Speleogenesis in Quartzites in the Southwestern Ibitipoca State Park

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Abstract

The Ibitipoca Mountain Range, in southern Minas Gerais (Brazil), hosts an important speleological district that is part of the Andrelândia Speleological Province, where caves have developed in quartzites of the São Tomé das Letras Formation, Carrancas Group – Andrelândia Sequence. This study analyzed the speleogenesis of four caves in Ibitipoca State Park: Gruta Martimiano II, Gruta das Bromélias, Gruta Manequinho, and Gruta das Casas. Structural, petrographic, geochemical, and hydrochemical analyses were conducted. The results indicate that speleogenesis occurs mainly in fine-grained quartzite layers embedded between coarser quartzites. The incongruent dissolution of feldspars and micas, combined with the low solubility of silica, generates secondary porosity, favoring sandification and channeling processes. The caves follow regional fractures oriented NE-SW, NW-SE, and W-E and are also influenced by bedding (SE/21º) and an open fold (antiform) with an NNE-SSW axial plane. Groundwater shows low dissolved silica concentrations (1.67 to 3.22 mg/L) and acidic pH (3.0 to 5.8), indicating limited chemical dissolution and a predominance of mechanical erosion. Speleogenesis occurs in fine quartzite layers containing mica, feldspar, and kaolinite, with thicknesses ranging from 1.0 m (G. Martimiano II) to 11.3 m (G. Manequinho).

Résumé

La chaîne de montagnes d'Ibitipoca, située au sud du Minas Gerais (Brésil), abrite un important district spéléologique faisant partie de la Province Spéléologique d'Andrelândia, où des grottes se sont développées dans les quartzites de la Formation São Tomé das Letras, Groupe Carrancas – Séquence Andrelândia. Cette étude a analysé la spéléogenèse de quatre cavités du Parc d'État d'Ibitipoca: Gruta Martimiano II, Gruta das Bromélias, Gruta Manequinho et Gruta das Casas. Des analyses structurales, pétrographiques, géochimiques et hydrochimiques ont été réalisées. Les résultats indiquent que la spéléogenèse se produit principalement dans des couches de quartzite fin, intercalées entre des quartzites plus grossiers. La dissolution incongruente des feldspaths et des micas, associée à la faible solubilité de la silice, génère une porosité secondaire, favorisant les processus de sableification et de canalisation. Les grottes suivent les fractures régionales orientées NE-SO, NO-SE et O-E et sont également influencées par le litage (SE/21º) et un pli ouvert (antiforme) avec un plan axial NNE-SSO. Les eaux souterraines présentent une faible concentration en silice dissoute (1,67 à 3,22 mg/L) et un pH acide (3,0 à 5,8), indiquant une dissolution chimique limitée et une prédominance de l'érosion mécanique. La spéléogenèse se produit dans des couches de quartzite fin contenant du mica, du feldspath et de la kaolinite, avec des épaisseurs variant de 1,0 m (G. Martimiano II) à 11,3 m (G. Manequinho).

1. Introduction

Siliciclastic caves, although less studied than caves in carbonate rocks, exhibit speleogenetic features associated with differential dissolution and mechanical processes, representing a wide range of formations and processes (MARTINI, 1979; WRAY, 1997; SILVA, 2004; FABRI, 2014; WRAY & SAURO, 2017). The most recognized siliciclastic karst regions worldwide are located in Venezuela, South Africa, Australia, Brazil, and India, with large-scale features and caves (WRAY & SAURO, 2017). In Brazil, siliciclastic karst regions are found in the Amazon (states of Roraima, Amazonas, and Pará), Chapada dos Guimarães (Mato Grosso), Serra Geral province (Paraná and São Paulo), Serra do Caraça (Minas Gerais), and the Andrelândia Speleological Province (PEA) (Minas Gerais) (SILVA, 2004).

Ibitipoca State Park (PEIB) covers 1,488 hectares in southern Minas Gerais and hosts one of the largest concentrations of quartzite caves in Brazil, totaling 64 mapped cavities (SEE, 2024). It also has the highest density of large quartzite caves in the country (RUBBIOLI et al., 2019). Preliminary studies have contributed to understanding the speleogenesis of the cave system in the Ibitipoca Mountain Range. The processes of sanding and piping, controlled by lithological, structural, and hydrochemical factors, influence the formation of caves in the quartzites of the São Tomé das Letras Formation (Carrancas Group – Andrelândia Sequence) (CORRÊA NETO et al., 1993; CORRÊA NETO et al., 1997; CORRÊA NETO, 1997; CORRÊA NETO & DUTRA, 1997; OLIVEIRA, 2021). However, knowledge gaps still exist regarding the formation of this siliciclastic karst.

Thus, this study aims to analyze and discuss the speleogenetic processes of four caves located in the southwestern portion of PEIB. Through structural characterization, petrographic, geochemical, and hydrochemical analyses, this research seeks to understand the influence of geological structures, lithology, and hydrochemical interactions on the evolution of underground conduits and surface landforms.

2. Methods

Through field campaigns, geological (structural, petrographic, and lithological) surveys, hydrochemical analyses, and characterization of speleological processes and features were conducted. Four main caves within Ibitipoca State Park (PEIB) were selected for study: Gruta Martimiano II (4,170 m), Gruta das Bromélias (3,447 m), Gruta Manequinho (966 m), and Gruta das Casas (557 m) (Figure 1).

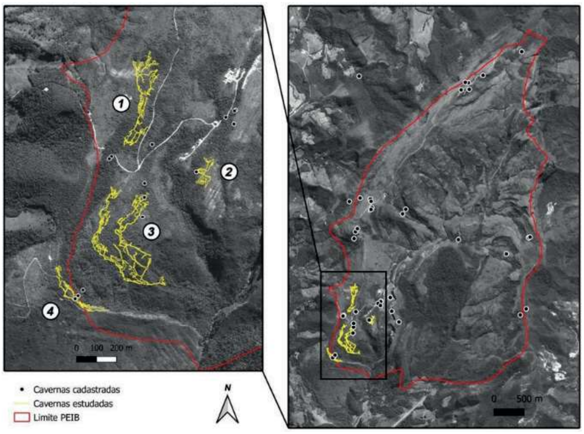

Figure 1: *Location of the Studied Caves in Relation to Ibitipoca State Park.*

2.1. Structural Characterization – Surface and Subsurface

Structural characterization involved measuring fractures, bedding, and foliation, totaling 1,705 structural attitudes. The data were analyzed using stereograms and plotted on maps to identify structural patterns controlling speleogenesis. Additionally, stratigraphic profiles were recorded to measure the thickness of fine-grained quartzite layers and assess their lateral continuity.

2.2. Petrographic and Geochemical Analyses

Twenty rock samples were collected for lithological and mineralogical characterization, analyzed using X-ray diffraction (XRD) and inductively coupled plasma optical emission/mass spectrometry (ICP-OES/MS) to determine major and trace element compositions.

2.3. Hydrochemical Analysis

Hydrochemical analyses were conducted at 23 groundwater sampling points, measuring physicochemical parameters such as pH, electrical conductivity (EC), resistivity (RES), temperature (T), oxidation-reduction potential (ORP), and total dissolved solids (TDS). These parameters were obtained using a Myron L Company Ultrameter II multiparameter instrument. Dissolved silica concentrations were determined using an Agilent 725 ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometry).

2.4. Sediment Collection from Cave Walls and Ceilings

An innovative experiment was conducted in Gruta das Casas, where two 50×50 cm glass plates were placed in two fossil conduits: one beneath saccharoidal coarse-grained quartzite from the ceiling and another beneath fine-grained micaceous quartzite from the cave wall. These plates remained in place for one year, collecting sediments that naturally fell onto them due to gravitational forces, assisted by rock «breathing»—the expansion and contraction caused by water absorption and loss. The collected sediments were weighed using a precision balance at the Hydrochemistry Laboratory of DEGEO

3. Results

3.1. Structural Control

The caves exhibit strong structural control influenced by bedding, subvertical fractures, and folding. Three fracture families, an antiform, and bedding planes were mapped. The polydeformed quartzite presents penetrative fractures that allow meteoric water percolation and infiltration into deeper layers. Stereographic analysis indicates two main preferential fracture systems: NE-SW, NW-SE, and W-E, which govern the development of underground conduits. In the southwestern portion of PEIB, the rock bedding dips toward the SE at approximately 21° (Figure 2)

3.2. Lithostratigraphic Influence

Speleogenesis predominantly occurs in fine-grained micaceous quartzite layers, which are primarily composed of feldspar/kaolinite and muscovite, with accessory minerals such as lepidocrocite, glauconite, and jaffeite. These layers vary in thickness from 1.0 m to 11.3 m, with the thinnest layer in Gruta Martimiano II and the thickest in Gruta Manequinho (Figure 3).

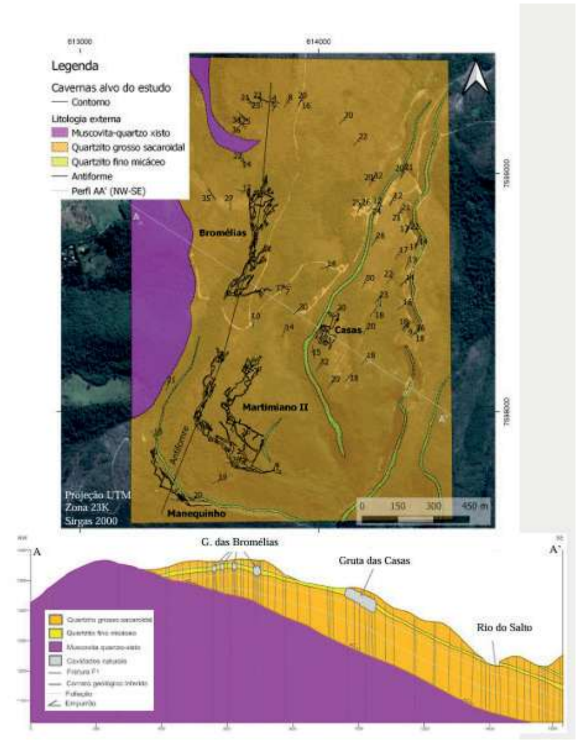

Figure 2: Geological map of the study area. The profile shows that the cavities develop in the fine micaceous quartzite found beneath the coarse saccharoidal quartzite. Fractures facilitate the percolation of rainwater, which accumulates in the fine quartzite and removes the material, thereby forming the cavities.

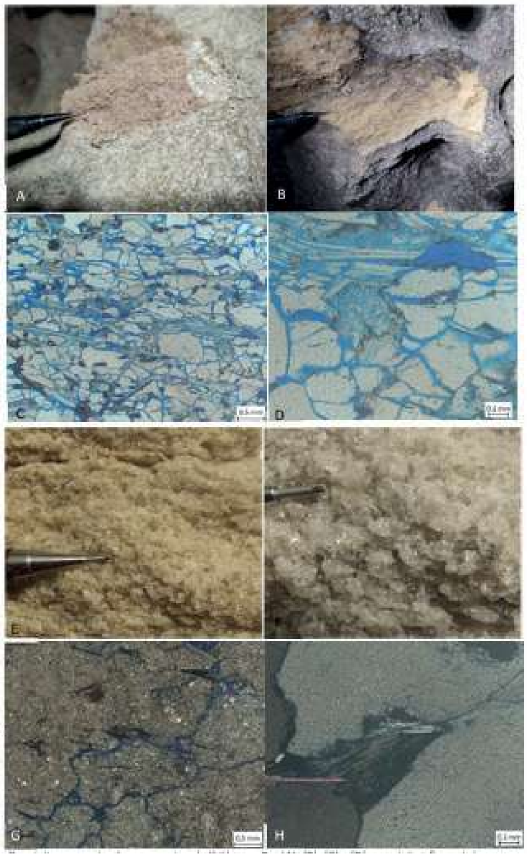

Figure 3: Quartzites found in the caves of Ibitipoca. In (A), (B), (C), and (D), fine micaceous quartzites with the presence of micas, feldspars, and high porosity (impregnated with blue epoxy resin). In (A) and (B), macroscopic view with colors ranging from white to pink; in (C), thin section with 0.5 mm zoom; and in (D), thin section with 0.1 mm zoom, both showing fine grain size, abundant micas, and secondary porosity. In (E) and (F), detail of the coarse grain size of the quartzite, whereas in (G) and (H), the thin section highlights low mica content, fractured grains, dissolution of quartz mineral edges, and low secondary porosity.

This lithology contains less resistant minerals such as feldspars and micas, which undergo incongruent dissolution, forming kaolinite. The dissolution along quartz grain boundaries due to water percolation is sufficient to initiate sanding processes, thus facilitating secondary porosity formation.

Conversely, coarse-grained saccharoidal quartzite, with SiO_2 content exceeding 94%, exhibits high resistance to dissolution, limiting speleogenesis progression. The fine quartzite layers, in contrast, contain SiO_2 ranging from 79% to 91% and Al_2O_3 between 3% and 13%, with the highest Al_2O_3 content (13%) found in Gruta Martimiano II, followed by Gruta das Bromélias (9%), and values below 2.01% in coarse quartzite samples.

As previously described, fine quartzite layers are interbedded within coarser quartzite layers. In some caves (Martimiano II, Bocão, and Rasteirinha), upper conduits developed within these fine-grained quartzite layers, revealing the repeated occurrence of this crucial lithological unit.

3.3. Hydrochemical Analyses

Hydrochemical analyses revealed low silica concentrations, ranging from 1.67 to 3.22 mg/L, and pH values between 3.0 and 5.8 (OLIVEIRA et al., 2023). Other elements detected in the analyses, such as Al, Ca, Na, Mg, and Fe, indicate the occurrence of additional hydrogeochemical processes, including the incongruent dissolution of feldspars and micas.

4. Discussion

4.1. Structural Control

Stereographic analysis indicates three main preferential fracture systems: NE-SW, NW-SE, and W-E, which govern the development of underground conduits. Bedding planes facilitate water percolation toward the Salto River (local base level), leading to the enlargement of conduits through dissolution and mechanical processes, which generate incasions followed by wall and ceiling collapses.

The mapped antiform in the northern portion of Gruta das Bromélias, located in the highest sector of the cave, contributes to the lateral expansion of conduits. The formation of entrances and skylights, associated with this structure, creates a direct pathway for rainwater infiltration into the system, accelerating dissolution and enhancing erosion processes.

4.2. Lithological Influence

The fine-grained quartzite layer is the primary lithological unit where speleogenesis initiates, either due to its composition, which contains more soluble minerals than coarse quartzite, or due to its finer grain size, making it more easily eroded.

Another active erosional process affecting fine-grained quartzite is the exudation-induced loss of water from the rock to the cave atmosphere, resulting in the disaggregation of sand grains that compose the quartzite. This process was confirmed by sediment collection using 50×50 cm glass plates installed in Gruta das Casas for one year. At sampling point CC1, 0.225 g of micaceous fine quartzite was collected from the cave wall, while at point CC2, 1.7074 g of quartzite sediment was collected from the ceiling.

This experiment demonstrates the volumetric loss of the cave without direct erosional agents and suggests that ceiling collapse may occur more rapidly than wall retreat. Once the fine quartzite layer is removed, collapse and conduit closure processes begin.

Additionally, vertical grooves ranging from centimeter to meter scales were observed in fine quartzite layers. These features result from gravity-driven movement of exudated water droplets, which emerge from cave walls and descend to the floor, forming vertical fluting. This mechanism gradually widens conduits and channels through mechanical quartz grain removal.

4.3. Hydrochemical Analyses

Hydrochemical data indicate that chemical dissolution plays a secondary but significant role in rock grain disaggregation and sandification, whereas mechanical erosion is the primary process driving conduit enlargement.

The characterization and analysis of subterranean water flow revealed hydraulic interconnectivity between the two largest caves of Ibitipoca (OLIVEIRA et al., 2023), forming an underground drainage system approximately 7.5 km long: the Bromélias-Martimiano II System, which also includes Gruta Vandinho, located between them.

5. Conclusion

The results of this study demonstrate that the speleogenesis of the caves in Ibitipoca State Park (PEIB) is controlled by three main factors:

Structural Control – The NE-SW, NW-SE, and W-E fracture systems dictate the orientation and development of underground conduits. Bedding planes, which dip SE at 21°, enhance erosional processes by directing water flow along the steepest slope toward the Salto River (local base level). Additionally, the antiform located in the northern portion and the main conduit of Gruta das Bromélias laterally expands the cave's area, resulting in the formation of five entrances. This expansion facilitates rainwater infiltration, increasing its microbasin contribution area and capturing part of the Rio Grande Basin flow into the Paraíba do Sul Basin.

Lithological Control – Speleogenesis initiates in fine-grained micaceous quartzites and progresses toward coarse-grained saccharoidal quartzites, which are less susceptible to dissolution but more prone to collapse. Dissolution features, such as channels, are only observed in fine quartzite layers, whereas in coarse quartzite, discontinuities are primarily enlarged by water erosion. Fine quartzite layers are enclosed above and below by coarse quartzite, and their complete removal triggers collapse processes, facilitated by bedding planes and fractures.

Hydrochemical Influence – The groundwater exhibits low silica concentrations, low levels of other dissolved elements, and acidic pH, indicating that chemical dissolution plays an essential role in sandification. This process allows mechanical erosion to act in conduit enlargement, transporting disaggregated quartz grains.

This study reinforces the importance of the Ibitipoca Mountain Range as a model for understanding quartzitic intra-stratal karst in Brazil. It highlights the interplay between lithology, structural controls, and hydrochemical processes in the formation of siliciclastic caves, where dissolution, erosion, and gravitational processes actively contribute to cave development.

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References.

CORREA NETO, A.V., FILHO, J.B., 1997. Espeleogênese em quartzitos da Serra do Ibitipoca, sudeste de Minas Gerais. anu. Inst. Geocienc. 20, 75–87.

CORREA NETO, A.V.; ANISIO, L.C.C.; BRANDÃO, C.P. 1993. Um endocarste quartzítico na Serra do Ibitipoca, SE de Minas Gerais. Anais VII Simpósio de Geologia de Minas Gerais, p. 83-86.

CORREA NETO, A.V.; ANISIO, L.C.C.; BRANDÃO, C.P.; CINTRA, H.B. 1997. Gruta das Bromélias (mg-042), Serra do Ibitipoca, município de Lima Duarte, MG: Uma das maiores cavernas em quartzito do mundo. Espeleo-tema 18: 1-12.

CORREA NETO, A.V.; DUTRA, G. 1997. A Província Espeleológica Quartzítica Andrelândia, sudeste de Minas Gerais. Anais XXIV Congresso Brasileiro de Espeleologia, p. 57-64.

FABRI, F. P., AULER, A., & AUGUSTIN, C. H. R. R. (2014). Relevo cárstico em rochas siliciclásticas: uma revisão com base na literatura. Revista Brasileira de Geomorfologia, 15(3).

MARTINI, J.E.J., 1979. Karst in black reef quartzite near Kaapsehoop, eastern Transval. ann. s. afr. geol. surv. 13, 115–128.

OLIVEIRA, G. L. C. D. 2022. Processos hidrogeoquímicos como gatilho para a espeleogênese no setor sudoeste do Parque Estadual do Ibitipoca-MG.

OLIVEIRA, G. L. C. D. ASSUNÇÃO, P. H. S. LIMA, P. E. S. BASTOS, T. V. RUDNITZKI, I. D (2024). Conexão hídrica entre as cavernas quartzíticas Bromélias e Martimiano II na Serra do Ibitipoca, MG. Revista Brasieira de Espeleologia – RBEsp. V. 01, Nº01. – ICMBio/Cecav

RUBBIOLI, E., AULER, A., MENIN, D., & BRANDI, R. (2019). Cavernas-atlas do Brasil subterrâneo. Brasília, ICMBio/CECAV. 370p.

SILVA, S.M. Carstificação em rochas siliciclásticas: estudo de caso na Serra do Ibitipoca, Minas Gerais. MG. 2004. 143f. Dissertação de mestrado em geografi a, Instituto de Geociências, Universidade Federal de Minas Gerais, BH-MG.

SOCIEDADE EXCURSIONISTA E ESPELEOLOGICA – SEE (2024). Projeto Cadastro e Avaliação dos Aspectos Espeleoturísticos das Cavernas do Parque Estadual do Ibitipoca – MG (IBITITUR).

WRAY, R.A.L. 1997. A global review of solutional weathering forms on quartz sandstones. Earth-Science Reviews 42: 137-160.

WRAY, R. A., & SAURO, F. (2017). An updated global review of solutional weathering processes and forms in quartz sandstones and quartzites. Earth-Science Reviews, 171, 520-557.MAMMOLA S. (2019) Finding answers in the dark: caves as models in ecology ffty years after Poulson and White. Ecography 42(7):1331–1351.