19th INTERNATIONAL CONGRESS OF SPELEOLOGY
BELO HORIZONTE - MG - BRAZIL - 2025
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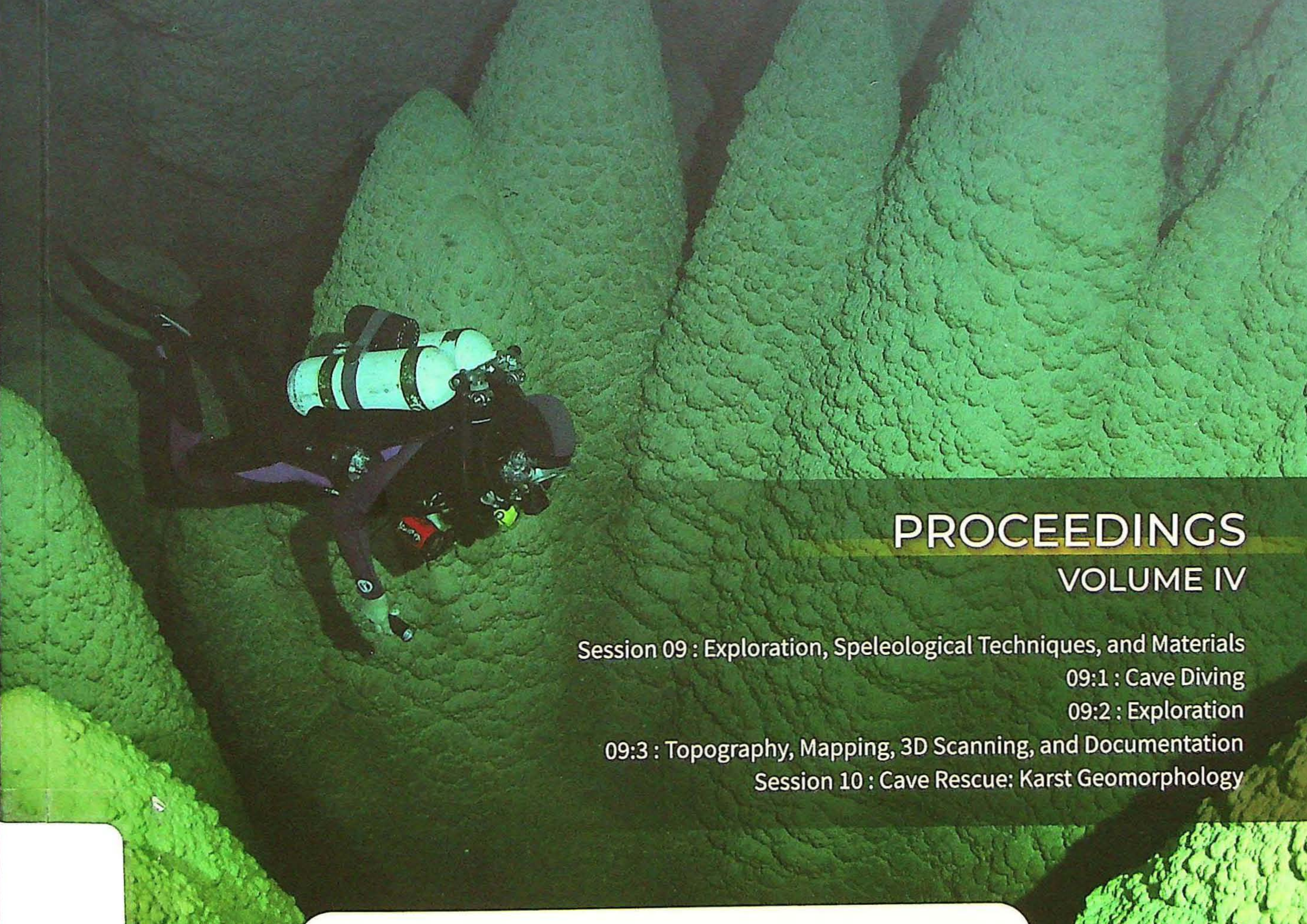
19th INTERNATIONAL CONGRESS OF SPELEOLOGY

38º Congresso Brasileiro de Espeleologia

20-27 DE JULHO DE 2025 - BELO HORIZONTE - MINAS GERAIS – BRASIL



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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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.

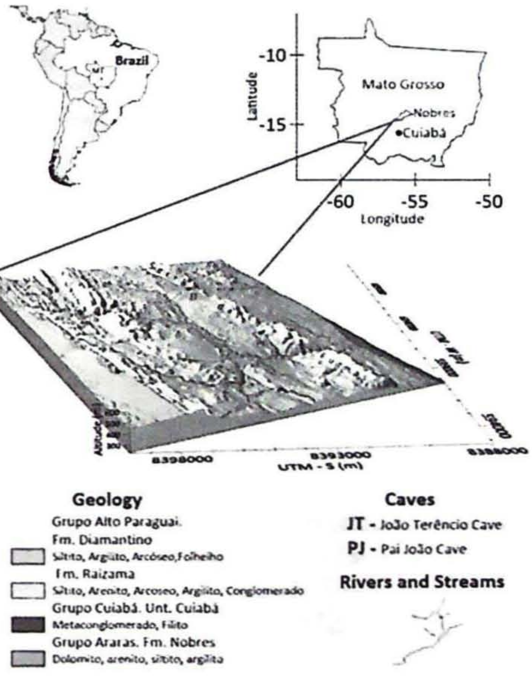

Figure 1: Location of caves, geology (CPRM, 2004) and geomorphology of the Serra das Furnas region.

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 $P_j = \frac{P_{amb}}{b_j} + a_j$ 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:

$$\frac{dP_j}{dt} = k_j \cdot (P_A - P_j) \quad \text{(eq 1)}$$

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:

$$P_j(t) = P_{0,j} \cdot e^{-k_j \cdot t} + P_A \cdot (1 - e^{-k_j \cdot t})$$

(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).

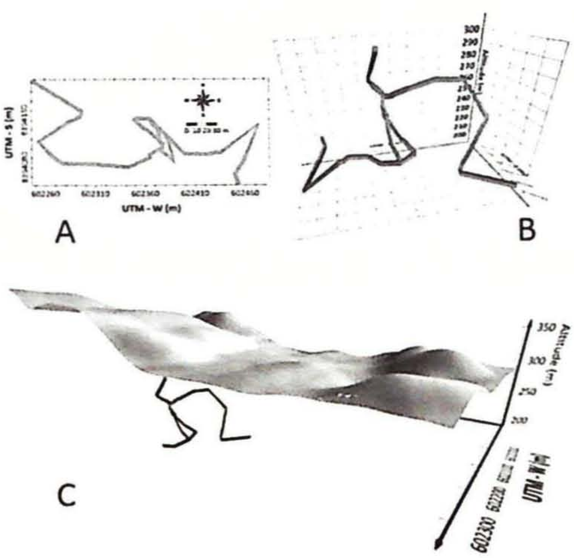

Figure 2: Pai João Cave lines: Plan view (A), simple 3D model (B) and 3D with the surface topography. The rectangular passages model consider 2-meter WFC distances to improve the visualization.

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.

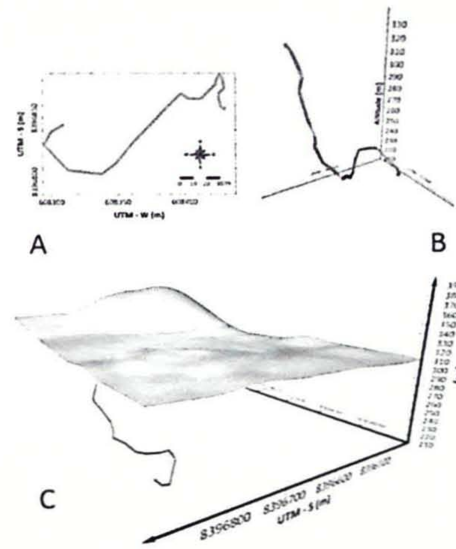

Figure 3: Plan view (A), simple 3D model (B) and 3D with the topography of the lines of sight of João Terêncio Cave. The rectangular passages model consider 1-meter WFC distances to improve the visualization.

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).

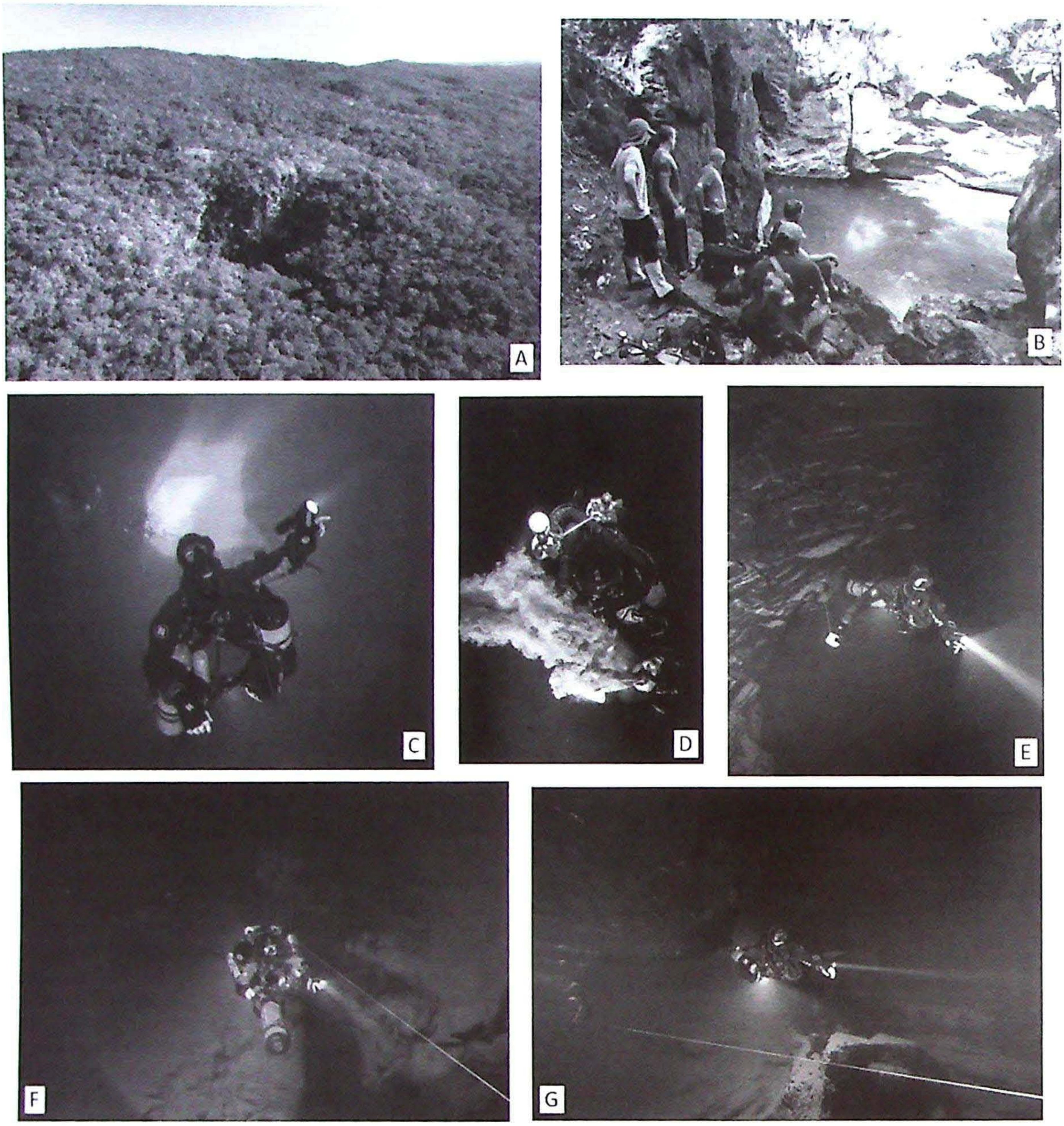

Figure 4: Images of Pai João Cave: A- Aerial view of the doline at Serra das Furnas; B- Cave entrance; C-Diver with cave entrance in background; D-Releasing fluoresceine dye E, F an G- Mapping and exploration at different points in the cave. Subaquatic images by Kirill Egorov.

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.

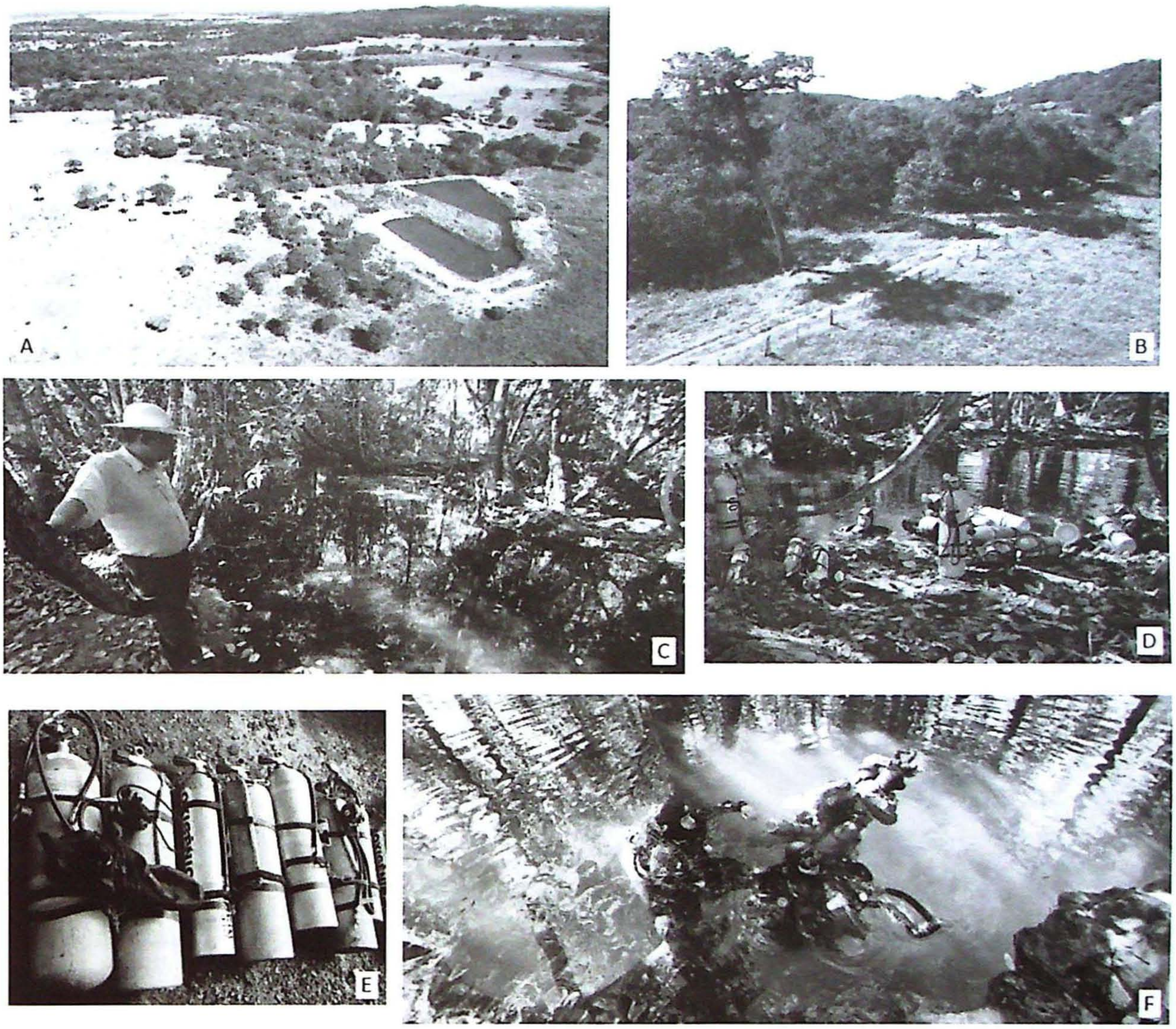

Figure 5: *A and B- Aerial views of João Terêncio Spring; C- Aspects of the spring; D, E and F- Start diving procedures at cave entrance.*

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.

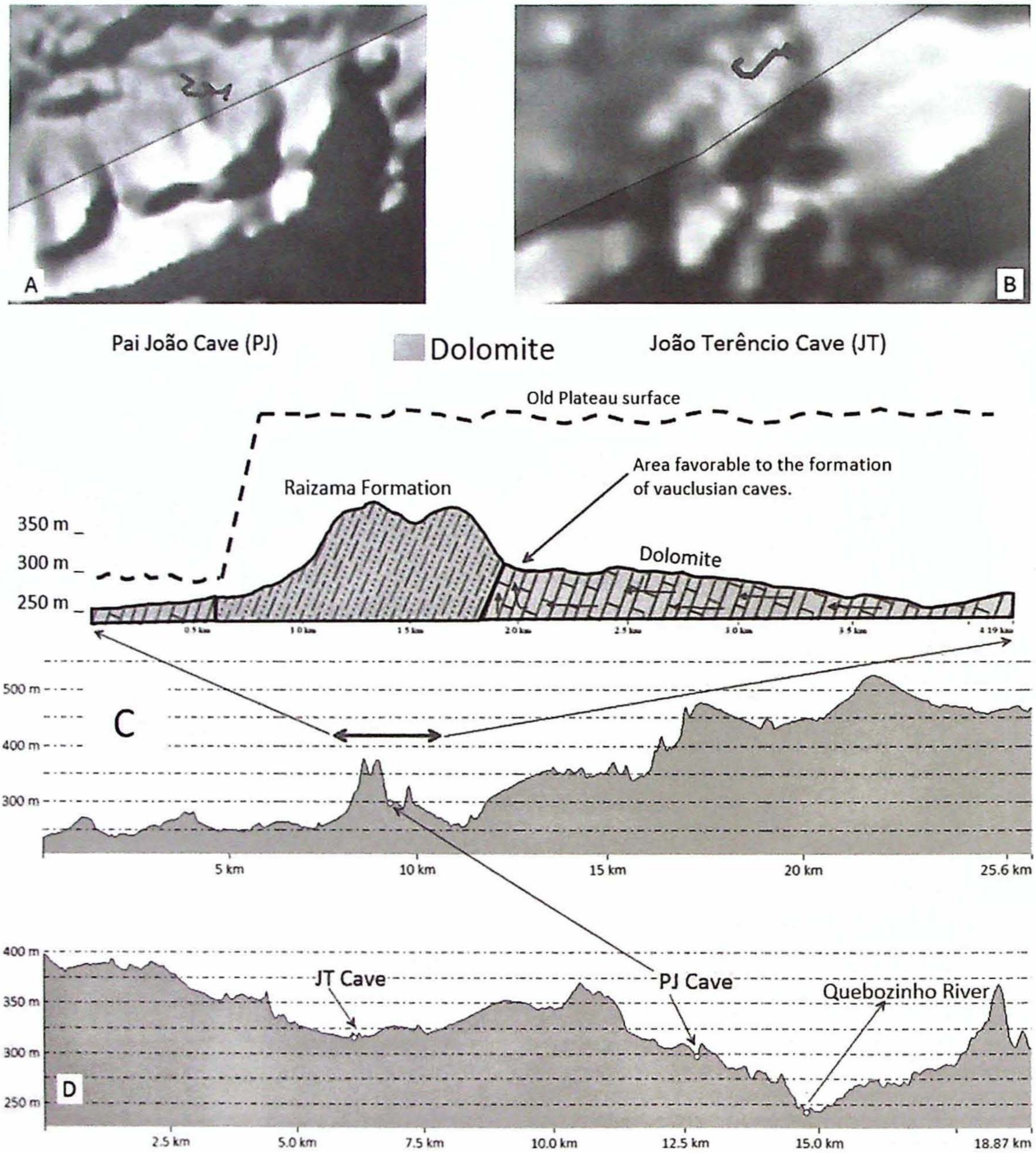

Figure 6: *A and B - Alignment of the caves with geological lineaments and the contact zone between the dolomite and rocks of Raizama Formation. C - Geologic profile near Pai João Cave and its approximate location in the regional topographic profile. D – Topographic profile showing the location of both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