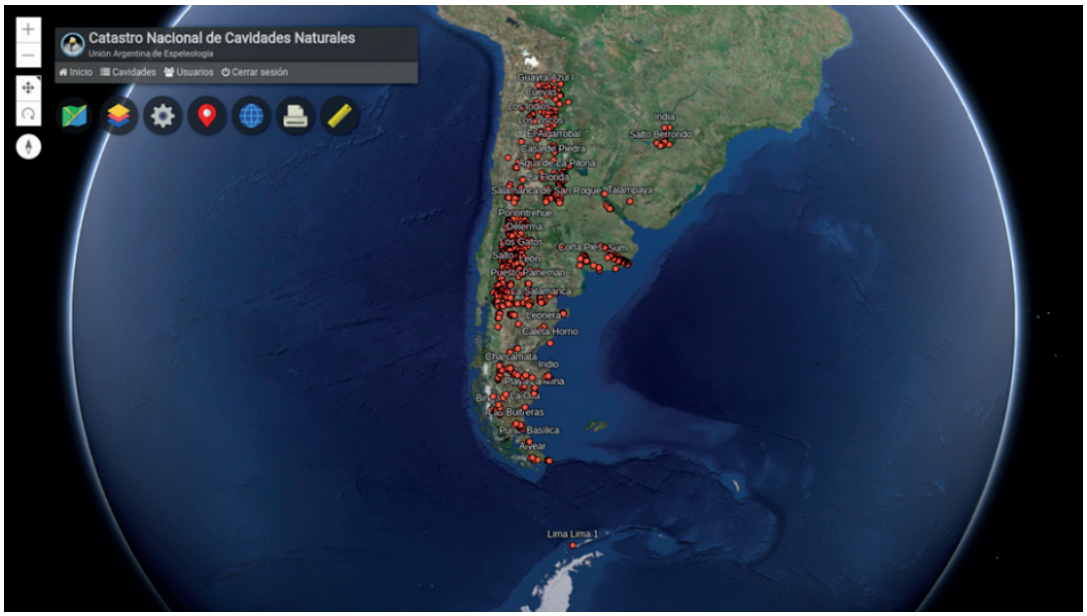

Figure 1: *Interactive 3D map view with satellite image.*

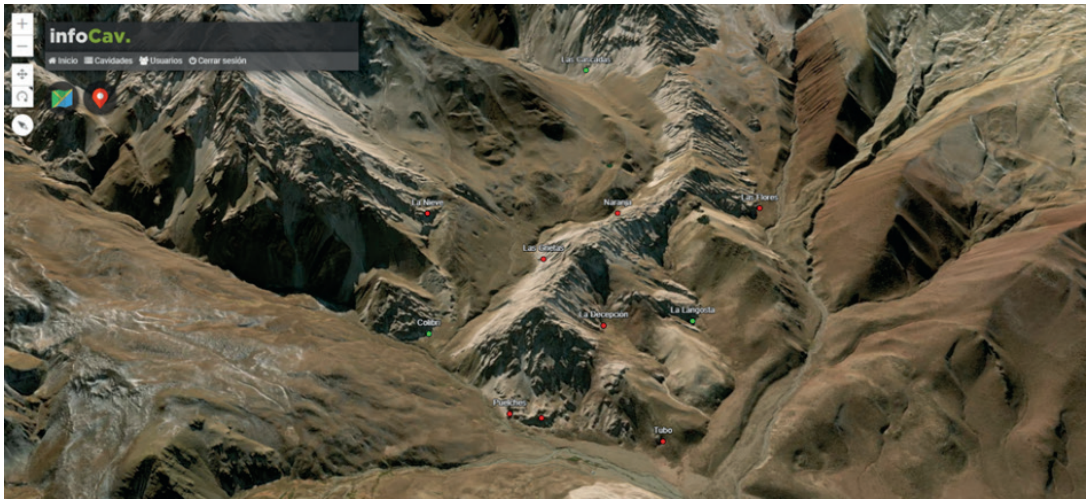

Figure 2: *Zoom view on a 3D map with geolocation of caves.*

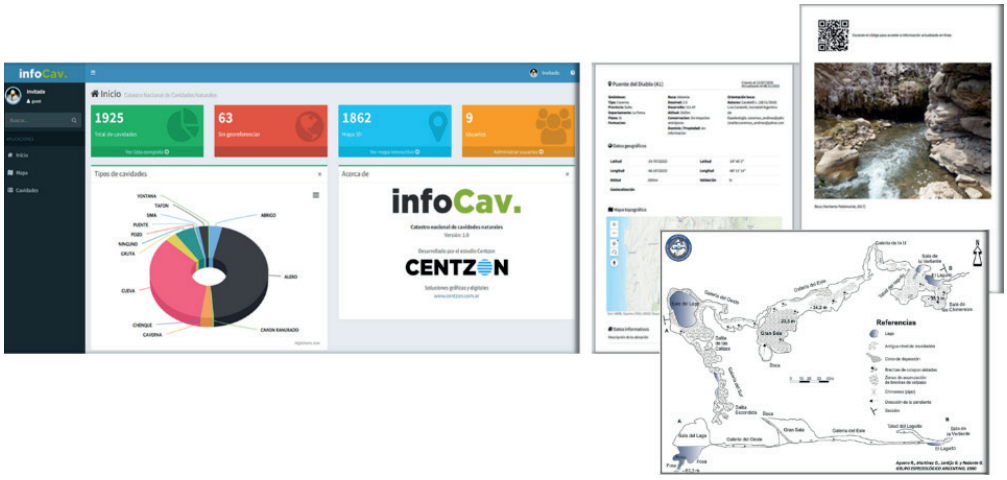

Figure 3: *Home screen and reports.*

3. Smartphones application

An application for smartphones is currently in the testing stage. This InfoCav mobile application for Android was created using IONIC and the programming language was Vue.JS. The Android IDE and the Capacitor tool were used for its compilation. It is expected to be published in Play Store by the end of 2025.

This app maintains the general structure of the InfoCav web version, the main information, and the geolocation of the cavities in the national territory. It shows a three-dimensional map that can be configured with satellite or topographic images. The images have been adapted to the size and shape of a cell phone screen (Fig.4). You can have access to information in real-time if there is an internet signal, or you can download the information in advance (Redonte G. & Díaz D., 2024).

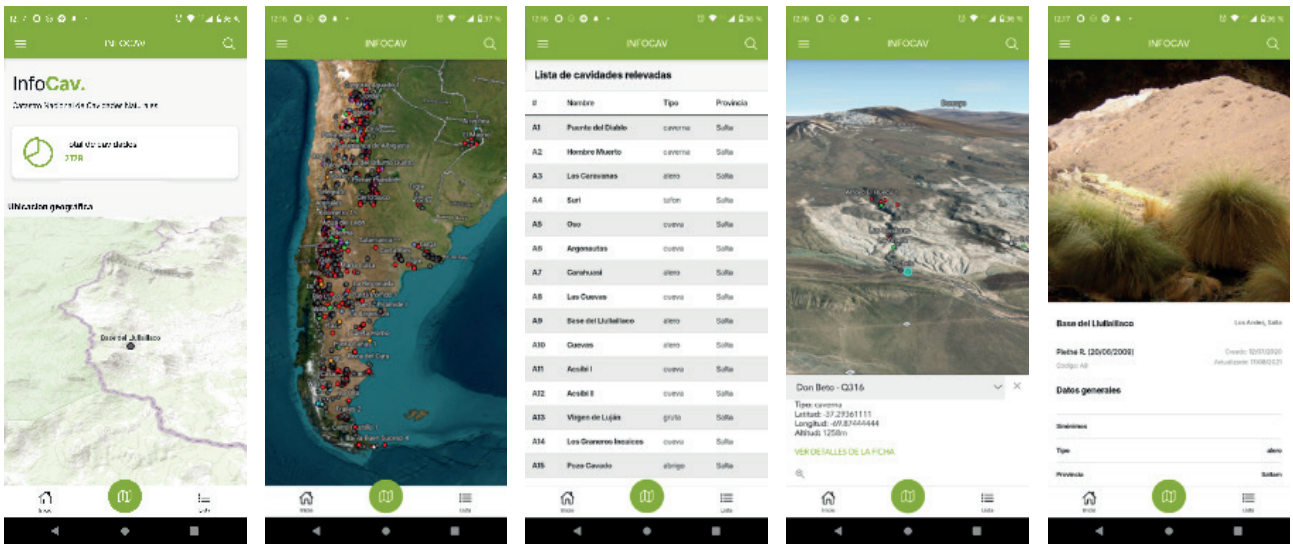

Figure 4: *View of some screens in the smartphone application.*

4. Conclusion

The implementation of InfoCav has facilitated the registration of natural cavities, has avoided duplications, and has provided remote and rapid access to existing information on registered caves, georeferencing, and existing bibliography. The possibility of exporting a report that consolidates data for each cavity of interest into a single PDF file facilitates an easy access to key information aiding in the planning of explorations and conservation studies. The new application for smartphones allows easier access to data while on an expedition, traveling, or away from the computer. Responsible management of data is administered by a representative of each federated group and shared with interested state agencies through a prior agreement. This will ensure the effective use of data and prevent misuse, such as activities that may pose safety risks to visitors or negatively impact the caves and their environment.

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Relevamiento topográfico, geoespeleología y arqueología de la Cueva de la Liebre, Rodeo, San Juan, Argentina

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Resumen

La longitud del resumen será de 200 palabras como máximo. No se permiten palabras clave. Para el resumen, escribe en una sola columna. Si el artículo está escrito en inglés, se recomienda un resumen en francés, pero no es obligatorio. Si el artículo está escrito en un idioma diferente al inglés, es obligatorio incluir un resumen en inglés (con el título en inglés al principio del resumen). Usa la fuente Calibri de 9 pts.

1. Introducción

Con el objetivo de realizar la topografía completa de la Caverna de La Liebre, es decir, recorrerla y topografiarla desde la entrada superior (o sumidero) hasta la entrada inferior o (surgencia), el Centro de Montaña de Tandil (CMT) organizó la Expedición Internacional «La Cañada 2023». En la expedición participaron cuatro grupos de espeleología, de cuatro países distintos: Centro de Montaña de Tandil (CMT-Arg), Centro Espeleológico Uruguayo Mario Isola (CEUMI- Uru) de Uruguay, el Grupo Universitario de Pesquisas espeleológicas (GUPE-Bra) de Ponta Grossa, Brasil y el Espeleoclub Atacama (ECA-Chi). La expedición obtuvo el apoyo del Municipio de Iglesia y de la Dirección Provincial de Patrimonio Cultural de San Juan. La expedición fue autofinanciada, contando con el auspicio de Cuerdas Mendy Hnos SRL y se realizó entre los días 5 al 11 de noviembre de 2023. Otros objetivos incluyeron la capacitación de integrantes para la exploración, prospección y relevamiento topográfico. Al final, se realizó un taller de introducción a la espeleología y difusión del patrimonio espeleológico de Rodeo, para funcionarios del área de turismo de la municipalidad y guías turísticos de la región.

Cabe destacar que el CMT ya había organizado tres expediciones anteriores, 2004, 2019 y 2021, siendo las dos últimas junto al CEUMI. Igualmente, la «Caverna de la Liebre» fue reportada por primera vez en 1987 por el Centro Espeleológico Córdoba (CEC) y la Unione Speleologique de l' Aglomeration Nancyenne (USAN) a partir de la Expedición Franco- Argentina NC 87.

El sitio "La Cañada" se encuentra en la zona precordillerana del noroeste de la Provincia de San Juan (Argentina), a escasos kilómetros de la localidad de Rodeo, en el departamento Iglesia, como demuestra la figura 1.

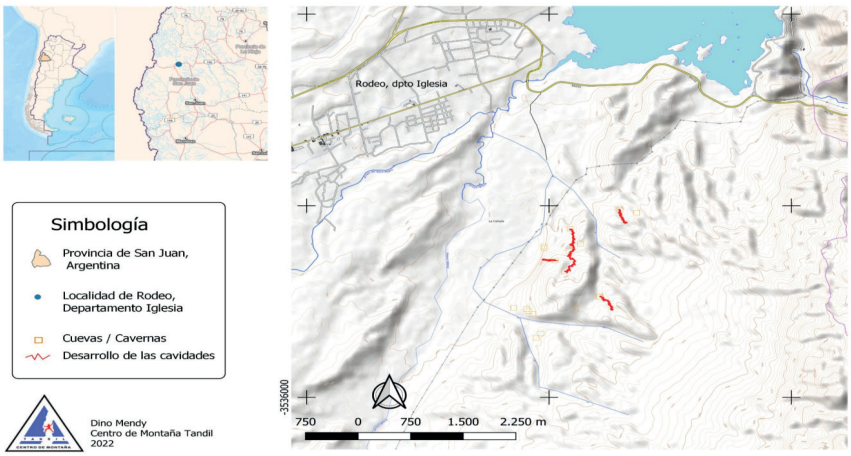

Figura 1: *Mapa de ubicación, Sistema cavernário de La Cañada, Rodeo, San Juan.*

En la figura se destacan algunas de las cavidades encontradas ya conocidas en la zona: La Liebre (2005,13 m), Del Indio (584 m), Espelaion 6 (488,76 m), Sol Dentro o Gruta Deseada (410 m) y Los Vascos (379,30 m), entre otras. Estas cavidades están registradas en el Catastro Nacional de Cavidades Naturales que gestiona la Unión Argentina de Espeleología (UAE) a través de su Comisión de Catastro.

El sitio de "La Cañada" se confina en un paisaje desértico desarrollado sobre badlandas (tierras yermas) constituido por lutitas, caracterizado por su aridez y erosión producto del agua y el viento debido a la falta de vegetación. El terreno donde se desarrollan estas cavernas, localizado en el piedemonte de la Precordillera Occidental, está formado por sedimentitas de edad terciaria neogena, específicamente del mioceno inferior a medio (SEGEMAR, 2006) correspondiente a aprox. 20 Ma y pertenecientes a la Formación Las Flores, del Grupo Iglesia. Esta unidad geológica está constituida por una sucesión de arcilitas y limolitas bien estratificadas en gruesos bancos muy compactos y areniscas finas de tonos rojizos, castaños y amarillo claro, con intercalaciones de yeso laminar.

2. Materiales y métodos

Previamente al trabajo de campo, se realizó el análisis de imágenes satelitales de google earth (recientes e históricas 2004/2022), y también se utilizó una imagen del satélite CBERS fusionada y con una composición colorida para obtener una resolución espacial de 2 m (INPE, 2022), cuyo objetivo fue buscar posibles entradas, sumideros, drenajes, chimeneas y conexiones.

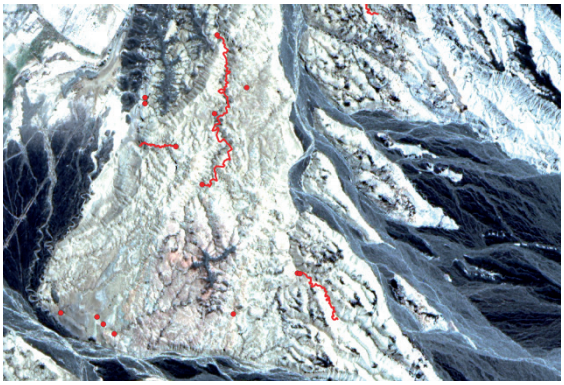

Figura 2: *Imagen CBERS fusionada composición colorida, con resolución espacial de 2 m. Detalle para los puntos identificados con potencial para la ocurrencia de cavidades.*

Ya en Rodeo, para operacionalizar el trabajo, el grupo de 15 personas (Figura 2) fue organizado en 4 equipos.

- El equipo 1 ascendió hasta la entrada superior de La Liebre y bajó por la cueva instalando los equipos necesarios para el accenso por técnica vertical del equipo de topografía (equipo 2).
- Mientras el equipo 1 realizaba ese trabajo, el equipo 2 topografiaba el primer tramo de la cueva, hasta el punto llamado "La Cascada", con un desnivel de 13 mts.
- El equipo 3 realizada la exploración y prospección de cuevas próximas.
- Por último, el equipo 4 realizaba registros audiovisuales en la zona, para la elaboración de un documental.

Figura 3: *Equipo de la Expedición Internacional La Cañada 2023.*

Figura 4: *Equipo 1 instalando los anclajes y equipos para el ascenso/descenso externo e interno en la Cueva de La Liebre. Nicolas Broquetas, Roberto Medrano y Guillo Mendy (izq para der).*

Figura 5: *equipo de topografía compuesto por Axel, Guillo, Heder, Mauricio y Bruno (de izq para der).*

El mapa topográfico de la cavidad tiene un nivel de detalle BCRA 4C, conforme lo propuesto por la British Cave Research Association (DAY 2002). Para añadir representaciones cartográficas sobre de la cavidad fueron realizados varios perfiles topográficos y todos los símbolos utilizados siguen lo dispuesto por la UIS.

Durante la topografia, fue realizado un entrenamiento con tres integrantes de la expedición, posibilitando conformar un equipo de tres personas para el primer día, cuatro para el segundo día y tres para el tramo final del último día.

Se realizó la topografía detallada en la cavidad conforme el método de ''diagonal abierta y cerrada". Las medidas de altura, profundidad, desnivel y extensión fueron tomadas con el uso de un distanciómetro Disto Leica D3, un Inclinómetro Ruhlmann, con una precisión de 0.05 y una brújula Suunto modelo KB-14/360R G Compass. Los datos se registraron en la aplicación "topodroid" y se produjo el "croqui" inicial. Notas de control fueron tomadas en papel. También fueron registradas coordenadas UTM con un GPS modelo Garmin Trekk en las entradas de la cavidad y en chimeneas, que fueron utilizadas para georreferenciar el croqui mediante el uso de un Sistema de Informaciones Geográficas (SIG). Los mapas fueron generados con el programa QGIS v 3.20.1 y finalizados en el programa InkScape.

3. Resultados

3.1. La Liebre

Los principales resultados alcanzados tienen que ver con cumplir los objetivos planteados por la expedición, que en el caso específico de La Liebre fue topografiarla en su totalidad. En este sentido, se pudo verificar que la Caverna Angualasto es parte del mismo sistema de la Caverna de la Liebre y se verificó que la Sima del Fardo no es un afluente de la liebre sino que corre paralelo en la cuenca de la llamada Sima Mier. Se encuentra en proceso de colapso verificando que los fardos se han hundido desde la última vez que se visitó el lugar en el año 2021.

Al final de tres días de topografia, la cueva de La Liebre presentó un desarrollo lineal de 2005,13 m, con una proyección horizontal de 2000,57 m y un desnivel total de 112 m. Con la producción del mapa final (figura 10) se ha constatado que La Liebre es la cueva de *piping* más grande del mundo, conforme el listado mantenido por Burger, P. (2024).]

Figura 7: *Entrada Inferior de La Liebre.*

Figura 8: *Entrada superior.*

3.2. Arqueologia e Paleontologia

En la Cueva de la Libre, y sus áreas circundantes, se han identificado distintos indicios que podrían dar cuenta de ocupación humana a lo largo del tiempo. En el sector de ingreso a la cueva, se pueden observar lascas dispuestas en forma dispersa, como así también algunos artefactos pulidos. Los indicios en la entrada, junto con los restos de materiales vegetales y otros elementos que permanecen a lo largo de la cueva, permitirían asociar este sitio no solo a un refugio, sino también como posible lugar de acopio de alimentos. A su vez, se observaron distintas cavidades asociadas al depósito de paquetes mortuorios.

Es interesante destacar que a 21 km de Rodeo está la ciudad de Angualasto, mismo nombre de la cultura de los pueblos originarios también conocidos como Sanagasta o Aimogasta, que corresponden al período tardío de las culturas del noroeste argentino. Se destaca que sus sitios se caracterizan por una gran cantidad de restos en superficie, incluyendo fragmentos de alfarería (GONZÁLEZ Y PÉREZ, 2000), como se destaca en la figura 9.

Figura 9: *Restos de choclo/maíz y trozo de cerámica.*

3.3. Taller con la comunidad

En el dia 10/11/23 fue realizada una presentación de introducción a la espeleología abierta al público, qua también presentó los hallazgos y exploraciones realizadas. La actividad ocurrió en la dirección de turismo y patrimonio por invitación de Fañy Pernas y Gonzalo Anes, directores del área de turismo de la municipalidad de Rodeo, San Juan.

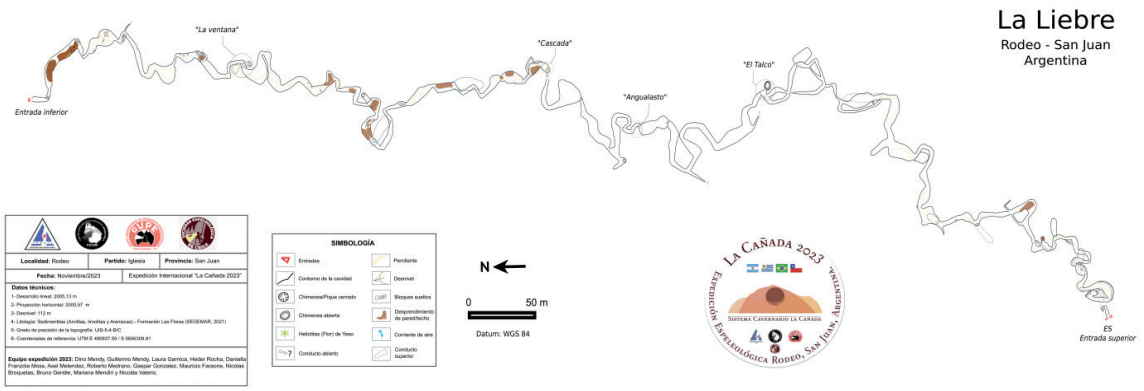

Figura 10: *Mapa topográfico de la cueva de La Liebre. Autor del mapa final: Heder Rocha.*

4. Discusión

4.1. Sistema cavernario La Cañada

En trabajos previos realizados en otros ambientes similares, como es el caso de las Bardenas (Navarra, España), investigadores han explicado en detalle que las características de estos depósitos arcillosos poseen altos valores de sodio intercambiable, un índice de dispersión medio y elevados coeficientes de expansión. Lo que contribuye al desarrollo de los procesos de piping, ya que la disolución del sodio desflocula las arcillas, acelera la pérdida de coherencia y facilita la exportación de materiales finos. A su vez, tanto la capacidad expansiva de las arcillas como la dispersión son factores importantes en el desarrollo de procesos de erosión ya que ambos causan agrietamiento, canalizando la escorrentía hacia el interior del sedimento y produciendo remoción intergranular.

Estas arcillas expansivas, ricas en sales de sodio, cambian sus propiedades físicas según su estado de hidratación. Las arcillas hidratadas resultan altamente cohesivas a la vez que impermeables, y contribuyen a mantener el equilibrio mecánico en las galerías formadas, evitando su desmoronamiento y permitiendo una mayor permanencia en el tiempo. Pero debido a que aumentan su peso al estar cargadas de agua, pueden también colapsar. De hecho, así como se observa ejemplos de zonas inestables, con colapsos recientes (por ejemplo, cueva del Fardo), se da también el caso inverso, de galerías con perfiles muy estables, tanto inactivas como hidrológicamente activas (por ejemplo, cueva de la Liebre) donde es frecuente el desarrollo de cauces secundarios entallados sobre sedimentos del suelo de las galerías. El terreno donde se desarrolla el sistema cavernario “La Cañada” está formado por sedimentitas, compuestas por arcillas mezcladas con sal de roca (halita) y yeso, es propicio para la formación de las cavernas cuando se disuelven las sales y que con la expansión de las arcillas al hidratarse facilitan el arrastre mecánico que provoca la erosión formadora.

La erosión del suelo por sufusión (*piping* o tubificación) podría definirse como la erosión mecánica por dispersión y disolución y exportación que acaece en los suelos, regolitos y sus materiales parentales (sedimentos o rocas no consolidadas) cuyos minerales son evacuados por flujos hídricos subsuperficiales, especialmente cuando los materiales constituyentes son mayoritariamente finos (arena, limo y arcilla), con un alto contenido en sodio y arcillas expansivas. Los elementos granulométricos de menores dimensiones son evacuados dando lugar a un ensanche de las grietas previas, más o menos verticales. Al colapsar suelen dan lugar a cárcavas superficiales, y paisajes de *badlands* cambiando el modelado previo de la superficie del terreno suprayacente.

A este proceso se suma el aparente efecto cuña de las intercalaciones de yeso laminar, que por un lado, precipitan en flores de yeso cuando en las paredes de los conductos (Figura 10), y por otro funcionan como una barrera para las arcillas cuando estas expanden y desfloculan al saturarse de agua.

Figura 11: *Flores de yeso.*

El sistema cavernario “La Cañada” podría ser descripto como del tipo “pseudokárstico”, ya que es un paisaje que contiene elementos de tipo kárstico, como cuevas, sumideros y arroyos subterráneos, pero que no se forman únicamente por disolución de la roca. Así, lo que se pudo observar en la última expedición es que el génesis de las cavidades es producto de un drenaje interno de origen subsuperficial que ocurre mediante la creación de conductos (“pipes”) donde se dan procesos de eluviación, erosión mecánica por dispersión y exportación de materiales, pero que también ocurre disolución.

4.2. Aspectos arqueológicos

Los distintos materiales que se pueden apreciar en el área son indicadores valiosos para entender las diversas prácticas culturales de los grupos que han utilizado este espacio geológico particular. No obstante, el estado de erosión y el deterioro visible producto del expolio que presenta este sitio hace necesario un un abordaje integral para salvaguardar y poner en valor este patrimonio. Siendo fundamental implementar políticas y asignar recursos que contribuyan al desarrollo de la investigación y profundización en el estudio de estas cuevas, aportando a su conservación y puesta en valor.

5. Conclusión

La cueva de La Liebre se destaca como la cueva de arcilla más grande del mundo y la cueva con el desnivel más grande de Argentina.

Agradecimientos

Agradecemos sinceramente la municipalidad de Rodeo y dedicamos este trabajo a Juan Mendy, fallecido en Febrero de 2025.

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Teste metodológico com dados 3D Lidar, para análise morfológica e monitoramento da Caverna Buraco do Inferno, Resende Costa-MG

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Resumo

Próximo ao centro urbano da cidade de Resende Costa-MG, aplicaram-se dois escaneamentos por laser 3D portáteis em caverna de granito chamada de Buraco do Inferno. Trata-se de uma caverna em junta aberta vertical, subdividida por níveis de blocos. O foco com dois escaneamentos executados, em mesmo dia, foi avaliar aplicação de análises geométricas para caracterização morfológica, verificar sua potencial variação térmica ao longo do dia, além de testar comparações entre as nuvens de pontos, visando à potencialidade de monitoramento espeleológico de integridade física de cavernas de estrutura complexa. Como resultado, constatou-se a viabilidade dos métodos, com algumas restrições, as quais servem de base para refinamentos com mais levantamentos futuros.

Abstract

Near the urban center of the city of Resende Costa-MG, two portable 3D laser scans were applied in a granite cave called Buraco do Inferno. It is a cave with a vertical open joint, subdivided by levels of blocks. The focus of two scans performed on the same day was to evaluate the application of geometric analyses for morphological characterization, verify its potential thermal variation throughout the day, in addition to testing comparisons between point clouds, aiming at the potential for speleological monitoring of the physical integrity of caves with complex structures. As a result, the viability of the methods was verified, with some restrictions, which serve as a basis for refinements with more future surveys.

1. Introdução

No Brasil, cavernas em litologias cristalinas, como granitos, gnaisses ou granitoides, abragem 626 ocorrências ou 2,53% do total (CECAV, 2023). Seu potencial, apesar de reduzido, apresenta importância em função da necessidade de ampliação do conhecimento e pesquisas em cavernas não-carbonáticas, principalmente quando de dimensões superiores. Uma delas é caverna Buraco do Inferno, adjacente ao centro urbano da cidade de Resende Costa (Figura 1), localizada a cerca de 40 km ao norte de São João del Rei, na região sul do Estado brasileiro de Minas Gerais.

A caverna Buraco do Inferno corresponde a caverna cristalina do tipo em junta aberta, conforme classificação de FINLAYSON (1991 apud HARDT, 2003), sendo formada em juntas com o topo aberto para o exterior, estando preenchido por detritos. No caso, a Buraco do Inferno é reticulada em condutos semiparalelos e seções majoritariamente verticalizadas em níveis variados em borda de batólito granítico.

Espeleogênese é associada aos processos de termoclastia, alívio de pressão com diaclasamento esferoidal, dissolução/corrosão e abatimento de blocos a partir dos planos de fratura de borda de batólito. Estes efeitos impulsionados a partir de eventos de pulsos neotectônicos de soerguimento do plioceno, reconhecidos na região (SAADI & VALADÃO, 1990).

Ressalta-se que apresenta resíduos sólidos, efluentes nas proximidades e interior da caverna, assim como vários trechos com presença de grafismos e pichações.

Mapeamento topográfico convencional pelo detalhe BCRA-4C, desenvolvido em pesquisa paralela (ROSSI et al., 2024), Figura 2, atingiu as seguintes dimensões:

- desenvolvimento linear= 46,08 m;
- área= 59,40 m2;
- desnível= 9,58m;
- volume= 1.283,04 m3;
- altura entrada principal= 6,87 m.

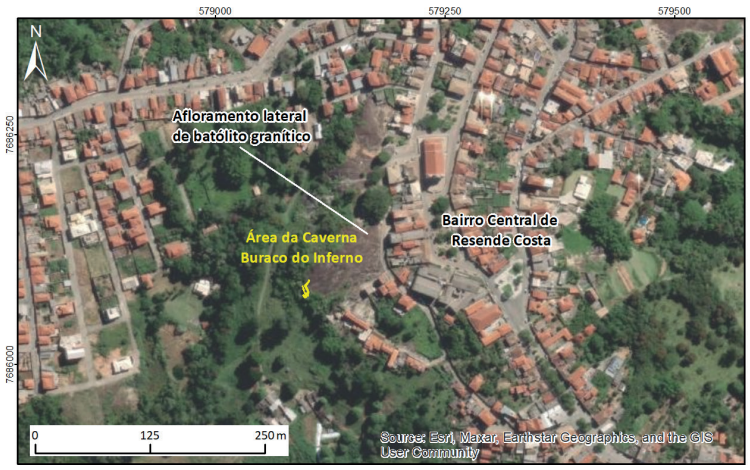

Figura 1: Inserção da Gruta Buraco do Inferno em relação a Resende Costa-MG.

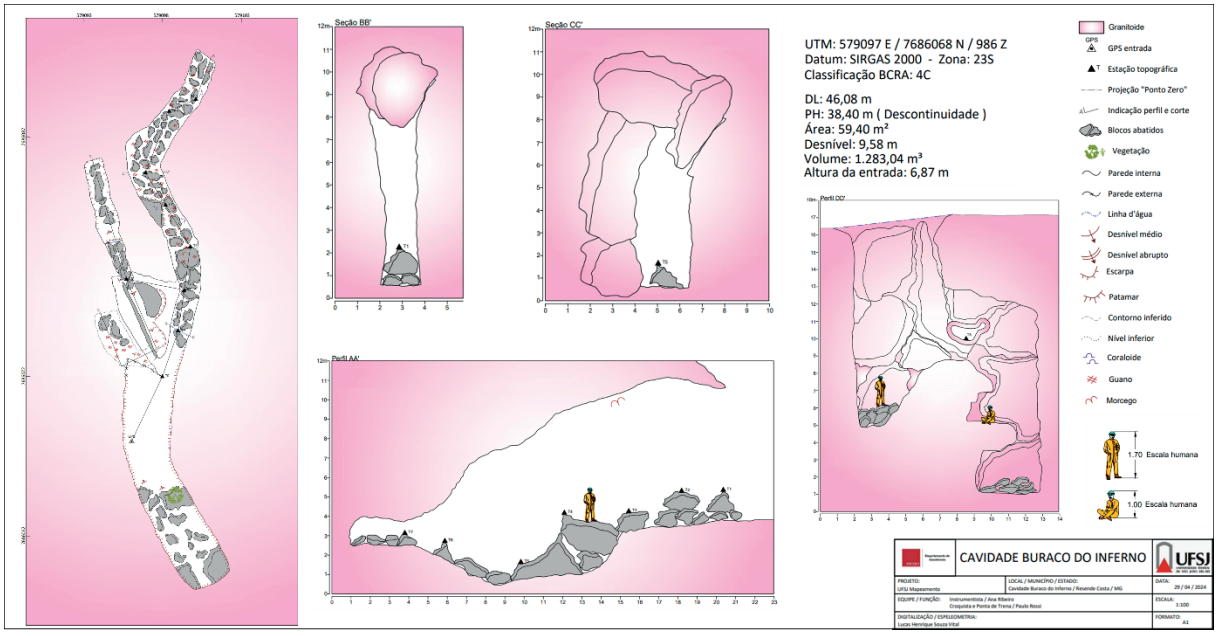

Figura 2: *Mapa topográfico convencional da Gruta Buraco do Inferno. Fonte : ROSSI et al. (2024).*

2. Métodos

Utilizou-se como sensor LIDAR o equipamento portátil FJD Trion S1, composto por 16 sensores, captando 320.000 pontos por segundo com alcance de 120m e precisão de 2 cm.

Em 24/09/2024, dois escaneamentos foram executados com as sequintes características :

- 1ª Captação (P1): intervalo entre 10 :55 horas e 12 :00 horas, cujas respectivas temperaturas foram 20,4 °C e 22,1°C (consulta INMET) ;
- 2ª Captação (S1): intervalo entre 14 :00 horas e 15 :01 horas cujas respectivas temperaturas foram 28,0°C e 29,0°C (consulta INMET) .

As análises foram executadas pelo *software* livre Cloud Compare (versão2.14.alpha – 09/12/2024). Ressalta-se que as nuvens de pontos não foram limpas ou alteradas, pois buscou-se verificar se o dado bruto apresenta mudança relevante de resultados, mesmo incluindo objetos externos como vegetação ou ruídos potenciais na análise.

Em cada nuvem de pontos obtida, foram aplicadas análises geométricas de covariância, com raio de abrangência de 50 cm, de : taxa de mudança normal, linearidade, planaridade, verticalidade, esfericidade, variação de superfície e rugosidade. Os resultados inicialmente foram interpretados no sentido classificar a morfologia cavernícola.

Em seguida, os resultados foram comparados visualmente e pelos histogramas gaussianos, quantitativamente filtrando a média e o desvio padrão, com o foco no reconhecimento das taxas de variância das diferenças dos resultados entre nuvens e sua correlação objetivou buscar parâmetros para o reconhecimento de diferenças de mudança morfológica na caverna e níveis de erro aceitáveis.

Posteriormente, as duas nuvens de pontos foram georreferenciadas entre si, buscando a maior aproximação locacional dos limites morfológicos. Demais testes foram aplicados pela delimitação de seções fixas no software para ambas nuvens, com 2,0 metros de distância (16 ao todo). As 16 seções foram extraídas : (i) com delimitação dos perímetros externos em linhas ; (ii) assim como as nuvens de pontos com largura de 50 centímetros. Cada um dos tipos de seção extraídos foram comparados entre as captações : (i) pelo atributo de extensão do perímetro da linha

(« *lengh* ») ; e (ii) comparando as nuvens de pontos das seções visualmente por cores e pela ferramente de avaliação de distância absoluta entre nuvens (« *C2C absolute distance* »), conforme Figura 3.

Outra etapa, com as nuvens georreferenciadas entre si, aplicou-se para o dado completo novamente a ferramente de avaliação de distância absoluta entre nuvens (« *C2C absolute distance* »). O resultado foi avaliado pela tematização das variações e interpretação da limitação da captação na relação entre operador/sensor portátil pela ergonomia, complexidade da caverna ou interferência de ruídos ou obstáculos. Por fim, testou-se a geração de superfícies interpoladas (« Mesh's ») nesta análise comparativa, verificando se há viabilidade tanto com nuvens de pontos, quanto com superfícies geradas.

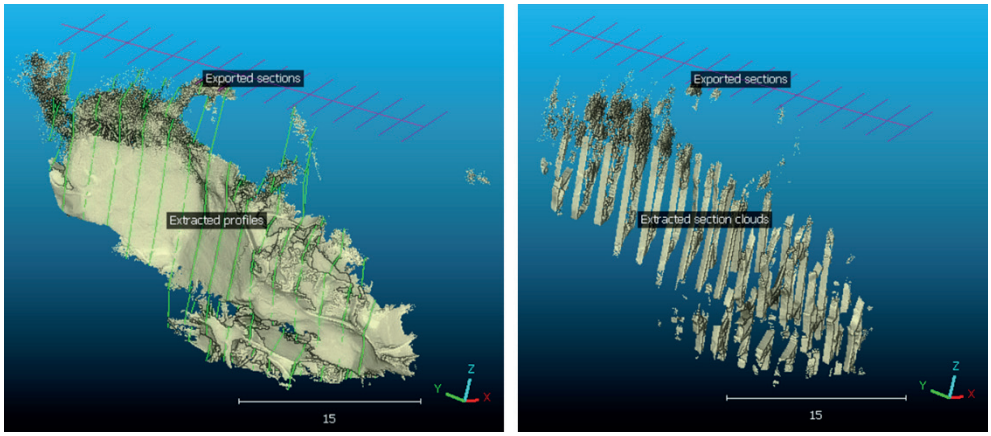

Figura 3: *Linhas de 16 seções padronizadas em nuvem de pontos 3D : seções em linha avaliadas pelo perímetro em cada nuvem (à esquerda) ; Nuvens de pontos de 50 cm de largura extraída em cada seção para cada nuvem (à direita).*

3. Resultados

Os resultados das análises geométricas das nuvens de pontos permitem interpretar a morfologia cavernícola da Gruta Buraco do Inferno (Figuras 4). Ela apresenta taxas de rugosidade, de variação normal e variação de superfície predominantemente inferiores (médias <10cm). As taxas de linearidade e esfericidade são médias (médias <20cm). As taxas de planaridade e verticalidade são superiores (médias >50cm).

Os resultados das análises geométricas e de distância absoluta entre nuvens de pontos (Tabela 1), pelas médias e desvios padrão, apontam covariância positiva (0,029) e correlação alta (99,98%), com variância das médias de 4,67 cm e variância dos desvios padrão de 1,02 cm.

Os resultados do teste pelas seções padronizadas em ambas as nuvens foram iguais entre elas, tanto pelo valor dos perímetros quanto pelo quantitativo de pontos recortados em cada seção (Tabela 2). Entretanto, avaliando a distância absoluta comparativa entre nuvens de algumas das seções, de perímetros mais complexos, há indicações de distâncias em porções de paredes e principalmente piso. Algumas não apontaram distaciamento comparativo, ou seja, completa igualdade (Figura 5).

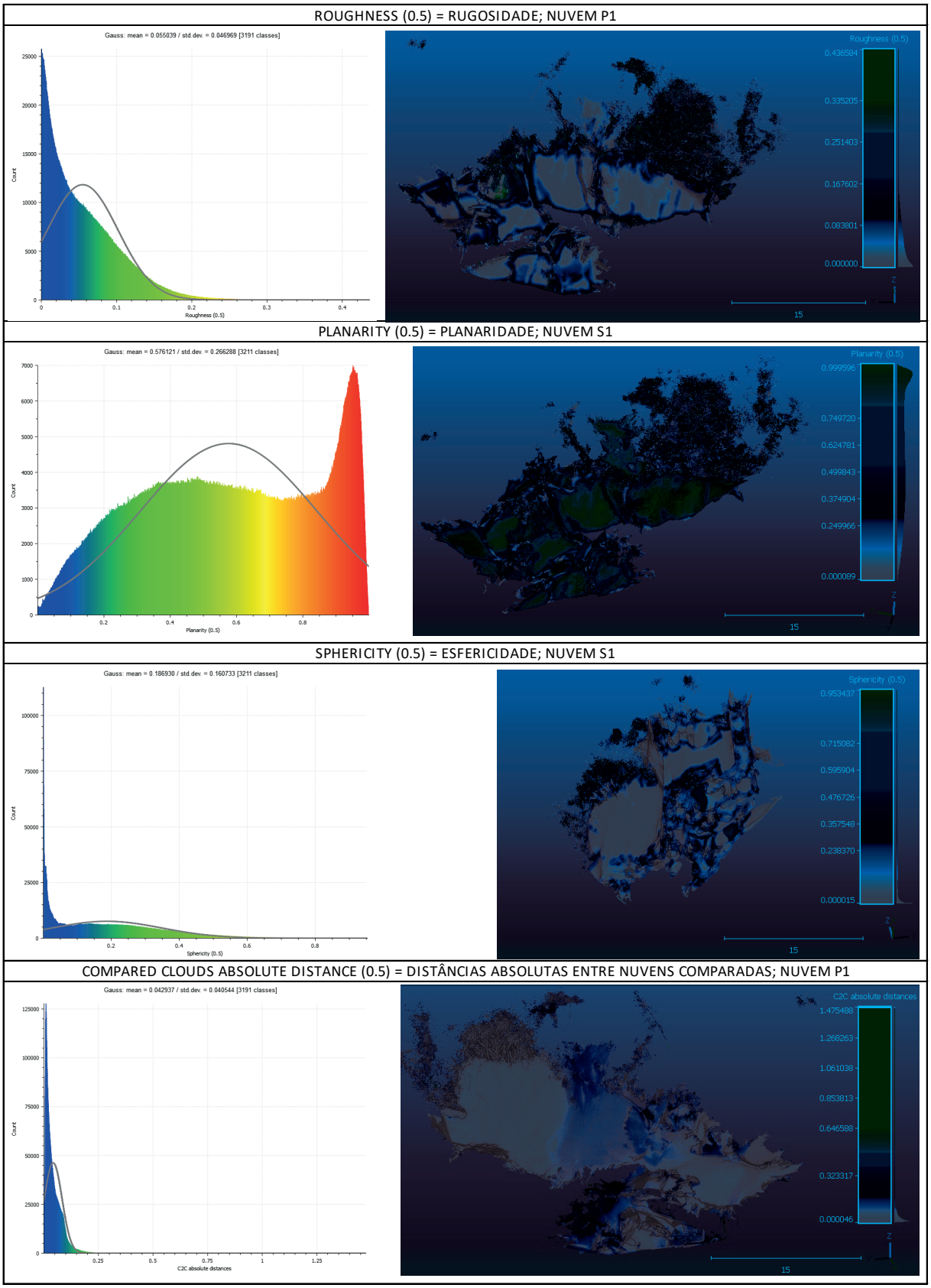

Figura 4: *Exemplos de histograma gaussiano e de visada tridimensional gerados para ambas as nuvens (P1 e S1) pelas análises geométricas e comparação da distância absoluta entre nuvens. Unidades em metros.*

Tabela 1: *Atributos de captação e valores gaussianos médios, de desvio padrão e suas diferenças resultantes das análises na nuvens de pontos captadas (P1 e S1).*

ID NUVEM DE PONTOS	P1	S1	
DATA CAPTAÇÃO	24/09/2024	24/09/2024	
INTERVALO CAPTAÇÃO	10:00 - 12:00	14:00 - 15:01	
TEMPERATURA (C°)	20,4 - 22,1	28,0 - 29,0	DIFERENÇA ENTRE RESULTADOS DAS NUVENS
NÚMERO DE PONTOS	10.179.224	10.307.853	128.629
ROUGHNESS (0.5); GAUSS MÉDIO	0,0550	0,0541	0,0009
ROUGHNESS (0.5); GAUSS DESV. PAD.	0,0469	0,0471	-0,0002
NORMAL CHANGE RATE (0.5); GAUSS MÉDIO	0,0932	0,0924	0,0008
NORMAL CHANGE RATE (0.5); GAUSS DESV. PAD.	0,0715	0,0729	-0,0014
C2C ABSOLUTE DISTANCES (0.5); GAUSS MÉDIO	0,0429	0,0424	0,0005
C2C ABSOLUTE DISTANCES (0.5); GAUSS DESV. PAD.	0,0405	0,0378	0,0027
PLANARITY (0.5); GAUSS MÉDIO	0,5733	0,5761	-0,0028
PLANARITY (0.5); GAUSS DESV. PAD.	0,2565	0,2662	-0,0097
LINEARITY (0.5); GAUSS MÉDIO	0,2380	0,2369	0,0011
LINEARITY (0.5); GAUSS DESV. PAD.	0,1738	0,1768	-0,0030
SURFACE VARIATION (0.5); GAUSS MÉDIO	0,0933	0,0924	0,0009
SURFACE VARIATION (0.5); GAUSS DESV. PAD.	0,0715	0,0729	-0,0014
SPHERICITY (0.5); GAUSS MÉDIO	0,1885	0,1869	0,0016
SPHERICITY (0.5); GAUSS DESV. PAD.	0,1579	0,1607	-0,0028
VERTICALITY (0.5); GAUSS MÉDIO	0,5883	0,5822	0,0061
VERTICALITY (0.5); GAUSS DESV. PAD.	0,3211	0,3172	0,0039

Tabela 2: *Atributos de captação das seções padronizadas na nuvens de pontos captadas (P1 e S1).*

SEÇÃO	CAPTAÇÃO P1		CAPTAÇÃO S1	
	Nº DE PONTOS	PERÍMETRO (m)	Nº DE PONTOS	PERÍMETRO (m)
16	12.598	50,71	12.598	50,71
15	43.962	42,64	43.962	42,64
14	96.477	44,56	96.477	44,56
13	74.031	45,22	74.031	45,22
12	98.301	59,79	98.301	59,79
11	80.817	45,28	80.817	45,28
10	74.874	71,40	74.874	71,40
9	117.038	89,81	117.038	89,81
8	160.166	66,24	160.166	66,24
7	250.976	67,18	250.976	67,18
6	281.161	84,18	281.161	84,18
5	292.136	76,64	292.136	76,64
4	239.462	62,56	239.462	62,56
3	239.315	56,33	239.315	56,33
2	180.817	53,56	180.817	53,56
1	117.812	40,89	117.812	40,89

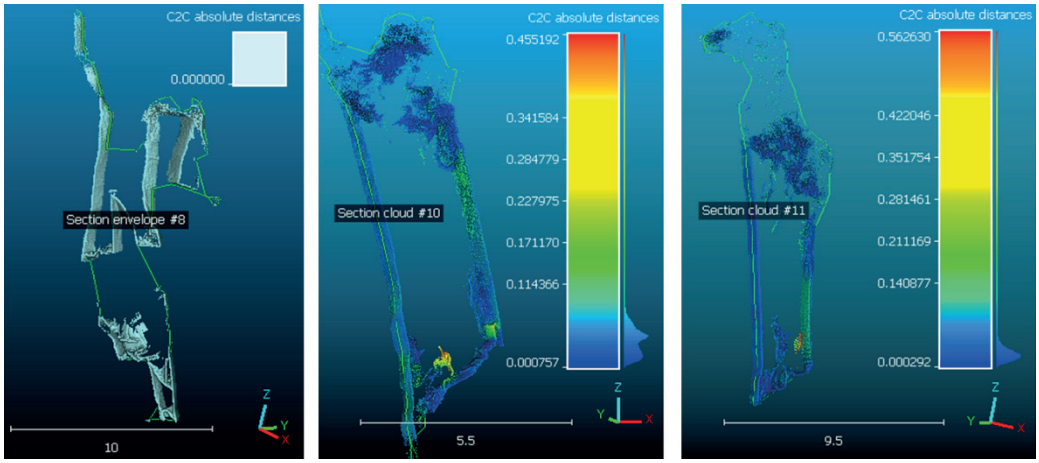

Figura 5: *Exemplos de análises de perímetros de seções e comparativo de distâncias absolutas entre nuvens de pontos de 50 cm de largura entre mesmas seções para ambas as nuvens captadas (P1 e S1). Unidades em metros.*

4. Discussão

As taxas resultantes das análises geométricas podem ser interpretadas pelo aspecto reticulado da caverna, controlada por juntas e diáclases verticais semiparalelas. Em soma, há abrangência das paredes planas verticalizadas, com as variações nas inflexões de ângulo, além dos contatos com tetos, pisos e níveis inclinados. Tetos e pisos, compuseram as demais irregularidades, decorrentes da composição por blocos e detritos. Há contribuição de ruídos de interferência na nuvem captada (vegetação ou humana).

Entre a primeira captação (nuvem P1) e a segunda captação (nuvem S1) houve aumento ligeiro do desvio padrão dos parâmetros geométricos, com exceção de planaridade, indicando aumento da dispersão dos dados e dos planos.

A segunda captação (S1) sendo mais dispersa, foi realizada sobre temperaturas 7,5°C superiores às da primeira (P1). Entretanto, não é possível atribuir assertivamente à variável temperatura as variações resultantes, já que tal comportamento não foi constatado nas análises comparativas das nuvens das seções. Nessas, algumas demonstraram total aderência, enquanto outras apresentaram algumas variações de distância absoluta. Isto, mesmo com a igualdade dos perímetros e número de pontos das seções padronizadas extraídas em cada nuvem (P1 e S1).

A correlação de 99,98% entre as nuvens e variância de 4,67 cm nos resultados de sua análises geométricas foram obtidas para nuvens em caverna sem alterações críticas. Ao mesmo tempo, podem indicar fatores de erro aceitáveis em comparações cavernícolas de monitoramentos futuros, como até 5 cm de variância e 95% de correlação. Superior a isso, podem apontar alteração da integridade física.

5. Conclusão

Na caverna granítica Buraco do Inferno, de complexa morfologia entre níveis verticais separados e cobertos por detritos, executaram-se dois escaneamentos em mesmo dia por senso portátil LIDAR. Os focos foram três : (i) aplicar nas nuvens de pontos análises geométricas para caractaerização morfológica cavernícola; (ii) avaliar viabilidade de rastreamento de alteração da integridade física da caverna através da comparação locacional e geométrica pelas nuvens de pontos; (iii) reconhecer potenciais interferências ambientais e humanas durante o processo de captação que impactam os resultados.

Nesse sentido, testaram-se quatro métodos complementares :

- Comparação das distâncias absolutas entre as nuvens ;
- Comparação quantitativa entre os resultados de análises geométricas de cada nuvem ;
- Comparação dos perímetros entre seções padronizadas extraídas em cada nuvem ;
- Comparação do número de pontos de nuvens extraídas nas seções padronizadas entre nuvens.

Conclui-se a plena viabilidade da aplicação dos métodos para caracterização morfológica de cavernas complexas, assim como no monitoramento de sua integridade física e estrutural. Isto mesmo com possíveis limitações ou interferências durante a captação. Os métodos aplicados, em associação com a interpretação visual das nuvens, permitem amplo monitoramento de qualquer caverna com o uso de sensores portáteis de LIDAR 3D.

O uso de superfícies interpoladas (« Mesh's ») se mostrou ineficiente em cavernas morfologicamente complexas (irregularidade de teto e pisos compostos por detritos e aberturas de fendas). A irregularidade da superfícies interpoladas alteraram as condições morfológicas naturais para efeitos comparativos de monitoramento.

Levantamentos futuros e aplicação em mais cavernas/litologias permitirão refinar as análises e particularidades dos métodos. Há ressalvas quanto à potencial aplicação para avaliar cavernas de amplas dimensões por nuvens únicas. Não se restrigem as análises para aplicação em nuvens parciais nesses casos. Limpeza das nuvens, excluindo vegetação e ruídos internos poderão detalhar as análises, mas trazendo peso ao fator tempo para conclusão do processo.

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Desempenho do scanner portátil BLK2GO na elaboração de mapas espeleotopográficos: um estudo de caso

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Resumo

Este estudo analisou a eficiência do scanner a laser portátil BLK2GO no mapeamento topográfico da cavidade PNCP_0262, no Parque Nacional Cavernas do Peruaçu (MG). A metodologia combinou coleta de dados em campo com o scanner, processamento da nuvem de pontos, extração de vetores e elaboração do mapa final. A portabilidade do BLK2GO dispensou bases fixas no interior da caverna, reduzindo tempo e riscos à equipe de campo. Os resultados indicaram que o equipamento é eficaz para mapeamento subterrâneo, oferecendo maior rapidez, se comparado às técnicas convencionais. A nuvem de pontos gerada permitiu identificar estruturas morfológicas da cavidade. Contudo, a resolução do scanner mostrou limitações na captura de espeleotemas e detalhes menores, exigindo complementação manual. Conclui-se que o BLK2GO é uma ferramenta promissora para espeleologia, especialmente em cavidades extensas como a PNCP_0262, por agilizar processos e minimizar impactos ambientais. A metodologia destacou-se na representação de grandes ambientes, mas recomenda-se a realização de esboços durante o trabalho de campo para auxiliar na identificação de elementos de menor escala, otimizando a integração entre tecnologia e registro manual. O estudo reforça o potencial do scanner em projetos de documentação espeleológica, desde que combinado a técnicas complementares para detalhamento fino.

Abstract

This study assessed the efficiency of the BLK2GO portable laser scanner for topographic of the mapping of the PNCP_0262 cavity, located in the Peruaçu Cave National Park (Minas Gerais, Brazil). The methodology integrated field data collection using the scanner, point cloud processing, vector extraction, and final map production. The BLK2GO's portability eliminated the need for fixed bases within the cave, reducing fieldwork time and minimizing risks to the team. Results demonstrated the equipment's effectiveness for subterranean mapping, offering greater speed compared to conventional techniques. The generated point cloud enabled the identification of the cavity's morphological structures. However, the scanner's resolution exhibited limitations in capturing speleothems and fine-scale details, necessitating manual supplementation. The study concludes that the BLK2GO is a promising tool for speleology research, particularly in extensive cavities such as PNCP_0262, as it streamlines workflows and minimizes environmental impacts. While the methodology excelled in representing large-scale environments, field sketches are recommended to aid in identifying smaller-scale elements, optimizing the integration of technology and manual documentation. This research hightlights the scanner's potential in speleological documentation projects, provided it is combined with complementary techniques for fine-scale detailing.

1. Introdução

As cavidades naturais subterrâneas, conhecidas popularmente como cavernas, lapas, furnas, grutas, etc., possuem grande representatividade no Brasil. São ambientes que abrigam complexas formações geológico-geomorfológicas, ecossistemas únicos com a presença de espécies endêmicas, além de resquícios paleontológicos, paleoambientais, arqueológicos e antropológicos (MONTEIRO, 2014). Atualmente, no Cadastro Nacional de Informações Espeleológicas (CANIE/ICMBio), encontram-se registradas mais de 23.300 cavidades. No entanto, diante das características ambientais que favorecem à ocorrência de cavidades naturais subterrâneas no país, Piló e Auler (2011) estimam que o número de feições seria superior a 200.000.

Diante deste grande potencial espeleológico, a identificação de novas cavidades naturais subterrâneas, via de regra, é feita através de prospecções espeleológicas, que podem ser realizadas por empresas de consultoria ambiental, durante processos de licenciamento ambiental ou grupos de espeleologia. Independentemente da forma utilizada para identificação de novas cavidades, a representação cartográfica destes ambientes subterrâneos é feita através de mapas espeleotopográficos.

Os métodos tradicionalmente utilizados na espeleotopografia são adaptações dos levantamentos topográficos realizados em superfície (SANCHEZ, 2016). Durante os levantamentos espeleotopográficos, os ângulos e distâncias são mensuradas com o emprego de bússola, clinômetro e trena a partir de bases que podem ser flutuantes ou fixas. No Brasil, não há uma metodologia específica para avaliar a precisão do levantamento espeleotopográfico, sendo os principais métodos utilizados o elaborado por British Cave Research Asssociation – BCRA e o da Union

Internationale de Spéléologie – UIS. Em síntese, os métodos supracitados englobam esboços elaborados sem a realização de medições em campo até levantamentos realizados com teodolitos ou estações totais.

Dentre os avanços tecnológicos registrados nos últimos anos, destaca-se no setor de geotecnologias o surgimento de novas técnicas e equipamentos que tem contribuído significativamente para agilizar o processo de mapeamento e aumentar sua acurácia. Neste contexto, pode-se destacar o Laser Scanner 3D, também conhecido como LiDAR Scanner (*light detection and ranging*) que se configura como um sistema de sensoriamento remoto ativo, e seu funcionamento se baseia na emissão de pulsos de laser na direção dos objetos. Existem dois tipos principais de scanner a laser, sendo encontrados equipamentos que utilizam o princípio da triangulação e os que se baseiam no tempo de retorno do sinal (TOMASSELLI, 2003). De modo geral, os sistemas são compostos por três itens básicos: unidade de medição laser (responsável por emitir e receber o sinal do laser), sistema de varredura optomecânico e uma unidade de registro de medições de apoio (NASCIMENTO JÚNIOR, SCHULER E CAVALCANTE, 2006).

Trata-se de uma tecnologia recente e extremamente versátil, com aplicações em áreas como construção civil, mineração, nos estudos ambientais e na espeleologia.

No contexto espeleológico, pode-se destacar trabalhos que tiveram como proposta a representação do ambiente subterrâneo através do escaneamento a laser, sendo possível citar o trabalho realizado por De Waele et al. (2018), na Itália. No Brasil, destacam-se os trabalhos de Araújo et al. (2015) e Araújo (2016) em cavernas ferríferas no estado do Pará; Brandi (2018) e Souza et al. (2023), em Minas Gerais.

O estado de Minas Gerais apresenta ocorrência predominante de cavernas conhecidas (ICMBIO, 2023), incluindo a porção norte do estado, onde está localizado o Parque Nacional Cavernas do Peruaçu. A área que compreende o PARNA Peruaçu pertence a região carbonática do Grupo Bambuí (RUBBIOLI et al., 2019), sendo composta por cavernas de grande extensão e complexidade. Neste cenário, o mapeamento 3D apresenta grande potencial para aumentar a eficiência da elaboração de mapas espeleotopográficos. Deste modo, tem-se como objetivo avaliar o uso de dados obtidos com o scanner portátil BLK2GO na elaboração do mapa topográfico da cavidade PNCP_0262, situada no PARNA Peruaçu, entre os municípios de Januária a Itacarambi, no estado de Minas Gerais (Figura 1).

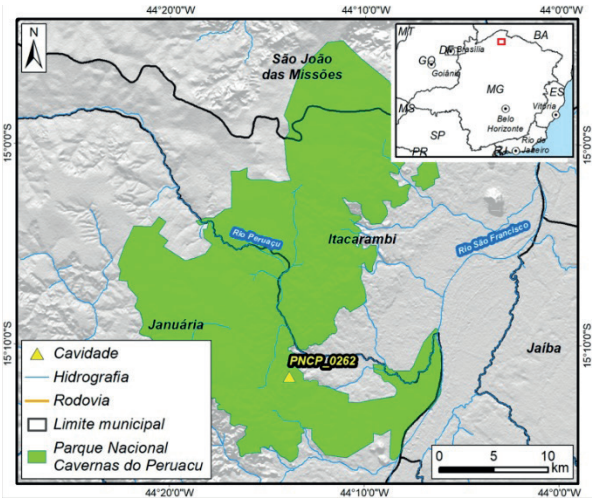

Figura 1: *Localização da cavidade PNCP_0262.*

2. Materiais e Métodos

A cavidade PNCP_0262 está inserida em rochas carbonáticas da formação Sete Lagoas, pertencente ao Grupo Bambuí (Figura 2 e Figura 3).

Figura 2: *Registro feito no interior da cavidade.*

Figura 3: *Destaque para os espeleotemas na cavidade PNCP_0262.*

A abordagem adotada para elaboração do mapa espeleotopográfico da PNCP_0262 com o emprego do scanner a laser abrangeu atividades que consistiram na aquisição de dados em campo, processamento, extração de vetores (pontos, linhas e polígonos) e elaboração do layout do mapa da cavidade.

Durante a atividade de campo, ocorrida no dia 24/04/2024, foi utilizado um scanner a laser modelo BLK2GO da empresa *Leica Geosystems* (Figura 4), que possui 279 mm de altura e 80 mm de diâmetro. O equipamento possui um campo de visão de 360° (horizontal) e 270° (vertical), uma taxa de medição de 420.000 pontos, com alcance mínimo de 0,5 m até 25 metros.

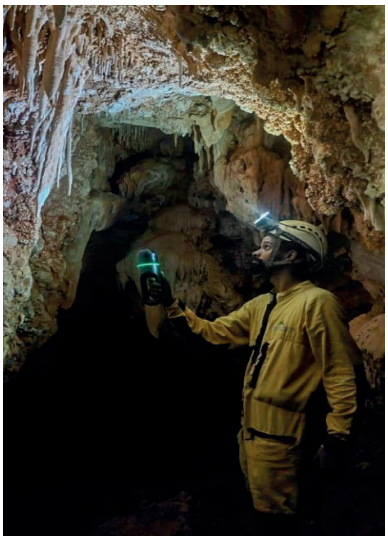

Figura 4: *Exemplo de uso do escâner BLK2GO no interior de uma caverna.*

Por ser um equipamento móvel, o escaneamento foi realizado sem o estabelecimento de bases no interior da cavidade. Neste sentido, houve a necessidade de realizar a amarração do levamento em campo a um sistema de referência. Utilizou-se como princípio o método de georreferenciamento proposto por Araújo (2016).

Primeiramente, foram definidas duas bases, representadas por esferas de poliestireno. A primeira, denominada B1, foi disposta próximo à entrada e a segunda (B2) na seção formada pelas paredes, teto e piso da cavidade. processamento dos dados. Em seguida, com um GPS de navegação Garmin modelo Etrex 30 foram coletadas as coordenadas da base B1. A partir desta base, com visada para B2 foi aferido o azimute para B2 com a bússola e a distância entre bases, com trena a laser (Figura 5).

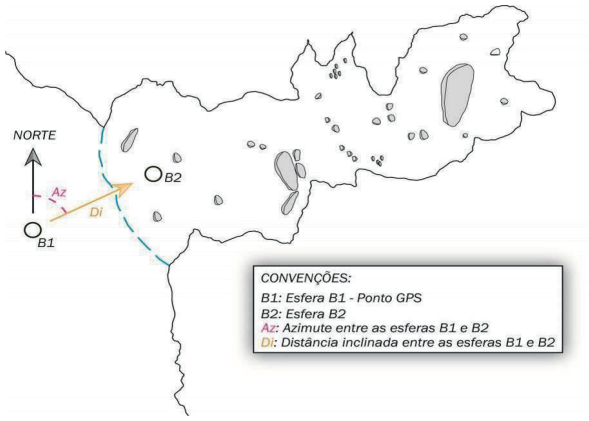

Figura 5: *Figura explicativa do método utilizado para georreferenciamento da nuvem de pontos.*

Após a etapa de campo, a nuvem de pontos referente à cavidade foi importada para o software Cyclone Register 360. Nos casos em que software não consegue proceder o alinhamento automático das seções, é possível processá-lo de forma manual. Em seguida, procedeu-se à conversão do arquivo para o formato '.laz'. Esse formato possibilita a manipulação do arquivo em softwares de modelagem digital, garantindo compatibilidade e eficiência no processamento das informações.

Em seguida, os dados foram transferidos para o software Cyclone 3DR. Nessa etapa foi realizado o aprimoramento da nuvem, eliminando elementos irrelevantes para o levantamento topográfico, que porventura tenham sido atravessados pelo feixe do laser. Ainda no mesmo software, identificou-se o posicionamento das bases representadas por esferas.

Após o processamento e a interpolação da nuvem finalizados, o arquivo é convertido para o formato '.asc'. Esse formato matricial oferece maior acessibilidade e é compatível com o software Geomagic.

A partir desta etapa de renderização e interpolação da malha, o arquivo retorna ao software Cyclone 3DR, em que ocorreu a vetorização da malha (Figura 6).

Figura 6: *Malha interpolada da cavidade PNCP_0262.*

Nesse processo, foram identificados todos os aspectos morfológicos da cavidade, tais como paredes, linha d'água, plano zero, desníveis abruptos e suaves. No entanto, devido à resolução do scanner, elementos como espeleotemas não foram vetorizados, exigindo uma etapa posterior de marcação manual desses pontos, nos quais tais atributos estão localizados. Por fim, foram mensurados a altura, volume e o desnível da cavidade.

Após a etapa de tratamento da nuvem de pontos da cavidade e a identificação dos contornos e dos elementos presentes na feição, essas informações foram exportadas e transferidas para o software ZWCAD 2021, a fim de elaborar o mapa topográfico. Nessa etapa, realizou-se o georreferenciamento da cavidade com base nos pontos B1 e B2, conforme elucidado anteriormente. Com o georreferenciamento concluído, mensuraram-se a projeção horizontal e a área da cavidade, uma vez que essas variáveis são bidimensionais e, portanto, extraídas diretamente do mapa espeleotopográfico. Dessa forma, por meio desse processo, foi possível obter os cálculos espeleométricos e a elaboração do mapa topográfico da cavidade PNCP_0262.

3. Resultados

Devido às dimensões da cavidade PNCP_0262, a coleta de dados em campo com o scanner portátil BLK2GO foi segmentada em 13 escaneamentos. Após a integração dos levantamentos, gerou-se uma nuvem de pontos com aproximadamente 64.200.000 pontos, apresentando um erro médio de 0,011 m (Figura 7).

Após a limpeza e o processamento da nuvem de pontos, extraíram-se os arquivos vetoriais que compõem o mapa topográfico. Os vetores referentes às paredes, linha d'água, plano zero, cortes e perfis foram obtidos de forma automática por meio da ferramenta "contorno externo" do software Cyclone 3DR. Por outro lado, os desníveis e blocos exigiram um trabalho de identificação e vetorização manual no mesmo software.

Em relação aos valores espeleométricos derivados do mapa topográfico elaborado a partir do escaneamento a laser, a projeção horizontal da cavidade atingiu 870,44 m, o desnível foi de 22,01 m, a área corresponde a 9.629,11 m^2 e o volume a 25.967,10 m^3 (Figura 7).

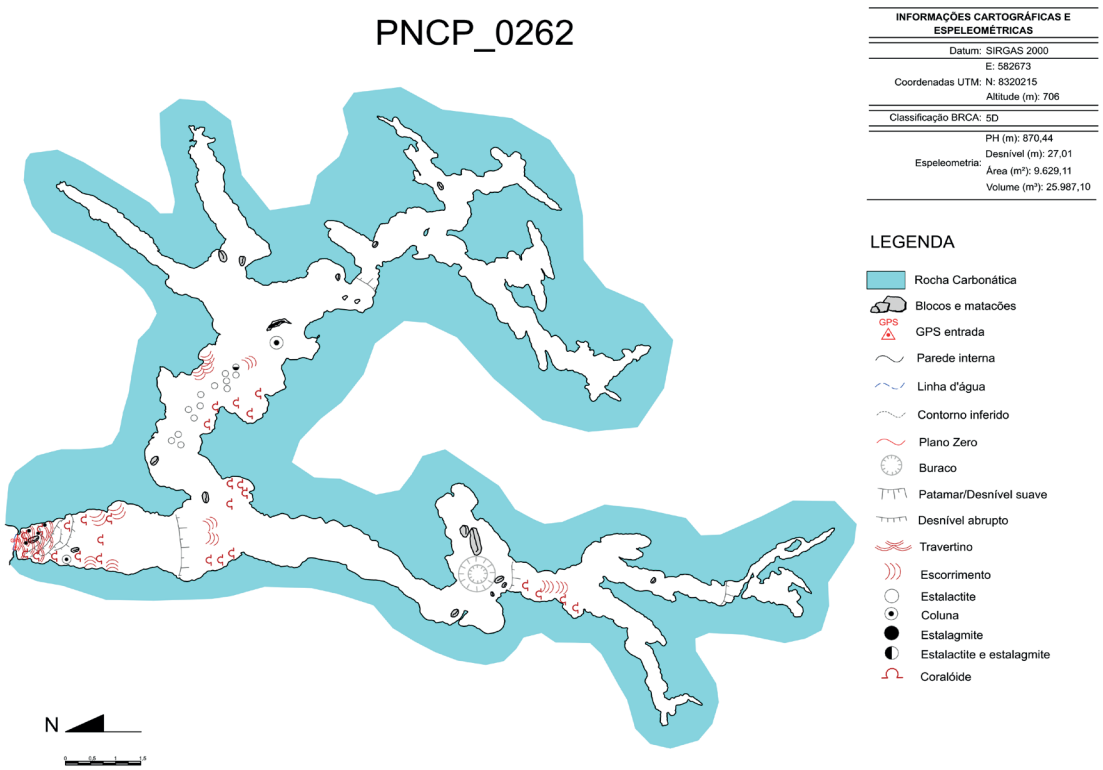

Figura 7: *Mapa espeleotopográfico da cavidade PNCP_0262 elaborado a partir de dados obtidos com o Leica BLK2GO.*

4. Discussão

A aplicabilidade do scanner a laser tem sido mencionada em diversos estudos no ramo da espeleologia (FERNANDES et al., 2024; SEVIL-AGUARALES et al., 2024; SOUZA et al., 2023; DE WAELE et al., 2018). Neste contexto, os autores destacam a eficiência do scanner a laser no mapeamento de cavernas, principalmente no que se refere à rapidez. Os autores De Waele et al. (2018) ressaltam o potencial do escaneamento a laser para obter estudos acurados em ambientes geomorfológicos desafiadores, que conseguem representar de forma detalhada a morfologia da cavidade.

Os resultados obtidos no levantamento topográfico realizado por Fernandes et al. (2024) ressaltam que através do escâner foi possível gerar um mapeamento com maior acurácia espeleométrica, sendo superior ao levantamento convencional.

Outro ponto positivo do escaneamento a laser é a menor probabilidade de perturbar o ambiente cavernícola, pois não há necessidade de instalar bases ao longo da cavidade. Na metodologia utilizada, apenas duas bases foram posicionadas na parte externa da cavidade.

Em relação aos pontos negativos associados ao uso dos escâners, pode-se citar a necessidade de iluminação no ambiente para facilitar a identificação de atributos na nuvem de pontos.

Outro ponto importante que deve ser destacado, é a vetorização manual de atributos internos da cavidade. Informações como espeleotemas devem ser capturadas ainda durante a atividade de campo, já que não é possível vetorizá-los manualmente a partir dos dados obtidos no escâner, dificultando sua identificação.

No entanto, embora sejam importantes para auxiliar os espeleólogos durante a exploração da cavidade, são representativos e não interferem nos valores espeleométricos utilizados nos estudos de relevância.

O tempo de escaneamento também é um fator limitador do método, sendo destacada maior eficiência para cavernas menores (DE WAELE et al., 2018). Contudo, no levantamento espeleotopográfico realizado para a cavidade PNCP_0262 o uso do escâner BLK2GO se mostrou eficiente. A metodologia adotada permitiu que o levantamento fosse realizado de forma segmentada na cavidade, o que não comprometeu a execução da atividade com resultado satisfatório.

5. Conclusão

O estudo realizado na cavidade PNCP_0262, localizada no Parque Nacional Cavernas do Peruaçu (Itacarambi-MG), demonstrou a eficácia do uso do scanner a laser portátil BLK2GO para o mapeamento topográfico em ambientes cársticos. A metodologia, fundamentada na aquisição de dados em campo, processamento de nuvens de pontos e vetorização, permitiu a geração de um mapa espeleotopográfico detalhado.

A integração de técnicas de georreferenciamento, e no método proposto por Araújo (2016), garantiu a precisão espacial dos dados, mesmo em ausência de bases no interior da cavidade. Contudo, a necessidade de vetorização manual de elementos como desníveis, blocos e necessidade de marcação manual ainda em campo dos espeleotemas revelou limitações inerentes à resolução do equipamento, reforçando a importância de registros complementares durante a fase de campo para atributos morfológicos mais sutis, ou até mesmo para condutos menores.

Os resultados corroboram estudos anteriores (DE WAELE et al., 2018; FERNANDES et al., 2024) ao evidenciar que o escaneamento a laser oferece vantagens significativas em relação aos métodos convencionais, como redução do tempo de campo, minimização de riscos à equipe e menor impacto ambiental, devido à dispensa de instalação de bases no interior da cavidade. A metodologia aplicada à PNCP_0262

mostrou-se particularmente eficaz para cavidades de grande porte, com morfologias complexas.

Como recomendações, propõe-se a realização de esboços da cavidade durante o campo, de forma a facilitar a identificação/posicionamento de espeleotemas, ou eventuais atributos de pequena escala relevantes na cavidade. Por fim, o estudo reforça o potencial do escâner BLK2GO como ferramenta versátil para a espeleologia, uma vez que requer menor permanência no sensível ambiente das cavidades.

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Projeto Unalândia (GREGEO): Topografia e Caracterização de Cavidades integrado à Capacitação em Espeleologia.

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Resumo

O projeto "Unalândia - conhecer para proteger", conduzido pelo GREGEO-UnB entre 2020 e 2023, realizou levantamentos espeleológicos nas regiões de Unaí e Natalândia (MG). Foram mapeadas e caracterizadas quatro cavidades: Lapa do Ancião, Lapa da Nuvem, Gruta do Chuvisco e Sumidouro da Pedra Rolada. As atividades envolveram técnicas tradicionais e digitais de topografia, além de registro fotográfico. O projeto também teve foco na capacitação de membros do grupo, promovendo treinamentos práticos. Os resultados contribuem para a documentação do patrimônio espeleológico local e reforçam a importância do apoio institucional para a continuidade das pesquisas na área.

Abstract

The project "Unalândia – knowing to protect," conducted by GREGEO-UnB between 2020 and 2023, carried out speleological surveys in the regions of Unaí and Natalândia (MG). Four caves were mapped and characterized: Lapa do Ancião, Lapa da Nuvem, Gruta do Chuvisco, and Sumidouro da Pedra Rolada. The activities involved traditional and digital topographic techniques, as well as photographic documentation. The project also focused on training group members by providing practical training sessions. The results contribute to the documentation of the local speleological heritage and emphasize the importance of institutional support for the continuity of research in this field.

Résumé

Le projet « Unalândia – connaître pour protéger », mené par le GREGEO-UnB entre 2020 et 2023, a réalisé des études spéléologiques dans les régions de Unaí et Natalândia (MG). Quatre cavités ont été cartographiées et caractérisées : Lapa do Ancião, Lapa da Nuvem, Gruta do Chuvisco et Sumidouro da Pedra Rolada. Les activités ont impliqué des techniques topographiques traditionnelles et numériques, ainsi qu'une documentation photographique. Le projet s'est également concentré sur la formation des membres du groupe en leur proposant des sessions de formation pratique. Les résultats contribuent à la documentation du patrimoine spéléologique local et soulignent l'importance du soutien institutionnel pour la poursuite des recherches dans ce domaine.

1. Introdução

O projeto **"Unalândia - conhecer para proteger"**, realizado nos municípios de Unaí e Natalândia (MG), foi conduzido pelo Grupo Espeleológico da Geologia da Universidade de Brasília (GREGEO-UnB) entre 2020 e 2023. A região é caracterizada por rochas carbonáticas do Grupo Bambuí e Grupo Paranoá, cujas particularidades geológicas e geomorfológicas foram detalhadas em ALMEIDA et al. (2022).

As atividades realizadas pelo GREGEO resultaram em uma robusta documentação da região, incluindo o inventário de cavidades identificadas (ALMEIDA et al., 2022a; 2022b; 2023), o uso de técnicas de sensoriamento remoto para prospecção (SOUZA e CASTRO, 2022), a caracterização das fitofisionomias (ROMERA et al., 2022), a avaliação de impactos ambientais (PANIAGO et al., 2022), arqueologia (ALMEIDA et al., 2022) e geoespeleologia (STUMPF et al., 2022 ; Ribeiro et al., 2022).

Este resumo apresenta os resultados obtidos a partir da terceira campanha do projeto, com foco na topografia e caracterização das cavidades **Lapa do Ancião, Lapa da Nuvem, Gruta do Chuvisco e Sumidouro da Pedra Rolada**, consolidando informações valiosas sobre o patrimônio espeleológico da região.

2. Materiais e Métodos

Para prospecção, foi aplicada técnicas de sensoriamento remoto para realce de formações carbonáticas e fotointerpretação utilizando imagens aéreas para delimitação de áreas com potencial para ocorrência de cavidades. Os caminhamentos em campo foram registrados com

GPS, com o objetivo de inspecionar paredões calcários e identificar a presença de cavidades. A topografia foi realizada com técnicas tradicionais (trena a laser e clinômetro + bússola Eyeskeys) e digitais (Disto X + TopoDroidX). Por fim, foi realizado registro fotográfico das cavidades para o acervo do GREGEO.

3. Resultados e discussões

Foram elaborados mapas de quatro cavidades. Os mapas da Lapa do Ancião, Lapa da Nuvem e Gruta do Chuvisco foram concluídos, enquanto a topografia do Sumidouro da Pedra Rolada encontra-se parcial.

As atividades de topografia visaram treinar os membros do GREGEO. Iniciantes foram instruídos em técnicas de topografia tradicional, enquanto os mais experientes receberam treinamento em topografia digital, sempre sob supervisão de membros veteranos, que conduziram o treinamento prático e escritório.

Os resultados da topografia, acompanhados de uma breve caracterização das cavidades, visam documentar o patrimônio espeleológico de Natalândia (MG).

3.1. Lapa do Ancião

A Lapa do Ancião (MG-2613) foi identificada na segunda campanha de campo (31/12/2021), e seu levantamento topográfico ocorreu entre 28 e 30 de dezembro de 2022, na terceira campanha de campo. Utilizou-se uma DistoX adaptada para o levantamento de dados, e o aplicativo TopoDroidX para a confecção do croqui.

A cavidade encontra-se à alta vertente do morro, com a entrada principal na face oeste, próximo ao sopé do paredão calcário. Uma segunda boca, de menor porte, ocorre na face leste do morro. O desenvolvimento é linear no sentido N-S, acompanhando o lineamento do morro na qual está inserida. Apresenta 236m de projeção horizontal e 16,7m de desnível (Fig. 1).

A entrada principal é inclinada, não muito ampla, e dá acesso a um declive, com blocos acumulados e restos vegetais (folhas, galhos, sementes e frutos). As camadas estão verticalizadas, favorecendo a percolação de água vadosa por entre o acampamento sedimentar vertical.

Grandes declives são observados no setor noroeste da gruta. Bancos de sedimentos clásticos coluvionares cimentados, sugerem que já houve preenchimento pelo menos parcial de alguns condutos, hoje erodidos permitindo a passagem. O conduto superior, próximo a entrada principal, possui teto baixo, com grande quantidade de blocos, espeleotemas e sedimentos lamosos. A porção sul do conduto principal tem passagem estreita com declives, em formato de fenda, e o teto fica gradualmente mais baixo rumo à segunda entrada da caverna. Há presença de fluxo de água que deposita sedimento argiloso e blocos, além da presença de espeleotemas variados.

A ornamentação inclui escorrimentos, coraloides, estalactites e cortinas. Destaque é atribuído às flores/pétalas de gipsita, associadas a cave blisters (Hill & Forti, 1997) (bolhas de caverna - tradução livre), sendo estes depósitos hemisférios e protuberantes, semelhantes a uma bolha, com paredes finas (Fig. 2). Encontram-se quebradas em algumas porções, mostrando que são ocas por dentro, com pequenas pétalas de gipsita e coraloides do lado de dentro.

Ocorrências arqueológicas são abundantes na região. Na Ancião, foi observado um fragmento cerâmico e uma pá de ferro, possivelmente utilizada em antiga atividade garimpeira. Troncos de madeira encontrados na extremidade norte também sugerem uso para suporte à escavações garimpeiras.

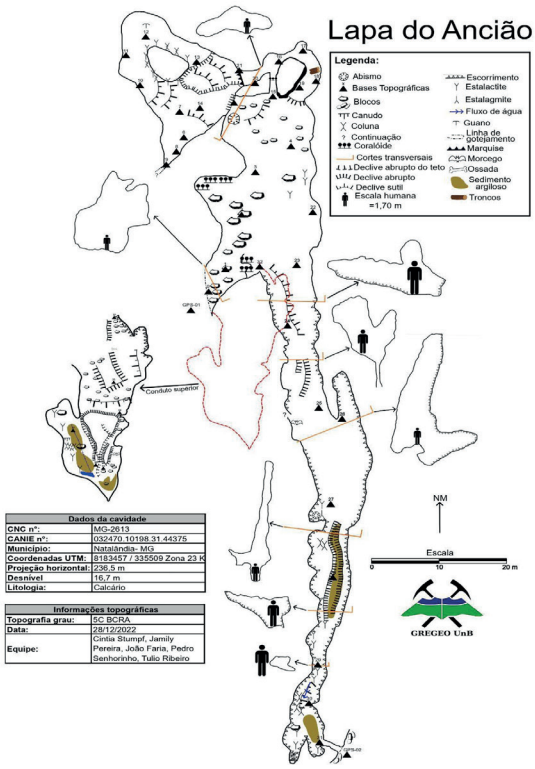

Figura 1: *Mapa da Lapa do Ancião. GREGEO (2025).*

Figura 2: *Fotografias ilustrativas da Lapa do Ancião. A) Entrada principal. B e C) Artefatos arqueológicos. D) Exemplo da ornamentação da cavidade. E e F) Pétalas de gipsita. G) Espeleotema bolha oca. F) Detalhe da foto em E.*

3.2. Lapa do Nuvem

A Lapa da Nuvem (MG-2596) foi identificada e topografada durante a segunda expedição do projeto (de 26/12/2021 a 02/01/2022). A cavidade apresenta 63m de projeção horizontal e 10m de desnível (Fig. 3). O nome da gruta foi atribuído em referência às "nuvens" de mosquitos, abundantes em um dos salões da cavidade.

A cavidade possui três níveis distintos e morfologia linear, alongada no sentido NW-SE, paralelamente ao paredão calcário. Esta disposição confere ao piso principal uma entrada ampla. Uma segunda abertura permite o acesso ao piso inferior.

Parte da cavidade apresenta o calcário cinza-escuro exposto, com pendentes em grande extensão ao longo dos três pisos. Os condutos internos abrigam espeleotemas como coralóides, escorrimentos e cortinas. O piso é acidentado, caracterizado por sedimentação lamosa e grande quantidade de blocos abatidos, sobretudo no pavimento inferior. No conduto principal, além de blocos, ocorrem sedimentos predominantemente argilosos. Comumente ocorre guano e fezes de animais, possivelmente de anuros. Ademais, ocorre folhiço próximo às entradas, e ossadas, tanto depositadas no substrato quanto incrustadas na rocha (abismo da ossada).

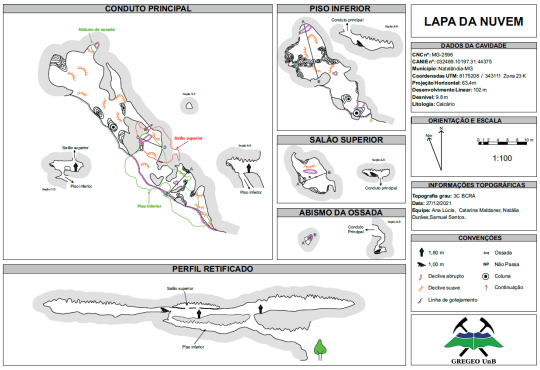

Figura 3: *Mapa da Lapa do Nuvem. GREGEO (2025).*

3.3. Gruta do Chuvisco

A gruta do Chuvisco (MG-2998) foi identificada durante a segunda expedição do projeto (31/12/2021). A topografia foi realizada na terceira expedição (2022). Utilizou-se metodologia tradicional com trena a laser, clinômetro, bússola, e croqui desenhado a mão. A cavidade apresentou 67m de projeção horizontal e 4m desnível (Fig. 4).

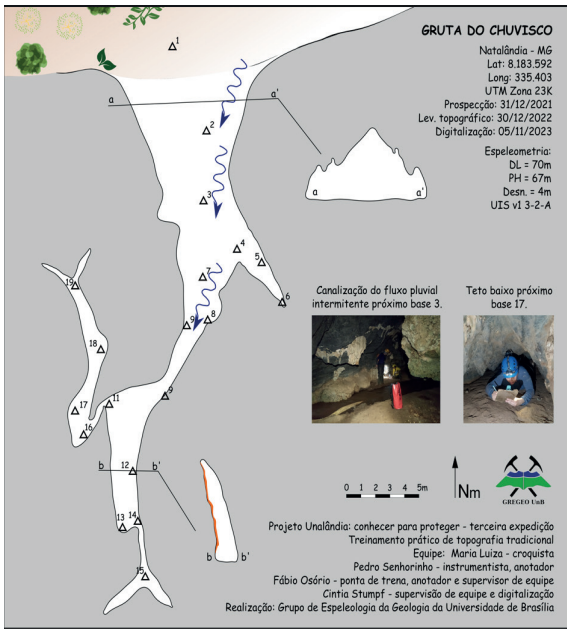

Figura 4: *Mapa da Gruta do Chuvisco. GREGEO (2023).*

O paredão calcário que abriga a zona de entrada da cavidade forma um amplo abrigo, com cerca de 30m de largura, abundante em pendantes. A entrada da cavidade situa-se a oeste deste abrigo, com formato triangular, onde a base é mais larga que o teto. Pendentes são abundantes e

podem ser observados alguns espeleotemas pouco expressivos, como pequenas estalactites, corrimento e coralóides.

O piso é argiloso, com bastante raízes, musgos e matéria orgânica vegetal, e alguns blocos de pequena dimensão. O aporte de água pluvial é notável. Toda a água da área vegetada à frente da ampla entrada é capturada para dentro da cavidade. O sedimento clástico lamoso observado é transportado pelo fluxo pluvial da área, como sugere a água de coloração amarronzada com sedimento suspenso observada (Fig. 5)

O conduto apresenta forma linear, estreitando em direção ao fundo (sul). O canal de drenagem é esculpido nos sedimentos do piso, acompanhando o conduto principal. Apesar do canal de drenagem não ser largo, e o fluxo ser intermitente, dependendo da captação pluvial externa, em episódios de chuva, o confinamento da água ao sair do amplo abrigo da entrada e seguir pelo conduto que afunila, possivelmente causa eventos de inundação. Os abundantes pendentes, somados a restos vegetais observados presos em partes mais elevadas das paredes e tetos são evidências de eventos de inundação na cavidade.

Após o estreitamento inicial, o conduto se abre em um salão amplo com teto alto, onde o fluxo de água segue para a porção mais baixa da cavidade, sumindo por um conduto estreito que não permite passagem humana (base 15). A passagem para o conduto secundário (base 11-19), se dá por rastejo em trechos de teto baixo, com aclive.

A cavidade encontra-se ativa. A água proveniente de enxurrada é a principal fonte de dissolução e evolução da caverna. O fluxo hídrico acompanha o gradiente hidráulico para as zonas rebaixadas, atribuindo um formato levemente meandrante ao conduto. A ornamentação é pouco exuberante, com grandes exposições de rocha fresca, o que é esperado para uma cavidade com constantes eventos de inundação que “lavam” as paredes e inibem a precipitação mineral.

Figura 5: *Entrada da Gruta do Chuvisco durante evento de chuva. Observar o fluxo de água entrando na cavidade.*

3.4. Sumidouro da Pedra Rolada

A cavidade Sumidouro da Pedra Rolada (MG-2680) foi identificada e parcialmente topografada durante a terceira expedição do projeto (29/12/2023). Sua entrada estreita dá acesso a um salão amplo e inclinado, formado pelo abatimento de grandes porções do teto.

O piso íngreme é composto por blocos instáveis. Estalactites e escorrimentos ornamentam o teto e paredes do salão, assim como pequenas estalagmites e coraloides, que ocorrem sobre blocos abatidos em porções restritas. Na porção nordeste, próximo à entrada, há um pequeno salão suspenso e isolado, rico em espeleotemas.

No final da descida, observa-se um fluxo hídrico raso, com baixa vazão mesmo na estação chuvosa. Este fluxo segue na direção S-SW, descendo em direção ao fundo da cavidade.

O mapa parcial (Fig. 6) cobre a porção inicial da cavidade, com morfologia predominantemente ramiforme, com perfil e seções irregulares, com 42m de projeção horizontal e 16m de desnível. Estima-se que a continuidade do mapa revele um conduto linear com direção NW-SE.

A topografia foi interrompida devido às condições de tempo. Durante períodos chuvosos, a cavidade atua como sumidouro, capturando grande quantidade de água superficial, formando fluxos torrenciais e cachoeiras, elevando o risco de inundação e dificuldade de saída.

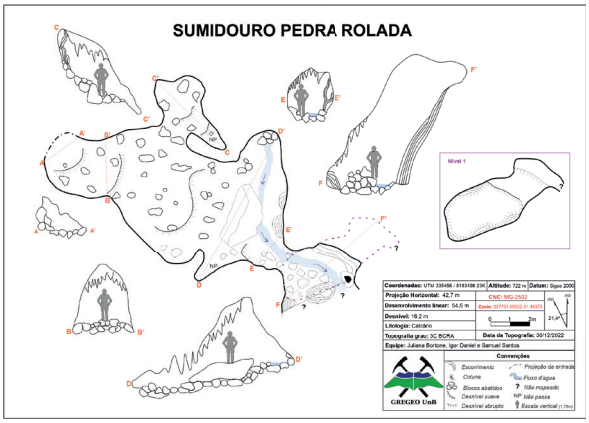

Figura 6:*Mapa parcial do Sumidouro Pedra Rolada. GREGEO (2022).*

4. Conclusões

Entre 2020 e 2023, o GREGEO realizou três campanhas de campo do projeto Unalândia - conhecer para proteger, na região de Natalândia e Unaí, Minas Gerais. As campanhas resultaram na identificação de 96 cavidades naturais, a finalização de 6 mapas topográficos, além de mais 2 mapas pendentes de digitalização, sendo, portanto, uma documentação científica significativa.

Um segundo propósito do projeto foi fornecer treinamento para membros do GREGEO, garantindo o engajamento dos membros e a continuidade do grupo. 24 membros participaram das expedições, além da participação de colegas de espeleogrupos parceiros (Meandros e EGB).

Este trabalho caracteriza mais quatro cavidades estudadas durante o projeto: Lapa da Nuvem, Lapa do Ancião, Gruta do Chuvisco e o Sumidouro da Pedra Rolada. Dentre essas cavidades, a do Ancião é a mais expressiva em dimensão quanto à ornamentação.

O GREGEO desempenha um papel de destaque na capacitação e formação de profissionais no Centro-Oeste, oferecendo treinamentos práticos em topografia, mapeamento e análise espeleológica, que são cruciais para o desenvolvimento de novos espeleólogos. A execução desse projeto ilustra a importância do apoio institucional para a continuidade das pesquisas e a formação de novos espeleólogos, sendo um exemplo do impacto positivo que parcerias como essa entre GREGEO e SBE através do Edital 01/2020 podem gerar na espeleologia brasileira.

5. Agradecimentos

A realização do projeto “Unalândia – conhecer para proteger”, se fez possível através do edital 2020/01 de financiamento da Sociedade Brasileira de Espeleologia (SBE). O GREGEO agradece ao Sr. Leandro Marques, Secretário Municipal do Meio Ambiente e Desenvolvimento Sustentável pela receptividade e auxílio durante toda a realização das expedições. Aos membros do GREGEO que participaram do levantamento de campo das topografias apresentadas: Fábio Osório, Jamily Pereira da Silva, Igor Daniel, Natália Durães, Maria Luiza, Pedro Senhorinho, Catarina Maldaner e Juliana Bortone (EGB). Agradecemos também a todos os gregelinos que contribuem diariamente para a continuidade do espeleogrupo. Vida longa ao GREGEO!

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The caves of the Amazon

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Abstract

Located in the heart of the Amazon, on the banks of the Tapajós River, thousands of kilometers from Brazil's most well-known cave regions, lies a remarkable karst area that hides its secrets within the dense Amazon rainforest. This area might have remained undiscovered for many more years if not for the curiosity and resilience of Erismar Silva, a primary school teacher who had been walking the region's roads in search of caves since 1993. She entered them barefoot, using only candles for light and recorded all the information she gathered in a small notebook.In 2005, an expedition led by the geologist Augusto Auler was organized to search for limestone caves in the region for paleoclimatic studies. During their search, they discovered an important cave in Aveiro, a town near Rurópolis, called Paraíso Cave, which was measured 578 meters during this first expedition. A new expedition was organized in 2007, by which time the measurement of the cave had surpassed 1,600 meters, making it the largest cave in the Brazilian Amazon. This discovery was published in an electronic caving bulletin called "Conexão Subterrânea." Upon hearing the news, Rodrigo Motta, a resident of Itaituba and an adventure enthusiast, decided to seek out the cave. He was amazed by what he found. In 2009, driven by his interest in discovering new caves, Rodrigo eventually met Mrs. Erismar, who was already locally known as "the cave woman." She showed him her famous notebook and took him to several caves. Rodrigo, along with a few friends, set off to explore the caves she had pointed out, as well as other locations suggested by local residents. He registered all of them in the National Cave Registry (CNC) of the Brazilian Speleological Society, thus revealing the speleological potential of the region. The caves in Rurópolis are all formed in sandstone, possess great scenic beauty, and hold undeniable archaeological and paleontological value. At the same time, Rodrigo began providing logistical support and collaborating with mapping teams and researchers who periodically returned to work in Paraíso Cave, which also led to the mapping of some of the main caves discovered by Mrs. Erismar and himself. By 2024, Paraíso Cave had extended to over 8 kilometers in length and the scientific findings from it are of extreme importance. In this work, we will present the history of the discoveries, photographs of the main caves of Rurópolis, as well as the famous Paraíso cave and its current map.

Resumo

Localizada no coração da Amazônia, às margens do rio Tapajós, a milhares de quilômetros das regiões de cavernas mais conhecidas do Brasil, situa-se uma área cárstica notável, que esconde seus segredos na densa floresta amazônica. Essa área possivelmente teria permanecido oculta ainda por muitos anos, não fosse a curiosidade e a resiliência de Erismar Silva, professora primária, que desde 1993 passou a percorrer a pé as estradas da região em busca de cavernas. Entrava descalça, utilizando apenas velas para a iluminação, e anotava todas as informações obtidas em um caderninho. Em 2005, houve uma expedição liderada pelo geólogo Augusto Auler para procurar cavernas em calcário na região, com o objetivo de realizar estudos paleoclimáticos. Em suas buscas, acabou por encontrar uma caverna importante em Aveiro, município situado ao lado de Rurópolis, a caverna Paraíso, que nesta primeira expedição atingiu 578 m. Uma nova expedição foi organizada em 2007, quando então a caverna passou dos 1.600 m, tornando-se a maior caverna da Amazônia brasileira. A informação foi divulgada em um boletim eletrônico de espeleologia, o "Conexão Subterrânea". Ao tomar conhecimento da notícia, Rodrigo Motta, morador de Itaituba e apaixonado por aventura, resolveu procurar pela caverna. Ficou impressionado com o que viu. Em 2009, interessado em descobrir novas cavernas, Rodrigo acabou encontrando a Sra. Erismar, que já era conhecida localmente como "a mulher das cavernas". Ela lhe mostrou o seu famoso caderninho, e o levou a algumas cavernas. Rodrigo se juntou com mais alguns amigos e saiu em busca das cavernas que ela havia indicado, e também de outras referências recebidas de moradores locais. Registrou todas no Cadastro Nacional de Cavernas (CNC) da Sociedade Brasileira de Espeleologia, expondo desta forma o potencial espeleológico da região. As cavernas de Rurópolis são todas formadas no arenito, possuem grande beleza cênica e um inquestionável valor arqueológico e paleontológico. Paralelamente, Rodrigo passou a dar suporte logístico e colaborar com as equipes de mapeamento e pesquisadores que voltavam periodicamente para trabalhar na caverna Paraíso, e que terminaram por mapear também algumas das principais cavernas descobertas pela Sra. Erismar e por ele. Em 2024, a caverna Paraíso passou dos 8 km de desenvolvimento, e os resultados científicos obtidos nela são de extrema relevância. Neste trabalho, apresentaremos a história das descobertas, as fotografias das principais cavernas de Rurópolis, além da famosa caverna Paraíso e seu mapa atual.

Resumen

Ubicada en el corazón de la Amazonía, a orillas del río Tapajós, a miles de kilómetros de las regiones de cuevas más conocidas de Brasil, se encuentra una notable zona kárstica que oculta sus secretos en la densa selva amazónica. Esta área podría haber permanecido oculta por muchos años más, de no ser por la curiosidad y la resiliencia de Erismar Silva, una maestra de primaria que, desde 1993, recorría a pie los caminos de la región en busca de cuevas. Entraba en ellas descalza, usando solo velas para iluminarse, y anotaba toda la información obtenida en un pequeño cuaderno. En 2005, se organizó una expedición liderada por el geólogo Augusto Auler para buscar cuevas de piedra caliza en la región, con fines de estudios paleo climáticos. Durante la búsqueda, descubrieron una cueva importante en Aveiro, un municipio cercano a Rurópolis, la cueva Paraíso, que en esta primera expedición alcanzó los 578 metros. Se organizó una nueva expedición en 2007, momento en el cual la cueva ya superaba los 1.600 metros, convirtiéndose en la cueva más grande de la Amazonía brasileña. Este descubrimiento fue publicado en un boletín electrónico de espeleología llamado «Conexión Subterránea». Al enterarse de la noticia, Rodrigo Motta, residente de Itaituba y apasionado por la aventura, decidió buscar la cueva. Quedó impresionado con lo que vio.

En 2009, motivado por su interés en descubrir nuevas cuevas, Rodrigo finalmente conoció a la Sra. Erismar, quien ya era conocida localmente como “la mujer de las cuevas”. Ella le mostró su famoso cuadernito y lo llevó a varias cuevas. Rodrigo, junto con algunos amigos, salió a explorar las cuevas que ella había señalado, así como otros lugares sugeridos por los habitantes locales. Registró todas ellas en el Catastro Nacional de Cuevas (CNC) de la Sociedad Brasileña de Espeleología, revelando de esta forma el potencial espeleológico de la región. Las cuevas de Rurópolis están formadas en arenisca, tienen una gran belleza escénica y un valor arqueológico y paleontológico innegable. Paralelamente, Rodrigo comenzó a brindar apoyo logístico y a colaborar con los equipos de mapeo e investigadores que regresaban periódicamente para trabajar en la cueva Paraíso, lo que también llevó al mapeo de algunas de las principales cuevas descubiertas por la Sra. Erismar y por él. En 2024, la cueva Paraíso había superado los 8 kilómetros de desarrollo, y los resultados científicos obtenidos en ella son de gran relevancia. En este trabajo, presentaremos la historia de los descubrimientos, las fotografías de las principales cuevas de Rurópolis, además de la famosa cueva Paraíso y su mapa actual.

1. Location and history

Figure. 1: *Location of the caves area.*

Rurópolis is a municipality located 220 km south of Santarém, in the heart of the Amazon (Figure 1). The city center was the first planned city created along the Trans-Amazonian Highway. There lives a remarkable woman known as “the Cave Woman.” In 1993, Erismar Silva (Figure 2), an educator and at that time a primary school teacher, accompanied her children on a visit to a cave in the region. She was amazed by what she saw. Enthusiastic about her discoveries, she decided to give a presentation with photos of the cave at the Center for Pedagogical Support for Scientific Development (CPADC). At the end of the presentation, to her surprise, she received 14 different suggestions for similar locations in the area.

Thus, Mrs. Erismar decided to search for these caves. Without any means of transportation, she walked more than 30 km a day along roads and through the forest to find the caves that had been indicated. On weekends she invited friends to accompany her, usually women. They would enter the caves barefoot, using only candles for lighting. For each cave she explored, she recorded its name and location in a small notebook.

Her enthusiasm inspired other local residents and, in 1996, Mrs. Erismar, along with five friends who owned land with caves and supported the cause, founded the Rurópolis Cave Exploration Association (AECR), where she became president. The organization’s goal was to promote the protection of local caves and, in the future, develop speleotourism in Rurópolis. In 2000, they established contact with IBAMA through the Environmental Secretariat of the city of Santarém-PA, which accompanied them on an exploration and provided basic information on equipment, safety and risks involved in visiting caves.

Meanwhile, in 2005, an expedition led by the geologist Augusto Auler was organized to search for limestone caves in the region for paleoclimatic studies. In Aveiro, a municipality near Rurópolis, they found a cave that suited their objectives, the Paraíso Cave. The mapping of the cave began, and, during this first survey, 578 meters were measured. Despite difficult access conditions—since, at the time, it was necessary to travel 90 km of dirt roads—a new expedition was organized in 2007 to collect new samples and continue mapping the cave. This expedition included Augusto Auler, Leda Zogbi, and Daniel Menin, and the cave reached 1,603 meters, making it the largest cave in the Brazilian Amazon. The discovery was published in the electronic caving bulletin *Conexão Subterrânea*.

Figure 2: *Mrs Erismar Silva in her school class.*

Upon hearing the news, Rodrigo Motta, a resident of Itaituba and an adventure enthusiast, decided to search for the cave. He was impressed by what he saw. In 2009, Rodrigo, who was the Director of Tourism for the Municipality of Rurópolis at the time, met Mrs. Erismar, who showed him her notebook containing all 43 caves she had discovered. She even accompanied him to some of the main caves. Rodrigo, along with a few friends interested in exploring the region, set out to find the caves Mrs. Erismar had pointed out, as well as other locations suggested by local residents. He registered all these caves in the National Cave Registry of the Brazilian Speleological Society, thus revealing the area’s speleological potential.

Beginning in 2014, Rodrigo Motta started providing logistical support and collaborating with mapping teams that periodically returned to map the Paraíso Cave, coordinated by Leda Zogbi from the Meandros group. During breaks from the arduous task of mapping the Paraíso Cave, they also managed to map some of the main caves discovered by Mrs. Erismar.

By 2024 the Paraíso Cave had surpassed 8 kilometers in length, and the scientific findings from it are of extreme importance. The other caves in Rurópolis, all formed in sandstone, have great scenic beauty and undeniable archaeological, paleontological and biological value, as many of them are hotspots of cave biodiversity.

2. The caves of Rurópolis

Among the first caves that Mrs. Erismar listed in her notebook is the ***Caverna das Mãos*** (Cave of the Hands). It is one of the largest sandstone caves in Brazil, with over 1.5 km of passages. A river flows through the cave, cutting across the sandstone massif along its entire length. The cave holds significant archaeological value, with numerous carvings and paintings at its various entrances, and handprints of both adults and children imprinted in positive relief on the walls, 350 meters from the entrance, deep within the aphotic zone of the cave (Figure 3).

Figure 3: *Hands on the wall – Photo: Daniel Menin.*

Figure 4: *Mandala – Photo: Philippe Crochet.*

This is a rare occurrence, even on a global scale. A large colony of bats sustains a rich subterranean fauna, including alligators that travel more than 300 meters into the cave. Particularly noteworthy are the beautiful mandalas located near one of the cave's entrances, close to the river's resurgence (Figure 4). To date, no information is available about the people who frequented the cave, nor has the parietal art within it been dated.

Located near the Caverrna das Mãos is the ***Lucas Cave***, also known as ***Gruta do Divino*** (Length: 360 m). A beautiful waterfall adorns its entrance, creating a stunning scenic landscape (Figure 5).

Figure 5: *Lucas cave entrance – Lucas cave - Photo Philippe Crochet.*

The rock in which the cave was formed has a very white layer that contrasts with the rest of the sandstone. In one section, claw marks can be observed on the wall, made by a giant sloth, a megafauna species that went extinct about 10,000 years ago, which possibly extracted some mineral salts from the walls (Figure 6). The cave was also frequently visited by indigenous people: at the entrance, various ceramic shards can be found, and 100 meters from the entrance, also in the aphotic zone, there are several charcoal paintings on the ceiling.

Figure 6: *Claw marks of a giant sloth – Lucas cave – Photo Philippe Crochet.*

The Brás Cave consists of a series of interconnected labyrinthine passages, with pillars and large chambers, featuring several domes on the ceiling. The floor, covered with soft sand, forms dunes throughout much of the cave (Figure 7).

Figure 7: *Bras cave – Photo Philippe Crochet*

The beauty of the rock in which the cave was formed is remarkable, with various shades of white, beige, and pink. Jaguar tracks have been spotted inside the cave. To date, no archaeological remains have been found in this cave.

The Prudente Cave is still being mapped but stands out due to the richness of its cave fauna (Figure 8).

Figure 8: *Prudente cave – A scorpion with mites eating a cricket.- Photo Mirjam Widmer.*

The Queimada Cave is located at the top of a hill, offering a panoramic view of the region, including hills and lakes. Near its entrance, there is a very interesting panel of black rock art (Figure 9).

Figure 9: *Queimada cave – Photo: Victor Ferrer.*

The Sapucaia Cave has not yet been mapped, but it impresses with the enormous size of its internal chambers (Figure 10).

Figure 10: *Sapucaia cave – Photo: Kevin Downey.*

The Caximbão Cave forms a large chamber, with a wide entrance that allows light to enter. Its internal walls are covered with highly representative paintings and carvings (Figure 11). It certainly holds significant potential for archaeological study.

Figure 11: *Caximbão cave – Photo: Csaba Egri.*

The Damas Cave features very original rock art at its entrance. It was named because one of the drawings resembles a checkerboard (Figure 12). Just inside the entrance, there is a drop of about 4 meters that must be bypassed along a narrow edge. Even inside the cave, rock paintings and carvings can be observed (Figure 13).

Figure 12: *Damas cave – Photo: Csaba Egri.*

Figure 13: *Damas cave – Photo: Daniel Menin.*

The Fernanda Caroline Cave, located on a hill, is very small but contains several interesting carvings and paintings, especially a painting in red and black (Figure 14).

Figure 14: *Fernanda Caroline cave – Photo: Daniel Menin.*

3. The caves of Aveiro

The caves of Aveiro have developed in limestone, with some forming at the contact between limestone and sandstone. Among the most notable is Paraíso Cave, which is the largest cave in the Brazilian Amazon, extending over 8 km (Figure 15). Access to this labyrinthine network, traversed by several watercourses, is through a single entrance slightly over 1 meter in both height and width. The cave is horizontal and shallow, with an internal temperature of approximately 28°C.

Paleoclimatic studies conducted on its speleothems have revealed important data about the climate of the Amazon region over the past 50,000 years. To date, 11 troglobitic animals have been identified in the cave, but collections have only been carried out in a small area, leaving much yet to be studied. A vertebra of a giant sloth, found in a passage over 1 km from the cave entrance, provided evidence that this animal inhabited the Amazon region for much longer than previously known. Annual expeditions take place to continue mapping the cave (Figure 16).

Figure 15: *Paraíso Cave – Photo: Ricardo Martinelli.*

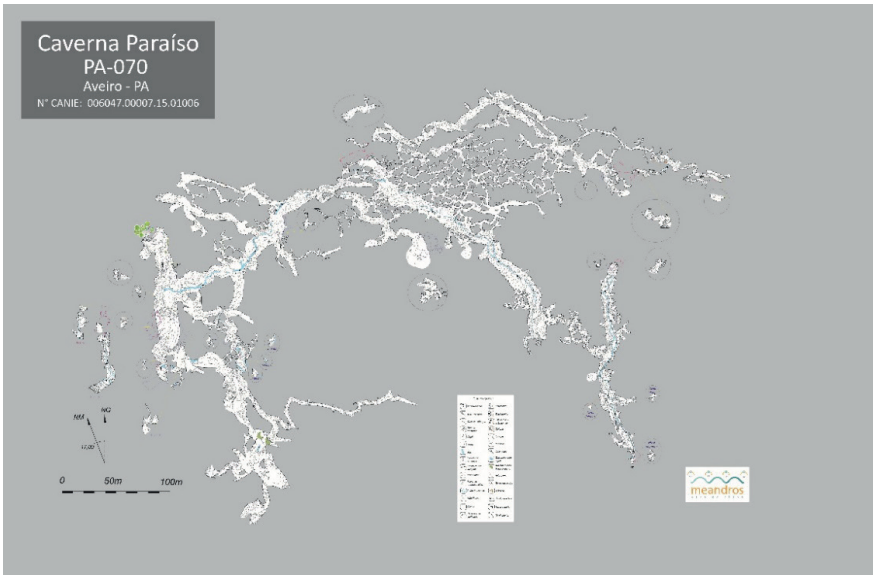

Figure 16: *Paraíso cave map: Meandros Espeleo Clube.*

4. Conclusion

Thanks to the pioneering work of Mrs. Erismar Silva and later Mr. Rodrigo Motta, the caves of Rurópolis and Aveiro are gradually being revealed. The potential of these caves for studies in various scientific fields, as well as for tourism, is undeniable. Unfortunately, the distance from major urban centers and the high cost of transportation to reach the region are factors that hinder this progress. We hope that, over time, these challenges will be overcome and that the region will gain the prominence it deserves on both the Brazilian and global speleological stage.

Acknowledgments:

We thank: Mrs. Erismar Silva for her love of caves and for sharing her treasures with us; Rodrigo Motta for all his help in locating and documenting this important heritage; Renata de Andrade and Marcela E. L. de Godoy for their help in reviewing this article; all the speleologists who contributed to mapping the caves and, finally, we thank the photographers and the entire team of the Lights in the Darkness project for enriching the photographic documentation of these caves.

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The Tamboril Cave: a heritage to be preserved

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Abstract

Known to the local population for a long time, Tamboril Cave is located in the northwest of Minas Gerais state, in the municipality of Unaí, 600 km from Belo Horizonte and just 170 km from Brasília. The earliest reference to the cave is recorded in the book The Caves of Minas Gerais (IBGE, 1939). Formed in the limestone of the Tocantins Province, the cave extends into a wide, richly ornamented main passage. About 500 meters from the entrance, a lake divides the cave into two distinct sections. The deeper section is less ornamented than the initial one, but it is no less striking: gigantic blocks, cones of collapsed rock, sandbanks, and sediment deposits create a nearly lunar landscape. The entire site boasts remarkable scenic beauty. The cave also stands out for its over 2.9 km length and its volume, both of which are significantly larger than the average cave in the region. Since the 1990s, the cave has been the subject of a tough legal battle. A mining company began extracting dolomite from the opposite side of the massif where the cave is located. Following several complaints and the intervention of the Public Prosecutor's Office, mining was halted in 2009 after environmental agencies found that irreparable damage had occurred in the cave. With its easy access and lack of entry control, the cave has been frequented by students, scientists, speleologists, and curious visitors over the last 20 years. Unfortunately, some visitors have vandalized parts of the cave with large graffiti, not only in the rooms near the entrance but also in more distant areas near the lake. Concerned with promoting the cave's conservation, Mrs. Olímpia Prado, owner of one of the plots of land where the cave is located, took on the mission of transforming the area into a Private Natural Heritage Reserve (RPPN). To establish rules for visiting the cave, it is important to develop a speleological management plan, and the foundation of all related studies is the cave map. The two existing maps, created by the GREGEO (1990) and SEE (1991) groups, were made using the methodologies available at the time, meaning they lack detail. As a result, an appeal was made to the speleological community to produce a new, more detailed and complete map. This effort began in September 2023, under the coordination of the Meandros Speleology Club. In this report, we will present the history, description, maps, and photographs of the cave.

Resumo

Conhecida pela população local há muito tempo, a Gruta do Tamboril está localizada no noroeste do estado de Minas Gerais, no município de Unaí, a 600 km de Belo Horizonte e a apenas 170 km de Brasília. A referência mais antiga sobre a caverna está registrada no livro As Grutas de Minas Gerais (IBGE, 1939). A caverna, formada no calcário da Província Tocantins, desenvolve-se em um conduto principal amplo e ricamente ornamentado. Aproximadamente 500 m da entrada, há um lago que divide a caverna em dois segmentos distintos. A parte mais profunda é menos ornamentada do que o trecho inicial, mas não perde em beleza: blocos gigantescos, cones de blocos desmoronados, bancos de areia e depósitos de sedimentos formam uma paisagem quase lunar. O conjunto todo apresenta uma beleza cênica notável. A caverna também se destaca pelo seu desenvolvimento de mais de 2,9 km e pelo seu volume, ambos bastante superiores à média das cavernas da região. Desde os anos 90, a caverna é alvo de uma dura batalha judicial. Uma mineradora começou a extrair dolomito do outro lado do maciço onde se encontra a caverna. Após várias denúncias e intervenção do Ministério Público, a mineração foi interditada em 2009, quando os órgãos ambientais constataram que danos irreparáveis haviam ocorrido na caverna. Por ser bastante acessível e sem nenhum controle de entrada, nos últimos 20 anos a caverna foi amplamente frequentada por estudantes, cientistas, espeleólogos e curiosos. Infelizmente, alguns visitantes vandalizaram trechos da caverna com grandes pichações, não apenas nas salas próximas à entrada, mas também nas mais distantes, próximas ao lago. Preocupada em promover a conservação da caverna, a Sra. Olímpia Prado, proprietária de uma das glebas de terra onde se encontra a caverna, assumiu a missão de transformar a área em uma Reserva Particular do Patrimônio Natural (RPPN). Para definir as regras de visitação da caverna, é importante elaborar um plano de manejo espeleológico, sendo a base de todos os estudos a serem desenvolvidos o mapa da caverna. Os dois mapas existentes, feitos pelos grupos GREGEO (1990) e SEE (1991), foram realizados com a metodologia disponível na época, ou seja, com pouco detalhamento. Por este motivo, fez-se um apelo à comunidade espeleológica para que fosse realizado um novo mapeamento mais detalhado e completo. Esse trabalho foi iniciado em setembro de 2023, sob a coordenação do Meandros Espeleo Clube. Neste trabalho, apresentaremos o histórico, a descrição, os mapas e as fotografias da caverna.

Resumen

Conocida por la población local desde hace mucho tiempo, la Cueva del Tamboril está ubicada en el noroeste del estado de Minas Gerais, en el municipio de Unaí, a 600 km de Belo Horizonte y a solo 170 km de Brasilia. La referencia más antigua de la cueva está registrada en el libro Las Cuevas de Minas Gerais (IBGE, 1939). Formada en la piedra caliza de la Provincia de Tocantins, la cueva se extiende a lo largo de un pasaje principal amplio y ricamente ornamentado. A unos 500 metros de la entrada, un lago divide la cueva en dos secciones distintas. La sección más profunda está menos ornamentada que la inicial, pero no es menos impresionante: bloques gigantescos, conos de rocas derrumbadas,

bancos de arena y depósitos de sedimentos crean un paisaje casi lunar. Todo el conjunto presenta una belleza escénica notable. La cueva también se destaca por su extensión de más de 2,9 km y su volumen, ambos muy superiores al promedio de las cuevas de la región. Desde la década de 1990, la cueva ha sido objeto de una dura batalla legal. Una empresa minera comenzó a extraer dolomita del otro lado del macizo donde se encuentra la cueva. Tras varias denuncias y la intervención de la Fiscalía, la minería fue suspendida en 2009, cuando las agencias ambientales constataron que se habían producido daños irreparables en la cueva. Debido a su fácil acceso y la falta de control en la entrada, la cueva ha sido frecuentemente visitada por estudiantes, científicos, espeleólogos y curiosos durante los últimos 20 años. Lamentablemente, algunos visitantes han vandalizado partes de la cueva con grandes grafitis, no solo en las salas cercanas a la entrada, sino también en las zonas más alejadas, cerca del lago. Preocupada por promover la conservación de la cueva, la Sra. Olímpia Prado, propietaria de una de las parcelas de tierra donde se encuentra la cueva, asumió la misión de transformar el área en una Reserva Privada del Patrimonio Natural (RPPN). Para establecer las normas de visita a la cueva, es importante desarrollar un plan de manejo espeleológico, y la base de todos los estudios que se realicen es el mapa de la cueva. Los dos mapas existentes, elaborados por los grupos GREGEO (1990) y SEE (1991), fueron realizados con la metodología disponible en ese momento, por lo que carecen de detalle. Por esta razón, se hizo un llamado a la comunidad espeleológica para realizar un nuevo mapa más detallado y completo. Este trabajo comenzó en septiembre de 2023, bajo la coordinación del Club de Espeleología Meandros. En este informe, presentaremos la historia, descripción, mapas y fotografías de la cueva.

1. Location and history

Figure 1: Location of the cave.

The Tamboril Cave is located about 10 km northwest of the city of Unaí (MG), which is 600 km from the state capital, Belo Horizonte, and 170 km from Brasília (Figure 1).

The exact date when visits to the Tamboril Cave began is unknown. The earliest reference to the cave can be found in the book The Caves of Minas Gerais (IBGE, 1939), which provides the cave's location and describes a visit made by Professor Olímpio Gonzaga in 1908 (Figure 2).

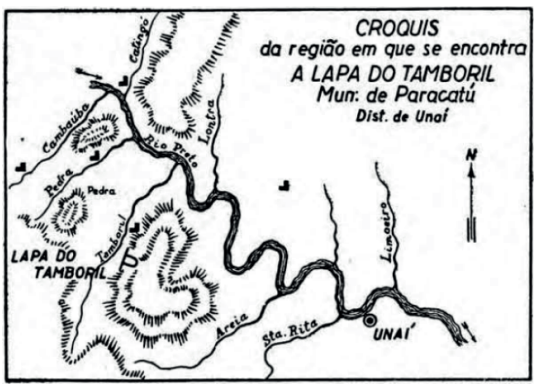

Figure 2: Location of the cave (IBGE 1939, 180).

In 1960, the area where the cave is located was acquired by Mr. Sinval Alves do Prado, who did not prevent visitor access. For many years, the cave hosted numerous groups of students, adventurers, scientists, and those interested in the cave. In the late 1980s, the mining company Britacal began extracting dolomite from the massif where the cave is located, but on the opposite side of its entrance. By 1994, environmental studies indicated the impact of mining activities on the cave. After several reports and intervention from the Public Prosecutor's Office of Minas Gerais, mining operations were suspended in 2009 due to internal damage found in the cave. In fact, the mining front was only a few meters away from reaching the cave and many speleothems were affected by the explosive detonations used in the mining operations (Figure 3).

Figure 3: Satellite image showing the cave projection.

On the other hand, in 2002, the cave was closed by the Unaí Regional Health Department due to suspected histoplasmosis outbreaks at the site. However, despite the signs placed at the entrance, visitors continued to frequent the cave. In 2022, a new study confirmed the presence of the Histoplasma capsulatum fungus in the cave, although it did not specify the exact locations where it was found.

Finally, due to the lack of control, some visitors unfortunately vandalized parts of the cave with large graffiti, not only in the rooms near the entrance but also in more distant areas. (Figure 4)

Figure 4: *Graffiti inside the cave – Photo: Leda Zogbi.*

2. Geology and description

In the geological context, the Tamboril Cave is located in the region belonging to the Tocantins Province, more specifically in the Brasília Fold Belt (Ribeiro, 2019). The cave has two entrances close to each other and extends in a north-south direction until the lake, which divides it into two main segments. In this initial section, the cave features exuberant ornamentation, and the path follows a series of gentle ascents and descents. The main passage is wide, reaching up to 57 meters in some areas, and in certain sections there are descents on both sides leading to rooms with low ceilings. There are also highly ornamented upper passages indicating the older river path. In some sections, there is an overlap of five passages at different levels.

Figure 5: *Ascend in the main passage - Photo: Leda Zogbi.*

The speleothems are impressive in terms of their quantity, size and beauty (Figure 5). Some columns reach up to 15 meters in diameter and 20 meters in height, while stalagmites and stalactites can grow up to 10 meters tall. There are also flowstone formations, shaped like waterfalls, that rise up to 20 meters high (Silva-Teixeira, Oliveira, and Lopes, 2001).

Just before reaching the lake, there is a section covered in sand, known as the “Prainha” (little beach), and a vast area near a smaller lake covered with underwater speleothems and cones of great beauty (Figure 6).

Figure 6: *Underwater speleothems - Photo: Kevin Downey.*

Figure 7: *Underwater cones - Photo: Kevin Downey.*

The lake has a maximum depth of 6 meters, and the reflection of the enormous stalactites in its blue waters is truly stunning (Figure 7). The water that forms the lake represents the outcrop of the water table, which connects to the interior of the cave through the principle of “communicating vessels,” via a geological fault zone (Ribeiro, 2019).

Figure 6: *Lake chamber - Photo: Kevin Downey.*

From this point, the cave shifts to a southeast direction, and its morphology changes considerably. Gigantic blocks (Figure 7), cones of collapsed rocks, sand cones and sediment deposits create an almost lunar landscape (Figure 8). The entire area exhibits remarkable scenic beauty. Eventually, the large passage divides into smaller ones, some of which are highly ornamented, featuring aragonite flowers and numerous underwater speleothems. At the end, a large travertine formation leads to a labyrinthine system of passages with low ceilings.

Figure 7: *Large blocks after the Lake chamber – Photo Leda Zogbi.*

Figure 8: *Large back chamber - Photo Kevin Downey.*

3. Topographic surveys of the Tamboril cave.

The Tamboril Cave was mapped in 1990 by GREGEO (Figure 9), and in 1991 by SEE (Figure 10). Both maps show the cave with a linear development of approximately 950 meters, though both left some passages unexplored.

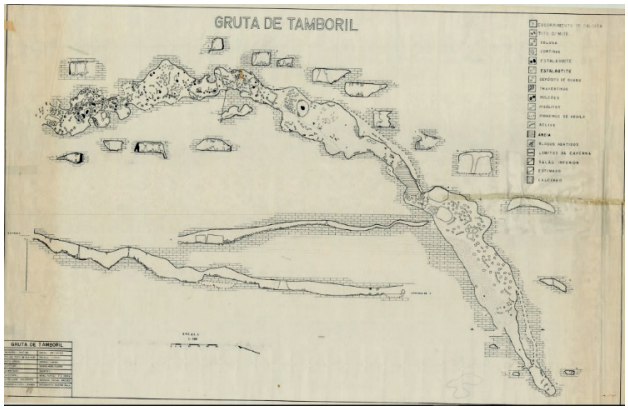

Figure 9: *GREGEO map, 1990.*

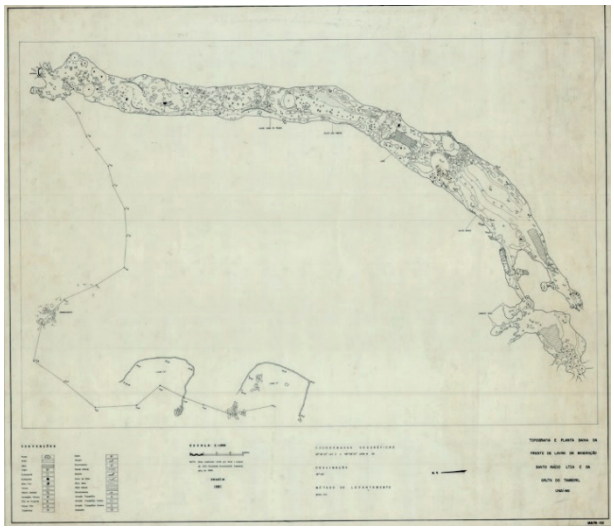

Figure 10: *SEE map, 1990.*

In 2023, a new mapping of the cave was initiated, coordinated by the Meandros Espeleo Clube. During the mapping, a dive was conducted in the lake, and several passages not included in the previous maps were explored. As a result, the cave reached a development of more than 2,900 meters (Figure 11). A few small passages still remain to be explored.

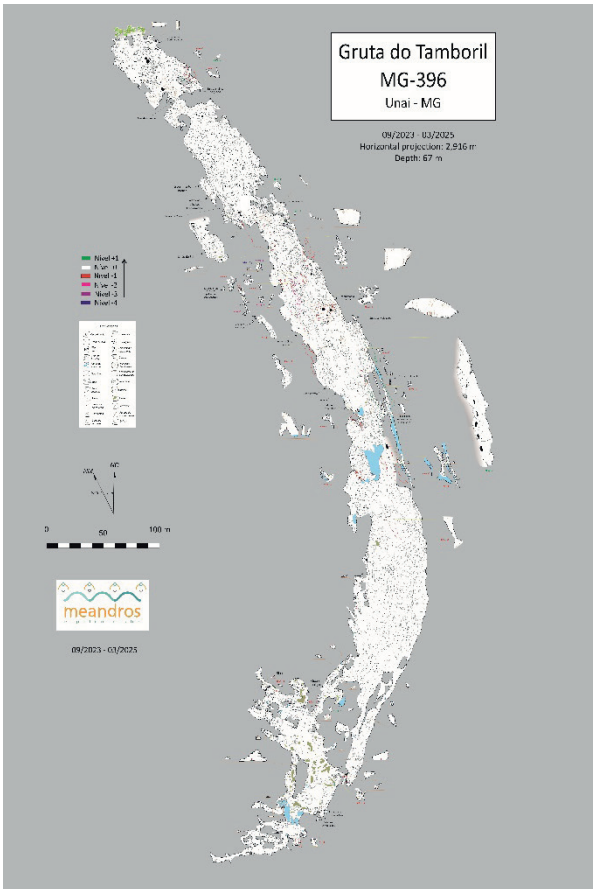

Figure 11: *Tamboril cave map by Meandros Espeleo Clube.*

4. Conclusion

The new map produced by Meandros will serve as the foundation for the cave's management plan, ensuring that visitation is regulated, thus limiting impacts and preventing vandalism. Mrs. Olímpia Prado has completed all the necessary legal procedures to request the transformation of the area into a Private Natural Heritage Reserve (RPPN) and is awaiting the completion of the process so that this important natural heritage of Brazil can be permanently preserved. As part of the cave's management plan implementation, the restoration of the vandalized speleothems is planned, allowing the cave's original beauty to be restored for future generations to admire.

Acknowledgments

We would like to thank all the speleologists from the following groups: Meandros Espeleo Clube, Geology Speleological Group of UnB (GREGEO), Speleological Group of Brasília (EGB), and Espeleo Planalto Central (EPC) for their collaboration in the creation of the map, and Marcela E. L. de Godoy for her help in reviewing this article.

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Session 10

CAVE RESCUE

Análise de acidente por matriz de risco e nível de potencialidade para atividades em caverna

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Resumo

As atividades espeleológicas profissionais ou turisticas devem possuir sistemas administrativos e operacionais em segurança. Esses sistemas devem atender minimamente suas atividades e podruzir a efetiva finalidade a que foi determinada. Para este estudo foi elaborado um cenário de possível acidente na Caverna Túneis. Para determinar o nível de dificuldade de sair da caverna pelo mesmo percurso de entrada em caso de acidente, foi elaborado um questionário com 5 situações de risco e 9 de perigo com 5 graduações. Após os participantes da pesquisa responderem ao questionário, foi realizado a associação entre a probabilidade versus dificuldade de sair da caverna. O questionário foi aplicado na primeira etapa para espeleólogos que conhecem a caverna e na segunda etapa para espeleólogos que não conhecem a caverna mas com auxilio do mapa. As respostas foram aplicadas a uma matriz de risco de 5x5 com nível de potencialidade de 1 a 4. Os resultados apresentaram potencialidade 3 para risco e 2 para perigo, na primeira e segunda etapas, respectivamente. Concordância de 75% e 100% entre etapas, para risco e perigo. O método de matriz e nível de potencialidade mostrou que pode ser utilizado para análise de risco na espeleologia.

Abstract

Professional or tourist caving activities must have safe administrative and operational systems. These systems must minimally serve their activities and achieve the effective purpose for which they were determined. For this study, a scenario of a possible accident in the Tunnels Cave was created. To determine the degree of difficulty in exiting the cave via the same entrance route in the event of an accident, a questionnaire was prepared with 5 risk situations and 9 dangerous situations with 5 grading levels. After research participants responded to the questionnaire, an correspondence was made between the probability versus difficulty of leaving the cave. The questionnaire was applied in the first stage to cavers who know the cave and in the second stage to cavers who do not know the cave but with the help of the map. The answers were applied to a 5x5 risk matrix with a potential level of 1 to 4. The results showed a potential of 3 for risk and 2 for danger, in the first and second stages, respectively. Agreement of 75% and 100% between stages, for risk and danger. The matrix and potentiality level method showed that it can be used for risk analysis in caving.

1. Introdução

No Brasil, as cavidades naturais são protegidas como um bem da união, BRASIL [Constituição (1988)]. Essas cavidades chamadas de cavernas ou grutas, na maioria do território nacional, possuem a necessidade de serem cadastradas e mapeadas, ou ainda, serem utilizadas como turismo para várias finalidades, AULER & ZOGBI (2005).

Para que as cavernas sejam suprimidas, em alguns casos, devem ser comprovadas a sua viabilidade por meio de levantamentos ambientais e sua compensação ambiental. Para que ocorra a autorização de supressão é necessário a comprovação que inclui, dentre várias etapas, o cadastramento e mapeamento da caverna, CRUZ & PILÓ (2019).

Para o mapeamento é necessário equipe qualificada, associada ao sistema de segurança das empresas que executam o serviço nestes tipos de licenciamento, quer seja para regularizar a compensação ambiental ou para as atividades voltas ao turismo. Para estas duas atividades devem ser elaboradas a análise de risco consonante a realidade de cada caverna.

Os sistemas de segurança são notoriamente regidos pelas partes administrativas e operacionais que possuem obrigatoriedade legal nas atividades laborais exigindo a implantação do Programa de Gerenciamento de Risco - PGR, BRASIL (1943, 2020).

Atividades em cavernas podem ocorrer vários tipos de acidentes com relevância simples até casos mais complexos. Dentre os tipos mais comuns estão associados a escorregões e tropeços no mesmo nível, torções de tornozelo e pé pelo fato das cavernas serem de pisos irregulares e possuirem materiais escorregadios. Outros tipos de recorrência estão relacionados a queda de rochas, atmosferas perigosas, queda com diferença de nível, hipotermia, perca ou defeito na iluminação, desorientação e etc, EPA (2005).

Cavernas geralmente apresentam terrenos acidentados e passagens estreitas, e podem permitir a passagem de apenas um indivíduo por vez. Isso pode prolongar o tempo para percorrer um trajeto ou chegar a um acidentado ferido e gerenciar uma extração. Intervenções primárias, como proteger uma via aérea, monitorar a respiração e a circulação do sangue, são atividades difíceis nesse panorama. Por exemplo, se um acidentado vomita durante a passagem em um duto estreito, manter a via aérea desobstruída pode ser desafiador. Passagens estreitas com blocos soltos prejudicam a passagem e podem gerar maiores riscos. O trajeto de saída pode ser penoso e demorado caso os integrantes da equipe não possuam habilidades, tenham cansaço, desorientação e até mesmo as condições físicas não serem adequadas. Em um percurso de 1 h e 45 minutos, membros da equipe tiveram que sair da caverna para acionar o resgate, sendo que o tempo gasto para o mesmo percurso a

equipe de resgate levou 10,5 horas para levar o acidentado à superfície por meio de maca de arrasto, COWART et al. (2014).

Em atividades de cavernas, fatores fisiológicos humanos devem ser levados em consideração devido a exigência do corpo de acordo com o grau de dificuldade nesse ambiente e sua geração de riscos, como por exemplo alterações cardiovasculares, endócrinas e metabólicas, imunológicas e hematológicas, muscular, acuidade visual, sistema termorregulador corporal, psicomotricidade, desmineralização óssea, alteração no ciclo menstrual, sistema renal além de efeitos psicologicos devido a permanência prolongada na caverna e o ciclo de repouso/atividade. Estes fatores possuem importantes associações com o desgaste físico e psicologico que se relacionam diretamente a geração de risco e perigo para espeleólogos que desenvolvem atividades profissionais em exploração e mapeamento de cavernas, Zuccarelli et al. (2019).

Avaliações de riscos devem ser realizadas em todas as etapas do processo que incluem desde a qualificação dos integrantes da equipe até a efetiva realização das atividades, incluindo sobretudo, ações na pré-viagem à caverna e retorno. Estas análises ajudam a minimizar os riscos, perigos e acidentes. A avaliação de risco é um mecânismo que todos envolvidos deveriam produzir. A análise não é garantia de segurança por completo e por esta razão deve ser realizada para cada caverna com associação do bom senso da equipe. Podem ser criados procedimentos e técnicas padrões para reduzir a probabilidade do erro humano diante dos cenários encontrados. As avaliações de riscos devem incluir situações de acidente, busca e resgate nos cenários envolvidos, oferecendo ações com um pré-plano, pelo menos, básico para orientar as ações da empresa ou Instituição responsável pela equipe, BLM (2008).

É importante conhecer os riscos para planejar a atividade de forma a minimizar a ocorrência de acidentes. A norma NBR ISO 21101 (ABNT, 2014) que trata do sistema de gestão de segurança para turismo de aventura, apresenta uma ferramenta de gestão de fácil aplicação, à Matriz de análise qualitativa de riscos, para isto, identificam-se os agente capazes de ocasionar acidentes no ambiente, em seguida, estima-se a probabilidade de que o acidente ocorra classificando-o em quase certo, provável, possível, improvável ou raro, em seguida, estima-se a severidade do dano classificando-o em: insignificante, menor, moderado, maior ou catastrófico. Após o cruzamento destes parâmetros obtém-se os níveis de riscos divididos em: extremo, alto, moderado e baixo. Diante disso, com a análise dos riscos, é possível estabelecer um plano de segurança para o visitante. É importante salientar que à análise de riscos em cavernas turísticas deve ser contínuo e, quando possível, atrelado a outras ferramentas de análise, DOS SANTOS et al. (2024).

Para avaliar o desempenho de analise de risco e sua gestão pode ser adotado rotineiramente o monitoramento, medição, análise e avaliação que são obrigações da gestão das atividades. São necessários determinar o que será analisado e monitorado, seus metódos adequados, dedicados e como estes são aplicados para assegurar melhores resultados. Adoções de documentações pertinentes nas análises das ações, seus resultados para assegurar conformidade com os requistos dos programas de gestão da segurança e requesitos legais aplicáveis. Ainda, devem ser levados em consideração, possíveis acidentes, dados históricos, expertises das pesssoas envolvidas e acatar retroinformações dos participantes, ABNT (2014, 2021).

Perante o contexto encontrado em âmbito internacional e nacional, este trabalho tem como objetivo geral, desenvolver um método de avaliar os riscos, perigos e o nível de potencialidade, quando de um acidente, para sair da caverna em um cenário fictício. Associado a esse método, o trabalho visa, estudar a percepção de risco e perigo dos espeleólogos nesse cenário, estruturar uma matriz de risco para avaliar os eventos de acidentes utilizando a relação entre a probabilidade destes eventos versus a dificuldade de sair da caverna, além de promover ações para evoluir na segurança em atividades nas cavernas.

2. Materiais e Métodos

Para determinar um cenário de acidente e a caverna, foram levados em considerações o local que possuisse um certo grau de dificuldade de chegar e sair de um certo ponto de uma caverna, situações que poderiam ser agravados caso a saída para a superfície fosse o mesmo trajeto de percurso de entrada, possuir disponível um mapa de boa qualidade com melhores detalhamentos e um ponto de passagem mais estreita. Nesse sentido, foi escolhido a caverna Gruta dos Túneis (MG-509) em Lagoa Santa/MG/Brasil que possui uma passagem estreita conhecida como Conduto do Parto. Foi desconsiderado outros pontos de entrada e saída da cavidade, considerando o foco de avaliação apenas no trajeto especificado no mapa (Fig. 1). Para ver o mapa completo acesse o QR Code nesta figura.

O ponto escolhido do possível acidente foi determinado após a passagem do Conduto do Parto, (Fig. 1) como « X ». Diante disso, o cenário elaborado foi : « Uma pessoa se encontra sozinha após a passagem estreita (Conduto do Parto) no sentido indo (acessando pela entrada principal) para o fundo da Gruta dos Túneis. O trajeto de saída é o mesmo de entrada ».

Para estruturar o estudo, foi criado um questionário, com informações do cenário, riscos, perigos e perguntas que se associavam entre « Probabilidade de ocorrência de determinados riscos » versus « Dificuldade de sair da caverna com ajuda ou não – P X D», com base em 5 tipos de riscos. Para o cenário envolvendo os perigos, gerados pelos riscos estudados, foram determinados 9 perigos que se associavam entre « Probabilidade de ocorrência de determinados perigos no ponto do cenário » versus « Dificuldade de sair da caverna com ajuda ou não », para o ponto do cenário. Cada respondente indicou a graduação, previamente elaborada, adotada em muito baixa, baixa, média, alta e muito alta para cada risco e perigo. Na Fig. 2, são indicados os eventos de riscos e perigos estudados.

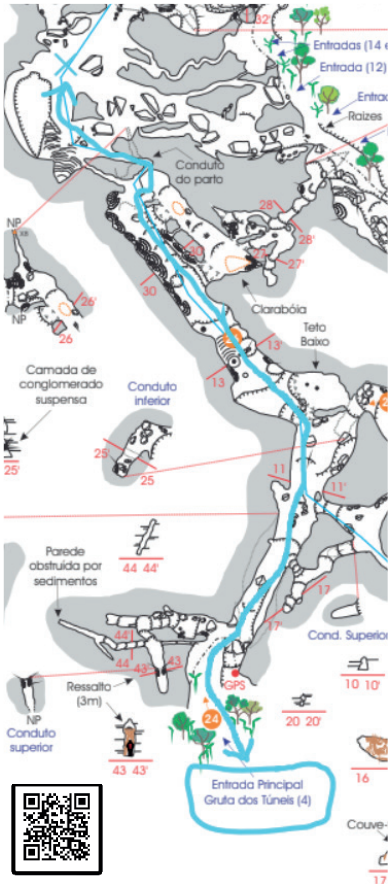

Figura 1: *Trajeto percorrido pelo acidentado. Ponto do acidente em « X ». Adaptado de ZOGBI (2014).*

Os questionários foram respondidos por espeleólogos, em primeira etapa do estudo, que conhecem a cavernana, o Conduto do Parto, sua entrada principal, trajeto pré-estabelecido bem como as características da caverna. A segunda etapa do estudo, foi respondido por espeleólogos que não conhecem a caverna mas tiveram acesso ao mapa completo dessa caverna.

Após serem computados as respostas, foram determinados valores para cada graduação de risco e perigo, sendo adotado como muito baixa = 1, baixa = 2, média = 3, alta = 4 e muito alta = 5 referente a uma matriz de risco. Nesse sentido, foi determinado entre as «Probabilidades dos riscos e perigos» versus «Dificuldade de sair da caverna com ajuda ou não», tendo como resultados possível de 1, 2, 3, 4, 5, 6, 8, 9, 10, 12, 15, 16, 20 e 25. Os resultados obtidos tiveram tratamento estatístico de média, desvio padrão da média e diferença entre os itens que foram separados por associações de «Probabilidade versus Dificuldade». Com isso, foi adotodo neste trabalho o método de Matriz de Risco 5 x 5 para determinar a graduação de risco e perigo dos dados encontados (Fig. 3) associados ao nível de potencialidade dos eventos para sair da caverna em caso de acidente.

Probabilidade de ocorrência						
	Muito alta 5	5	10	15	20	25
	Alta 4	4	8	12	16	20
	Média 3	3	6	9	12	15
	Baixa 2	2	4	6	8	10
	Muito Baixa 1	1	2	3	4	5
PXD		Muito Baixa 1	Baixa 2	Média 3	Alta 4	Muito alta 5
		Dificuldade de sair da caverna com ajuda ou não				

Figura 3: *Matriz de Risco 5 x 5 de P X D com 4 níveis de potencialidades divididos por cor.*

A Matriz de risco foi dividida em 4 níveis de potencialidade dos eventos, para caracterização dos eventos de P X D sendo adotados de 1 a 4 = 1 (baixo potencial), 5 a 9 = 2 (médio potencial), 10 a 16 = 3 (alto potencial), 20 a 25 = 4 (potencial severo). Desta forma, quanto maior o potencial encontrado, maior a dificuldade de sair da caverna. Foi considerado que as características de socorro são: baixo potencial (a vítima consegue sair da caverna sem ajuda), médio potencial (a vítima necessita de ajuda de leigos para sair da caverna), alto potencial (a vítima somente consegue sair da caverna com equipe especializada) e potencial severo (a vítima somente consegue sair da caverna com equipe especializada, utilizando métodos de desobstrução e ou técnicas verticais). Neste estudo, não foi considerado uso de técnicas verticais. Os valores da média e desvio padrão foram comparados entre si, primeira com a segunda etapas, para verificar a concordência entre as respostas obtidas.

Os valores dos eventos entre P X D, nas duas etapas, foram calculados pela média e desvio padrão das respostas dos questionários, sendo referenciado nos valores possíveis de graduação do risco e perigo, o qual possui o limite de 25.

3. Resultados

Na primeira etapa do estudo foram computadas 12 respostas e na segunda etapa, 14 respostas.

Na Fig. 2 estão apresentados a associação entre« Probabilidade de ocorrência de determinados riscos e perigos » versus « Dificuldade de sair da caverna com ajuda ou não – P x D » e os seus respectivos valores de graduação para a primeira e segunda etapas do valor máximo de 25.

Foi observado que o risco « Desonrientação ou falta de conhecimento ou não possuir o mapa da Gruta » teve a maior graduação com 14,50 e a menor foi « Queda no mesmo nível do solo » com 7,83, considerando nas duas etapas.

Para o perigo « Torção de membro inferior (tornozelo ou joelho ou pé) », este, teve a maior graduação com 11,92 na primeira etapa, seguido de « Fratura de membros inferiores (perna ou tornozelo ou joelho ou pé) » com 10,00 na segunda etapa e o menor foi « Inconsciência ou desmaio por tempo longo (maior que 20 min.) » com 6,58 na primeira etapa e « Torção de membro superior (mão ou punho ou cotovelo ou ombro) » com 6,85 na segunda etapa.

Por comparação entre as etapas das graduações de risco, tiveram maiores discrepâncias entre «Queda em diferença de nível » com 19% e para graduações de perigo « Torção de membro inferior (tornozelo ou joelho ou pé) » com 24,5%. Os valores de graduação de risco e perigo entre P x D obtidos, com associação ao nível de potencialidade de 1 a 4 dos eventos, estão apresentados na Fig. 4.

Nível de potencialidade dos eventos	Graduação de P x D	Proporção dos eventos P X D e seus níveis de potencialidade			
		(Risco)		(Perigo)	
		1ª Etapa	2ª Etapa	1ª Etapa	2ª Etapa
1 (baixo potencial)	1 a 4	0 %	0 %	0 %	0 %
2 (médio potencial)	5 a 9	40 %	20 %	88,9 %	88,9 %
3 (alto potencial)	10 a 16	60 %	80 %	11,1 %	11,1 %
4 (potencial severo	20 a 25	0 %	0 %	0 %	0 %

Figura 4: *Nível de potencialidade dos eventos baseado na graduação de P X D.*

Os resultados apresentaram nível de potencialidade 3 para 60% dos eventos de risco e nível de potencialidade 2 para 88, 9% dos eventos de perigo para a primeira etapa. Nível de potencialidade 3 para 80% dos eventos de risco e nível de potencialidade 2 para 88,9% dos eventos de perigo na segunda etapa. Os eventos dos riscos tiveram uma concordância de 50% e 75% entre etapas, e concordância de 100% entre as etapas dos eventos de perigo.

Probabilidade de ocorrência de determinados riscos no ponto do cenário	Dificuldade de sair da Gruta com ajuda ou não, associados aos riscos no ponto do cenário	P x D 1ª Etapa $\overline{X} \pm \sigma$*	P x D 2ª Etapa $\overline{X} \pm \sigma$*
1. Queda no mesmo nível do solo.		7,83 ± 4,39	8,00 ± 4,82
2. Queda em diferença de nível.		8,75 ± 4,78	10,77 ± 5,34
3. Falta de iluminação (perda ou quebra ou falha ou falta de energia da bateria ou outra situação que a lanterna não produza luz) com a pessoa com agravo de algum perigo (lesões, fraturas, torção e etc).		12,25 ± 4,95	11,69 ± 7,27
4. Falta de iluminação (perda ou quebra ou falha ou falta de energia da bateria ou outra situação que a lanterna não produza luz) com a pessoa sem agravo de algum perigo.		12,17 ± 7,26	10,00 ± 6,15
5. Desorientação ou falta de conhecimento ou não possuir o mapa da Gruta.		14,50 ± 7,61	12,85 ± 6,77
Probabilidade de ocorrência de determinados perigos no ponto do cenário	**Dificuldade de sair da Gruta com ajuda ou não, associados aos perigos no ponto do cenário**	-	-
1. Torção de membro inferior (tornozelo ou joelho ou pé).		11,92 ± 5,11	9, 00 ± 6,20
2. Torção de membro superior (mão ou punho ou cotovelo ou ombro).		8,67 ± 5,22	6,85 ± 3,92
3. Fratura de membros inferiores (perna ou tornozelo ou joelho ou pé).		8,75 ± 3,81	10,00 ± 5,32
4. Fratura de membros superiores (braço ou mão ou punho ou cotovelo ou ombro).		6,75 ± 3,14	8,54 ± 4,48
5. Fratura ou corte na cabeça.		8,67 ± 3,77	8,85 ± 4,35
6. Fratura e corte nos membros inferiores (perna ou tornozelo ou joelho ou pé).		9,00 ± 3,65	8,62 ± 5,24
7. Fratura e corte nos membros superiores (braço ou mão ou punho ou cotovelo ou ombro).		6,83 ± 2,15	8,69 ± 4,43
8. Inconsciência ou desmaio por tempo curto (menor que 20 min.).		7,00 ± 3,85	7,61 ± 3,37
9. Inconsciência ou desmaio por tempo longo (maior que 20 min.).		6,58 ± 3,68	8,46 ± 4,03

* - Média e desvio padrão.

Figura 2: *Estudo de Probabilidade x Dificuldade para os eventos de riscos e perigos estudados na primeira e segunda etapas.*

4. Discussão

Pelos perfis dos espeleólogos que responderam ao questionário, não podemos afirmar que o tipo de avaliação realizada em relação a graduação dos riscos e perigos possuem nítida clareza de conhecimento do assunto e isto pode ter consequências associadas a má interpretação do mapa na segunda fase, já que a graduação de risco não foi atingida e equiparada na primeira etapa. Neste mesmo sentido, não podemos afirmar que espeleólogos que conhecem a caverna, os quais não receberam o mapa, possuem conhecimentos suficientes para graduar os riscos apontados no trabalho.

Foi identificado tanto para os riscos como para os perigos que culminaram na impossibilidade da vítima sair da caverna com ajuda de equipe especializada, a não percepção dos respondentes para passar o acidentado na Passagem do Parto. Isto foi evidenciado por existirem algumas baixas graduações de P X D que envolvam maior complexidade no acidentado associado a necessidade de desobstrução na Passagem do Parto para passar a maca com este acidentado.

O evento 5 (Fig. 2) de risco « Desorientação ou falta de conhecimento ou não possuir o mapa da Gruta » teve a maior relação de P X D, no entanto, este risco como sendo eminente em uma situação real, possui uma elevada dificuldade para sair da caverna caso isto ocorra. Neste mesmo sentido, são válidos às associações nos eventos 3 e 4 de risco que envolvam a falta de iluminação. Foi identificado para estes dois quesito, por possuirem baixa graduação (10 a 12,25) entre P X D, sendo aind, menor que 50% da graduação máxima de 25. Isto indica, que não foi reconhecido devidamente pelos respondentes o quanto é importante a iluminação para sair da caverna.

Em relação ao conhecimento do risco, as graduações entre a primeira e segunda etapas mostraram uma concordância menos expressiva, ao passo que para perigo não foi observado diferença. Desta forma, pode ser entendido que para o risco os respondente tiveram maior dificuldade de identificação e associação a um certo prejuízo ao acidentado, mesmo que obtidos resultados de graduações de riscos maiores que as graduações de perigos.

Para alguns eventos dos riscos relacionados a « iluminação e desorientação », perigos relacionados a « fratura de membros inferiores » e « Inconsciência ou desmaio por tempo longo (maior que 20 min.) » não foi percebido que possívelmente o acidentado teria condições de sair da caverna sem ajuda especializada. Isto foi percebi pelas baixas graduações atingidas, tendo ainda o evento « Inconsciência ou desmaio por tempo longo (maior que 20 min.) » atingir um dos menores valores de P X D do estudo. Era de se esperar que estes eventos ao serem relacionados a P X D atingisse um maior nível de potencialidade para sair da caverna.

5. Conclusão

Este trabalho demonstrou que a percepção e conhecimento dos riscos e perigos em uma caverna podem ter divergências significativas por parte de quem realiza a análise e o gerenciamento de riscos envolvidos.

Em relação a estratégia de determinar e usar o nível de potencialidade de sair da caverna com a relação « Probabilidade x Dificuldade » mostraram que esta ferramenta pode ser útil em estudos de riscos em cavernas. Além disso, pode ser utilizada para extrair informações cruciais dos espeleólogos nos quesitos percepção, conhecimento e critérios de avaliação no decorrer de análise e gerenciamento em ações de risco e socorro. O uso e divisões dos níveis de potencialidade demonstraram que ao serem aplicados para estudar a dificuldade de um acidentado de sair da caverna com ajuda ou não de equipe especializada de socorro, permitiu identificar a relação entre um tipo de acidente com a necessidade de equipe especializada de acordo com características da caverna estudada.

A matriz de risco utilizada, identificou aspectos importantes para análise e gerenciamento dos riscos, no entanto, ela pode ser melhorada para criar outros parâmetros de eventos não previsto neste trabalho, assim como, elevar os critérios de avaliação.

O estudo propiciou uma visão mais aprofundada entre a percepção do espeleólogo e possíveis situações de riscos, perigos, complicações de socorro para suas atividades laborais e o quanto elas podem ter repercusões positivas ou negativas para uma análise de risco e seu gerenciamento. Uma análise de risco utilizando relações de « Probabilidade versus Dificuldade », níveis de potencialidade e questionário para obter maiores detalhes dos riscos devem ser estruturada de forma a reduzir as incertezas envolvidas nas avaliações, aumentar a capacidade de tais ferramentas com intuito de atingir os objetivos das análises.

Para qualquer tipo de atividade em caverna, deve ser produzido uma análise de risco fundamentada no conhecimento da equipe, mas é necessário sua validação, aprofundamento e abordagem dos possíveis eventos de acidentes.

Pelos dados levantados e suas discussções apontadas, o tipo de ferramenta utilizada para a análise de risco mostram aspectos relevantes de avaliações por questionário e percepção de risco dos espeleólogos. Embora o estudo aponte divergências na primeira fase, a segunda fase fornece, ao método utilizado, uma representação sastifatória de avaliação que convergeram positivamente e por esta razão o estudo poder ser fundamental para outras avaliações. Importante salientar que mesmo não tendo encontrado divergência, entre os perigos na segunda etapa, a análise e gerenciamento dos riscos devem possuir constantes promoções de ações para melhorar a segurança em atividades nas cavernas por parte dos espeleólogos.

O estudo mostra que somente o conhecimento de caverna e suas características não é o suficiente para produzir o aprofumento adequado em um programa de gerenciamento de riscos e suas devidas análises. Importante desenvolver estudos de análise de risco no ambito laboral espeleológico e promover ações precisas para melhorar a persepção dos riscos e perigos nestas atividades.

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The issue of cave rescue in the Russian Federation

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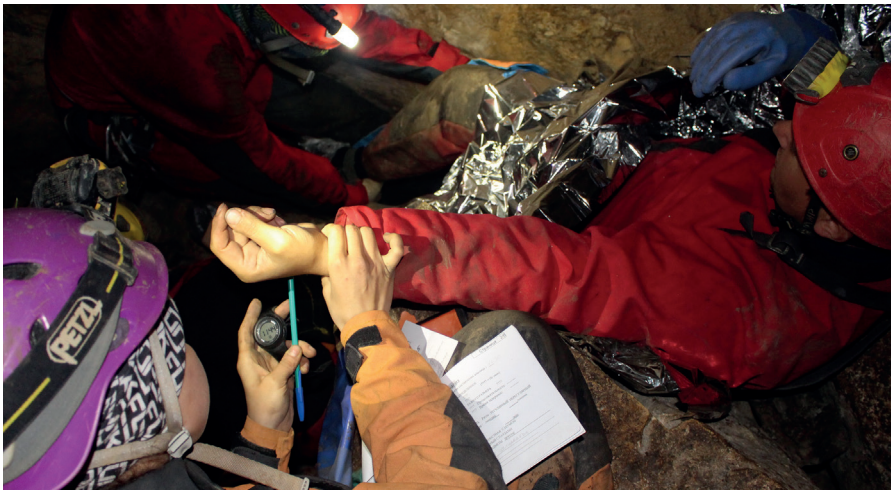
Résumé

Grâce aux progrès technologiques, les spéléologues s'enfoncent de plus en plus profondément sous terre. Ils réussissent à passer les zones étroites et inondées de la cavité. En cas d'accident dans une partie inaccessible de la cavité, les secours n'arrivent pas immédiatement et les spéléologues doivent d'abord compter sur leurs propres forces. Pour cela, il est utile qu'ils soient formés aux premiers secours et aux méthodes de sauvetage dans les cavités. L'article décrit les étapes du développement de l'organisation des spéléologues russes en une communauté de réponse rapide aux urgences dans les cavités.

The Russian Federation stretches from the Baltic and Black Seas in the west to the Pacific Ocean in the East, from the Arctic Ocean in the north, to the borders of China, Mongolia, Kazakhstan, Azerbaijan, Georgia and Abkhazia in the south. The area of more than 17 million square kilometers has a population of just over 146 million. The road infrastructure is unevenly developed. Significant territories remain difficult to access for ordinary researchers and private groups. In order to reach interesting areas for speleological research, it is often necessary to spend considerable effort, money and time.

According to the estimates of Alexey Gunko, who conducted the statistical research, around 300 people are involved in speleological research in Russia per year. There are at least 2,000 organisedspeleotourists per year, including children and novice schools. Spontaneous (wild) speleotourism - about 15,000 visits per year. Accidents in caves are relatively rare. In most emergencies, the groups manage on their own. Due to this state of affairs, the Ministry of Emergency Situations of the Russian Federation does not take caving into account, does not prepare its rescuers for rescue operations in caves at the level of developing techniques and standards.



The legislative framework for the responsibility of the heads of rescue groups of the Ministry of Emergency Situations in the event of an accident with the rescuers themselves has not been devised. For the head of the rescue team of the Ministry of Emergency Situations, there is a great risk of personal responsibility if he sends his people into the cave. At the same time, according to the law of the Russian Federation, only certified rescuers of the Ministry of Emergency Situations can carry out rescue operations on the territory of the Russian Federation, with few exceptions. Some regional emergency departments study and train cave rescue techniques on their own initiative. But these are rather isolated cases. An even more difficult situation arises in the case of an emergency in caves outside the borders of the Russian Federation - in areas of traditional research interests of Russian speleologists. In such cases, in order to organize a rescue operation, the EMERCOM squad must receive a team from the central office in Moscow. This is possible only after an official request for assistance at the interstate level from the authorities of the state in whose territory the emergency occurred. This usually requires a lot of time and effort.

The rescuers of the Ministry of Emergency Situations themselves saw problems in this current state of affairs and made an attempt at the legislative level to make it possible to involve qualified volunteers in rescue operations. The Russian Union of Rescuers was created for this purpose. The organisation also provided for a department of speleo-rescuers. However, over the years of its existence, this department has shown its inefficiency, never once taking part in any of the rescue operations in the caves. Nothing is known about this organisation now. If it exists, it is only formally. Speleologists still have to rely on their own strength in the depths of the cave.

All of the above has created the prerequisites for the self-organization of speleologists for rescue operations in caves.

In many Russian speleology clubs, the beginner training program includes first aid exercises and self-rescue techniques. Competitions of speleologists with elements of self-rescue and transportation of victims on stretchers are regularly held in the country. The important part here is not the competitions themselves, but the preparation process for them. During numerous training sessions, motivated speleologists practice rescue techniques to the point of automatism. This yields positive results. Practice shows that such trained volunteers, under the guidance of a qualified rescuer, can be involved in the execution of elements of rescue operations. Since 2005, it has been possible for those who wish to master the SSF rescue technique at seminars held by the Ukrainian Speleological Association (USAAA) in Crimea once a year. In 2006 and 2008, Bernard Tourte and Sergio de la Garcia came to Russia to teach SSF rescue techniques.

The existence of problems concerning organising volunteers and the need to find a solution to these difficulties, were vividly highlighted by the incident in 2008, during the search for a speleologist who disappeared in the vicinity of a cave in the mountains of Abkhazia. To search for the missing speleologist, the volunteers managed to organize themselves, arrive at the place and start searching only on the sixth day! In fact, it was a miracle that he was heard and found. It's miraculous that he was alive by the sixth day, with all his fractures and other injuries. All this made us seriously think about the current situation and analyse it.

The result of the analysis of this situation was the birth of the following ideas:

1. To involve disparate communities of Russian speleologists in cooperation with each other for rapid response to accidents in caves in the Russian Federation and abroad.
2. Create a database of qualified speleologists and speleologists-doctors.
3. Create a system of socially active speleologists who are ready to join the collection and dissemination of relevant information in their regions, collect the necessary equipment and organise rescue groups.
4. Establish cooperation with regional emergency departments.

Campaigning and explanatory work has begun. Since 2011, the Union of Volunteer Speleo-Rescuers has been active on the popular social network. A database of rescuers and medical speleologists has begun to form. The first practical tests of the emerging union of volunteer speleo-rescuers took place in 2012. First, in a search operation for a Russian citizen who disappeared in India. The body of the deceased was found in a remote area of Dudhasar Waterfall (Goa). All work was carried out in coordination with the local authorities. In August of the same year, a rescue and evacuation operation was organised and carried out to transport the body of the deceased caver through a siphon and to the surface from a depth of 1160 m in the Ilyukhina cave (Abkhazia). More than 100 people (including from Belarus and Ukraine) took part in the operation. Abkhazian rescuers took the body at the entrance to the cave.

The work was structured as follows; In the event of an emergency

in the cave, the expedition members contacted their teammates at home or contacted one of the coordinators directly. The emergency alert was quickly distributed among the coordinators, the information was clarified and, in case of a request for help, a decision was made to initiate an operation. Roles were assigned, and a hierarchy of leadership was established. At the same time, local regional peculiarities and interpersonal relations between members of speleological communities were taken into account. The head of the operation gave the primary instructions. Some coordinators were engaged in calling rescuers and forming groups, others took over logistics, certain members collected equipment and necessary funds, and the rest established contacts with local authorities and representatives of the Ministry of Emergency Situations of the Russian Federation.

The Union of Volunteer Cave Rescuers is built on the principles of a «social contract» on cooperation in the name of saving human life. Members of the union are considered to be speleologists who identify themselves with the union and are ready to take part in search and rescue operations or help in other ways. Both individuals and legal entities can be members of the union. The union's development and management are normally carried out by its most active members on the basis of independence and equality. The latter is due to historical background, the peculiarities of the mentality of local residents and interpersonal relations between the leaders of the speleological communities. In the event of an accident in the cave, the relationship of the speleologists is transformed into a system of strict discipline under the direction of the head of the rescue operation.

The semi-legal status of the association of volunteer speleologists and well-established relations with local authorities and the Ministry of Emergency Situations of the Russian Federation allowed them to act flexibly and effectively, bypassing bureaucratic obstacles. This was especially true when the issue of time was of the essence.

In 2013, the union was registered with the Ministry of Justice and received the status of a legal entity. This was mainly necessary for the convenience of communicating with representatives of local authorities and officials of the national administration, to resolve legal and business issues.

The Union has added new areas to its development program:

5. Training events for the training of qualified rescuers.

6. Formation of rescue teams and rescue equipment funds.

In 2013, SSF teachers were invited to conduct an international training seminar in Crimea on search and rescue techniques in flooded cave areas. Following the results of the seminar, an inter-regional squad of underwater speleo-rescuers was formed. In 2014, representatives of the union participated in the SSF international seminar on first aid in caves (ASV - Vercors - French course). In 2015, SSF teachers were invited to conduct an international training seminar in the heart of the Urals (Sumgan Cave complex, Bashkir Republic) in three directions at once: 1. Transportation of the victim in the dry part of the cave. 2. First aid in caves (ASV course). 3. Search and transportation of the victim in the flooded part of the cave. The seminar brought together about 70 people from different regions of the Russian Federation and Ukraine. Following the results of the seminar, regional groups of speleo-rescuers were formed in the most developed speleological centers (Moscow, Leningrad\Saint Petersburg, Krasnoyarsk, Irkutsk, Bashkir Republic). The main focus was on the development and support of local speleo-rescue centers, the formation of specific rescue equipment funds, and the training of more rescuers. A guideline was adopted to ensure that qualified rescuers were, if possible, took part in every complex expedition.

The organization of educational and training events by local regional centers was stimulated. In parallel, an All-Russian seminar on cave rescue techniques was held once a year. Further analysis of safety issues in caves and taking into account the experience of Ukrainian colleagues prompted the organization of training events to improve rope movement and attachment techniques (rope mounting for moving along it) in the cave for novice speleologists. An attempt was made to popularize common norms and standards. To do this, the most successful instructors traveled to different regions and personally conducted training seminars. The latter has had some success. But it also had a side effect, namely the disappearance of its own local initiatives to organize training seminars. Thus, some centers are no longer completely self-sufficient. We are currently working on this issue.

The efforts expended are gradually bearing fruit. On average in the country, the level of mastery of cave techniques is increasing. In several cases, the presence of qualified rescuers on expeditions helped to avoid tragic developments as a result of accidents. The injured were successfully evacuated from the cave without any health complications. Our efforts have been noticed. We have commendations from the Ministry of Emergency Situations of the Russian Federation and the Ministry of Emergency Situations of Abkhazia. Some of the members of the union were awarded medals of the Ministry of Emergency Situations, others were awarded with commendations.

In recent years, there have been requests for solutions to new problems. Technological progress has made it possible for speleologists to work in small groups at great depths. Caves with depths of more than 1,500 meters are being explored in the Caucasus and Central Asia. And the two caves are Kruber's/Voronya and Ilyukhin passed the mark of -2200 meters. The descent and ascent in these caves takes several days. Access to these caves without a helicopter can also take days. Due to this, in case of an emergency in the bottom of the cave, qualified rescuers will arrive to the victim in a few days. At best, if there is a connection to the bottom of the cave, availability of a mobile connection from the surface at the entrance to the cave - according to the most optimistic forecasts - at least two days is required for the arrival of a rescue-team. In more realistic scenarios, it will take 3-4 days. Meanwhile, the bottom levels can be flooded by 200-300 m during floods. Thus, it is the members of the research group who must provide first aid, transport the victim to a safe place and provide him with comfortable environment to stabilize his condition before the arrival of a medic and rescuers.

The following is actions are being carried out by us to solve these issues:

7. Advocating the installation of communicating equipment in the caves.

8. We have created a medical commission (largely copying it from ECRA) for operational consultations.

9. Began to introduce first aid courses in caves for cave explorers. We try to conduct them on the eve of expeditions (on the way to the cave).

10. Stimulating the training of explorers in victim transportation techniques.

11. We continue to advise the exploration speleologists to join the general safety system in the form of a union of volunteer speleologists.

At the moment, the community has 16 coordination centers, and two are located in the union states: one in Belarus, the second in Abkhazia. Over the years of the union's history, about 200 people have been trained in various specialties. In addition to regional teams, we have started forming modular rescue teams focused on rapid emergency response both here and abroad, to work in international teams.

On a personal level, good relations have been established with the units of the Ministry of Emergency Situations of the Russian Federation in Siberia (Krasnoyarsk, Irkutsk), the Urals (Ufa, Perm), Moscow, the Caucasus (Sochi), Crimea (Simferopol and Feodosia) and the Ministry of Emergency Situations of Abkhazia. Thus, the "active" caving regions of the Crimea, the Caucasus (including Abkhazia), the Ural Mountains and, partially, Siberia are "covered". We are working on the issues of "securing" expeditions in Uzbekistan and our individual participants

in foreign expeditions. Cooperation has been established with the organization of Lisa-Alert search engines. Since 2021, ECRA members. From 2024 - UIS security commissions.

There are two legal entities with different areas of interest in the Union of Volunteer Speleo-Rescuers (SDS). The non-profit Foundation Commonwealth of Volunteer Cave Rescuers carries out activities to organize search and rescue operations here and abroad, ensure international cooperation, providing medicine in caves and training in transporting victims in flooded caves. Another legal entity, the Union of Volunteer Cave Rescuers, specializes in organizing and conducting seminars on transporting victims in dry parts of the cave, the basics of rope attachment and movement techniques, the development of training programs and standards, and conducting various grant activities.

We continue to strive for development and improvement. We don't stop there. We analyze other people's experiences, general trends, and the results we have achieved ourselves. We try to adapt to the changing conditions. We strive to expand and strengthen ties. The main guideline is to ensure that those who need help (here or abroad) can receive it.

Espeleologia e a Segurança em Áreas Remotas: Desafios e Estratégias de Identificação de Riscos e Prevenção de Acidentes

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Abstract

Speleology is the study and exploration of caves and other underground systems. However, this activity involves risks, especially due to its location in remote areas. Caving safety must be carefully planned, considering the specific challenges of these environments. This article will explore the main challenges and strategies for identifying risks and preventing accidents in these areas.

1. Introdução

A segurança em áreas remotas tem se tornado um tema de extrema importância nos últimos anos para as empresas de consultoria que atuam diretamente com estudos voltados ao meio ambiente, em especial, a espeleologia, juntamente com as organizações governamentais e universidades que atuam em projetos de pesquisa. Em sua maioria, as áreas de estudos estão localizadas em ambientes remotos e de difícil acesso. A ausência de infraestrutura, comunicação e o isolamento somado à presença de riscos naturais das áreas remotas e/ou humanos torna o trabalho nessas áreas um desafio constante, o qual requer um bom planejamento. Neste artigo, discutiremos os principais desafios enfrentados na gestão dos riscos no que tange à segurança de equipes nas áreas remotas e as estratégias que podem ser adotadas para garantir à prevenção de acidentes. Vale ressaltar que, para empresas, existem obrigações legais para proteção aos trabalhadores, as quais, contudo, não serão objeto deste artigo.

2. Materiais e métodos

Levantamento dos desafios da espeleologia e suporte à segurança em áreas remotas.

Inicialmente, é fundamental entender o que caracteriza uma área remota. Pode-se definir áreas remotas como localidades isoladas e de difícil acesso, com comunicação restrita, seja por questões geográficas, climáticas e ausência de infraestrutura básica. O isolamento dessas áreas dificulta muito o acesso de equipes de resgate, em caso de algum evento com vítima(s), o que aumenta o tempo de resposta em situações de emergência. Essa demora na resposta na emergência acaba por ser uma vulnerabilidade crítica, principalmente em casos de acidentes graves. A seguir enumeramos alguns dos principais riscos em área remota.

Principais riscos da área remota

Condições ambientais

A natureza é um ambiente não controlado, o qual traz riscos à segurança das equipes de estudo de campo. Há diversos riscos ordinários em atividades exercidas nos trabalhos de campo, tanto nos períodos chuvosos quanto nos de seca, seja durante caminhamentos ou dentro das cavidades, sendo os principais: terrenos irregulares e com desníveis, de difíceis caminhamentos; árvores caídas; buracos abertos por animais; furos de sondagem encobertos; fauna selvagem; presença de abelhas, vespas e marimbondos em árvores, paredões ou no solo; blocos; troncos; animais errantes; animais peçonhentos ; plantas urticantes e espinhentas; desplacamentos e desmoronamentos de solo ; paredes e de partes de cavidades; umidade elevada dentro das cavidades; iluminação precária; desníveis dentro de caverna; a presença de fungos, vírus e bactérias, devido à grande quantidade de matéria orgânica; a presença de gases (cavidades com presença de grande quantidade de matéria orgânica em decomposição); vetores de doenças tropicais; dentre outros.

As diferenças entre os riscos da sazonalidade, basicamente, se diferenciam pela maior probabilidade no período de seca dos riscos à exposição solar (calor extremo), incêndios, terrenos escorregadios devido à grande quantidade de serapilheira, galhos secos e pontiagudos. Já no período chuvoso os riscos se diferenciam em parte, decorrendo de terrenos escorregadios devido à chuva, tanto pelo terreno molhado quanto pela formação de limo; queda de árvores; descargas atmosféricas; neblinas densas; chuvas torrenciais; aumento súbito de drenagem (cabeça d'agua); inundação de cavidade e capim alto. Salienta-se, ainda, que alguns animais podem ter comportamentos diferentes de acordo com a sazonalidade, o que pode representar riscos diferentes em cada período.

Esses são fatores naturais que podem comprometer a integridade física dos profissionais que executam atividades em áreas remotas. Sendo assim, o conhecimento prévio das áreas de estudo é fundamental para o planejamento de campo seguro e assertivo.

Agressão humana

As áreas remotas também podem apresentar presença de pessoas com atividades criminosas, o que pode representar uma ameaça. Essas atividades podem envolver o tráfico ilícito de entorpecentes, a exploração ilegal de recursos naturais, homicídios e abandono de cadáveres, dentre outras situações. As dificuldades de vigilância tornam essas áreas um alvo potencial para criminosos, que se aproveitam da dificuldade

do monitoramento para o exercício de suas atividades ilegais. Outro ponto a considerar são as áreas de conflitos por questões de posses de terras, áreas indígenas, invasões, deslocamentos em estradas vicinais e/ou dentro de áreas privadas (mesmo havendo autorização prévia), além de outros fatores, muitos dos quais dotados de imprevisibilidade.

Fadiga

Fadiga mental é uma redução reversível do desempenho mental das pessoas, podendo gerar sonolência e monotonia, comprometendo a capacidade de produção de trabalho e as expondo a maior possibilidade de erros e acidentes. Embora possa ocorrer em qualquer ambiente laboral e mesmo em domicílios, tal condição é potencialmente perigosa quando associada à condução de veículos (BORGHINI et al, 2014) e operação de máquinas e equipamentos (SÁNCHEZ et al, 2009).

Os estudos de campo em área remota acabam por exigir um esforço físico e mental dos indivíduos. Essa fadiga deve ser gerida, uma vez que diminui a atenção e a concentração dos indivíduos, potencializando a exposição de risco e comportamentos não seguros.

Desorientação geográfica

A desorientação geográfica é um risco a ser considerado, especialmente em trilhas longas, áreas remotas ou de difícil acesso, nas quais a falta de pontos de referência e a complexidade do terreno elevam esse risco. A desorientação geográfica pode ocorrer por diversos motivos e muitas vezes resulta da combinação de vários fatores. Em alguns ambientes, especialmente em áreas com florestas densas ou montanhosas, neblina, a ausência de pontos de referência, como marcos naturais (rios, picos, vales, dentre outros) ou marcos artificiais (placas, sinalizações, fitas, dentre outras), dificulta a capacidade de se manter com orientação adequada. O cansaço físico e mental pode afetar a capacidade de concentração e percepção espacial e de risco, levando à perda de orientação espacial, tratando-se de risco relevante a ser sempre considerado.

Desidratação e insolação

A desidratação é um risco significativo durante os caminhamentos em áreas remotas. O corpo está exposto a esforços físicos intensos, exposição ao sol e, muitas vezes, a um ambiente desafiador. A desidratação ocorre quando a perda de líquidos supera a ingestão de água, afetando o equilíbrio de eletrólitos essenciais e, com isso, a função normal do organismo. Quando há falta de água, várias funções começam a ser afetadas e os sintomas podem evoluir rapidamente, dependendo da gravidade da desidratação.

3. Resultados

Estratégia de identificação de riscos e prevenção de acidentes.

Dentre todos os desafios aqui apresentados para a segurança em área remota, existem diversas ações que podem ser adotadas por empresas, instituições e pesquisadores, para garantir a segurança e saúde das pessoas em áreas remotas. Essas estratégias envolvem uma combinação de tecnologia, planejamento de campo, treinamentos especializados, equipamentos de proteção individual e estrutura de apoio a emergência. Abaixo, destacamos algumas ações:

Equipamentos de Proteção Individual (EPI)

Os Equipamentos de Proteção Individual (EPIs) são equipamentos utilizados para proteger o usuário contra a exposição a riscos à saúde e à segurança no ambiente de trabalho. O uso de EPIs dentro da hierarquia de controle de riscos é a última alternativa, no entanto, para atividades e ambiente natural eles continuam sendo extremamente importantes e se apresentam como a melhor alternativa, já que atividades são realizadas em áreas não controladas, nas quais os riscos não podem ser completamente eliminados. Como mencionado neste artigo, os caminhamentos envolvem diversos riscos, tais como, quedas de mesmo nível e de nível diferente, ofensas por animais peçonhentos, exposição a condições climáticas adversas, dentre outros. O uso de EPIs adequados é primordial para diminuir ou evitar lesões, mitigando riscos, oferecendo proteção física e emocional, além de promover segurança ao indivíduo na realização de suas atividades. Importante ressaltar, que todo EPI deve possuir número de Certificado de Aprovação (CA) pelo Ministério do Trabalho e Emprego. Tais certificações garantem que o EPI passou por diversos testes para garantir a proteção ao usuário. O uso constante e correto dos EPIs durante toda a atividade é crucial para garantir a finalidade a que se destina. Assim, como a escolha, a utilização correta e a verificação de validade, também a manutenção dos EPI e a inspeção desses se apresentam como fundamentais. Por isso mesmo é que inspecionar regularmente os EPIs (checando, tateando e limpando) para garantir que não haja danos ou desgaste que possam comprometer sua eficácia, reparando o que é passível de reparação ou substituindo o EPI quando for o caso, são medidas imprescindíveis à segurança dos usuários. Podemos mencionar como equipamentos de proteção em campo:

Capacete de segurança tipo alpinismo: tem a função de proteger a cabeça em caso de quedas de mesmo nível e/ou nível diferente e/ou contra impactos causados por objetos, galhos, blocos, dentre outros.

Figura 1: *Capacete de segurança tipo alpinista .*

Botina de segurança cano médio: tem a função de proteção dos pés contra lesões por torções, quedas ou impactos, fornecem suporte adequado para os tornozelos, resistência à água e aderência a terrenos irregulares, barreira contra animais peçonhentos, solado antiperfurante, biqueira de composite contra impactos.

Figura 2: *Botina de segurança.*

Perneiras: tem a função principal de proteger as pernas contra riscos diversos, como lesões por impacto, espinhos e picadas de animais peçonhentos. Devem ser utilizadas tanto durante os caminhamentos quanto dentro das cavidades.

Figura 3: *Perneira de segurança.*

Macacão de espeleologia: tem como objetivo proteger o corpo do espeleólogo contra os diversos riscos presentes durante o caminhamento e no ambiente subterrâneo. Entre estes riscos estão arranhões e cortes, uma vez que as cavidades, frequentemente, possuem superfícies ásperas, pontiagudas, rochosas e irregulares. Os ambientes subterrâneos, especialmente cavernas úmidas, podem ser propícios à proliferação de bactérias, fungos e outros microrganismos. O macacão ajuda a reduzir o contato direto com esses microrganismos e outras substâncias e elementos presentes no ambiente cavernícola, minimizando o risco de infecções cutâneas. O macacão, também, funciona como um isolante térmico, uma vez que as cavernas são ambientes úmidos e frios. O macacão de espeleologia deve ser constituído de tecido de alta visibilidade (cores vibrantes), afim de facilitar a identificação da equipe em campo e, em caso de resgate, ser localizado com mais facilidade.

Figura 4: *Macacão de espeleologia.*

Óculos de segurança com proteção UV: possuem a função de proteção dos olhos contra o vento, poeira, projeção de partículas, insetos que possam colidir em direção ao rosto, galhos, pedras, capim, entre outros. Os óculos devem ter proteção UV para reter claridade excessiva e conter a radiação ultravioleta.

Figura 5: *Óculos de segurança UV.*

Luvas de raspas cano longo: tem a função de proteção das mãos e antebraços contra ferimentos, escoriações, picadas de animais peçonhentos. Também, são importantes para atividades que envolvem o uso de cordas e, ainda, para a proteção das mãos ao se apoiar em pedras, árvores ou ao manusear equipamentos, como facões nas aberturas de picadas.

Figura 6: *Luva de raspa.*

Respirador PFF2: tem a função de proteger o indivíduo nas atividades dentro de cavernas que possuam a presença de material orgânico e guano. Esse respirador deve ser utilizado durante toda a permanência dentro da cavidade natural subterrânea.

Figura 7: *Respirador PFF2.*

Além destes equipamentos de proteção individual que possuem o Certificado de Aprovação (CA) deve se considerar, também, os seguintes equipamentos:

Protetor solar: o protetor solar é essencial para proteção contra queimaduras de sol e na prevenção ao câncer de pele. Deve ser aplicado nas áreas expostas antes do início das atividades e o recomendado é reaplicar de 4 em 4 horas, ou sempre que necessário.

Repelente: o uso de repelentes é fundamental para a proteção contra picadas de insetos, as quais podem causar desde reações alérgicas e irritações na pele, até a transmissão de doenças. A escolha do repelente para atividade de espeleologia é essencial. Especialistas recomendam repelente a base de ICARIDINA. Deve ser aplicado nas áreas expostas antes do início das atividades e reaplicar de 4 em 4 horas, ou sempre que necessário.

Balaclava: o uso da balaclava é importante para a proteção de raios UV´s e picadas de animais peçonhentos e insetos vetores de doenças tropicais.

Bastão de luz de emergência: também conhecido como bastão sinalizador ou bastão luminoso, é um equipamento de segurança importante para as atividades em área remota. Sua principal função é oferecer uma fonte de visibilidade e sinalização em momentos de emergência, especialmente em condições de baixa visibilidade, como à noite, em nevoeiro denso ou em ambientes de difícil acesso, especialmente desprovidos de luminosidade natural.

Capuz de fuga ou máscara de apicultor: estes dispositivos, tem objetivo de proteger o usuário de picadas de abelhas, marimbondos ou vespas. Eles devem estar próximos ao corpo, para acionamento rápido em caso de avistamento ou ataque repentino de abelhas, marimbondos ou vespas.

Bastão de caminhada: utilizar o bastão de caminhada durante o caminhamento pode ser um terceiro apoio importante, especialmente em terrenos irregulares ou para caminhadas longas. Eles oferecem diversos benefícios, como a redução do impacto nas articulações, melhora da estabilidade, apoio em subidas e descidas, redução da fadiga, entre outros benefícios. Muito importante ajustar corretamente para que ele seja utilizado da maneira correta.

Uso de tecnologia avançada

Atualmente, existem equipamentos de sinalização e comunicação que funcionam via satélite. O equipamento SPOT ou "*Garmin inReach*". Eles são um dispositivo de rastreamento via satélite utilizado para garantir a segurança e a localização em áreas remotas ou onde não há cobertura de redes de telefonia móvel. Ele é projetado para ser usado em situações de emergência ou para monitoramento em tempo real de equipe. O SPOT utiliza satélites para enviar sinais e mensagens, o que garante que ele funcione em locais onde os sinais de celular não alcançam. O telefone satelital, também, funciona via satélite permitindo ligações de emergência.

Figura 8: *SPOT localizador.*

Os drones também podem ser utilizados para uma avaliação prévia de risco dos locais, auxiliando no planeamento de campo em gabinete.

Os detectores de descarga atmosférica são dispositivos que sinalizam sobre a aproximação de raios. Eles detectam a atividade elétrica na atmosfera e emitem alertas sonoros e visuais, permitindo ação preventiva seja realizada. Estes detectores são ferramentas fundamentais para garantir a segurança em atividades ao ar livre.

Figura 9: *Drone.*

Os rádios de comunicação individual são equipamentos que asseguram a comunicação constantes entre equipes.

Figura 10: *Rádio de comunicação individual.*

4. Discussão

Treinamento

O treinamento das equipes envolvidas nos estudos em área remota é fundamental e uma das ações mais importantes para garantir a segurança de pessoas. Podemos incluir treinamentos em primeiros socorros em áreas remotas, conhecimento do comportamento de animais selvagens e peçonhentos, gestão de crises e treinamentos comportamentais, todos cruciais para a segurança dos trabalhos em campo. Salienta-se que devem ser realizados sempre, com a reiteração de práticas e temas, de modo a fomentar a entronização dos conceitos.

Planejamento e logística

O planejamento detalhado que considere as especificidades do local e os riscos envolvidos é de fundamental importância. O plano deve incluir a definição de pontos de acesso e rotas de fuga, a identificação de áreas vulneráveis, mapas com grid e a distribuição de recursos de segurança de maneira eficiente. O planejamento, também, envolve a criação de protocolos para situações de emergência de acordo com cada área. Nos estudos que ocorram em áreas remotas, nas quais sejam necessários o apoio local do Corpo de Bombeiro Militar e o atendimento hospitalar, o planejamento deverá contemplar toda a etapa de apresentação da área de estudo, quantidade de profissionais envolvidos, equipe de resgate mínima, mapa com quadrantes, kit de primeiros socorros e mapeamento de atendimento por unidade hospitalar. É importante coletar informações diretamente com os hospitais locais, do tipo de atendimento prestado, bem como soros disponibilizados em caso de acidentes com animais peçonhentos.

Plano de atendimento a emergência

O Plano de Atendimento a Emergência (PAE) é fundamental para garantir a segurança das equipes em situações de risco. O PAE antecipa e define protocolos em situações de emergência. Durante uma emergência o tempo de resposta se apresenta como um fator fundamental, de sorte que a equipe treinada em conformidade com o que consta deste documento terá como agir de forma coordenada, facilitando a comunicação e direcionado todo o atendimento de resgate com decisões rápidas.

Um plano de atendimento de emergência envolve diversos fatores, tais como segurança, primeiros socorros, apoio logístico e autoridades locais (como bombeiros e polícia), além de atendimento médico-hospitalar. O PAE ajuda a coordenar as ações entre esses grupos, garantindo que todos trabalhem de maneira integrada e coordenada, para uma resposta rápida e eficaz.

O PAE, ainda, estabelece procedimentos para a prestação de primeiros socorros e possíveis cenários de emergência.

Análise de risco da atividade

A análise de risco da atividade é fundamental como uma ferramenta de prevenção de acidentes, garantindo a segurança de todos envolvidos nas atividades de uma área remota. Inicialmente, é necessário identificar todos os riscos potenciais envolvidos em cada atividade. Esses riscos podem ser classificados como riscos físicos, químicos, biológicos, ergonômicos e/ou ambientais. Para essa identificação é necessário observar o ambiente de trabalho, os passos de cada atividade realizada, os materiais e equipamentos envolvidos, bem como as condições de trabalho. É muito importante que essa identificação dos riscos seja feita em conjunto com um profissional que domine a atividade que será realizada, em conjunto com profissionais da área de segurança do trabalho.

Com os riscos previamente identificados, se faz necessária a avaliação das probabilidades de suas ocorrências e o impacto que esses podem causar. Avaliados os riscos, deve-se iniciar a definição de medidas de controle para eliminá-los ou, ao menos, reduzi-los. Essas medidas envolvem desde treinamentos específicos até a utilização de EPIs adequados e a implantação de sistemas de segurança amplos e em conformidade com cada caso.

A análise de risco da atividade é uma ferramenta essencial para garantir que as operações sejam realizadas de maneira segura e eficiente. Ao identificar, avaliar e controlar os riscos existentes, a proteção e segurança de todos os envolvidos nas atividades aumentam consideravelmente.

Diálogo de saúde segurança e meio ambiente

Iniciar as atividades com um diálogo sobre saúde e segurança é um componente fundamental para promover uma comunicação aberta, constante e efetiva entre todos os envolvidos em campo. O diálogo aberto sobre saúde e segurança permite identificar e discutir potenciais riscos e perigos presentes no ambiente das atividades. Por meio dessa comunicação, é possível antecipar problemas e implementar medidas preventivas eficazes, como mudanças no planejamento e adequações a cada realidade.

Apoio local

Envolver parcerias com autoridades locais ou empresas da região pode melhorar a segurança de áreas remotas, como por exemplo, no caso de apoio para um resgate. A colaboração com forças de segurança locais, grupos comunitários ou empresas que operam nas proximidades pode proporcionar informações valiosas sobre a segurança da área e garantir uma resposta mais rápida em caso de incidentes.

A conversa com pessoas regionais é de extrema importância à obtenção de informações sobre espécies de endêmicas da região e seus comportamentos, tais como serpentes, abelhas e marimbondos, animais selvagens, tipo de vegetações, característica em geral do lugar, propriedades próximas à área de estudo, dentre outros fatores, o que também aumenta a segurança dos envolvidos nos estudos.

5. Conclusão

Os trabalhos e estudos de espeleologia em áreas remotas representam, sem dúvida, um grande desafio de segurança devido às condições adversas destes ambientes e às dificuldades relacionadas às respostas em casos de emergência. O bom planejamento de campo em gabinete é fundamental para assegurar a segurança e saúde todos envolvidos nas atividades. Os treinamentos constantes; as questões comportamentais, individuais e coletivas; bons equipamentos de segurança individuais e de comunicação efetiva; além de outros fatores acima listados, são fundamentais para garantir a segurança dos espeleólogos e demais atividades em área remota.

E o fundamental: em caso de dúvidas ou insegurança a melhor escolha e paralisar os campos e refazer as análises necessárias, para que em momento posterior os trabalhos possam se desenvolver de forma segura para todos os envolvidos.

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Cave rescuers education in Hungary

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Abstract

Not only rescue equipments but human resources of our rescue team must be updated regularly. That is why we do recruiting new potential members in 2-3 years frequency. New candidates must be well trained cavers with good technical skills, which we make possible by completing the appropriate level of the Hungarian speleo education system. The applicants have to pass an entrance exam in a cave practice, where we check that the applicant has those human qualities that cannot be tested by formal rules. Such are, for example: teamwork, problem-solving ability, solidarity, sense of responsibility, tolerance, ability to withstand stress, endurance, stamina, endurance of difficulties, ability to make decisions, ability to assess situations, self-awareness, fortitude, self-discipline, etc. Those who meet the admission requirements will participate in a four-day demonstration stretcher packing, moving a stretcher on easy terrain, safe moving a stretcher on sloping terrain, moving a stretcher in narrow areas, building a stand, counterweight system, refitting systems into each other, lowering, head-to-foot maneuver, first aid, communication, etc. After that they become probationary members and have two years to master the knowledge presented.Those who have acquired the necessary knowledges and pass an exam on their knowledge within two years will become regular members of the HCRS. During the real rescue operations, there are various sub-tasks, such as the construction of a communication system, the construction of traction systems in the vertical passages, stretcher transport, etc. These tasks are carried out in separate groups headed by the group leader. The group leaders are selected from regular members of HCRS with several years of experience. The most prepared members can be rescue managers. They can demonstrate this readiness by conducting complex rescue exercises.

1. Introduction

The quantity and quality of human resources are crucial in cave rescue. When the Hungarian Cave Rescue Service (HCRS) was founded in 1961, its membership consisted of 26 enthusiastic cavers who had already participated in ad hoc rescue teams. Since then, the founders have aged out, and new generations have taken their place. Over the decades, a total of 314 individuals have been members of the organization. Initially, the team comprised well-intentioned and experienced cavers without specialized training. However, this has changed drastically over the years. Nowadays, being a skilled caver is not enough. To become a fully-fledged cave rescuer, one must master the use of modern rescue equipment and advanced rescue techniques. The structured recruitment and training process necessary for this is now conducted in an organized manner.

2. How does one become a cave rescuer?

The HCRS opens recruitment every 2-3 years (Hegedűs, 2025), typically receiving 5-10 applicants per session. Being an experienced caver remains a fundamental requirement. The necessary caving knowledge can be acquired through the Speleo Education System, organized and managed by the Education Department of Hungarian Speleological Society (Hegedűs, 2017). The minimum requirement for application is a “Technical 2” (T2) level certification. Applicants undergo a four-day selection process, during which their technical skills are assessed, as well as personal attributes necessary to integrate into the team. Teamwork is critical since individualism has no place in real rescue operations. Problem-solving skills are also essential, as each rescue mission differs in terms of location, injuries, and challenges, requiring adaptability to extreme situations. Decision-making ability and a strong sense of responsibility 7

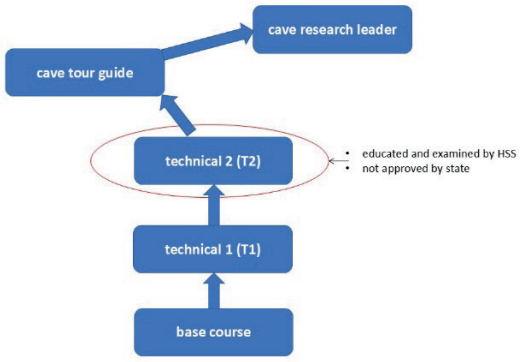

Figure 1: *Speleo education system in Hungary (Hegedűs, 2017).*

are also vital. Rescuers must minimize trauma while saving people in distress, often experiencing pain. Additionally, prolonged rescues in difficult conditions are physically and mentally demanding, requiring endurance, perseverance, tolerance, stress resistance, mental resilience, and self-discipline.

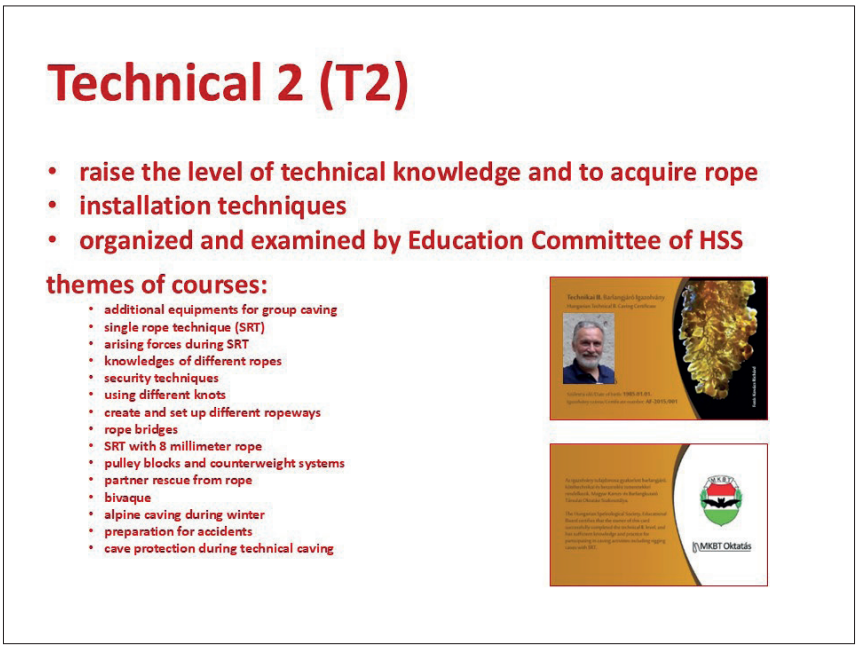

Figure 2: *The T2 course material and the certificate of completion (Hegedűs, 2017).*

Following the selection process, different decisions can be made regarding applicants. Those deemed suitable for training become probationary members of HCRS. The probation period lasts a minimum of one year and a maximum of two years. During this time, candidates must acquire the specialized knowledge necessary for full membership. It also helps determine if the initial evaluation of personal attributes was accurate and whether they can integrate into the organization effectively.

Applicants who meet some requirements (e.g., possessing a T2 certification but lacking sufficient experience) may be offered the opportunity to join as supporting members. Supporting members participate in the organization's activities and training exercises but are not involved in actual rescues. They can reapply for full membership at a later time.

Probationary members attend training-specific small drills and regular large-scale exercises that ensure HCRS remains prepared. Two large-scale exercises are held annually, typically over a long weekend, simulating complex cave rescues with a live person in a stretcher. These exercises may have an international scope, involving collaboration with cave rescue teams from neighboring countries. Smaller exercises, mostly held in winter, are thematic and can vary in duration, ranging from a weekday evening to a full weekend. Training is conducted both on the surface and in caves.

Skills to be mastered include:

- Stretcher packing
- Moving a stretcher on easy terrain
- Safe stretcher movement on sloping terrain
- Maneuvering a stretcher in narrow passages
- Building a stand
- Counterweight systems
- Integrating systems
- Lowering techniques
- Head-to-foot maneuvering
- First aid
- Communication
- Etc.

Probationary members must demonstrate proficiency in each module through an accreditation exam. Those who successfully acquire all skills within two years, actively participate in HCRS activities, and demonstrate the necessary personal qualities are assessed by the leadership and granted full membership. At this point, they are recognized as cave rescuers and can be deployed in real rescue situations.

3. Advancement to higher levels of expertise

3.1. Team Leaders

Rescue operations involve multiple tasks that must be carried out independently or in small groups, such as:

- Stretcher transportation
- Ropeway construction
- Communication system setup
- Logistics
- Medical assistance etc.

Each team has a leader who supervises and directs the task at hand. These leaders are experienced cave rescuers who have demonstrated their ability to manage tasks effectively and make the best decisions during training exercises. Leadership roles are assigned on a rotational basis during exercises, allowing volunteers to test their capabilities. Evaluations are conducted after each exercise to determine the appropriateness of self-assessments. This process determines eligibility for leadership roles. Leaders are not permanently assigned to a specific

task but are deemed qualified for it when necessary.

The medical team functions differently. Its leader is elected by the medical team members and serves as their representative on the HCRS board. The medical team determines the necessary equipment, medications, and supplies within the allocated budget and ensures the first aid preparedness of the team through regular training and assessments.

3.2. Operation Leaders

Each rescue mission has a single responsible leader who oversees the entire operation. They typically coordinate activities from the surface and must have complete situational awareness. From this position, they make overarching decisions and direct team leaders, managing both underground and surface operations. Operation leaders are selected from highly experienced cave rescuers. They prepare by planning, organizing, and leading large-scale exercises with full authority, allowing them to develop the necessary skills. While exercises differ from real rescues, they provide valuable preparation. Exercises require site selection, obtaining permits, and coordination, while real rescues involve liaising with authorities and collaborating with other organizations. In real situations, the professional leader of HCRS designates the operation leader.

4. Reserve Members

Individuals who, due to age, health, family, work, or other life circumstances, can no longer meet the demands of active membership may request reserve status. They are not held to the same requirements as full members and can participate in HCRS activities as their circumstances allow (e.g., training exercises). Their involvement in rescues depends on the operation leader's assessment. Reserve status is not necessarily permanent—if circumstances change, a member can request reinstatement as a full member.

5. Current Status

Over its 60+ year history, HCRS has had a total of 314 members. The current organizational structure consists of a central unit in Budapest and two regional units in Aggtelek and Pécs (Hegedűs, 2022).

Figure 3: *HCRS members between 1961-2022 (Hegedűs, 2022).*

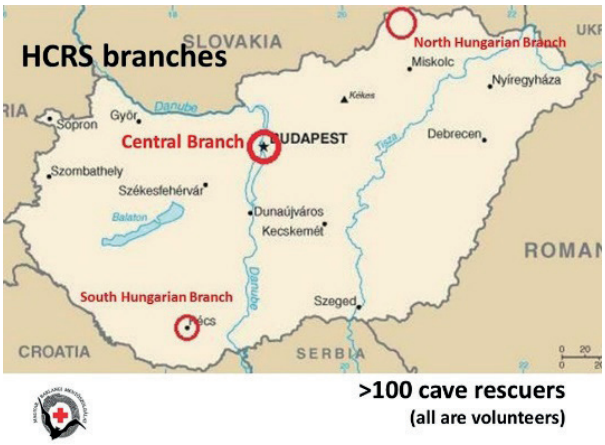

Figure 4: *The organization of the HCRS (Hegedűs, 2022).*

The personnel composition is as follows:

- 62 full members
- 12 doctors
- 10 operation leaders
- 6 probationary members
- 36 reserve members
- 5 honorary members
- 38 supporting members

(BMSZ, 2025)

Acknowledgments

We express our gratitude to our predecessors who founded our organization over 60 years ago and to all those who have operated and developed it to a level where it can successfully conduct complex, multi-day, internationally coordinated rescue operations.

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The result of 60 years of hungarian cave rescue

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Abstract

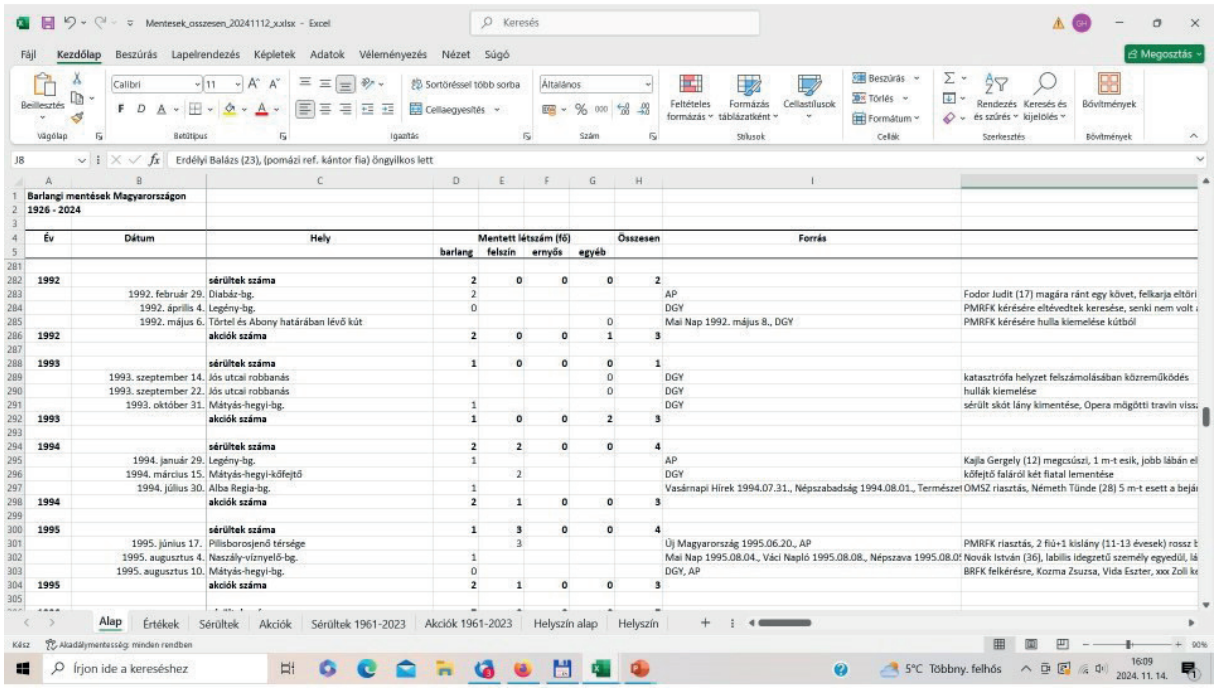
Before the 1960s, the rescue operations that became necessary in the caves were carried out by occasional groups of more experienced cavers. The most frequent participants in the rescues felt that sooner or later their activities had to be given an organized framework, so in 1961 they decided to form the Cave Rescue Service. In the more than 60 years that have passed since then, the Hungarian legal environment has changed several times, and the cave rescue organization itself has adapted to it. But not only the legal environment has changed, but also the equipment, preparation and activities of cavers also. In the past, caving activity was completely unregulated, and then gradually written and unwritten rules were born. As a result of all this, the nature of accidents and thus the rescue activity has also changed. In the past, a relatively large number of rescue operations became necessary mainly due to getting lost or inadequate and therefore non-existent lighting. With the gradual gating of caves and the development of the education system for cavers, the number of cases decreased, but the less frequent accidents became more serious. These cases required the development of rescue techniques, medical care, and cave rescuers as a human resource. At the same time, the skills acquired by cave rescuers can also be used well in some cases occurring on the surface, and these skills are increasingly used by other organizations. All this development can be clearly demonstrated through the statistical data presented in the presentation.

1. Introduction

Even in the first half of the 20th century, there were occasional cave rescues, but these were mostly due to people getting lost in caves or using inadequate lighting equipment. After World War II, travel opportunities in Hungary became limited, and more people, especially children, sought adventure in caves. Due to inadequate equipment and the lack of established rules for cave tourism, the number of disappearances in caves increased. When someone failed to return home on time, parents or relatives usually turned to the police for help. If there was suspicion that the missing persons might be in a cave, the police consistently sought assistance from the same cavers, knowing they could navigate these environments safely and often achieved success. This collaboration led to a well-established partnership. The increasing number of such incidents made it necessary to formalize this group, leading to the founding of the Hungarian Cave Rescue Service (HCRS).

2. Data Collection

More than 60 years have passed since the organization's founding, and I decided to collect and analyze the results of its activities over this period. Over several years, I reviewed documents from the archives of HCRS, the Hungarian Speleological Society (HSS), and various caving associations, as well as contemporary newspaper articles. The latter provided valuable insights, as cave accidents were not daily occurrences, and when they did happen, journalists consistently reported on them. Naturally, multiple reports often covered the same incident, offering varying levels of detail. By cross-referencing different articles, I was able to determine the time and location of the accidents, the names and ages of those involved, the nature and cause of their injuries, and in many cases, the names of the rescuers. I structured this data in a way that allows for future additions as new information emerges.



Barlangi mentések Magyarországon
1926 - 2024

Év	Dátum	Hely	Mentett létszám (fő) barlang	felszín	ernyős	egyéb	Összesen	Forrás	
1992		sérültek száma	2	0	0	0	2		
	1992. február 29.	Diabáz-bg.	2					AP	Fodor Judit (17) magára ránt egy követ, felkarja eltöri
	1992. április 4.	Legény-bg.	0					DGY	PMRFK kérésére eltévedtek keresése, senki nem volt
	1992. május 6.	Törtel és Abony határában lévő kút				0		Mai Nap 1992. május 8., DGY	PMRFK kérésére hulla kiemelése kútból
1992		akciók száma	2	0	0	1	3		
1993		sérültek száma	1	0	0	0	1		
	1993. szeptember 14.	Jós utcai robbanás				0		DGY	katasztrófa helyzet felszámolásában közreműködés
	1993. szeptember 22.	Jós utcai robbanás				0		DGY	hullák kiemelése
	1993. október 31.	Mátyás-hegyi-bg.	1					DGY	sérült skót lány kimentése, Opera mögötti travin viss
1993		akciók száma	1	0	0	2	3		
1994		sérültek száma	2	2	0	0	4		
	1994. január 29.	Legény-bg.	1					AP	Kajla Gergely (12) megcsúszi, 1 m-t esik, jobb lábán el
	1994. március 15.	Mátyás-hegyi-kőfejtő		2				DGY	kőfejtő faláról két fiatal lementése
	1994. július 30.	Alba Regia-bg.	1					Vasárnapi Hírek 1994.07.31., Népszabadság 1994.08.01., Természet	OMSZ riasztás, Németh Tünde (28) 5 m-t esett a bejá
1994		akciók száma	2	1	0	0	3		
1995		sérültek száma	1	3	0	0	4		
	1995. június 17.	Pillisborosjenő térsége		3				Új Magyarország 1995.06.20., AP	PMRFK riasztás, 2 fiú+1 kislány (11-13 évesek) rossz
	1995. augusztus 4.	Naszály-víznyelő-bg.	1					Mai Nap 1995.08.04., Váci Napló 1995.08.08., Népszava 1995.08.0	Novák István (36), labilis idegzetű személy egyedül, lá
	1995. augusztus 10.	Mátyás-hegyi-bg.	0					DGY, AP	BRFK felkérésre, Kozma Zsuzsa, Vida Eszter, xxx Zoli ke
1995		akciók száma	2	1	0	0	3		

Figure 1: Basic data.

3. Data Analysis

I processed the collected data in multiple ways, and I present the results in this study. I also use graphical representations, making it easy to observe changes in the nature of cave accidents over time, even without extensive numerical analysis. Additionally, I identified which caves had the highest number of incidents. These findings can help in preparing for the most common types of emergencies and highlight caves where extra caution is necessary. The data also reveal how HCRS's activities have evolved. To ensure comparability and track changes over time, I divided the period from 1961 to 2020 into ten-year intervals. Although I have data beyond 2020, I chose not to include partial decades to maintain consistency. However, the trends observed remain valid beyond 2020 as well.

4. Results

Between 1961 and 2020, HCRS conducted a total of 236 rescue operations, assisting 339 individuals, some in life-threatening situations. The following charts provide a more detailed breakdown of the results.

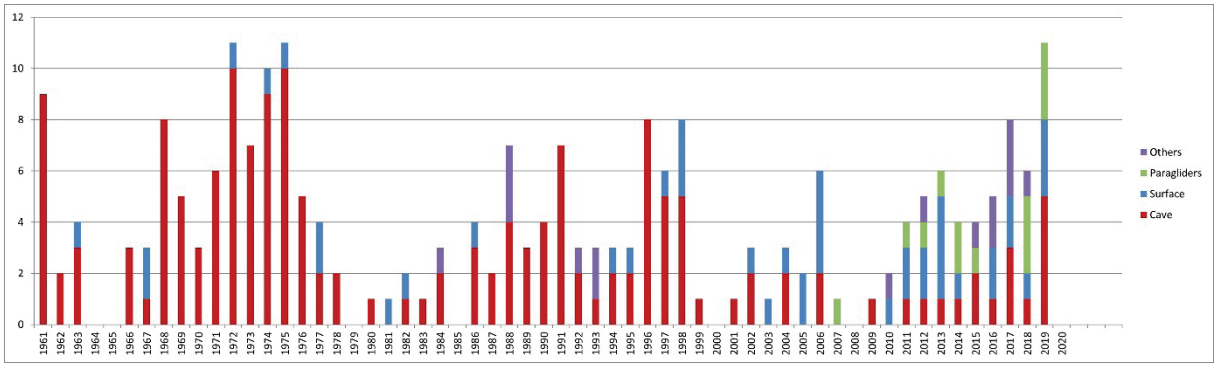


Figure 2: Number of rescue operations (1961-2020).

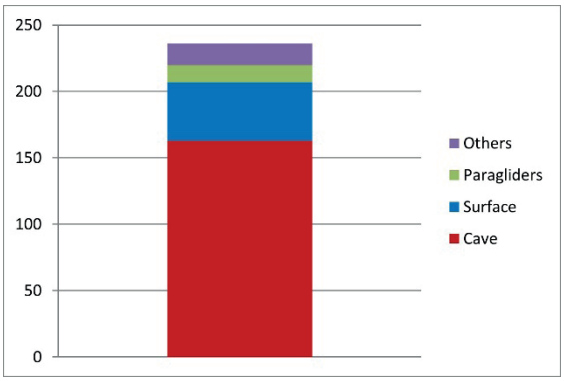


Figure 3: Number of rescue operations=236 (1961-2020).

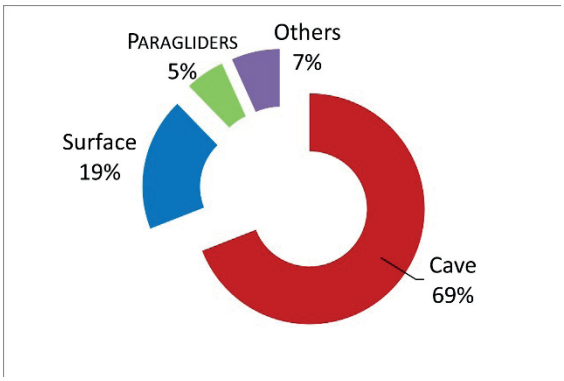


Figure 4: Total % of rescue operations (1961-2020).

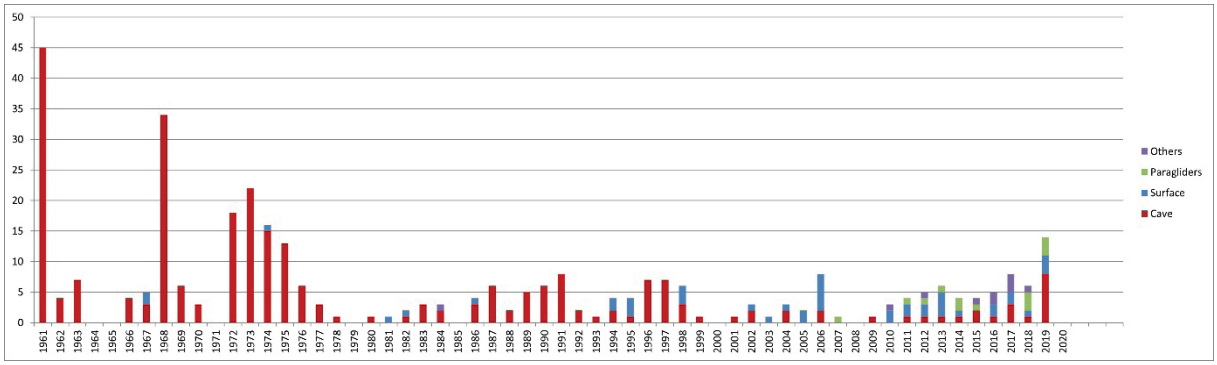


Figure 5: Rescued victims (1961-2020).

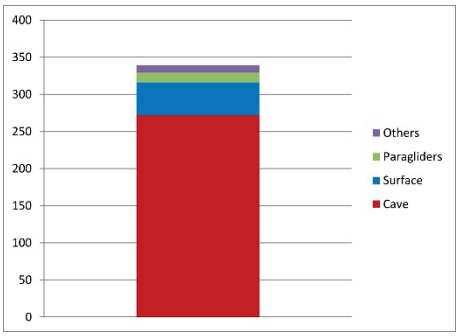


Figure 6: Number of rescued victims=339 (1961-2020).

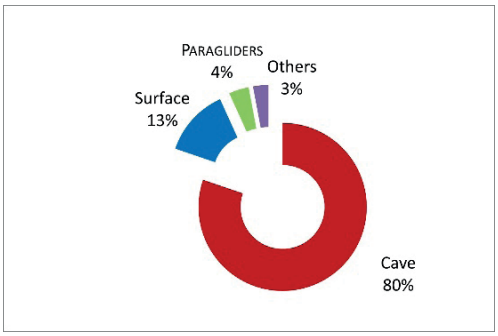


Figure 7: Total % of rescued victims (1961-2020).

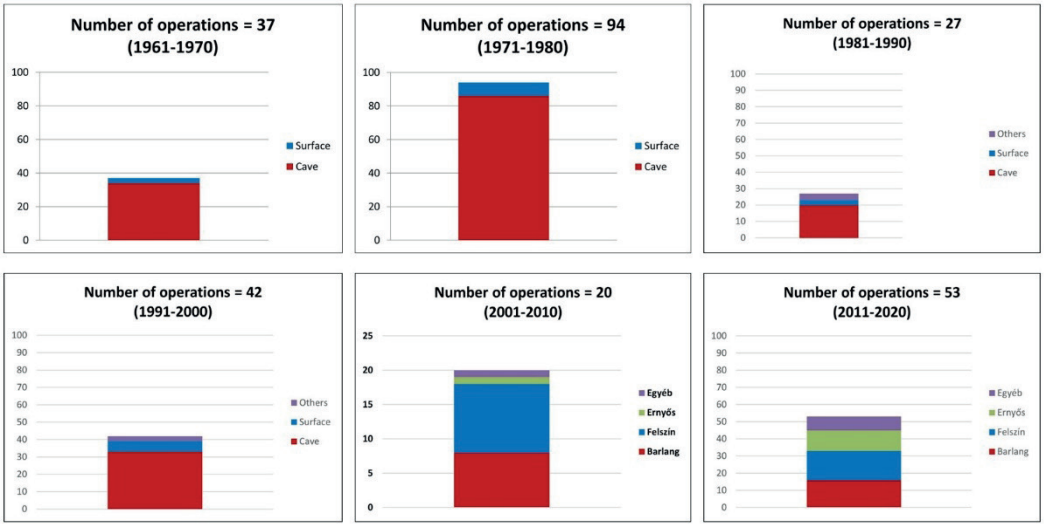


Figure 8: Changing of rescue operation structure between 1961-2020.

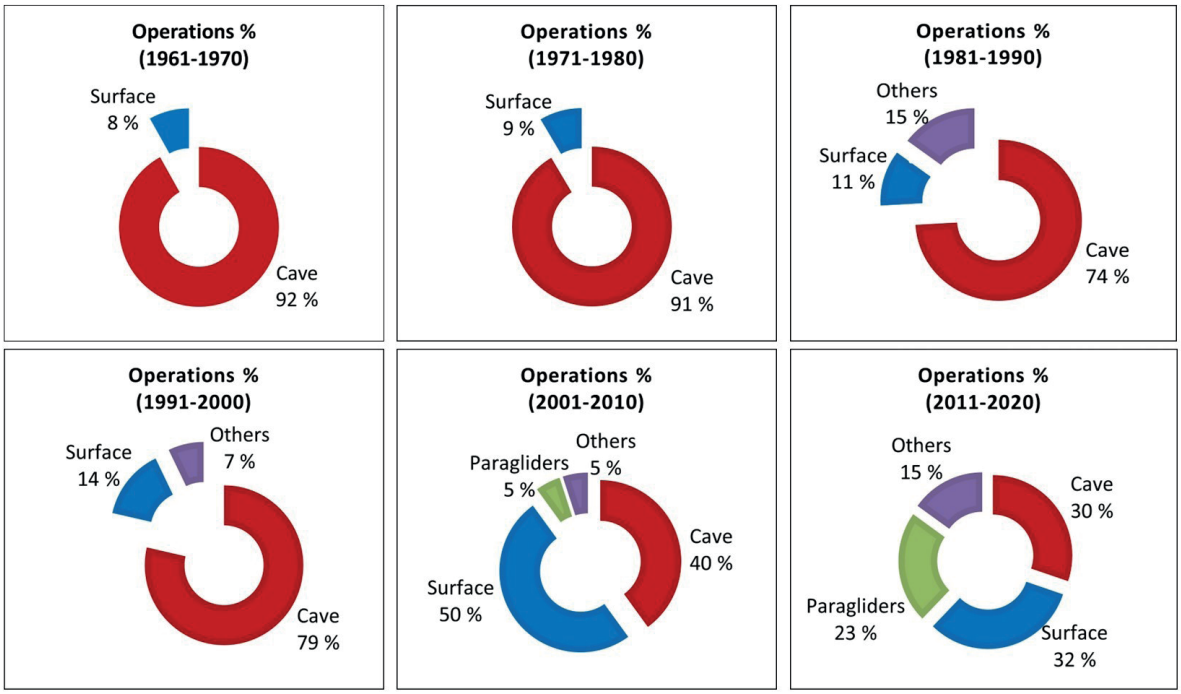


Figure 9: *Changing of rescue structure (%) between 1961-2020.*

5. Conclusions

The data clearly show that in the early years of HCRS, cave rescues dominated its activities. At the time, most caves were freely accessible, with no legal restrictions on entry. Many rescues took place in caves in and around Budapest, primarily due to people getting lost or lacking proper equipment—especially adequate lighting. In some cases, children attempted to descend into cave depths using clotheslines taken from home. Over time, caves were gradually closed off, initially for safety reasons and later increasingly for conservation purposes. Legal regulations have since been established, strictly governing cave access. These rules specify who can enter caves, in what group sizes, with what level of experience, and with what equipment (currently we can not use carbide lamp only electric lights), under the supervision of certified guides or researchers. National parks issue permits outlining these regulations, and park rangers enforce compliance.

In addition, the Speleo Education system was established in 1984 and renewed in 1999, providing structured training for cavers. The data indicate that the number of cave accidents has decreased over time, and HCRS has expanded its activities to other rescue operations. Today, HCRS frequently assists people in distress in difficult-to-access surface locations. State rescue organizations, such as firefighters and paramedics, have increasingly recognized the specialized skills of cave rescuers in such situations.

One notable group requiring assistance is paragliders who sometimes end up stranded in treetops. Since 2007, HCRS has had a written agreement with two paragliding associations to assist in these rescues. Another interesting category includes non-human rescues, such as retrieving dogs or cats that have fallen into wells, and similar tasks.

The charts illustrate a significant shift in HCRS's activities. In the 1960s, 92% of its operations were cave rescues, but by the 2020s, this figure had dropped to 30%. Today, the majority of HCRS's rescue operations involve the new challenges mentioned above.

Acknowledgments

Cavers generally prefer handling muddy buckets over writing reports, but some have always felt the need to document important events. Cave accidents are always significant, especially for those involved. I am also grateful to the journalists—too numerous to list—who found these incidents worth reporting. Some went beyond simple news coverage, conducting interviews with cave rescuers and sharing valuable safety advice to help prevent future accidents. Without their work, this data collection would not have been possible.

References

Hungarian Cave Rescue Service archive

Hungarian Speleological Society archive

Meteor Tájékoztató (1957-2025)

Meteor Yearbook (1968-2003)

Turista Magazin (1971-2025)

Természetbarát Híradó (1991-2008)

Lot of newspapers

Listing all my data sources would far exceed the scope of this study, so I will not attempt to do so. These results are being published here for the first time

Development of head protection compatible with Petzl Nest stretchers

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Abstract

The impetus for development of a new head protection integrated with a stretcher for cave rescue came from experience. During a cave exploration in April 2023 a stone fell on the top of the head of a caver from a height of roughly 25 m. The impact resulted in instant coma with suspicion to brain and backbone injury. The ensuing rescue lasted a day and a half due to the necessity of cave passage enlargement and foremost the inability to move her in accordance with medical guidelines. Luckily the nearby Italian CNSAS utilizes a stretcher with integrated head protection enabling simultaneous head fixation and protection which they were willing to borrow. Unfortunately, we were unable to purchase one after the rescue as the producer's stock ran out and they were not planning another series. Thus we decided to develop our own solution variant. This head protection can be mounted on or removed from the Petzl Nest stretcher. It is large enough to accommodate most head sizes, control of and access to the patient is instant, it accommodates a breathing apparatus, and is designed to withstand tests in accordance with the European standard EN 12492 in horizontal and in vertical positions.

1. The accident

In April 2023 a group of cave explorers was slowly preparing to ascend through a series of pits and narrow passages in a newly discovered cave called Vranjedolska jama up to the entrance some 100 m above them. After two years of arduous work the cave finally gave in and admitted the explorers to access the lower cavernous passages with an active stream – probably one of many sinks at the edge of the famous Cerkniško karst polje. The girl followed her brother who was already above the first re-belay and gave her rope free. She was still fiddling with her ascenders just above the ground when the rest of the group heard a blunt thud and a stone rolling on the ground somewhere in her direction. She hung unconscious on the rope with a cracked helmet when the members of the group cautiously approached her. Carefully they removed her from the rope and lay her in a makeshift shelter. Some of them had just passed a course of cave first aid, so in theory they knew what to do, but practising theory on a seriously injured friend was another matter. But they had to put feelings aside if they had her best interests at hard. According to the book they checked breathing and heartbeat, possible large wounds, made a body check, head immobilization and compiled the accident module. Then two of them ascended to give the call for help.

The call reached the Cave Rescue Service at 20:25 and the medical team was with the victim just before midnight. On the AVPU scale they identified almost total unresponsiveness – which did not improve throughout the rescue – and a suspect on sub cranial lesions and collar and possibly thoracic vertebra damage. Luckily she was not hypothermic and well tended for before their arrival. She was kept hydrated through an intravenous channel and administered pain relief therapy and mild sedation. For the first time in the Slovene cave rescue history she was also strapped on a breathing apparatus and given pure oxygen for breathing.

The main problem consisted in moving her safely through the cave to the exit. The passage between the chamber where the accident happened and the entrance was too narrow in many places for the stretcher to pass (figure 1), let alone keeping it constantly in horizontal position. The cave enlargement team toiled incessantly in several groups towards their goal. At times the bivouac with the victim and the medical team was left without communication for hours because of the interruptions due to the blasting work. At the bottom of the cave attendants to the medical team became increasingly worried about continuous discharging of material through the lowest pit where the accident had happened. Multiple attempts of cleaning the pit of material proved futile and there was no alternative of safer rigging. Nobody wished a second victim to care for. Therefore, there was only one passage of this perilous part with ample spacing between successive climbers.

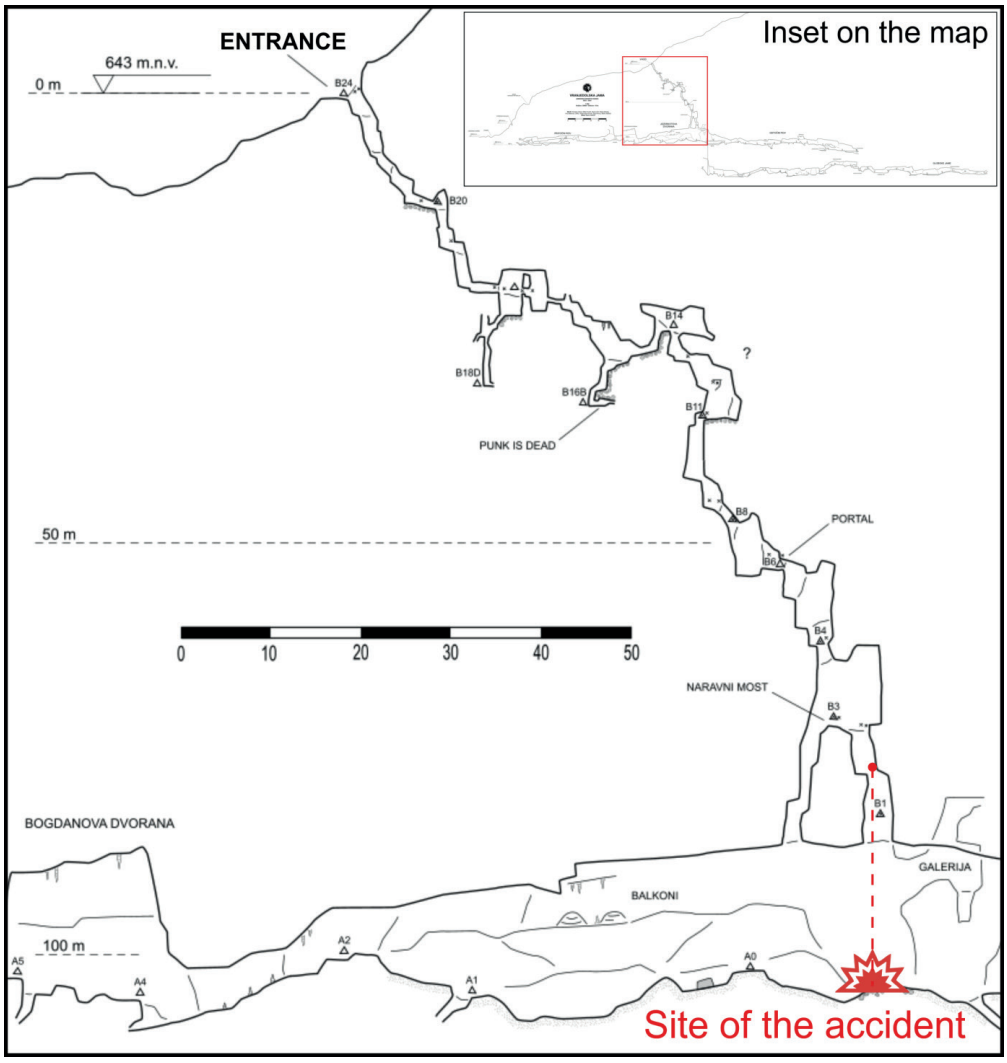

Figure 1: *Extended view of the entrance passages of the cave Vranjedolska jama.*

2. The problem of movement of victims with head injury in caves

The main problem consisted in moving the patient immobilized in accordance with medical guidelines, or at least something close to that as cave emergency procedures can only approach medical procedures on the surface. The cave rescue adapted guidelines for safe transfer of patients with head injury should include (Ahčan 2006, Nathason et al. 2020):

- The victim must lie flat with collar and head immobilization.
- Movement of the victim must be limited to the bare minimum.
- Movement of the victim to the stretcher must be done with 4 persons with strict fixation of the backbone.
- All movement is done in horizontal position.
- There should be a designated consultant in referring hospital with overall responsibility for the organisation, of safe transfer of the patient.
- Local guidelines should be drawn up between the cave medical team and the consultant. These should approach national guidelines as close a feasible.
- Although transfer is often urgent, stabilisation of the patient should be underway before transfer.
- It is advised patients with a brain injury be accompanied by a clinician with appropriate training and experience in the transfer of patients with acute brain injury. If unavailable, other medical practitioners must attend.
- Monitoring during transport should adhere to guidelines.
- The transfer team should have the possibility of contact with the consultant during transport.

The stretcher of choice being employed in the Slovene Cave Rescue Service is the Petzl Nest (NEST, 2025) and as far as our knowledge goes, many other rescue teams all-over the world have adopted it. This stretcher is not only present in caves, but by means of Petzl's leading role as a producer of rope access and rope rescue equipment, all sorts technical rescue from urban to confined space. This stretcher offers several advantages in caves: it is relatively light; it has an excellent bridle with a good system of passing the stretcher from horizontal to vertical orientation and back; its integrated TPU canvas flaps and hood offer relatively good water protection; and not the least it has proven as a sturdy and reliable piece of rescue equipment throughout many practices and interventions.

But it has its pitfalls too. Its supporting structure is not totally stiff (cannot be treated as a spinal board). The absence of attention to head protection and head immobilization is blatant. Various groups have

devised a multitude of techniques for head immobilization in this stretcher. They may be categorized in two groups. The first employs an additional stretcher that is put into the Nest (e.g. a spinal board). The second consists in fixing directly on the stretcher additional means of head and neck immobilization (e.g. block head immobilizers). None of them, however, is without flaws. The insertion of another stretcher into the Nest means that the rescue team has to carry two instead of one and the addition of block head immobilizers prevents any sort of head protection from foreign objects as they prevent the wearing of a helmet.

3. The state of the art

These flaws are not unknown to the rescue community and have been more or less successfully addressed already by some producers such as Ferno (FERNO 2025). They developed durable polycarbonate head protectors (literally lids covering the top part of the stretcher) intended to be coupled with their Titan basket stretcher. There are two variants: a more compact one intended for technical applications (FERNO LITTER 2025) and a taller general purpose one (FERNO LITTER PLUS 2025). Both protect the head and the neck against falling objects while leaving the possibility to apply proper head fixation and if need be breathing support. While these head protection solutions are indicated for usage and much welcome in free spaces, they are prohibitively large in confined environments such as conduits piping or in our case caves.

Figure 2: *The Italian CNSAS solution of head protection fastened to the AlpDesign Barella speleo stretcher (ANTONINI et al., 2015).*

The Italian Mountain and Cave Rescue organization identified both shortcomings, the lack of proper head protection in existing cave-going stretchers and the prohibitive size of existing head protections for cave rescue. They were testing various concepts of compact yet effective head protection already 15 years ago. Eventually, they came up with an adapted shape of a motorcycling helmet with a flat backside that could be fastened to a board by means of a hook and loop self-adhesive tape and additionally fixed by tightening it to the board with webbing (figure 2 and 3). It is composed of three protective elements: the base of the shell with cushioning for the head is fixed to the board; the top of the shell coming attached to the base by means of metal fasteners; and a polycarbonate visor hinged to the top part of the shell.

Figure 3: *The Italian head protection being fixed on the stretcher in practice.*

As mentioned, the stock of these head protections was depleted so they could not offer us one. In addition to that they decided to develop a new version. The improvement to the old version should be lightness and easier assembly.

4. The stretcher integrated head protection

The Italian team, however, was only in initial stages of the project not knowing when or if the new head protection will be ready. The important difference to our organization was that they already had a solution that they could deploy in the case of an accident, while we did not have it.

At that stage the decision was taken. We had able engineers and certification and PPE production specialists in our ranks. Financing was granted through our financer the Administration for Civil Protection and Disaster Relief through a dedicated project.

By being a member of the European Union Slovenia has to comply with its legislative framework. That is why we initially enquired at one of the notified bodies what category a head protection fixed on a stretcher might be in. First to come to our minds are probably the groups of *personal protective equipment* (PPE) and *medical devices* (MD). The definition of PPE as stated by the Regulation on Personal Protective Equipment (Regulation 2016/425/EU) is somewhat peculiar. It states that PPE means:

a. equipment designed and manufactured to be **worn** or **held** by a person for protection against one or more risks to that person's health or safety;

b. interchangeable components for equipment referred to in point (a) which are essential for its protective function;

c. connexion systems for equipment referred to in point (a) that are not held or worn by a person, that are designed to connect that equipment to an external device or to a reliable anchorage point, that are not designed to be permanently fixed and that do not require fastening works before use.

The response of the representative of the notified body was that the described head protection is not an item of PPE. It is neither **worn** nor **held** nor it is a component or a connexion system. It actually fixed on a stretcher, which is not an item of PPE. The primary function of stretchers is not harnessing a body but a means of transporting it.

Stretchers could also fall within the scope of medical devices and as an extension of that head protectors could make part of it. But again the notified body's specialist rejected such a hypothesis.

From the legislative point of view there was no coverage of such a device. On one side of the coin the news was bad, since the market could not take advantage of standardized safety regulations put forward by technical experts and the legislation. On the other side of the coin, however, this was good because, we were not impeded by the mentioned

framework to produce, use and sell such equipment. In case of accidents it would have to be demonstrated that we as producers and users took care of the following:

- Requirements for the equipment should reflect the state of the art in similar equipment such as helmet for mountaineering (in accordance with EN 12492 or the UIAA 106).
- Production followed a quality assurance programme;
- An instructions manual was available explaining correct usage, limitations, markings, transport, storage, maintenance, inspections and lifetime.
- The Cave Rescue Service made available a publication on proper techniques of usage of this equipment.
- All users passed an equipment awareness course with documented attendance and examination.

The EN 12492 and the UIAA 106 standards are very similar in their requirements, but in some points the UIAA 106 is stricter. Figure 4 is graphically explaining the main tests required for the conformity to be reached. Peak impact forces are not relevant in the case of head protection since the energy is transferred to the stretcher, not the head of the victim.

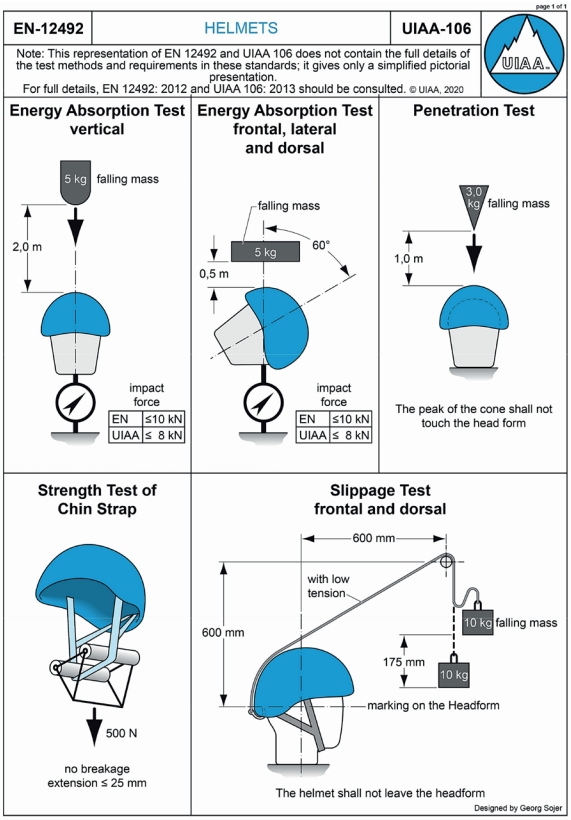

Figure 4: *requirements of the EN 12492 and the UIAA 106 (UIAA 2020).*

The main three tests consist of:

- A blunt 5 kg mass falling on the centre of the head protection from a height of 2 m;
- An anvil like 5 kg mass falling from a height of 0,5 m;
- A pointed 3 kg mass falling from a height of 1 m.

None of the tests must result in the mass touching the head of the mannequin. For our application all mentioned tests must be performed in horizontal and in vertical position.

The *chin strap* test is not relevant for the head protection. The *slippage* test, on the other hand, can be used to test the resilience of the visor against opening.

Additional requirements set for the head protection were that:

Figure 5: *First printed prototype of the head protection mounted on an older Petzl Nest model.*

- it is easily attached on and detached from the stretcher;
- it should fit all head sizes and head forms;
- it should accommodate head fixation and head bandaging compatible with medical guidelines;
- it is packable in a way that it can be transported in standard caving packs;
- it is reasonably lightweight;
- access to the patient's head is quick;
- control of the patient's state of consciousness must never be hindered;
- it does not impede breathing;
- it protects against dripping water and spray;
- within reason it should prevent the accumulation of condensation (ventilation should be good);
- it should not give the patient a feeling of discomfort due to confinement or seclusion.

Based on these propositions we made the first prototype and tested its functionality (figure 5 and 6).

Figure 6: *First head protection prototype accommodating a KED and a neck brace.*

With the first prototype we identified some dimensional shortcomings for the largest head sizes and we had to produce a second model before going for production.

The final products will not be 3D printed but layered composites consisting of a mix of carbon layers for strength and rigidity and fiberglass for durability and impact absorption.

The production series is initially only meant for the Slovene Caver Rescue Service needs. If established as useful and safe we will not limit other interested parties to order them.

4. Conclusion

We left the girl in deep coma with group of concerned doctors and rescuers still down at the bottom of the cave and we feel we owe you a proper finish of the story.

Petzl Nest stretcher was not up to the task. Therefore, our medical doctor ordered the to surface the Italian stretcher to be brought. The Italians were more than willing to oblige and in a matter of hours the stretcher was with the victim. Before the start of evacuation she was administered stronger sedation to keep her calm and given a new bottle of oxygen. The evacuation was risky because of the movement itself but also because of the necessity to verticalize the stretcher in a couple of tight spots. Despite that she remained stable sleeping her Sleeping beauty sleep. The head protection worked flawlessly. In a slanting crack we had to tilt the stretcher sideways and it slid a bit into the crack. I saw the head protection scratching against the wall and deforming a bit as we were struggling to push it through the squeeze, but the face inside the protection rested calm and unperturbed.

34 hours after the accident she left the cave in a similar state as immediately after the stone hit her. After reaching the hospital the doctors kept her in artificial coma for another week. She left the hospital after two months and multiple operations. It was established she had a diffuse axon brain damage, burst fractures of C1, C3 and C5 cervical vertebra. She had a stenosis of the spinal cannel on C6, which was why she could not control one hand very well before they operatively enlarged the channel. And she had fractures in T3, T4 and T5 thoracic vertebra. But luckily she only had a minor oedema and minor intracranial haemorrhage. Those are certainly important factors contributing to her successful healing process.

After half a year her rehabilitation was over with full recovery.

Without prompt and medically correct reaction of their caving colleagues, good decisions of the medical team, and the whole cave rescue service working in unison to the final goal of evacuating her from the cave she might never have seen light again. We believe that the choice of the right stretcher for the transport played a role in that success.

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