Pliocene-Holocene evolution of a cratonic, sandstone covered karst system: NE Brazil

Lucas Padoan de Sá Godinho (1), Ivo Karmann (2), Darryl Granger (3), Fernando Verassani Laureano (4), Tom Dias Motta Morita (5), Gabriela Duarte (6)

(1) Instituto de Geociências, Universidade de São Paulo, São Paulo, Brazil (corresponding author), lucaspsgodinho@gmail.com
(2) Instituto de Geociências, Universidade de São Paulo, São Paulo, Brazil, ikarmann@usp.br
(3) Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, Indiana, USA, dgranger@purdue.edu
(4) Instituto de Geociências, Universidade de São Paulo, São Paulo, Brazil, verassani@gmail.com
(5) Instituto de Geociências, Universidade de São Paulo, São Paulo, Brazil, tomdmmorita@gmail.com
(6) Instituto de Geociências, Universidade de São Paulo, São Paulo, Brazil, gduart@usp.br

Abstract

Large cave systems in northeastern Brazil record ancient and modern karstification events associated to different tectonic uplift and subsidence cycles. Low uplift and denudation rates in the craton environment allowed multiple base level fluctuation events to rework cave passage levels at approximately the same elevation. Paleokarst landscape and interstratal karstification were recognized as early phases of dissolution since the Paleozoic and the Paleogene to Neogene transition (i.e. before and after burial of the major limestone unit by sandstone rocks). The analysis of modern karst landscape features, cave passage morphology and geology, lithostratigraphic relations, hydrochemical analysis of karst waters and geochronological analysis of cave deposits (cosmogenic ^{26}Al and ^{10}Be, OSL and U-Th dating) were applied in this study. This allowed to reconstruct a complex evolution history of the major phase of karst development since the Pliocene, after the second evidenced limestone exposure cycle. Multiple episodes of local base level fall and rise interpreted from cave erosion and deposition features suggest climate change control on surface river power increase (incision trends) and vegetation cover weakening (aggradation trends).

1. Introduction

Base level change is one of the major controls in the evolution of a karst system (Ford, 1971; Ford and Williams, 1989). Tectonic and climatic dynamics can influence base level fluctuations, so cave passages may record aggradation and erosion trends as they search equilibrium with a new established base level (Farrant and Smart, 2011; Calvet et al., 2024). Thus, erosion and deposition features in cave conduits allow the interpretation of past environmental conditions associated with aquifer and landscape evolution (Palmer, 1987, 2007).

Most karst systems in Brazil develop in limestone rocks deposited during the Neoproterozoic in a cratonic environment. The stable tectonic conditions imply in slow rates of uplift, denudation and regional groundwater lowering. This favors the development of single level, wide, and low gradient cave passages. Deposition and erosion records in cave passages tend to be superimposed at the same elevation, giving rise to a complex cave stratigraphy, characteristic of the tropical karst in stable terrains (Audra and Palmer, 2015).

In the São Desidério karst area (Figure 1), northeastern Brazil, large limestone cave systems develop at the margins of a sandstone covered plateau and preserve sedimentary records that indicate successive base level fluctuations. The causes associated with those changes in base level are not well understood, so careful study of cave geology, karst geomorphology and hydrogeology may help to connect local and regional aspects of the karst system evolution.

The aim of this research was to recognize major stages of evolution in the São Desidério karst system, taking into account modern groundwater recharge and discharge landscape features, cave passage morphology, and geochronological analysis of cave deposits.

Figure 1: Collapse sinkholes with limestone cliffs, aligned in the ENE-WSW direction, parallel to a major cave system. The low gradient landscape that surrounds the sinkholes is covered by sandstone. The major axis of the sinkhole in the foreground is 180 m, and its depth is 90 m. Photo: Gabriel Lourenço.

2. Materials and methods

Open access satellite images, topographic maps and digital elevation models (SRTM - USGS, BDGEX - Brazil) where used to delineate topographic divides and drainage basin geometry in an area of approximately 600 km². From this, surface recharge karst features were define, and morphometric parameters of enclosed depressions were defined (Williams, 1972).

Spring inventory was carried out in the field in order to identify aquifer discharge points in this area (Feitosa and Feitosa, 2008). Hydrochemistry analysis of karst waters (springs, drippings, and cave rivers) was conducted to investigate the origin of the acidity responsible for cave enlargement. Geological map analysis (SBG - Brazil) and the survey of 8 cross sections in the field (rock exposures and pumping well data), ranging from 1 to 60 km in extension, where used to characterize the lithostratigraphy, typify karst recharge styles and recognize paleokarst features.

Survey data (Bambuí and GGEO caving clubs) from representative caves were used to analyze 6.8 km of passage morphology. Cave geology research (Palmer, 1987, 2007) in the field was carefully performed in order to identify erosion and deposition conduit features that indicate base level fluctuation.

Finally, 40 samples for geochronological analysis (cosmogenic ^{26}Al and ^{10}Be, OSL and U-Th) were sampled from quartz rich clastic sediments and calcite speleothems in the caves (Granger, 2006; Rhodes, 2011; Richards and Dorale, 2003). Major stages of evolution of the karst system was interpreted from this multiple method approach.

3. Results

Geological cross sections revealed that the erosive contact surface between the Bambuí Group limestones (Neoproterozoic, lower unit) and the Urucuia Group sandstones (Cretaceous, upper unit) is characterized by a paleovalley morphology. Sinkholes developed on the sandstone are ubiquitous in the covered karst zone, indicating that subjacent limestone caves drag large volumes of quartz sands to the underground limestone conduit system.

The limestone rock is exposed to the surface near the base and mid hillslope elevations of the São Desidério River valley (local base level). Allogenic recharge from the sandstone drainages form blind valleys at the contact with the limestone. Authogenic recharge through sinkholes is widespread when the limestone rock is exposed to the surface. Spring inventory showed that 21 intermittent and 22 perennial springs are responsible to the discharge of the limestone karst and the insoluble sandstone aquifers.

Mapping of surface karst depressions and springs showed that the longest cave system in the area (named João Rodrigues) has its recharge on surface coming from the Tamanduá River watershed (sandstone covered karst zone), while the discharge spring drains to a different surface watershed, at the margins of the São Desidério River.

Cave morphology is characterized by wide, low gradient phreatic passages (cave levels) oriented parallel to the intersection between the strike of the limestone bedding planes (NE-SW to NW-SE) and prominent normal faults (ENE) (Figure 2). The limestone beds are folded and show average dip angle equals to 21°, as a consequence of the Brasiliano Orogeny that affected the borders of the São Francisco Craton during the Neoproterzoic.

Figure 2: Upper cave passage level in the Sopradeira cave. Fluvial bars covered by calcite (to the right), wall notches (to the left), remnants of quartz sand deposits in the walls (top left), and ceiling channels (at the top) indicate fluvial aggradation reworking of the passage (base level rise) after phreatic passage development and subsequent vadose incision (base level fall).

Two major cave levels where recognized: the lower at 525 m.a.s.l. and the upper at 555 m.a.s.l. Those are connected by vadose canyon passages that follow the dip direction of the limestone strata.

Plan view morphology of the cave systems is characterized by a dendritic pattern, locally superimposed by network or anastomosing flood maze passages, depending on the dip of the strata and the occurrence of prominent vertical angle fault zones.

Hydrochemical analysis of karst waters showed that Ca^{2+} and HCO_3^- represents 60-80% of the ionic species in solution, while SO_4^{2-} usually constitutes <20% of dissolved species. Average Ca^{2+} concentrations in the karst waters was 80 mg/l. Linear regression analysis of the Ca^{2+}, Mg^{2+} and HCO_3^- concentrations show a good correlation (r = 0,93). High concentrations of SO_4^{2-} (20 mg/l) occur in the deep phreatic zone (≈ 60 m depth in pumping wells) and some cave drippings. Saturation index analyses showed that karst springs are saturated all over the water year, except during major flooding events.

The burial ages of clastic cave deposits vary from 3.03 ± 0.19 My (^{26}Al and ^{10}Be) to 1.8 ± 0.1 ky (OSL). Minimum ages of cave formation in three different cave systems gets progressively younger in the upstream direction of the surface river (base level). Cave deposits at the top (2.15 ± 0.18 My, ^{26}Al and ^{10}Be age) and bottom (1.16 ± 0.18 My, ^{26}Al and ^{10}Be age) of a major vadose canyon with vertical amplitude of 30 m mark the timing of a major base level drop.

Calcite flowstone speleothems that cover fluvial river bars in the upper passage level shows a wide range of crystallization ages (337.9 ± 15.6 ky, 228.2 ± 3.5 ky, 85.8 ± 6.2 ky, U-Th age). Subaquatic speleothems with stromatolitic lamination (speleomicrobialites) locally form thick crusts (≈ 10-30 cm) on the sinkhole cliffs and all-around collapsed cave passage walls and ceiling (Figure 3). The subaquatic speleothems occur up to 40 m above the modern cave river level and they consist of interchanged vadose (soda straw) and phreatic (stromatolitic lamination) facies. Ages of deposition vary from 4.3 ± 0.052 ky to 2.2 ± 0.248 ky.

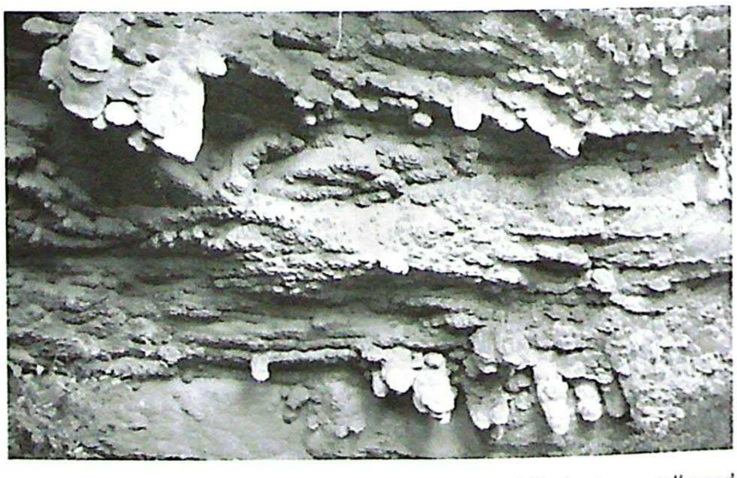

Figure 3: Speleomicrobialites preserved on the cliff of a large collapsed sinkhole (the same as in the background of Figure 1). Major axis of the larger speleothems on the top left corner of the picture are approximately 4 m long.

4. Discussion

The older karstification event corresponds to the Paleokarst formed between the erosive contact of the Bambuí Group and the Urucuia Group. This karstification phase is characterized by the paleovalley morphology, and its formation is associated to the erosive hiatus between the Ediacaran and the upper Cretaceous (a gap of approximately 400 My).

After the deposition of the Urucuia Group, continental uplift took place in the interior of the South American Platform (Almeida et al., 2000), giving rise to a regional plateau landscape in the Cenozoic (Valadão, 2009). Interstratal karstification was triggered by the new established hydraulic gradient of the plateau escarpment (≈ 1,000 m relief). The evidences of the interstratal karstification are the sandstone sinkholes in the covered karst zone.

Limestone exposure occurred during the incision of the São Desidério River valley. Carbonic acid dissolution was dominant to cave passage enlargement in the phreatic and vadose zones. Punctual pyrite oxidation in interlayered mudstone and limestone successions is interpreted to have influenced dissolution by sulfuric acid in the vadose zone, as indicated by higher SO_4^{2-} concentrations in cave drippings and pumping wells.

The saturation index from karst springs suggests that cave enlargement by dissolution is active only during major floods. During most of the water year, waters are saturated chemical with calcite and corrosion is predominantly inactive.

The extension of the longest underground cave system flow route and the average dip of the limestone strata were used to estimate the maximum depth of groundwater flow in conduits between 150-270 m from the surface, following the equation proposed by Worthington (2001).

Acidic water infiltration in the sandstone to limestone contact along the Tamanduá River created an alternative underground flow path and head gradient to the São Desidério River. Due to the large catchment area of the Tamanduá River (long watershed axis ≈ 100 km), the João Rodrigues cave system developed large underground galleries and eventually pirated the Tamanduá River flow to the São Desidério River. The time constrain for this stage is indicated by the minimum age of karst conduit formation in the area (3.03 ± 0.19 My, ^{26}Al and ^{10}Be age).

Knickpoint migration along the São Desidério River is responsible for the erosive retreat of the sandstone plateau escarpment. Cave systems get progressively younger to the upstream direction, as suggested by cosmogenic burial ages, indicating that new limestone exposures are formed during the knickpoint migration process.

An important base level drop event occurred approximately between 2-1 My, leading the caves to entrench vadose canyons down to a new elevation. The São Desidério River is the local base level, so this event represents an increase in the surface river power and erosion capacity.

After the base level drop and the development of the lower cave passage level, successive fluvial erosion reworking and aggradation events were superimposed, affecting the lower and upper cave passages. The wide range of cave deposit ages younger than 500 ky, in different elevations, is the evidence to the interpretation of constant base level fluctuation. The cause for an erosion to aggradation trend shift is interpreted as a transition from more humid climatic conditions to drier periods. This climate change leads to less developed vegetation cover and a more efficient hillslope transport of sediments to the bottom of the surface valleys, as the process described by Langbein and Schumm (1958) and Acosta et al. (2015), ultimately causing cave passages to fill up with clastic sediments.

Breakdown reworked cave passage morphology, and this process is associated to different causes: cave floods and weakening of fracture planes by dissolution at high hydraulic gradients; vadose infiltration and precipitation of secondary carbonate and sulphate minerals in the fractures (crystal wedging); erosion of the land surface and removal of cave roof support, leading to collapse sinkhole development.

Subaquatic speleothems cover breakdown walls in the caves. They are preserved as scattered crusts along entire cave systems (> 10 km of cave passages). Three major vadose growth phases of the speleomicrobialites, interlayered with subaquatic growth phases, indicate that the regional water table varied in a 3-40 m amplitude during the last 6 ky.

5. Conclusion

The São Desidério karst system was formed during different phases of exposure and burial of the Bambuí Group limestones. The earlier phase of evolution is related to the erosive unconformity between the Bambuí Group limestone and the Urucuia Group sandstone (Paleozoic to Mesozoic hiatus), where a paleokarst is evidenced by a buried paleovalley landscape. Interstratal dissolution followed after the uplift of the continental crust and the formation of a regional plateau, probably in the Paleogene to the Neogene transition. The most prominent phase of cave systems development started in the Pliocene, after the modern exposure of the limestone rocks to the surface.

Several base level change episodes were recognized in the cave systems during the last 3 My. They reflect the increase of the river power and erosion capacity of the major river on surface (local base level) when base level drops, and a change from more humid to drier climatic conditions leading to aggradation when the base level rise.

Acknowledgments

We extend our gratitude to the Brazilian research funding agencies Fapesp, process n° 2018/15774-5, CAPES and CNPq for sponsoring this research. We also thank to the Bambuí and GGEO caving clubs from Brazil, for giving access to the cave maps. Finally, we thank to the many caver friends who participated in the field trips, for so many hours of fun and science in the underground.

References

ACOSTA, V. T., SCHILDGEN, T. F., CLARKE, B. A., SCHERLER, D., BOOKHAGEN, B., WITTMANN, H., von BLANCKENBURG, F. (2015) Effect of vegetation cover on millennial-scale landscape denudation rates in East Africa: Lithosphere, v. 7, n. 4, p. 408-420.

ALMEIDA, F. F. M., NEVES, B. B. B., CARNEIRO, C. D. R. (2000) The origin and evolution of the South American Platform: Earth-Science Reviews, v. 20, p. 77-111.

AUDRA, P., PALMER, A. N. (2015) Research Frontiers in Speleogenesis: Dominant Processes, Hydrogeological Conditions and Resulting Cave Patterns: Acta Carsologica, v. 44, n. 3, p. 315.

CALVET, M., GUNNELL, Y., DELMAS, M., BRAUCHER, R., JAILLET, S., HÄUSELMANN, P., DELUNEL, R., SORRIAUX, P., VALLA, P. G., AUDRA, P. (2024)

Valley incision chronologies from alluvium-filled cave systems: Earth--Science Reviews, v. 258, 40 p.

FARRANT, A. R., SMART, P. L. (2011) Role of Sediment in Speleogenesis: Sedimentation and Paragenesis: Geomorphology, v. 134, n. 1, p. 79-93.

FEITOSA, E. C., FEITOSA, F. A. C. (2008) Metodologia Básica de Pesquisa de Água Subterrânea, in, Feitosa, F. A. C., Manoel Filho, J., Feitosa, E. C., Demetrio, J. G. A. Hidrogeologia: Conceitos e Aplicações, Rio de Janeiro, CPRM, LABHID, 812 p.

FORD, D. (1971) Geologic Structure and a New Explanation of Limestone Cavern Genesis, in The Transactions of the Cave Research Group or Great Britain: Symposium on the Origin and Development of Caves, v. 13, n. 2, p. 81-94.

FORD D., WILLIAMS P. (1989) Karst geomorphology and hydrology, Ed. Unwin Hyman Ltd. London, 601 p.

GRANGER, D. E. (2006) A Review of Burrial Dating Methods Using 26Al and 10Be: Geological Society of America Special Papers, v. 415, p. 1-16.

LANGBEIN, W. B., SCHUMM, S. A. (1958) Yield of Sediment in Relation to Mean Annual Precipitation: Transactions, American Geophysical Union, v. 39, n. 6, p. 1076-1084.

PALMER, A. N. (1987) Cave Levels and Their Interpretation: The NSS Bulletin, v. 49, p. 50-66.

PALMER, A. N. (2007) Cave Geology: Cave Books, Dayton, 454 p.

RICHARDS, D. A., DORALE, J. A. (2003) Uranium-series chronology and environmental applications of speleothems: Reviews in Mineralogy and Geochemistry, v. 52, n. 1, p. 407-460.

RHODES, E. J. (2011) Optically stimulated luminescence dating of sediments over the past 200,000 years: Annual Review of Earth and Planetary Sciences, v. 39, p. 461-488.

VALADÃO, R. C. (2009) Geodinâmica de superfícies de aplanamento, desnudação continental e tectônica ativa como condicionantes da megageomorfologia do Brasil oriental: Revista Brasileira de Geomorfologia, v. 10, n. 2, p. 77-90.

WILLIAMS, P. W. (1972) Morphometric Analysis of Polygonal Karst in New Guinea: Geological Society of America Bulletin, v. 83, p. 761-796.

WORTHINGTON, S. R. H. (2001) Depth of Conduit Flow in Unconfined Carbonate Aquifers: Geological Society of America, v. 29, n. 4, p. 335-338.