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CARSTE EM ROCHAS SILICICLÁSTICAS NA CHAPADA DIAMANTINA: GEOESPELEOLOGIA DA GRUTA DO CANAL DA FUMAÇA, VILA DE IGATU, ANDARAÍ (BA)

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SALVADOR
2024

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Orientador: Prof. Dr. Ricardo Galeno Fraga de Araújo Pereira

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“[Igatu] de pequeno que era, cresceu e prosperou devido às grandes riquezas encontradas, principalmente no célebre Canal da Fumaça, que foi tão abundante em diamantes que os trabalhadores os recolhiam em tigelas, quando faziam as apurações”.

Gonçalo de Athahyde Pereira, 1937.

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RESUMO

A formação de relevos cársticos em rochas siliciclásticas é fato já reconhecido e estudado pela ciência nas últimas décadas. Neste sentido, a região da Chapada Diamantina, no centro do Estado da Bahia, que é notória pela presença de amplos sistemas de cavernas instalados em rochas carbonáticas, atualmente vem ganhando visibilidade também para terrenos cársticos siliciclásticos, sobretudo na Serra do Sincorá. Esta unidade de relevo montanhoso, que alcança 1.700 m, é sustentada pelos metarenitos e metaconglomerados da Formação Tombador (Grupo Chapada Diamantina, Supergrupo Espinhaço), de idade Mesoproterozoica. Nela, destacam-se a Gruta do Lapão, no município de Lençóis, com 1,6 km de desenvolvimento e a Gruta do Castelo, no Vale do Pati, município de Mucugê, com 383 m de desenvolvimento. Ambas são pontos de visitação turística dentro do Parque Nacional da Chapada Diamantina e, por isso, têm maior visibilidade no meio acadêmico e para o público em geral. Por sua vez, a Vila de Igatu, no município de Andaraí, abriga valiosos sistemas cársticos, com complexas redes de condutos subterrâneos e relevo ruiniforme, ainda pouco estudados e compreendidos. Na área da Bacia Hidrográfica do Rio Coisa Boa, um dos afluentes do Rio Paraguaçu, são reconhecidas 12 cavernas, algumas das quais já reconhecidas em trabalhos anteriores e cadastradas em bancos de dados espeleológicos. Nesse trabalho, foi realizada a caracterização de um dos sistemas cársticos, a Gruta do Canal da Fumaça, através da cartografia espeleológica, análises estruturais por sensoriamento remoto e em campo, descrições de amostras de rocha através de microscópio óptico e eletrônico de varredura, além da determinação da composição química (FRX) e mineralógica (DRX). Observou-se que estruturas NNE-SSW, NNW-SSE e ENE-WSE, associadas à deformação transpressiva sinistral que estruturou a Serra do Sincorá, exerce importante influencia na abertura dos condutos e na formação do relevo ruiniforme, atuando como frentes preferenciais de intemperismo. A avaliação petrográfica sugere que o ataque químico se dá, principalmente, sobre os filossilicatos (pirofilita e caulinita) que compõem a matriz dos metarenitos da área, sendo mais solúveis em pH ácido. Secundariamente, os grãos de quartzo também são afetados. Esse processo, denominado fantomização, reduz a coesão entre os grãos e, então, os processos de *piping* os removem mecanicamente. Por outro lado, identificou-se também um profundo impacto da atividade de garimpo de diamante, desenvolvida nos séculos XIX e XX. Modificações como escavações e detonações de condutos, construções de muros e pilares, alteraram significativamente o interior da caverna, colaborando, inclusive, para aumentar suas dimensões de extensão e volume. Tendo isso em vista, foi proposto um modelo de evolução para a Gruta do Canal da Fumaça, considerando os processos geológicos cársticos e também as alterações antrópicas.

Palavras-chave: Cavernas, Metarenitos, Serra do Sincorá.

ABSTRACT

The development of karst reliefs in siliciclastic rocks is a fact already recognized and studied by science in recent decades. In this sense, the Chapada Diamantina region, in the center of the State of Bahia, which is notorious for the presence of extensive cave systems installed in carbonate rocks, is currently also gaining visibility for siliciclastic karst terrain, especially in the Sincorá Ridge. This unit of mountainous relief, which reaches 1,700 m, is supported by metasandstones and metaconglomerates of the Tombador Formation (Chapada Diamantina Group, Espinhaço Supergroup), of Mesoproterozoic age. The highlights include the Lapão Cave, in the municipality of Lençóis, with 1.6 km of extension and the Castelo Cave, in the Pati Valley, municipality of Mucugê, with 383 m. Both are touristic sites within the Chapada Diamantina National Park and, therefore, have greater visibility in academia and the public. In turn, the Village of Igatu, in the municipality of Andaraí, is home to valuable karst systems, with complex networks of underground conduits and ruiniform relief, still poorly understood. In the area of the Coisa Boa River Basin, one of the tributaries of the Paraguaçu River, 12 caves are recognized, some of which already described in previous works and registered in speleological databases. In this work, the characterization of one of the karst systems, the Canal da Fumaça Cave, was carried out through speleological cartography, structural analyzes by remote sensing and field measurement, descriptions of rock samples through optical and scanning electronic microscopes, in addition to determination of chemical (FRX) and mineralogical (DRX) composition. It was observed that NNE-SSW, NNW-SSE, and ENE-WSE structures, associated with the sinistral transpressive strike that structured the Sincorá Ridge, exert an important influence on the opening of the conduits and the formation of the ruiniform relief, acting as preferential weathering fronts. The petrographic assessment suggests that the chemical attack occurs mainly on the phyllosilicates (pyrophyllite and kaolinite) that make up the matrix of metasandstone in the area, being more soluble in acidic pH. Secondarily, quartz grains are also affected. This process, called phantomization, reduces the cohesion between the grains and then piping processes remove them mechanically. On the other hand, a profound impact of the diamond mining activity, carried out in the 19th and 20th centuries, was also identified. Modifications such as excavations and detonations of conduits, construction of walls and pillars, significantly altered the interior of the cave, even helping to increase its extension and volume. With this in mind, an evolution model was proposed for the Canal da Fumaça Cave, considering karst geological processes and also anthropogenic changes.

Keywords: Caves, Metasandstones, Sincorá Ridge.

SUMÁRIO

CAPÍTULO 1
INTRODUÇÃO GERAL

Apesar do notável aumento de estudos nas últimas décadas (Dutra, 2001; Melo e Giannini, 2007; Hardt, 2011) o conhecimento acerca dos relevos cársticos em rochas siliciclásticas no Brasil ainda é bastante defasado, se comparado às pesquisas desenvolvidas em terrenos de rochas carbonáticas. Piló e Auler (2011), ao estimar o potencial espeleológico no país, sugerem que conhecíamos, até aquele momento, menos de 1% das cavernas em rochas areníticas e cerca de 1% em rochas quartzíticas, enquanto essa estimativa sobe para 7% para as litologias calcárias. Por outro lado, cabe salientar que o Brasil, ao lado da Venezuela, são detentores dos mais notáveis terrenos com sistemas cársticos em rochas siliciclásticas nas Américas, tais como a Serra do Espinhaço (Fabri, 2011) e os Tepuis (Aubrecht et al., 2012).

Essa assimetria se reflete também no conhecimento geoespeleológico na Chapada Diamantina. A região se apresenta como importante área de ocorrência de cavernas em rochas carbonáticas, com destaque para a região de Iraquara (Cruz-Junior, 1998) e Itaetê (Pereira, 1998). Por outro lado, para as rochas siliciclásticas do Supergrupo Espinhaço, que sustentam o relevo de serras naquela área, pouco se conhece sobre o patrimônio espeleológico, apesar do potencial demonstrado por trabalhos recentes.

Auler e Sauro (2019) destacaram a Gruta de Torras, no distrito de Igatu, município de Andaraí, Chapada Diamantina, como a 8ª maior, em desenvolvimento horizontal (3,6 km), entre as cavernas areníticas e quartzíticas da América do Sul. Esta mesma gruta foi incluída no Inventário do Patrimônio Geológico da Chapada Diamantina (Pereira, 2010; 2016a), no qual foram avaliados seus valores de uso científico, turístico e de conservação. Por sua vez, Souza (2019) apresenta detalhada caracterização geoespeleológica da Gruta do Castelo, uma das mais expressivas e visitadas cavernas da Chapada Diamantina, a qual demonstra o potencial espeleoturístico para a região. Em termos de estudos hidrogeológicos, a área também exibe grande potencial para a compreensão da dinâmica hídrica subterrânea em sistemas cársticos siliciclásticos, como demonstrado por Auler et al. (2020) ao aplicar o uso de traçadores na análise da água na Bacia do Rio Coisa Boa, em Igatu.

Apesar de muito pertinentes, estes trabalhos representam um avanço ainda tímido diante da relevância e do potencial científico dos sistemas cársticos siliciclásticos na Chapada Diamantina. O desconhecimento acerca dos processos de formação e dos fatores que impactam diretamente esses sistemas é um dos maiores entraves à uma boa gestão e conservação do seu patrimônio espeleológico.

Nesse contexto, inserem-se os problemas científicos que norteiam essa proposta de pesquisa: qual é o status atual do conhecimento acerca do patrimônio espeleológico na Chapada Diamantina, considerando cavernas em litologias carbonáticas e siliciclásticas? De que forma ocorreu a gênese e a evolução do carste siliciclástico, existente na Formação Tombador, na região do distrito de Igatu, Chapada Diamantina? Quais foram os processos geológicos envolvidos e quais fatores influenciaram sua origem? Como a atividade de garimpo de diamante, durante os séculos XIX e XX, modificou e impactou essas cavernas?

Buscando responder essas questões, esse trabalho está organizado em formato de dois artigos. O primeiro, apresenta uma revisão bibliográfica sobre o patrimônio espeleológico e cárstico na Chapada Diamantina. Já o segundo traz um estudo de caso sobre um dos sistemas cársticos em Igatu, a Gruta do Canal da Fumaça, que apresenta registros da evolução natural, além de profundas modificações pela atividade garimpeira.

Ao responder estas questões, espera-se, portanto, contribuir com o avanço do conhecimento científico acerca do carste em rochas siliciclásticas, bem como auxiliar na gestão do PARNA Chapada Diamantina e na valorização dos geossítios existentes no território do Projeto Geoparque Serra do Sincorá, contribuindo para a geoconservação e implementação dessa proposta, viabilizando uma candidatura futura para a UNESCO *Global Geoparks* - UGGp.

Contexto Geológico

A Chapada Diamantina está inserida na Serra do Espinhaço Setentrional, no Aulacógeno do Paramirim, feição morfotectônica da porção norte do Cráton São Francisco (Alkmim, 2004). Esta unidade é interpretada, segundo Cruz e Alkmim (2006) como uma sucessão de dois riftes sobrepostos de idade paleo e neoproterozóica, preenchidos, respectivamente, por rochas do Supergrupo Espinhaço e Supergrupo São Francisco (Figura 1).

O Supergrupo Espinhaço é a unidade mais expressiva, em área, dentro do aulacógeno, e corresponde a instalação de um ramo dos riftes estaterianos de 1,75 Ga (Neves et al., 1995). Exibe uma significativa assimetria faciológica entre suas porções leste e oeste, as quais correspondem, respectivamente, à Chapada Diamantina e à Serra do Espinhaço Setentrional, separadas pela zona de cisalhamento denominada Barra do Mendes - João Correia, uma descontinuidade estrutural de direção SE-NW (Guimarães et al., 2012).

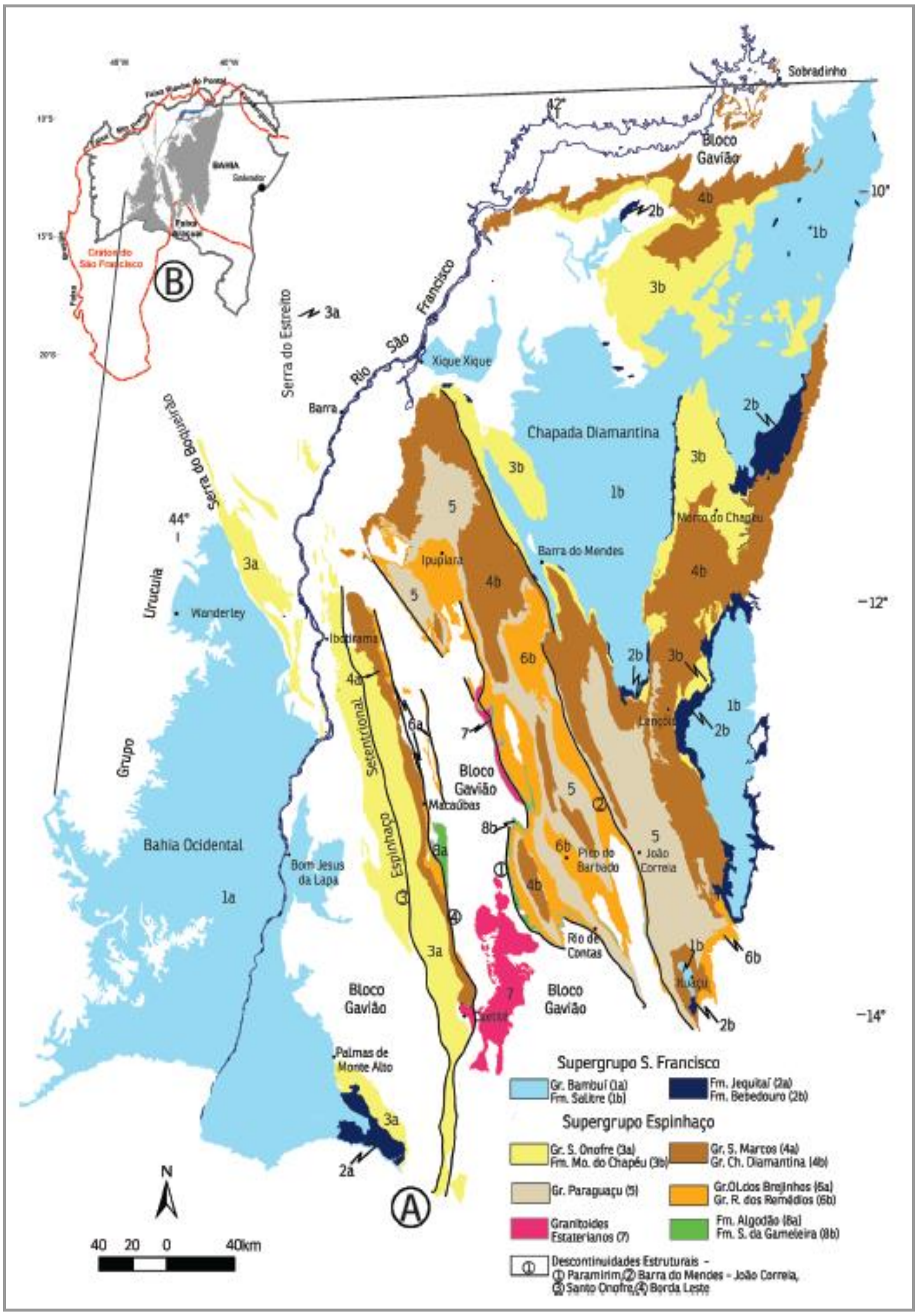

Figura 1. Mapa geológico simplificado dos Supergrupos Espinhaço e São Francisco.
Fonte: Guimarães et al. (2012).

Na porção leste do aulacógeno, a Serra do Sincorá é sustentada por rochas metassedimentares siliciclásticas do topo do Grupo Paraguaçu, sobrepostas por rochas basais do Grupo Chapada Diamantina (Pedreira, 2002). Este segundo, mais proeminente na região, delineando relevo de serras e planaltos com altitudes que variam entre 1.000 a 1.350 metros, é compartimentado em Formação Tombador, Formação Caboclo e Formação Morro do Chapéu (Silva, 1994). Entretanto, cabe salientar que autores como Schobbenhaus (1996), dentre outros, não incluem esta última unidade no grupo.

A Formação Tombador é considerada por Guimarães et al. (2012) como o mais importante marcador estratigráfico do Supergrupo Espinhaço no Estado da Bahia, devido sua perdurável continuidade lateral, abrangendo toda a área da Chapada Diamantina. Estes autores descrevem a unidade como metarenitos e metaconglomerados, submetidos a diagênese avançada e/ou anquimetamorfismo, com a presença de estruturas sedimentares bem preservadas, tais como marcas de onda e estratificação cruzada.

Segundo Otero (1991), a Formação Tombador compreendida entre a região de Lençóis e Mucugê exibe registro de um ambiente continental, com depósitos de complexo aluvial, representados por sistema de leques aluviais e sistema fluvial entrelaçado. Castro (2003) constata também uma fase transgressiva na qual se registram sistemas gradativos para leque subaquoso e marinho de tempestade.

Carste em Rochas Siliciclásticas

Ford e Williams (2007) consideram carste como um terreno com formas e sistemas de drenagens diferenciados, decorrente da combinação de rochas com altas taxas de solubilidade e o desenvolvimento de porosidade secundária, através do alargamento de fraturas e descontinuidades por processos de dissolução. São feições características dos relevos cársticos as cavernas, dolinas, lapiás e espeleotemas (Christofoletti, 1980).

Ao longo da evolução científica sobre o tema, muita ênfase foi dada à ocorrência desta forma de relevo em rochas carbonáticas, uma vez que estas apresentam alta solubilidade e grande diversidade de feições. No entanto, é crescente a quantidade de trabalhos que corroboram com a hipótese de que os terrenos cársticos também possam se desenvolver sobre outras litologias, sobretudo nas rochas siliciclásticas (Renault, 1953; Mainguet, 1972; Jennings, 1983; Rodet, 1996; Quinif, 2010).

Estes autores sustentam suas teorias através da exploração e do estudo de ocorrências de uma série de feições cársticas em rochas areníticas e quartzíticas ao redor do mundo. Wray e Sauro (2017) destacam 35 locais, distribuídos pelos cinco continentes, onde foram documentados feições e sistemas cársticos nessas litologias, e apresentam uma concisa literatura que demonstra a ação do intemperismo químico e da dissolução sobre essas rochas.

Os trabalhos mais conceituados na área sugerem a hipótese de que a carstificação em rochas siliciclásticas se desenvolve em duas etapas. Na primeira há predominância de processos químicos, nos quais a ação da água e ácidos orgânicos dissolvem o cimento silicoso, as bordas dos grãos de quartzo e/ou a matriz/ cimento. Esse ataque desagrega os grãos do arcabouço, em um processo denominado “arenização” (Martini, 1981), quando a rocha é monominerálica (quartzosa), ou “fantomização” (Quinif, 2010), para rochas poliminerálicas (Wray e Sauro, 2017). A segunda etapa consiste na remoção mecânica desses grãos, em um processo físico denominado “*piping*” (Martini, 1984) conforme ilustrado na Figura 2.

Figura 2. Modelo de evolução de uma caverna siliciclástica. Fonte: Silva (2004).

O Brasil está na lista dos países que abrigam as mais relevantes ocorrências de sistemas cársticos siliciclásticos do mundo, ao lado de Venezuela, Austrália e África do Sul (Fabri et al., 2014). Destacam-se a região da Chapada dos Guimarães, no Mato Grosso (Borghi et al., 2002; Hardt, 2011), os sistemas cársticos arenítico no Paraná (Spoladore, 2005; Melo e Giannini, 2007; Melo et al., 2015; Pontes et al., 2020) e na Serra do Itaqueri, em São Paulo (Hardt, 2011; Montano et al., 2014; Parra et al., 2022), na Serra da Capivara, Piauí (Silva e Maia, 2024), além das cavernas quartzíticas da Serra do Ibitipoca (Corrêa Neto e Filho, 1997; Silva, 2004) e da Serra do Caraça (Dutra, 2001) em Minas Gerais.

Localização da Área de Estudo

A área de estudo deste trabalho corresponde à Bacia Hidrográfica do Rio Coisa Boa, no distrito de Igatu, município de Andaraí. A área está inserida na vertente leste da Serra do Sincorá, sendo abrangida pelo perímetro do Parque Nacional da Chapada Diamantina, no centro do Estado da Bahia. A Figura 3 exibe um mapa de localização da área de estudo e situa as cavernas já registradas no Cadastro Nacional de Informações Espeleológicas (CANIE).

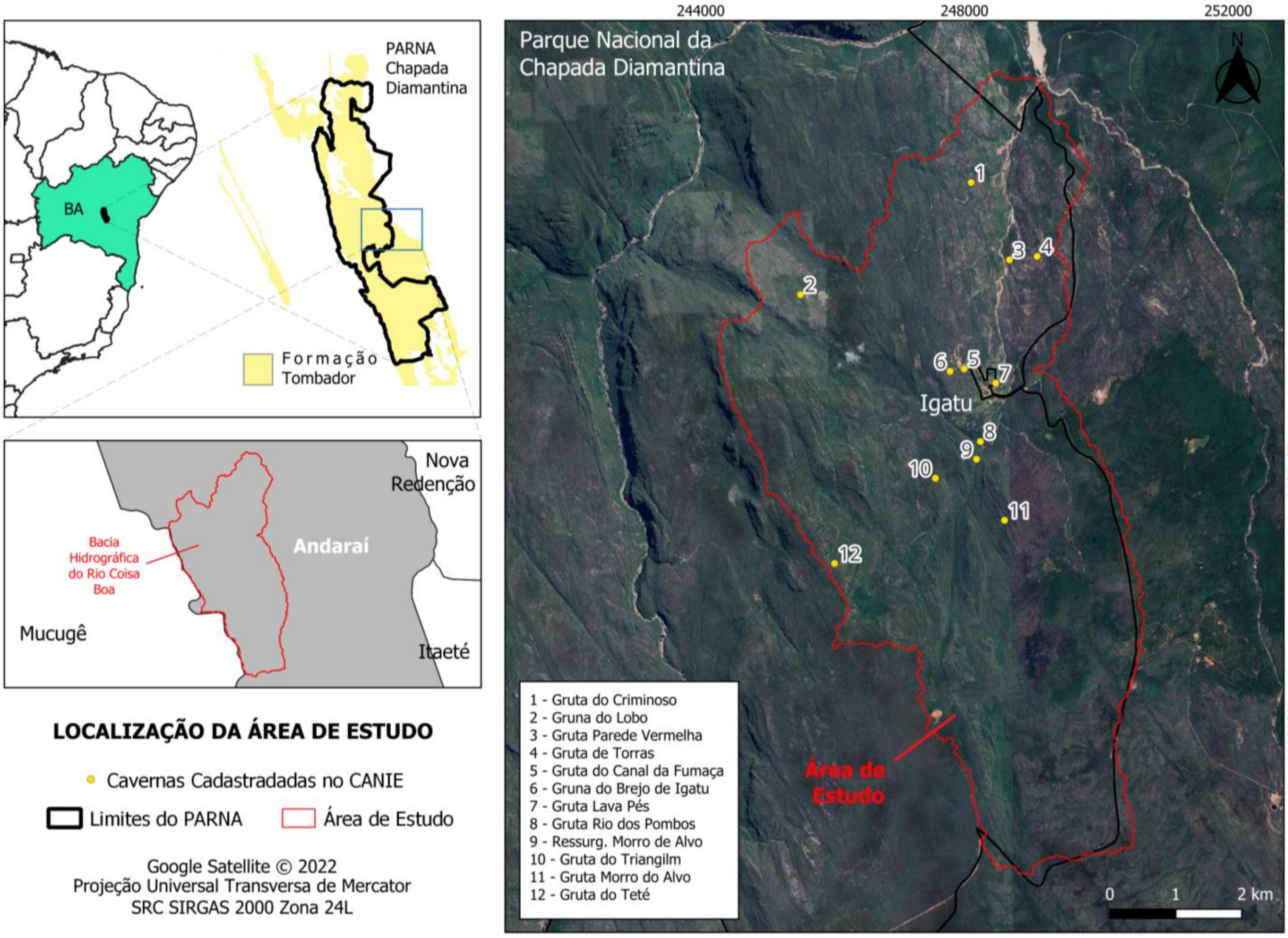

Figura 3. Mapa de localização Bacia Hidrográfica do Rio Coisa Boa, área de estudo do trabalho, com a localização das cavernas cadastradas no CANIE.

Na área da bacia, são reconhecidas 12 cavernas, já cadastradas no banco de dados do Centro Nacional de Pesquisa e Conservação de Cavernas (CECAV). Suas informações estão limitadas ao nome e coordenadas geográficas das cavidades, sendo poucas delas devidamente mapeadas. Até o momento, nenhum trabalho aprofundado de caracterização geológica destas cavernas foi desenvolvido, o que acarreta em uma lacuna de conhecimento e, por consequência, dificuldade em garantir sua conservação.

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CAPÍTULO 2

ARTIGO 1 – CAVES, KARST FEATURES AND SPELEOLOGICAL HERITAGE IN CHAPADA DIAMANTINA, BAHIA, BRAZIL

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Nota Técnica

Caves, Karst Features and Speleological Heritage in Chapada Diamantina, Bahia, Brazil

Cavernas, Carste e Patrimônio Espeleológico na Chapada Diamantina, Bahia,Brasil

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Abstract: Chapada Diamantina is among the best known and most visited landscapes in Brazil. Located in the state of Bahia, Northeast region of the country, it is characterized by mountains and plateaus that developed on Proterozoic sedimentary and metasedimentary rocks. Much of its territory is covered by carbonate and siliciclastic rocks, where relevant karst systems develop, marked by the occurrence of sinking streams, sinkholes, and caves with a great diversity of morphologies, speleothems, subterranean fauna, and paleontological and archaeological records. Relevant carbonate systems occur in Iraquara, such as the Lapa Doce, Torrinha, and Pratinha caves, which represent important tourist attractions. Also in these rocks, stand out the Brejões Cave, with a 106-m high entrance, and the Toca da Boa Vista, the largest cave in South America, extending across 114 km. Cultural manifestations are present in the prehistoric cave paintings at Santa Marta Shelter and recent religious pilgrimages at Mangabeiras Cave, in Ituaçu. In turn, siliciclastic karst systems are mainly in *Serra do Sincorá*. The Lapão and Castelo caves have expressive speleogens and speleothems, as well as the Torras Cave, in the Igatu region, ranked as the second largest in Brazil considering siliciclastic rocks.

Keywords: Carbonate Karst, Siliciclastic Karst, Caves, Speleology, Chapada Diamantina

Resumo: A Chapada Diamantina está entre as paisagens mais conhecidas e visitadas do Brasil. Localizada no estado da Bahia, região Nordeste do país, é caracterizada por serras e planaltos, desenvolvidas sobre rochas sedimentares e metassedimentares do Proterozóico. Grande parte do seu território é coberto por rochas carbonáticas e siliciclásticas, onde se desenvolvem sistemas cársticos relevantes, marcados pela ocorrência de sumidouros, dolinas e cavernas com grande diversidade de morfologias, espeleotemas, fauna subterrânea e registros paleontológicos e arqueológicos. Sistemas carbonáticos relevantes ocorrem em Iraquara, como as cavernas Lapa Doce, Torrinha e Pratinha, que representam importantes atrativos turísticos. Também nestas rochas destacam-se a Gruta dos Brejões, cuja entrada alcança 106 m de altura, e a Toca da Boa Vista, a maior caverna da América do Sul, com 114 km de extensão. As manifestações culturais estão presentes nas pinturas rupestres pré- históricas do Abrigo Santa Marta e nas recentes romarias religiosas na Gruta das Mangabeiras, em Ituaçu. Por sua vez, os sistemas cársticos siliciclásticos são encontrados principalmente na Serra do Sincorá. As grutas do Lapão e do

Castelo possuem espeleogens e espeleotemas expressivos, assim como a Gruta das Torras, na região de Igatu, classificada como a segundamaior do Brasil em rochas siliciclásticas.

Palavras-chave: Carste Carbonático, Carste Siliciclástico, Cavernas, Espeleologia, Chapada Diamantina.

1. Introduction

According to the 2020 Brazilian Speleological Heritage Statistical Yearbook (ICMBio, 2021), the state of Bahia ranks third in number of recorded caves. With 1,694 cavities, this represents 7.88% of the total amount of caves in the country, with only the states of Minas Gerais (45.41%) and Pará (12.76%) having greater numbers. Considering the dimensions of the state and the strong presence of thick soluble geological units, in regions which are largely still unexplored, it is assumed that the real number of caves in Bahia is considerably higher.

A significant portion of this speleological heritage is in the Chapada Diamantina territory, where geological, geomorphological, and hydrologic conditions favor the development of karst in different types of rock. The region has been the target of a series of expeditions to explore, map, and carry out academic studies over the last decades, which has contributed to a vast accumulation of knowledge about these systems.

Due to its relevance, part of this heritage is secured through environmental protection areas. These are under either federal jurisdiction, such as the Chapada Diamantina National Park, or state jurisdiction, such as the Environmental Protection Areas of Marimbus/Iraquara and Gruta dos Brejões/Vereda do Romão Gramacho. In addition, several Geopark proposals and projects have been developed in this region, such as Serra do Sincorá, Morro do Chapéu, and Grutas de Iraquara.

Thus, herein will present the main characteristics of these karst terrains, with emphasis on the cave systems that develop in them, seeking to cover aspects of the physical, biological, and cultural/historical environment based on literature review and fieldwork. It must be highlighted that Chapada Diamantina comprises relevant karst relief and caves both in carbonate and siliciclastic rocks.

2. Geographic Location

Chapada Diamantina consists of a group of mountains and plateaus located in the central region of the state of Bahia, in northeastern Brazil (Figure 1). Covering an area of 65,619 km², Chapada Diamantina occupies just over 10% of the state's land area. It represents the northernmost part of a mountain range that extends from the south of the state of Minas Gerais to the north of Bahia, known as '*Serra do Espinhaço*'.

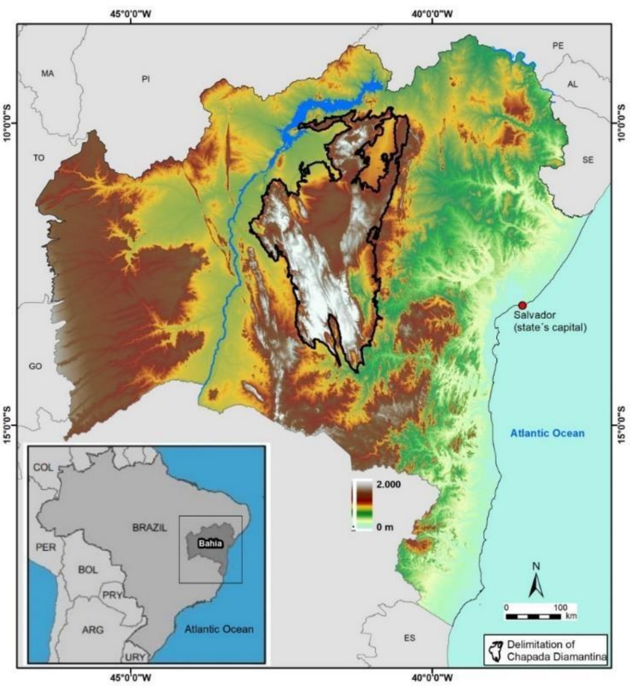

Figure 1. Location map of Chapada Diamantina, Bahia, Brazil.

According to Pereira (2010), the term Chapada Diamantina refers to two different entities. The first one refers to the physical environment, comprising a geographic region, characterized by mountainous relief forms, plateaus, and karst systems, developed essentially on sedimentary and metasedimentary Proterozoic rocks. The second oneis related to social, political, and cultural aspects, referring to the territorial identity of local communities from 23 municipalities. In the present paper, we will adopt the first definition, which was used to establish the boundary line of the Chapada Diamantina territory.

The region is home to the springs of the main rivers and watersheds of Bahia, including the Paraguaçu River, which supplies Salvador, the state capital, and a set of important tributaries on the right bank of the São Francisco River. It is important to note that, in the São Francisco River, there are 14 hydroelectric plants, which provide energy to several Brazilian states. These aspects highlight the hydrological importance of this region. Furthermore, Chapada Diamantina currently represents one of the main ecotourism destinations in Brazil (BRITO, 2005), with its geodiversity elements acting as its main tourist appeal.

The climate in Chapada Diamantina is complex and strongly influenced by the relief. In general, it varies between hot caatinga (thorny forest) in the lowlands to a more tropical one on higher altitude, according to the Köppen climate typology (SEI, 1998). Two seasons are well defined, with periods of more significant rainfall, concentrated between November and May, and periods of drought, which occur between June and October, although rainfall rates vary greatly between the eastern and western slopes (BARRETO, 2010).

2. Geology and Geomorphology

Chapada Diamantina is part of the Paramirim Aulacogen, a morphotectonic feature of the northern portion of the São Francisco Craton (ALKMIM, 2004). According to Schobbenhaus (1996), this Aulacogen corresponds to two overlapping and partially inverted intracratonic basins, in which rocks of the Espinhaço Supergroup (Paleo/Mesoproterozoic) and the São Francisco Supergroup (Neoproterozoic) were deposited. These rocks supporta set of mountain reliefs and plateaus in the central part of the state of Bahia (Figure 2).

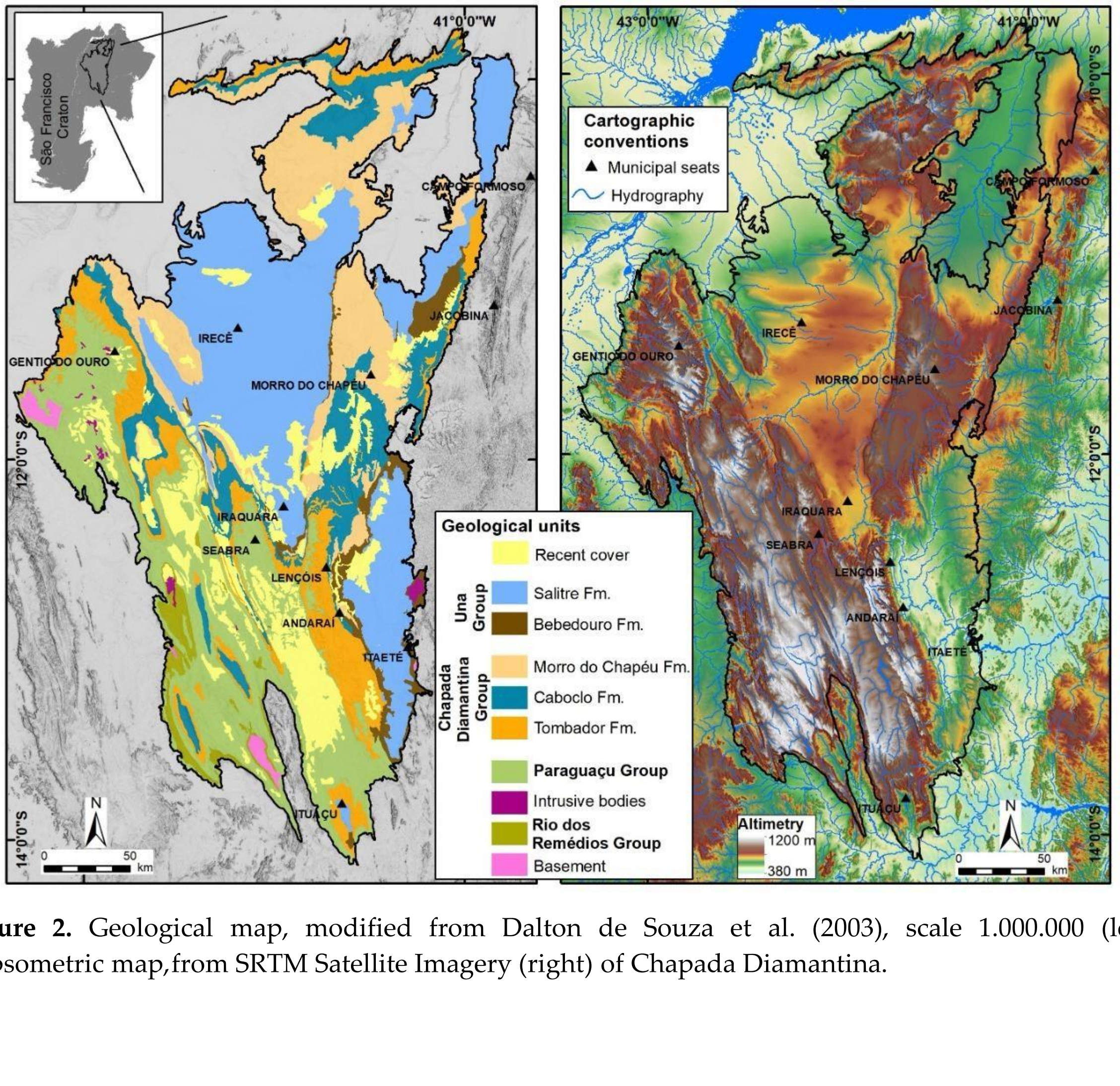

Figure 2. Geological map, modified from Dalton de Souza et al. (2003), scale 1.000.000 (left) and hypsometric map,from SRTM Satellite Imagery (right) of Chapada Diamantina.

In this region, the Espinhaço Supergroup is divided into three groups: Rio dos Remédios, Paraguaçu, and Chapada Diamantina (INDA; BARBOSA, 1978; PEDREIRA, 1994).

The Rio dos Remédios Group is dated to the Statherian period (~1.75 Ga) and is related to the beginning of the intracontinental Espinhaço Rift. It consists of acidic volcanic rocks overlain by sediments deposited in lacustrine and intertwining river systems (GUIMARÃES, 2005). In turn, the Paraguaçu Group shows evidence of a marine ingression. It is composed of eolian and fluvial sediments of a coastal environment overlain by deposits of tidal and deltaic systems (PEDREIRA; DE WAELE, 2008; GUIMARÃES; SANTOS; MELO, 2008; MAGALHÃES et al., 2015).

The Chapada Diamantina Group outcrops throughout the area. From bottom to top, it is composed of the Tombador, Caboclo, and Morro do Chapéu formations (BARBOSA; DOMINGUEZ, 1996). These formations were deposited in the Mesoproterozoic, along with cycles of sea-level transgression and regression, and subsequently subjected to advanced diagenesis and/or anchimetamorphism (GUIMARÃES; ALKMIM; CRUZ, 2012).

The Tombador Formation has great vertical and lateral persistence. It is composed of sandstone and conglomerates deposited in a coastal environment by alluvial, eolian, and tidal-dominated estuarine systems (MAGALHÃES et al., 2014). The Caboclo Formation presents an association of siliciclastic and carbonate lithofacies, such as sandstones, conglomeratic sandstones, and pelites, in addition to calcarenites, laminites, and stromatolites (ROCHA; PEREIRA; SRIVASTAVA, 1992). The Morro do Chapéu Formation consists of basal conglomerates and sandstones interspersed with pelites (GUIMARÃES; PEDREIRA, 1990).

The Una Group represents the rocks of the São Francisco Supergroup in the oriental half of Chapada Diamantina. Deposited during the Neoproterozoic Era, they occur in four carbonate basins and/or sub basins, as follows: Irecê Basin, Campinas Sub Basin, Una-Utinga Basin, and Ituaçu Syncline. According to Teixeira, Misi and Silva (2007), sedimentation occurred in a single large basin, which was later segmented during the Brasiliano tectonic events. This group encompasses the Bebedouro and Salitre formations.

A complex association of glacial diamictite (tillite), mudstone, and sandstone facies, related to the global Neoproterozoic glaciation events, constitutes the Bebedouro Formation (MISI et al., 2007), which occurs on the flanks of the synformal structures related with the carbonate basins of the Una Group. In turn, the Salitre Formation represents a sea-level advance, resulting from deglaciation, and is composed of thick layers of carbonate rocks, such as limestones, calcarenites, dolomites, and individual stromatolites (MISI; VEIZER, 1998).

At the end of the Neoproterozoic, during the Brasiliano orogeny, the distensional regime inverted, leading tothe closure of these two basins where the rocks of the Espinhaço and São Francisco Supergroups were deposited (ALKMIM; CHEMALE; ENDO, 1996). This inversion occurred in a compressional regime through the reactivationof normal fault structures of the Statherian rift, with main NNE-SSW orientation (CRUZ; ALKMIM, 2006). It generated anticlines and synclines in a complex tectonic style, evidenced in peculiar relief features (GUIMARÃES; SANTOS; MELO, 2008).

In terms of geomorphology, Chapada Diamantina is strongly characterized by mountains, whose broad plateaus and deep valleys with steep slopes give it a remarkable scenic beauty. As evidence of its relevance, the three largest summits in northeastern Brazil are located here: Barbado, at 2,033 m, Itobira, at 1,970 m, and Almas, at 1,958 m (GIUDICE, 2012); and most of the main rivers of the state of Bahia are born in this region.

Lima and Nolasco (2015) propose two main geomorphological domains for Chapada Diamantina: the karstic domain and the lithostructural domain. This subdivision was determined by geological features, such as lithology and structures that affect these rocks. These aspects created conditions for differential erosion and, consequently, contrasting landforms.

According to these authors, the karstic domain is associated with carbonate rocks of the São Francisco Supergroup and is characterized by flat to gently undulating reliefs, which reach altitudes between 700-800 m in the Irecê Basin and 500-600 m in the Una-Utinga Basin. These terrains are distinguished by typical karst system features, such as sinkholes, fluviokarst valleys, and a large network of caves, which form extensive galleries reaching up to tens of kilometers in length.

The lithostructural domain is supported by sediments of the Espinhaço Supergroup. Their Neoproterozoic folds are reflected in the irregular relief, marked by massive mountains and plateaus limited by scarps and deep valleys, such as the Sincorá and Bastião ridges. Like others, they present crests that are remarkably parallel and elongated in the NNW-SSE direction, reaching altitudes of 1,700 m and 1,200 m, respectively (PEDREIRA, 1994). In the most prominent fractured zones, vertical planes increase the weakness of the rock and accelerate erosive processes. In these places, larger valleys develop, such as Capão and Pati, whose lateral slopes can reach more than400 m in height.

3. Caves and Karst Features

Chapada Diamantina houses karst systems developed in both carbonate and siliciclastic rocks, as presented in Figure 3. The figure shows a map with the occurrences of caves registered in the National Registry of Speleological Information (CANIE) for the geological units considered here as karstifiable. Some less-soluble units also have registered caves, such as the Morro do Chapéu Formation, but they need to be further investigated before they can be classified as karst areas.

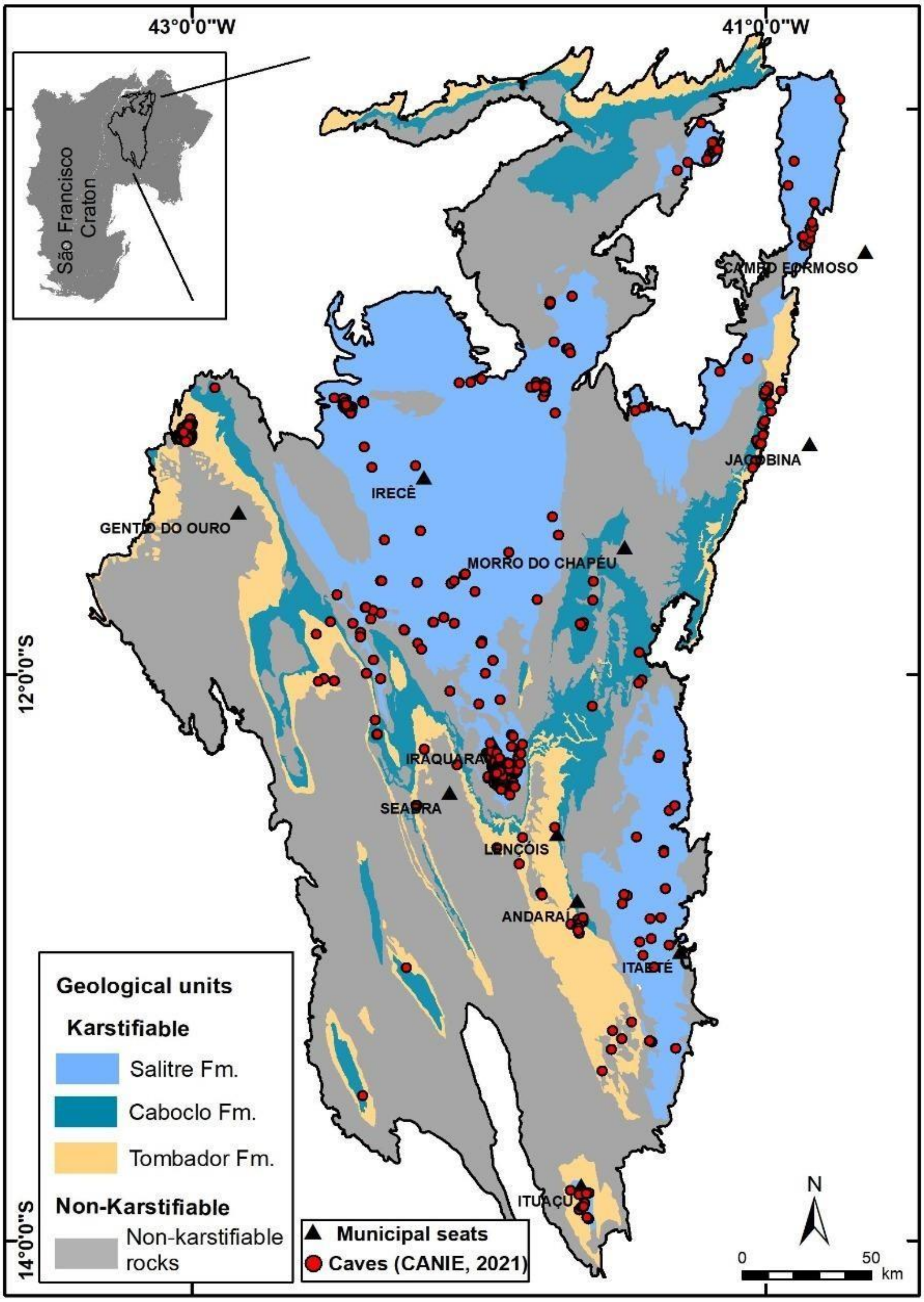

Figure 3. Map of cave occurrences by geological unit, in Chapada Diamantina.

The carbonate karst systems occur mainly in the Neoproterozoic rocks of the Salitre Formation, which belongs to the Una Group. This unit outcrops discontinuously in the Irecê, Una-Utinga, and Ituaçu basins and in the Campinas Sub-Basin. They also occur, on a smaller scale, in the Mesoproterozoic carbonate rocks of the Caboclo Formation, Chapada Diamantina Group.

The siliciclastic karst systems develop mainly in the Mesoproterozoic rocks of the Tombador Formation. In the southern-central portion, relevant caves occur in the area encompassed by the Chapada Diamantina National Park, in Serra do Sincorá, such as the Lapão and Castelo caves, with important tourist potential (FERREIRA, 2009), as well as the underexplored caves in the region of Vila de Igatu.

The presence of caves is also worth mentioning on the slopes of *Serra do Tombador*, in the easternmost part of Chapada Diamantina, and in Gentio do Ouro, in the western portion. Some caves are also present in the Morro do Chapéu Formation. However, due to a lack of information about them, these caves will not be described in this chapter.

3.1. Carbonate Systems

3.1.1. Irecê Basin

The Irecê Basin, in the central-northern region, is the largest carbonate outcrop area of the Salitre Formation and the one with the highest occurrence of caves in the Chapada Diamantina area. This flat land, with altitudes between 600 and 800 m, receives allogenic recharge from waters with high dissolution potential that flow from the surrounding siliciclastic mountains. This has favored the development of a very expressive karst relief, with the occurrence of numerous cave systems, sinkholes and sinkhole clusters, entrenched valleys with steep slopes, blind valleys, and resurgences.

The municipality of Iraquara stands out due to its high number and variety of speleological systems (LAUREANO; CRUZ JR, 2002). This number is so expressive that the area has several zones at risk of collapse and subsidence, as presented by Salles et al. (2019), in the karst hazard index map.

Nicknamed as the “City of Caves”, it attracts thousands of visitors every year, representing an important speleotourism center in the country. One of the main attractions is the Lapa Doce System, in which, according to Rubbioli (1995), a large collapse sinkhole measuring 160 m in length and 50 m in depth separates the Lapa Doce I, with 9.3 km of extension, from the Lapa Doce II, with 16.5 km (Figure 4A). However, a recent cave diving expedition was able to connect both caves, but its results have not yet been published.

Another important system is the Torrinha Cave. With 13 km, it stands out for the rich variety of forms and composition of speleothems, with aragonite flowers and gypsum needles that exceed 50 cm in length (Figure 4B). Pontes et al. (2023) proposed a speleogenesis model for the Torrinha Cave System based on the presence of burial stylolites and structural features, which control the cave geometry, at the heterolithic carbonates of Salitre Formation.

In turn, Pratinha Cave surprises visitors with its unique beauty, emerging from crystalline waters of an emerald blue color (Figure 4C), which supplies a large lake and then flows into the Santo Antônio River. According to Valle (2004), there is a convergence of regional groundwater flow towards the spring of Pratinha, thus defining it as the main outlet of the karst system in the southern sector of the Irecê Basin.

In Iraquara, as well as in much of Chapada Diamantina, it is common to identify archaeological sites near the entrance of caves. Caves such as Lapa do Sol and Santa Marta preserve expressive rock paintings, such as geometric, anthropomorphic and zoomorphic figures (Figure 4D).

On the northeastern edge of the basin, along the Jacaré River channel, on the border between the municipalities of Morro do Chapéu and São Gabriel, other relevant karst systems develop, with the presence of caves, dolines, canyons, and karst valley. The course of the river, when on the surface, creates favorable conditions for vegetation to survive, displaying an exuberant green that contrasts with the dry landscape of the caatinga.

The Brejões Cave System is particularly noteworthy, especially for its entrance, which reaches 106 m in height (Figure 4E). A collapse between Brejões I and II, which together reach 7.8 km of development, separates the cave into two segments (BERBERT-BORN; KARMANN, 2002). Furtado et al. (2022a, b) identified, through remote sensing and geophysical methods, a complex fracture system which is essential to cave and canyon development.

Human presence is quite remarkable in this cave, because of both the prehistoric records in rock art and the currentreligious manifestations that attract, today, thousands of people.

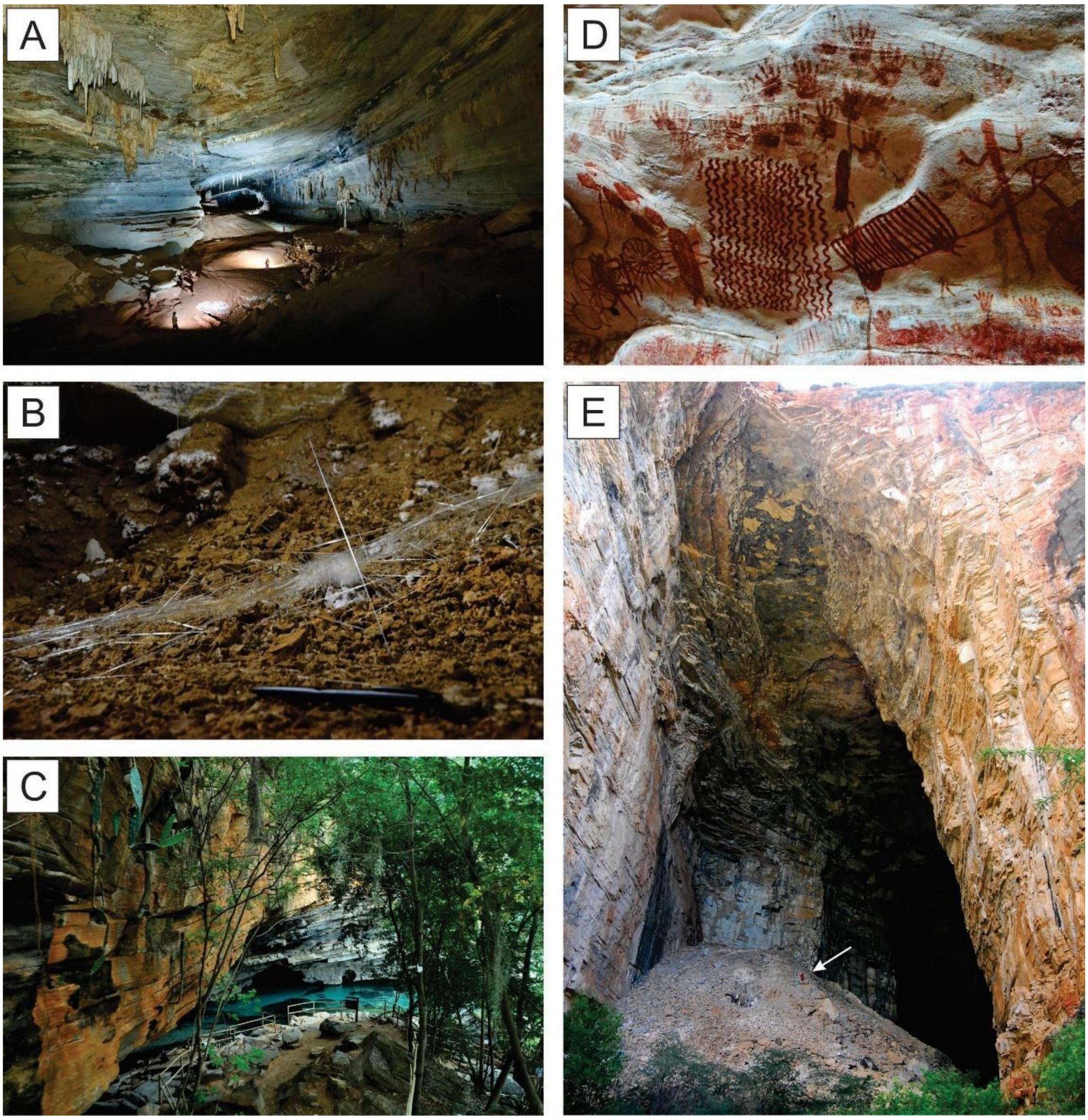

Figure 4. (A) Gallery of Lapa Doce I Cave (Photo: Solon Almeida Neto); (B) Gypsum needle speleothems in Torrinha Cave; (C) Resurgence of translucent emerald-blue waters from Pratinha Cave; (D) Rock paintings in the Santa Marta Shelter; (E) 106-m high entrance of Brejões Cave (person for scale indicated by white arrow).

3.1.2. Una-Utinga Basin

The Una-Utinga Basin, in the southeastern portion of Chapada Diamantina, corresponds to the areas where the rocks of the Una Group occur in the watersheds of the Una River, to the south, and the Utinga River, to the north. In addition, it covers the watersheds of the Santo Antônio and Paraguaçu rivers, in its central portion.

The most expressive karst features are concentrated in the southern region of the basin, where caves with a morphological pattern of large collapse galleries are common and the water level can usually be encountered in voluminous underground lakes (PEREIRA, 1998).

This is the case of Poço Encantado, in the municipality of Itaetê, one of the most popular postcards of Chapada Diamantina (KARMANN; PEREIRA; MENDES, 2002). The site receives its name due to a phenomenon that illuminates the lake, which occurs between the months of April and September, by sunrays that penetrate through the entrance of the cave (Fig. 5A). Poço Encantado has developed in dolomites and has about 506 m of horizontal projection, with an approximate height of 100 m from the entrance shaft to the water level, in addition to about another 65 m underwater (RUBBIOLI, 1998). There are speleothems in the form of rafts, which occur on the surface of the lake, in addition to rimstone dams and stalactites, in smaller numbers.

Also noteworthy is the Lapa do Bode Cave, the largest cave in the region, with 5.3 km of development. It exhibits a network of horizontal passages, with straight and angular conduits, in which elliptical morphologies predominate, commonly with vadose carving, forming “keyhole” sections. Lapa do Bode is also home to a unique and rich biodiversity (GNASPINI; TRAJANO, 1994), with the presence of several species, including highly specialized troglobites.

It is possible that there is communication through an aquifer between the caves of Poço Encantado and Lapa do Bode, since the same species of troglobitic catfish occurs in them. Other evidence of this connection includes a correlation between water level variations in both caves.

3.1.3. Campinas Sub-Basin

The Campinas Sub-Basin comprises the deposits of the Una Group that outcrop in the northeastern region of Chapada Diamantina, an area drained by the Salitre River Basin. Cenozoic sediments, resulting from the dismantling of these Neoproterozoic ones, cover most of these deposits. In this case, extensive cave systems develop, from which the local communities extracted, in the past, saltpeter to produce gunpowder.

Close to the community of Laje dos Negros, in the municipality of Campo Formoso, is Toca da Boa Vista, the largest cave in Brazil and South America, with 114 km of development, and Toca da Barriguda, the second largest in the country, with 35 km mapped. Developed in the rocks of the Salitre Formation, on the left bank of the Rio Pacuí, one of the tributaries of the Rio Salitre, these two caves has been considered part of the same system, although speleologists have not yet found a connection (AULER; SMART, 2002).

They present a maze morphology, according to Palmer's classification (1991) and developed at a specific stratigraphic level, without any relation to the current surface landforms or fluvial morphologies. These aspects, together with the presence of features such as dissolution domes, suggest a formation by hypogenic processes (KLIMCHOUK et al., 2016; AULER et al., 2017; CAZARIN et al., 2019), closely related to structural aspects (ENNES-SILVA et al., 2015).

Both caves exhibit exuberant secondary deposits. In Toca da Boa Vista, we highlight the Discos Voadores passage (Fig. 5B), with subaqueous speleothems, such as rafts, cones, and shelfstones, in addition to deposits of septaria (contraction cracks filled with calcite) (Fig. 5C). In Toca da Barriguda, gypsum and bassanite speleothems are present, in addition to an abundance of more common speleothem forms, such as stalactites, stalagmites, and flowstones (AULER; SMART, 2002, 2003).

3.1.4. Ituaçu Syncline

In the southernmost part of Chapada Diamantina, Neoproterozoic rocks of the Una Group occur within the Ituaçu Syncline, an open synform structure with about 50 km of wavelength and axial trace oriented along a NNW-SSE direction (CRUZ; ALKMIM, 2007). In this region, where the municipality of Ituaçu is located, there are also important karst systems.

In *Serra das Araras* there is a series of caves, which can be accessed either through openings in the escarpments or through collapse sinkholes. The entrance of the Cortinas Cave presents a vertical shaft measuring 50 m and is largely ornamented by draperies and calcite flowstones. Lapa do Bode also shows impressive ornamentation, with the presence of exuberant stalactites and columns (Fig. 5D), as well as aragonite flowers. In addition, it also stands out for its biological and paleontological potential.

Another expressive cave in Ituaçu is Lapa da Mangabeira. The importance of this area is mainly due to Catholic religious manifestations, which include pilgrimages that attract about 100 thousand people every year to the cave (BARBOSA, 2009). The cave has infrastructure to receive the devotees, with stairs and artificial lighting, providing access to the chapels and the altar where masses are held (Fig. 5E). The pilgrims usually light candles, leave offerings, and drink the “sacred” waters of the cave.

3.1.5. Caboclo Formation and the Cristal Cave

At Fazenda Cristal, located in the municipality of Morro do Chapéu, eastern portion of Chapada Diamantina, carbonate facies at the base of the Caboclo Formation emerge, marked by the presence of internationally relevant stromatolites. These structures are formed through microbial activities in aquatic environments (SRIVASTAVA; ROCHA, 2002). Expressive karst features, such as caves and sinkholes, develop in these rocks.

Cristal Cave, which is located also in this area, has 6.7 km of development, with a labyrinthine maze pattern in three preferred directions. According to La Bruna et al. (2021), sets of vertical fractures that coincide with the axial planes of open anticlinal folds control conduits and galleries (Fig. 5F). A particularity of this cave is the silicification of limestones at the stratigraphic level where it develops, possibly associated with hydrothermal processes (SOUZA et al., 2021). This factor may explain the scarcity of speleothems in the cave.

Large collapse sinkholes also occur in the area, such as the entrance to Velha Duda Cave and the Buracão Sinkhole, marked by steep walls, reaching 120 m in diameter and 50 m in depth (BERBERT-BORN; HORTA, 1995).

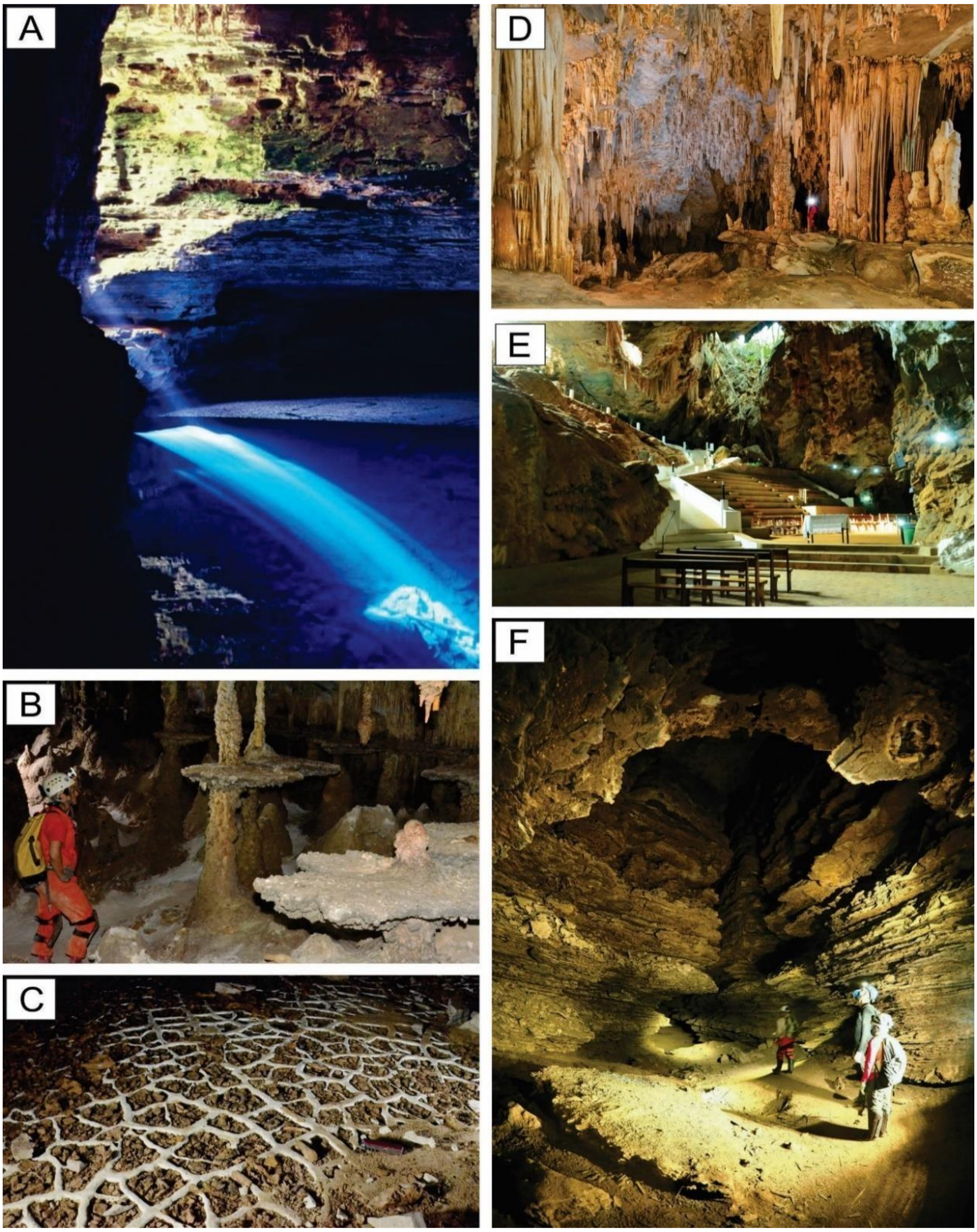

Figure 5. (A) Light phenomenon in the translucent lake of the Poço Encantado Cave; (B) Discos Voadores Hall and (C) Septarian speleothems of Toca da Boa Vista; (D) Speleothems of Lapa do Bode Cave, in Ituaçu (Photo: Solon Almeida Neto); (E) Church structure in the Mangabeira Cave; F) Conduit of Cristal Cave (Photo: CristalDOM Project – Prof. Francisco Hilário Bezerra, UFRN).

3.2. *Siliciclastic Systems*

3.2.1. Lapão Cave

Lapão Cave is located in the municipality of Lençóis and, despite having been an important tourist attraction at the end of the last century, it currently receives a modest number of visitors. With 1.6 km of development and a series of karst features such as sinking streams, sinkholes, and speleothems, it is among the most relevant caves in siliciclastic rocks in South America and worldwide (AULER, 2004; WRAY; SAURO, 2017).

Inserted in the eastern face of *Serra do Sincorá*, the cave develops at the contact between a conglomerate facies, which outcrops in the cavity ceiling, and a sandstone facies, which forms its walls and floor. In plan view, it presents a pattern of rectilinear morphology, with strong structural control of predominant NW-SE direction. The cave also has some narrow passages with low ceilings and large halls.

Within the Lapão Cave flows the Lapão River, whose sinkhole is located at an elevation of 634 m, while its resurgence is positioned at 495 m, about 80 m below the level of the main entrance to the cave (Figure 6A). The alluvial sediments deposited inside the cave serve as evidence of intense floods associated with this river. In addition, reports from local guides confirm episodes of fast water level rise in the underground river level during heavy rains. This phenomenon, together with the analysis of the geomorphology and hydrological dynamics of the region, suggests that river captures are developing upstream from the cave, increasing the catchment area of this river basin.

The diversity of secondary chemical deposits recognized in this cave includes stalagmites of large dimensions, small stalactites, coralloids, microgours, and helictites (Figure 6B). Many of these rare speleothems were damaged by visitors, with a significant portion having been broken and removed from the cave, on some occasions even used in the construction of house walls.

The Lapão Cave also stands out for its historical and cultural aspects and importance, mainly related to the exploration of diamonds. In the late 19th century and beginning of the 20th century, the cavity, as well as a good part of Chapada Diamantina, was the target of intense mining activity, which left marks in the form of caves and tunnels. Miners in search of diamond-containing river terraces built these structures to reach the diamonds (Figure 6C).

3.2.2. Castelo Cave

Castelo Cave is located in the municipality of Mucugê and receives an intense flow of visitors, estimated in about 9,000 people annually, based on verbal information from regional guides. This rate of visitation leaves evident marks along the cavity, such as the trampling of clastic and chemical deposits, as well as broken speleothems.

This cave is understood as a relict feature of the karst processes related to relief evolution in the Vale do Pati region. The Lapinha Hill, where the cavity develops, testifies that it has remained from the process of differentiated erosion of the antiform structure present there. Ruiniform reliefs are present in this hill, marked by intense weathering action concentrated along vertical fracture planes, generating erosive surfaces with clear structural control, which are characteristic of karst reliefs in sandstone rocks, according to Wray (2013).

The entrance to the cave is at an elevation of 1,320 m, more than 350 m above the Funis River, the current base level of the slope. The Castelo Cave has about 380 m of horizontal development and 35 m of altitudinal difference. Each of its three entrances provides access to a conduit of predominantly linear geometry, in some points meandering. These conduits, which are preferentially oriented in the E-W direction, relate to water bodies that are sometimes visible and sometimes confined by the debris of blocks and clastic deposits.

It is common to observe lithological variation between the sandstone facies that make up the ceiling and walls of the cavity, which involves, according to microscopic analyses by Souza (2019), a difference in the mineralogical composition of the rock and in the percentages of matrix and pores that can control the genesis of the cave. There are also frequent features of initiation and evolution of karst porosity, such as *tafoni* (Figure 6D), evidence of the dissolution of cement and/or rock matrix, especially taking advantage of discontinuities associated with primary structures, such as bedding planes and cross-bedding.

Castelo Cave has a wide variety of speleothems that, despite being mostly small, have a rich diversity of shapes and colors. Essentially, coralloids, cauliflower-shaped speleothems, crusts, and microgours are present. The presence of a geoform known as "stone arch", in the external part of the cavity, close to its entrance, suggests that the Castelo Cave must have been larger, but has suffered collapses (Figure 6E).

3.2.3. Vila de Igatu, Andaraí

Vila de Igatu, also known as Xique-Xique de Igatu, is a district of the municipality of Andaraí, on the eastern edge of Chapada Diamantina. Its history closely relates to diamond exploration (NOLASCO; MEDEIROS; OLIVEIRA, 2001). At the peak of mining activity, it was home to tens of thousands of people. Today, with the decline of mining in the region, the village counts less than 400 inhabitants. This mining activity left important historical, cultural and architectural records, which led to the listing of the area as a geoheritage site (NOLASCO et al., 2017).

Part of these records is associated with the karst relief, especially the caves, which developed in the sandstones and conglomerates of the Tombador Formation. Many of these caves were accessed and modified by miners who,in search of diamonds in the alluvial deposits, unblocked conduits obstructed by sediment, excavated new galleries, and altered the course of underground rivers. Today, it is a challenge to distinguish between natural andanthropic processes in the evolution of each cave.

Although well-known by local residents, few technical and scientific studies have been carried out in these caves. There are eleven caves registered in the National Registry of Speleological Information (CANIE) for this locality, but oral reports suggest that the number of occurrences is much higher. Only a minority of this cave set is mapped and documented. However, there is a significant amount of research on local biodiversity, with the region being considered a hotspot for neotropical subterranean fauna, highlighting the occurrence of troglobitic species, such as mollusks, scorpions, spiders, and fish (GALLÃO; BICHUETTE, 2015).

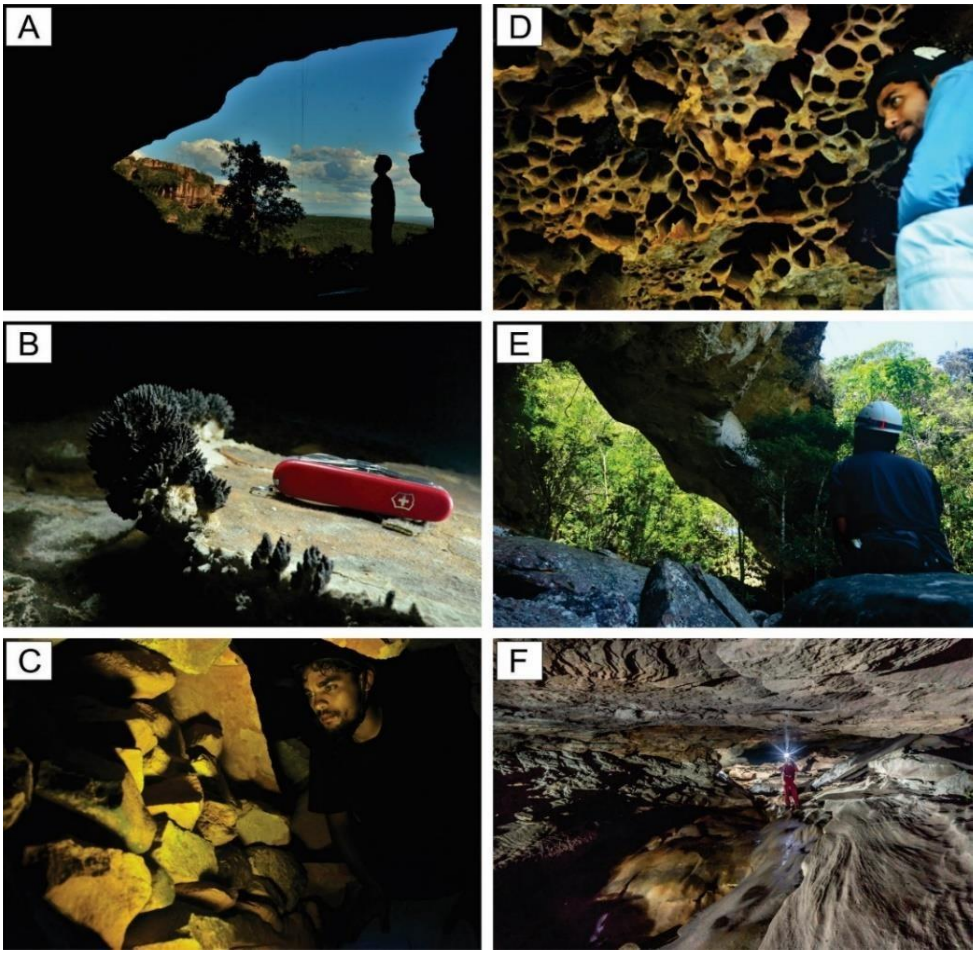

Figure 6. (A) Internal view of the entrance of Lapão Cave; (B) Helictites and (C) containment structures made of stones, from the diamond-mining period in Lapão Cave; (D) *Tafoni* dissolution features and (E) "Stone Arch" structure of Castelo Cave; (F) Gallery of Torras Cave (Photo: Daniel Menin).

The most relevant cave in the Igatu region is Torras Cave (Fig. 6F). With 3.6 km of horizontal development, Auler and Sauro (2019) classify it as the 2nd largest in Brazil and 8th largest in South America, among caves that developed in sandstone and quartzite rocks. Rock dissolution features are present in its interior, along sub-vertical fracture planes, as well as collapse marks, along the sub-horizontal bedding planes. This evidence suggests an initial formation through the dissolution of sandstones, with subsequent enlargement due to collapsing.

4. Conclusions

Chapada Diamantina occupies an area of 65,619 km² in the central region of the state of Bahia. It is characterized by reliefs with mountains, plateaus, and karst systems, developed in Proterozoic sedimentary and metasedimentary rocks. Karst systems are found in this territory in carbonate rocks of the Salitre and Caboclo formations, as well as in siliciclastic rocks of the Tombador Formation. Important features are present in these terrains, such as caves, sinkholes and resurgences, speleothems, among others.

As presented in this paper, the Chapada Diamantina caves are of exceptional importance in several aspects. Their scientific value is particularly noteworthy, with different disciplines finding, in these environments, relevant records of geological history and of the species (including human ones) that have already inhabited, or still inhabit, the region. Also noteworthy are the historical and cultural values, which are present, for example, in archaeological and current religious manifestations in several caves.

The Karst Systems in Chapada Diamantina house the longest cave of the southern hemisphere - the Toca da Boa Vista, with about 120 km mapped and located at the municipality of Campo Formoso. Furthermore, at the district of Igatu, located at the municipallity of Andaraí, in the mesoproterozoic siliciclastic rocks of the Tombador Formation, the Torras cave with 3.6 km mapped is one of the longest caves in the world in this kind of lithology.

Many of these karst landscapes are important tourist attractions, nationally and internationally, receiving thousands of visitors a year. At the center of Chapada Diamantina, the municipality of Iraquara houses one of the highest concentrations of caves in Brazil, and represents one of the most important speleotourism centers in the country. The successfully experience obtained at this municipality could be adopted in other karst districts.

It should be noted, however, that karst reliefs, especially caves, have their specificities and are usually quite sensitive environments to anthropic impact. Therefore, it is necessary that the structure and planning of tourist activities are based on scientific recommendations and proposals aligned with local knowledge. Only then can we avoid risks both to visitors and to the speleological heritage.

The municipalities where the diversified karst systems are located, in general, are characterized by low socioeconomic indexes. The use of this heritage for speleotourism activities could be an alternative to foster sustainable use, of part of these karst regions, and provide alternatives for employment and incomes.

Despite its diversity, with karst systems installed in rocks of distinct ages and lithologies, the researches related to speleogenesis and other geodiversity aspects are concentrated only in a few karst terrains of Chapada Diamantina. Even though these researches have a localized character, they were able to recover relevant and detailed information from the geological and geomorphological record, such as of climate changes in the northeast of South America.

Finally, it is worth highlighting the enormous potential that this territory still holds, for a better characterization of the systems that have not yet been adequately studied, especially those in siliciclastic rocks, as well as for the exploration and discovery of new ones.

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CAPÍTULO 3

ARTIGO 2: SILICICLASTIC CAVE OR DIAMOND MINE? CASE STUDY IN IGATU VILLAGE, CHAPADA DIAMANTINA (BA)

SILICICLASTIC CAVE OR DIAMOND MINE? CASE STUDY IN IGATU VILLAGE, CHAPADA DIAMANTINA (BA)

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ABSTRACT

The Igatu Village, such as part of southeastern Chapada Diamantina (Bahia, Brazil), was deeply modified by diamond mine activity. Caves were special targets to miners, since they act as diamond-bearing sediments trap, and the Canal da Fumaça was one of the most important and rich of them. Would it be a natural cave or an artificial diamond mine? In order to answer this question, we developed speleological and geological studies, which evolved cave survey, structural analysis through remote sensing and on the field, petrographic characterization through optical and electronic microscope, as well as chemical (XRF) and mineralogical (XRD) assessment. Data indicate that structures associated to sinistral transpressive strike play a fundamental role in conduit opening and ruiniform relief formation, acting as preferential weathering fronts. Petrological description suggest that chemical attack occurs mainly in the phyllosilicate (kaolinite + pyrophyllite) matrix, which are more soluble at acid medium, and secondary in the quartz grains. The phantomization reduces grain cohesion and thus piping processes take place to remove them mechanically. On the other hand, anthropic impact during mining activity was strong and leaved several marks, such as constructions, excavation, and detonation, which certainly increased cave dimensions. Finally, we propose a model for natural and anthropogenic evolution of the Canal da Fumaça Cave.

1. INTRODUCTION

Chapada Diamantina is a unique landscape in northeastern Brazil and was the scene of diamond mining throughout the 19th and 20th centuries, as recorded in its name (“Diamond Plateau”). The activity was so intense that, once exhausted the surface deposits in the first cycles of exploration, miners began to prospect the depths of caves. According to Nolasco et al. (2001) the cavities acted as traps for diamond rich alluvial sediments, whose exploration left several changes into these caves.

Onac (2019) classifies as "mined caves" the natural cavities from which mineral resources were explored. Examples of them spread around the world (*cf.* Frank, 1998; Algeo, 2004; Mickelson, 2008; Crothers et al., 2013). In Brazil, cave mining involved mainly the extraction of saltpeper during the 18th and 19th centuries, especially in the states of Bahia and Minas Gerais, as described by naturalists (Couto, 1809; Spix e Martius, 1824; Eschwege, 1833; Mattos, 1938) and recent publications (Gomes & Piló, 1992; Souza & Auler, 2015; Baeta, 2018; Faria & Filgueiras, 2019; 2021).

In Chapada Diamantina, one important example of mined cave explored by diamond mining is the Lapão Cave, municipality of Lençóis. Auler (2004) and Wray and Sauro (2017) set it between the more relevant in siliciclastic rocks in South America and the world. The cave extends up to 1.6 km and record singular karst features, as well as impacts of mining, such as artificial tunnels and support walls (Parra, Pereira & Purificação, 2023).

In a similar context, the Igatu Village, municipality of Andaraí, has several mined caves, such as Torras Cave (Pereira, 2010). With a significant 3.6 km in development, it was considered the 8th longest in South America between sandstone and quartzite caves (Auler & Sauro, 2019). Furthermore, the literature mentions the Canal da Fumaça Cave (Andrade, 2008), one of the richest mines in Igatu, which supported the development of the village (Pereira, 1937, p. 469).

Despite the well-documented mined cave occurrence at the Igatu Village and region, the relationship between the genesis of these underground conduits, the filling by diamond-bearing sediments and, finally, the extraction of these deposits by miners remains unclear. This comprehension is affected by the difficulties in distinguishing karstic features from the changes superimposed by the miners at these systems. Therefore, this paper aims to discuss the geological processes that lead to cave development, through morphological, structural, petrographic, chemical and mineralogical analysis applied to the Canal da Fumaça Cave. Herein we propose a model for the evolution of this terrain over a natural perspective, but considering the anthropic processes occurred during historical time.

2. MATERIAL AND METHODS

For the development of this work, geoprocessing and spatial analyses in GIS ambient were first applied. Subsequently, field campaigns aiming cave survey and topography, description of the host rock and associated clastic deposits, as well as samples collection were carried out. Finally, we applied laboratory analysis aiming petrographic, chemical, and mineralogical characterization of the samples. These steps will be detailed below.

Geoprocessing included the elaboration of basic cartography and structural lineaments extraction, both using QGIS 3.28 and, for the last one, using ALOS PALSAR Digital Elevation Model (12m resolution), obtained from Alaska Satellite Facility, Earth Data, NASA, and Google Satellite image from HCMGIS plugin. We carried out the lineaments extraction at the scales 1:20,000, 1:5,000, and 1:2,000 and prepared the rose-diagrams through the QGIS plugin Line Direction Histogram.

Fieldwork was performed in two campaigns, in the months of March and August, 2023. The first one focused the speleological survey and mapping, which was carried out with BCRA 4C accuracy level using Leica DISTO-X. The second one involved morphological assessment of cave passages and the description of host rock facies and clastic deposits preserved. Bedding and fractures planes were measured with BRUNTON compass, following strike-dip notation (Right Hand Rule). Structural data treatment involved the elaboration of rose-diagram and stereogram in Stereonet.

Fresh and weathered rock samples were collected, aiming the assessment of chemical weathering processes by comparing them. Altered and friable samples were impregnated with a mixture of Epoxy Resin 1.204 and Epoxy Hardener 1.601, in a 3:1 proportion. Therefore, they were colored with Keystone Blue Dye OCON-241, allowing the observation and description of intergranular porosity. Thin sections were prepared and described at optical microscope. Polish sections were prepared and metalized with carbon, and then described in JEOL JSM-G010LA scanning electronic microscope (SEM) equipped with a detector for Energy Dispersive X-Ray Spectroscopy (EDS). SEM analysis were carried out at the Geology Department of São Paulo State University (UNESP).

The mineralogical composition of samples were determined by X-ray diffraction (DRX), in a Bruker D2 Phaser diffractometer (CUKalfa, 30 kV, 10 Ma, 4 to 90 degrees 2θ), at the Ionizing Radiation Laboratory (LARIN) of the Center for Applied Natural Sciences (UNESPetro), at UNESP. Before the analysis, the samples were ground to a fine powder in Marconi MA-590 electronic mortar and pestle and then pressed in a plastic sample holder. Whole-rock chemical compositions – mayor, minor and trace elements – were obtained by X-Ray Fluorescence (FRX), through Bruker S8 Tiger at Multitask Laboratory (LabMulti) of Energy and Environment Interdisciplinary Center (CIENAM), Chemistry Institute, Federal University of Bahia (UFBA). For these analyses, samples were ground again in a manual agate mortar, ensuring a particle size smaller than 177 μm (Mesh No. 80). A mixture of rock sample and Hoechst Wax C Micropowder, in a proportion 9:1, was used to prepare powder pellets, arranged in boric acid and compressed in a hydraulic press at 5 tons for 3 minutes.

3. STUDY AREA

Chapada Diamatina is located in the central portion of Bahia state and acts as a watershed divide between the São Francisco River basin, to the west, and the east river basins that flow into the Atlantic Ocean, especially the Paraguaçu. With an area of 65,619 km² and covering 75 municipalities, it can be defined as a set of mountains, plateaus and karst systems, developed in Proterozoic sedimentary and metasedimentary rocks (Pedreira, 1997; Pereira, 2010).

The Igatu Village is a district in the municipality of Andaraí, situated on the southeastern portion of Chapada Diamantina, the Sincorá Range. The region is 434 km away from the state capital Salvador and occupies the eastern limits of Chapada Diamantina National Park. Within the village's territory is the Igatu Urban Park (PUI), created in 2007, aiming the environmental and historical heritage protection (Russ & Nolasco, 2012). The limits of this park partially covers the land overlying the Canal da Fumaça Cave, object of study in this work.

3.1. Climate and Hydrology

Climate of the region is complex and influenced by the altitude. According to Koppen classification, the study area is between a tropical highland (Cwb) and tropical rainforest (Am') climate areas (SEI, 1998). The annual average temperature is 24.0ºC and the average precipitation is about 1,060 mm (INMET, 2022). Two seasons are well defined: the wet one is concentrated in austral summer, between December and March, when the rainfall represents about 50% of annual precipitation. The dry season occurs in winter, between June and September.

The Igatu Village is within the hydrographic basin of the Coisa Boa River, a tributary of the Paraguaçu River. With an area of 43.8 km², the basin has a low drainage density (< 7.5 channels/km²) and is elongated in the NNE-SSW direction, with rapid surface runoff (Rodrigues et al. 2011). Trough water tracing studies, Auler et al. (2020) identified and characterized subterranean flows in the basin area. According to the authors, parameters such as time travel, distance and velocity are associated with conduit morphological aspects, which in turn are controlled by stratigraphic and structural factors.

3.2. Geological Aspects

Chapada Diamantina are in the context of the Precambrian covers of the São Francisco Craton (Almeida, 1977), which are divided in Mesoproterozoic Espinhaço Supergroup and Neoproterozoic São Francisco Supergroup (Guimarães, Alkmim & Cruz, 2012). These units constitute the Paramirim Aulacogen, a succession of two overlapping rifts, partially inverted during Neoproterozoic Brazilian tectonic cycle (Schobbenhaus, 1996; Cruz & Alkmim, 2006; 2017; Alkmim & Martins-Neto, 2012). Inversion deformed the basins through folds and thrusts (Alkmim et al., 1996; Cruz & Alkmim, 2007), in addition compartmentalized the Chapada Diamantina in western and eastern domains, limited by the NNW-SSE oriented João Correia – Barra do Mendes lineament (Jardim de Sá et al., 1976).

For the eastern domain, in which the study area is located, two deformation phases are recognized. The first one, ductile-brittle, had a regional WSW-ENE to E-W stress field and generated open and smooth folds formed by interestratal flexural sliding, as well as reverse and thrust faults (Danderfer, 1990; Santana, 2011; Moitinho, 2011). The second had brittle-ductile character and corresponds to a sinistral transpressive strike, with an N-S to NW-SE tension field, which resulted in faults and brachy-anticlinal folds that structured the Sincorá Range (Pedreira & Margalho, 1990; Maia, 2011; Santos, 2011; Cruz et al. 2018).

The Espinhaço Rift started at about 1.75 Ga (Neves et al., 1995; Danderfer et al., 2009). Sandstone and basal conglomerates of pre-rift Serra da Gameleira Formation compose initial basin sequence (Guimarães et al., 2008). Overlying are the syn-rift volcanosedimentary sequences of the Rio dos Remédios Group, followed by post-rift terrigenous deposits of the Paraguaçu Group (Guimarães et al., 2008; Loureiro et al., 2009; Magalhães et al., 2015). Above, the Chapada Diamatina Group are represented by the siliciclastic facies of the Tombador Formation and carbonate-siliciclastic sequences of the Caboclo Formation (Babinski et al., 1993; Ferronatto et al., 2021). Schobbenhaus (1996) removed the subsequent Morro do Chapéu Formation, due to the existence of an erosive surface. Finally, the Neoproterozoic São Francisco Supergroup, deposited into extensive sinclines, contains glacial deposits of the Bebedouro Formation and the cap carbonates of Salitre Formation (Guimarães et al., 2011; Santana et al., 2021; Caxito et al., 2022).

The rocks of the Tombador Formation, which compose the study area, hold the relief of mountains and plateaus characteristic of the region. In the Sincorá Range, Magalhães et al. (2016) divided the formation into a lower sequence, where fluvial and estuarine facies predominate, an intermediate one, with fluvial and alluvial fan deposits, without marine influence, and an upper sequence, which marks the beginning of a new transgression. These systems deposited sandy facies, often pebbly, interspersed with conglomerates supported sometimes by clasts, sometimes by the matrix (Bonfim & Pedreira, 1990; Filho et al., 1999). Geochronological studies pointed to ages of 1,394 ± 14 Ma (Gruber et al., 2011) and 1,436 ± 26 Ma (Guadagnin et al., 2015), and petrographic analyses set a high diagenesis stage to an anchi-metamorphism grade toward the south of the Sincorá Range (Varajão & Gomes, 1997; Battilani, 1999; Souza, 2017).

The conglomerates, especially those clasts-supported, host the diamonds (Sampaio et al., 1994). Their primary origin remains uncertain, although diamond-bearing intrusive rocks are known in the northern region of São Francisco Craton (Battilani, 2007; Pereira, 2007; Nannini, 2017). Most of deposits mined in Chapada Diamantina are of the detrital type, hosted in colluvium or in alluvial gravels, derived from the weathering and erosion of the Tombador conglomerates (Svisero, 1994; Carvalho, 2010; Lima et al., 2022). Nolasco et al. (2001) describe these deposits in more detail, based on popular nomenclature. An important type is the channel deposit, contained in superficial or subterranean vertical fractures, filled with gravel and quartz sand, which can range 5m in width and 20m in depth, often with water flow at the bottom.

3.3. Geomorphological Aspects

Chapada Diamantina is part of the northern portion of Serra do Espinhaço, a mountain range that extends from Minas Gerais to northern Bahia (Eschwege, 1833; Derby, 1906). According to Lima and Nolasco (2015), it is a region marked by montainous relief with pronounced scarps, deep valleys, and high plateaus. These authors positioned the outcrop area of the sediments of Tombador Formation in the lithostructural domain, in which deformation planes, associated to synclines and anticlines, control the erosional process. Furthermore, variations in resistence of different lithologies induce the action of differential erosion, favouring the irregular terrains.

At southern Chapada Diamantina, the Sincorá Range reaches 1,700m high. According to Pedreira (1994), its rough terrains belongs to the Post-Gondwana Surface, a denudation cycle that act over the eastern Brazil during the Upper Cretaceous (King, 1956). The western slope of the Sincorá Range is scarped and oriented in NNW-SSE direction, while the eastern side has a smoother relief, where the siliciclastic layers dip beneath the rocks of the Una-Utinga basin, to the east. The largest layers of diamond conglomerates outcrops on the eastern side, leading to the settlement of the main mining locations, such as the Igatu Village. At this region, structural valleys with scarped slopes occur, sometimes forming canyons (Lima &

Nolasco, 2015). In addition, truncated families of fracture planes create a ruiniform relief (Bonfim & Pedreira, 1990). The Coisa Boa River basin has a high declivity, with minimum and maximum altitudes, respectively, 351 and 1,216m (Fig. 2A).

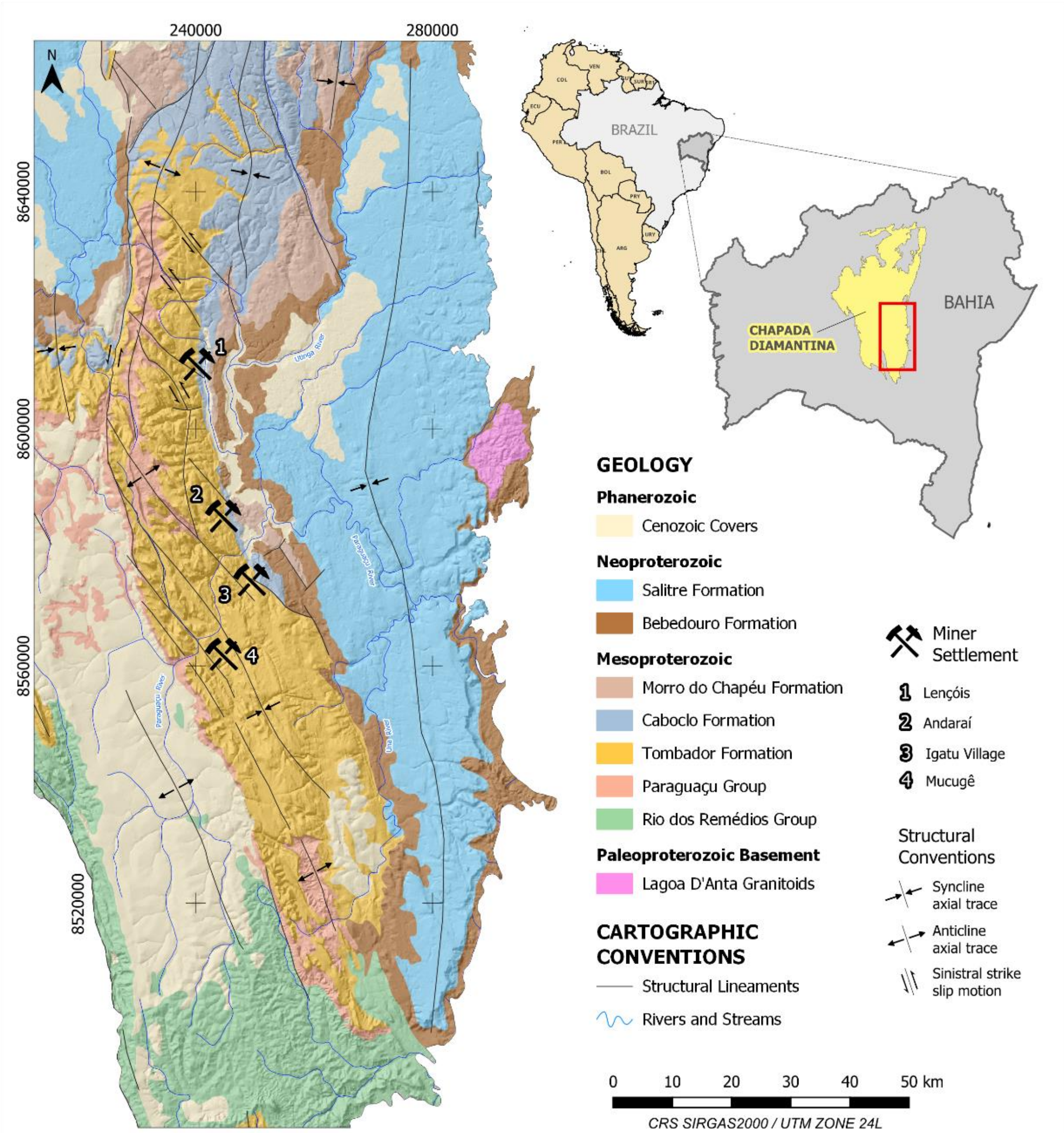

Fig.1. Location and geological map of the Sincorá Ridge, southeast of Chapada Diamantina and the main miner settlement. Lithology and structures data based on Bonfim & Pedreira (1990), Pedreira (1994), and Souza *et al.* (2003).

The 150 years of mining deeply modified local landscape and morphology (Santos et al., 2010). Diamond prospect resulted in emptying of riverbeds, fractures, channels, and caves systems, once filled by sediments (Russ, 2012; Castro et al., 2021). The remobilization of sand and gravel caused the Paraguaçu River silting, on the flatlands downstream of the village, which may have lead the formation of the Marimbus Wetland (Lima et al., 2023).

3.4. History

The history of diamond exploration in Brazil begins in Minas Gerais, where the mineral was found near the gold mines, around 1720 (Sarmento, 1731; Barbosa, 1991). Due to Portuguese control, other diamond regions did not prosper for around a century, until Brazil's independence in 1822, when the production monopoly was overthrown and new deposits were discovered (Svisero, 2017). In Chapada Diamantina, diamond discover remains uncertain. First official record dates of 1844 (Acauã, 1855, p. 215). However, Nolasco et al. (2017) assert that mineral sources were probably already known, but with no record due to the prohibition. In any case, at the end of first half of 19th century, an intense migratory flow affected the region, forming large mining areas and then, the first settlements, such as Mucugê, Lençóis, Andaraí, and Xique-Xique, nowadays Igatu (Pereira, 1937; Giudice e Souza, 2009).

In addition to the gem-form, diamonds in Chapada Diamantina were found as a dark impure and porous variety, known as carbonado, which consists of a diamond, graphite and amorphous carbon mixture, formed at higher levels of the Earth's mantle (Haggerty, 2014). With hardness close to the diamond, the carbonado had important use in industry and was strongly demanded during the transition of 19th and 20th centuries, supporting the local economy (Svisero, 2017). At the mines, during this period, hydraulic blasting predominates, the use of gunpowder is intensified and underground mines begin to be more explored (Nolasco et al., 2017).

At the end of the 20th century, mechanized mining, with the use of dredging and excavation machines replaced artisanal techniques (Pimentel, 2014). Due to deep environmental impact (Santos et al., 2010), the activity was censured and so prohibited with the consolidation of the Chapada Diamantina National Park (Guanaes, 2006). Nowadays, mining gave place to nature tourism that have been used to historical, cultural, and environmental approaches (Guanaes, 2001; Carvalho & Nolasco, 2007; Russ & Nolasco, 2012; Loureiro et al. 2021).

The Igatu Village experienced its heyday at the beginning of 20th century, when it housed at least 4,600 inhabitants (Jesus, 2009). Today, after the mining decline, no more than 500 people live there and the memories of these old times are partially preserved as ruins. Castro, Nascimento and De Paula (2021) consider the Igatu Village as part of the Brazilian geomining heritage, since its landscapes incorporate natural and anthropic elements derived from diamond exploration. In addition, the National Historical and Artistic Heritage Institute (IPHAN) listed the village's Landscape, Architectural, and Urban Complex.

4. RESULTS AND DISCUSSION

4.1. Structures and Cave Morphology

The structural lineaments analysis, at scale 1:2.500 and 1:5.000, showed that the Canal da Fumaça Cave is positioned over a 3 km long deformation corridor, marked by a high density of lineaments with a predominant NNW-SSE trend to the north, which inflects towards NNE-SSW nearby the cave, to the south (Fig. 2B). Remote sensing data suggest that the structure relates to the N-S to NW-SE sinistral transpressive strike of D_2 deformation phase, which affects the Sincorá Ridge, as described by Pedreira & Margalho (1990), Maia (2011), Santos (2011), and Cruz *et al*. (2018). However, features that support this correlation were not identified in the field.

Even so, it is notable that the main elongation direction of the cave is crossed by the NNE-SSW main lineament at the southern corridor, which suggests a close correlation between them. In the cave area surface, vertical fracture planes that section the outcropping rocks mark the lineaments, mainly at NNE-SSW, NE-SW, ENE-WSW, and NNW-SSE directions (Fig. 2C).

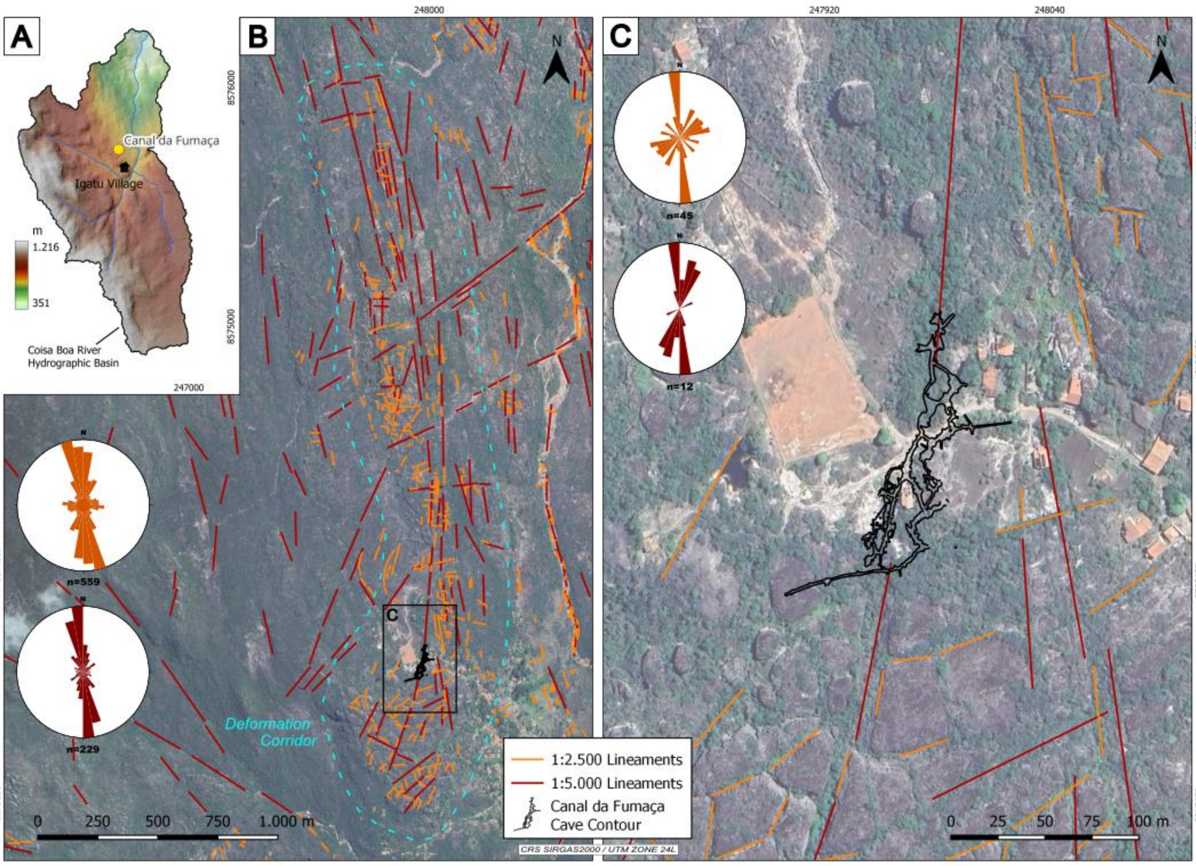

Fig.2. A) Hypsometric map of the Coisa Boa River Hydrographic Basin, locating the Igatu Village and the Canal da Fumaça Cave; B) Structural lineaments indicating a NNW-SSE to NNE-SSW oriented deformation corridor affecting the cave development; C) Local view at main lineaments as vertical fracture planes (fissures and channels) that control cave conduits and ruiniforme relief.

The floor plan map of Canal da Fumaça Cave is shown in the Fig. 3. To date, the cave has 644m in linear development, 624m in horizontal projection, and 29m in vertical range mapped. The distance between extremes is 172m, pointing to an overall slope of 17% or 9.6 degrees, with dip from SSW to NNE. Conduits are straight and their connectivity is high (around 90 connections), which leads to a network maze pattern, according to Palmer's classification (1991). However, this morphological analysis must take account that the cavity passed by profound anthropogenic changes, in which the widening of existing conduits and excavation of new ones increased the cave's length and connectivity.

Field measures show close relation between structures and cave development. Subvertical fracture planes occurs parallel both to the primary (NNE-SSW) and to secondary (ENE-WSW and NNW-SSE) orientations of cave elongation. Planes plotted on the floor plan, such as the rose diagrams of galleries trend and fractures measured, show this correlation (Fig. 3). In addition, bedding planes measurement pointed to an N dip trend with gentle angles of up to 15 degrees, as seen in stereogram (Fig. 3), which conducts water flow in that direction and, consequently, contributes to the cave elongation. Similarity between bedding inclination and overall cave slope (17º) suggests that the cave developed relatively trough a specific rock strata. Water flows along the bedding dip tend to be fast (Auler *et al*., 2020), which increases the erosion potential and, consequently, the enlargement of galleries and channels.

Fractures families identified in field are in conformity with structural lineament directions obtained by remote sensing. These structures are often represented by eroded fractures planes that reach 15m in depth and 8m wide, forming a network of fissures and channels in oblique directions (Fig. 4A) that connect surface to subterranean galleries (Fig. 4B and 4C). Where these families of fracture intersect, especially to the south and to north of the cavity, ruiniform relief occurs, such as foreseen by Wray and Sauro (2017) to karstic terrain in siliciclastic rocks.

The principal and longest passage, which determine the preferential elongation of cave, is oriented in the NNE-SSW direction. This same conduit is strongly affected by NNE-SSW subvertical fractures that occurs alone (Fig. 4D) and, sometimes, as a zone of dense fractures with cataclastic aspect (Fig. 4E). In this second case, the block falling from the ceiling seems to be more intense, contributing to the development of larger galleries. Subhorizontal fractures also occur, sometimes filled by fibrous quartz and bounding rock strata, which contrast in color (N342/25 plane in Fig. 4E).

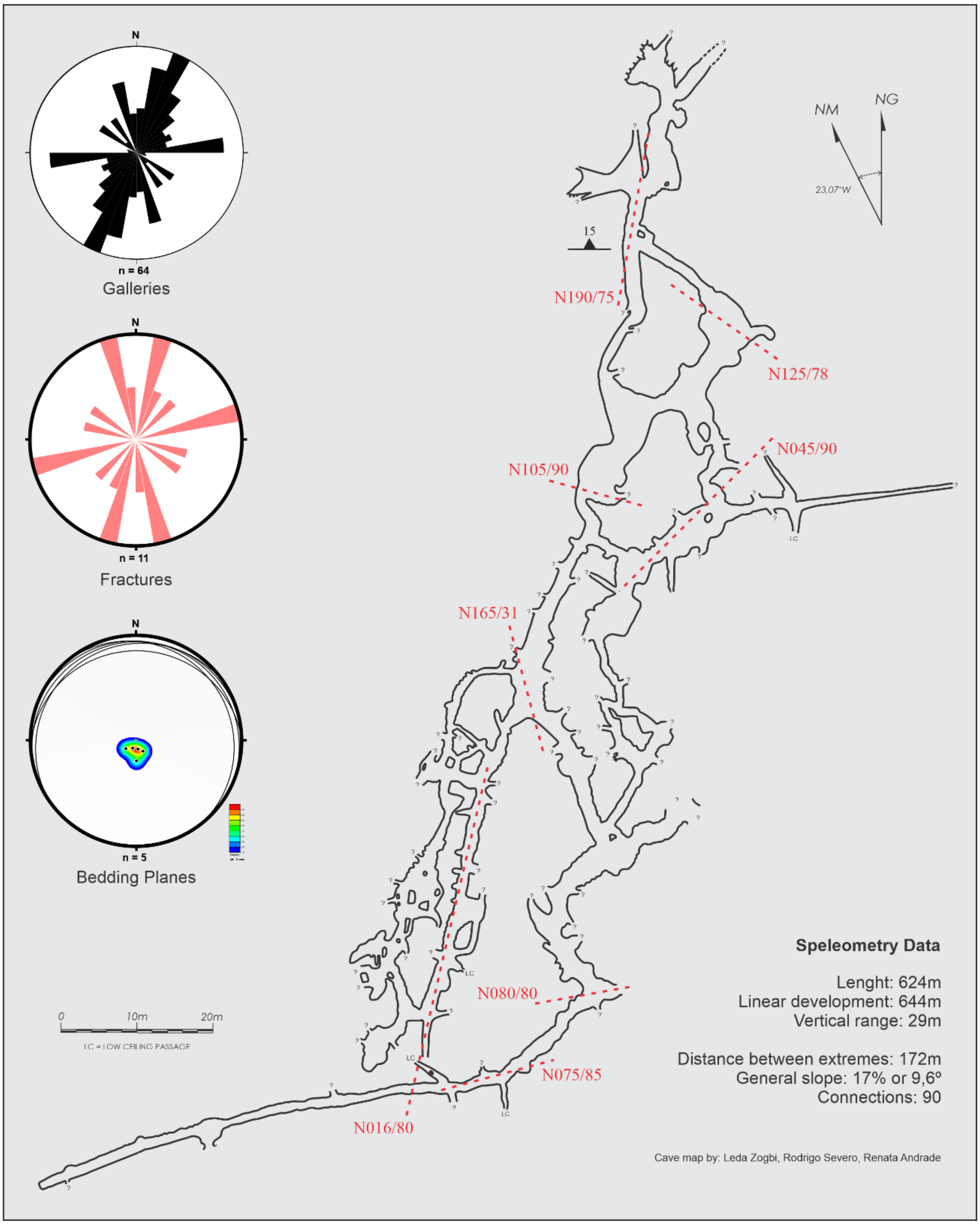

Fig. 3. Decal of Canal da Fumaça Cave map illustrating the main structure measured and its relation with conduit development. Rose diagrams point to great coherence of cave galleries and fracture planes direction (NNE-SSW, NNW-SSE, and ENE-WSW). Stereograms with bedding planes dip data show orientation tending to N, which guide the water flow and lead the conduit development toward this direction.

Structural control of karst features, such as caves, sinkholes, depressions, and karstic valleys in siliciclastic rocks is largely discussed in the literature (*c.f.* Ribeiro *et al.*, 2005; Melo e Giannini, 2007). First, discontinues of joints and faults help to increase the secondary porosity creating voids that act as starting points and enhancing karstification processes (Silva & Maia, 2024). These planes allow and increase the water flow, expanding the weathering front through the rock. According to Mecchia *et al.* (2019) model, undersatured water percolating in the fissures cause quartz dissolution on the walls and, by diffusion, decreases the silica concentration in intergranular water, triggering the weathering of the rock surface and first centimeters inside. Thus, mechanical processes are responsible to remove loose grains and enlarge the structures.

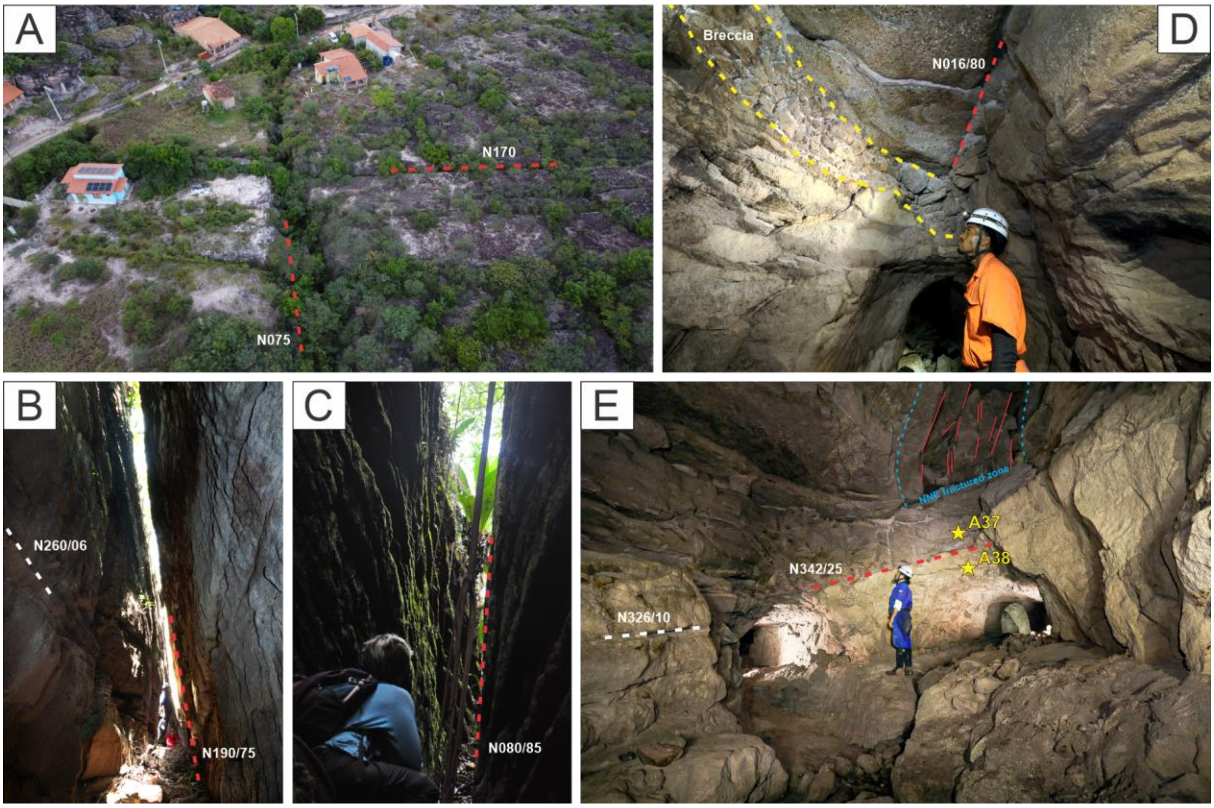

Fig. 4. A) Terrain above the cave crossed by a network of deep fissures (channels), which connect the surface, to underground conduits. Two main families are recognized, one NNE-SSW to NNW-SSE oriented (B) and other ENE-WSW oriented (C), both parallel to directions of development of cave passages; D) NNE oriented fracture plane, controlling the main extension direction of the cave and clastic breccia filling paleo-conduit; E) Largest gallery of Canal da Fumaça Cave, where subhorizontal fracture plane filled by fibrous quartz controls differential weathering of rock and NNE oriented fracture zone controls the ceiling block fall and the drainage course. Photos B, D, and E by Cristina Alves de Macedo.

4.2. Lithology and Weathering

The surrounding relief of the Canal da Fumaça Cave is conditioned by the alteration degree of the rocks. Terrains to the south and north of the cave are composed by unweathered rock, which support an irregular, sloping, and ruiniform relief, resulting from the intersection between fractures planes. In turn, the rocks in which the cave develops show an advanced alteration degree. Exceptions occur in the southernmost conduits of the cave, where the anthropogenic dismantling of the channels has exposed fresh rocks (sample A34). On the surface, the weathered rocks lead to smoothed and flat reliefs. Fig. 5 illustrates those characteristics of the relief and the distribution of rock sampling.

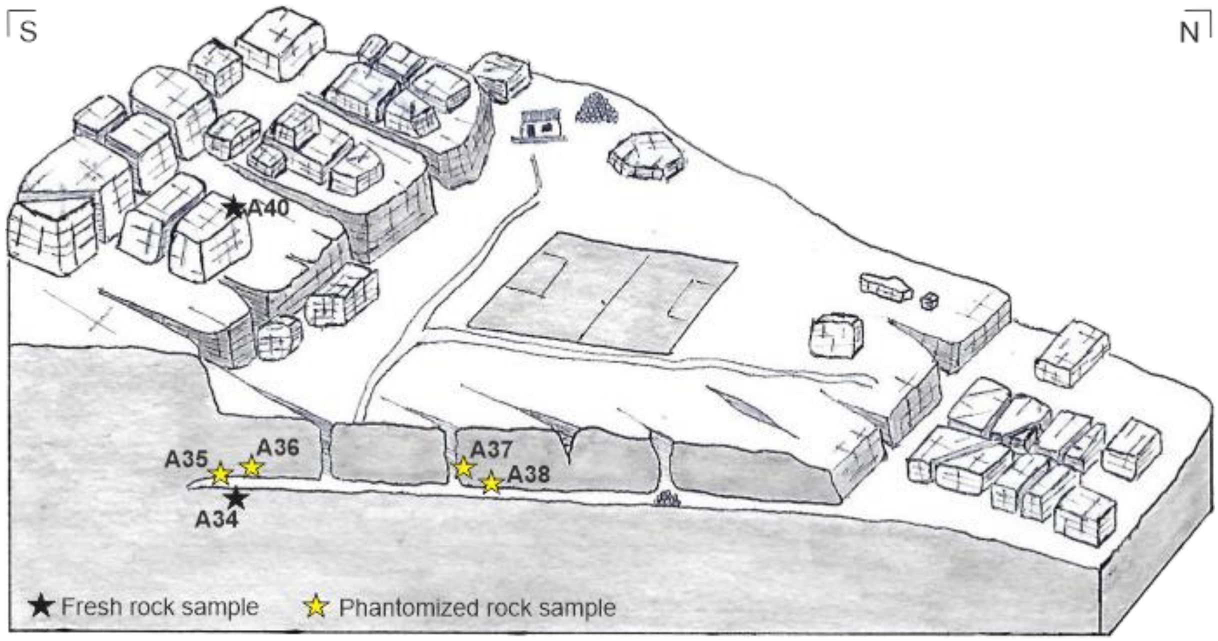

Fig. 5. Conceptual model of Canal da Fumaça Cave System. The cavity occurs in a flat smoothed terrain, where the rock weathering is advanced, between areas of ruiniforme relief in fresh rock.

In general, the cave rock facies and in its surroundings are sandy, composed by quartz and rare feldspar grains at an advanced level of alteration. Its grains are poorly selected, angular to sub-angular and of low sphericity. Packing is open to normal and, when there is contact between grains, they are concave-convex, suggesting low-grade chemical compaction during diagenesis. The matrix is abundant, consisting of phyllosilicates (kaolinite and pyrophyllite), which increases the aluminum amount of rock samples (Table 1). In fresh rock sample A34, collected inside the southern conduit of the cavity, that matrix occurs as fine-grained aggregates (Fig. 6A). On the other hand, in sample A40, collected from fresh rock in southern ruiniform terrains above the cave, it occurs as brownish masses of euhedral pyrophyllite, with lamellar to radial habit (Fig. 6B).

Occurrence of pyrophyllite indicates that the regional anchi-metamorphism, described by Varajão & Gomes (1997), Battilani (1999), and Souza (2017), affected the study area. Thus, lithology can be classified as quartz-metasandstone. The aluminosilicates can be assumed as orthomatrix, resulted from recrystallization of depositional silicate fine minerals (protomatrix). Furthermore, the quartz grains are – at the boundaries and, sometimes, the whole grain – consumed by the metamorphic reaction with kaolinite to form pyrophyllite, as described by Hemley *et al*. (1980) e Matsuda *et al.* (1992):

$$Al_2Si_2O_5(OH)_4 + 2SiO_2 = Al_2Si_4O_{10}(OH)_2 + H_2O \qquad \textbf{(1)}$$

According to those authors, the equilibrium curve for that dehydration reaction, at 1 kbar, pass through 260ºC and 273ºC. Illite crystallinity analysis for Tombador Formation, carried by

Souza (2017) indicate temperature in the order of 300ºC and 10-12 km of burial, reaching an anchi-metamorphism grade indicative of prehnite-pumpellyite to greenschist transition facies, during the Neoproterozoic deformation.

Thin-sections and SEM images evidence the influence of deformation on rock porosity. If, on the one hand, the structural forces and metamorphic reaction induced microfratures and surface cracking of quartz grains, enhancing the porosity, on the other, pyrophyllite growing filled part of the voids and reduces porosity again (Fig. 6C). Nevertheless, these reaction surfaces must concentrate the weathering during telodiagenesis, once they act as high free-energy sites, as proposed by Hurst & Bjorkum (1986) and Burley & Kantorowicz (1986). Syntaxial quartz overgrowth cement, formed during mesodiagenesis and occurs incipiently, also helps to obliterate primary porosity.

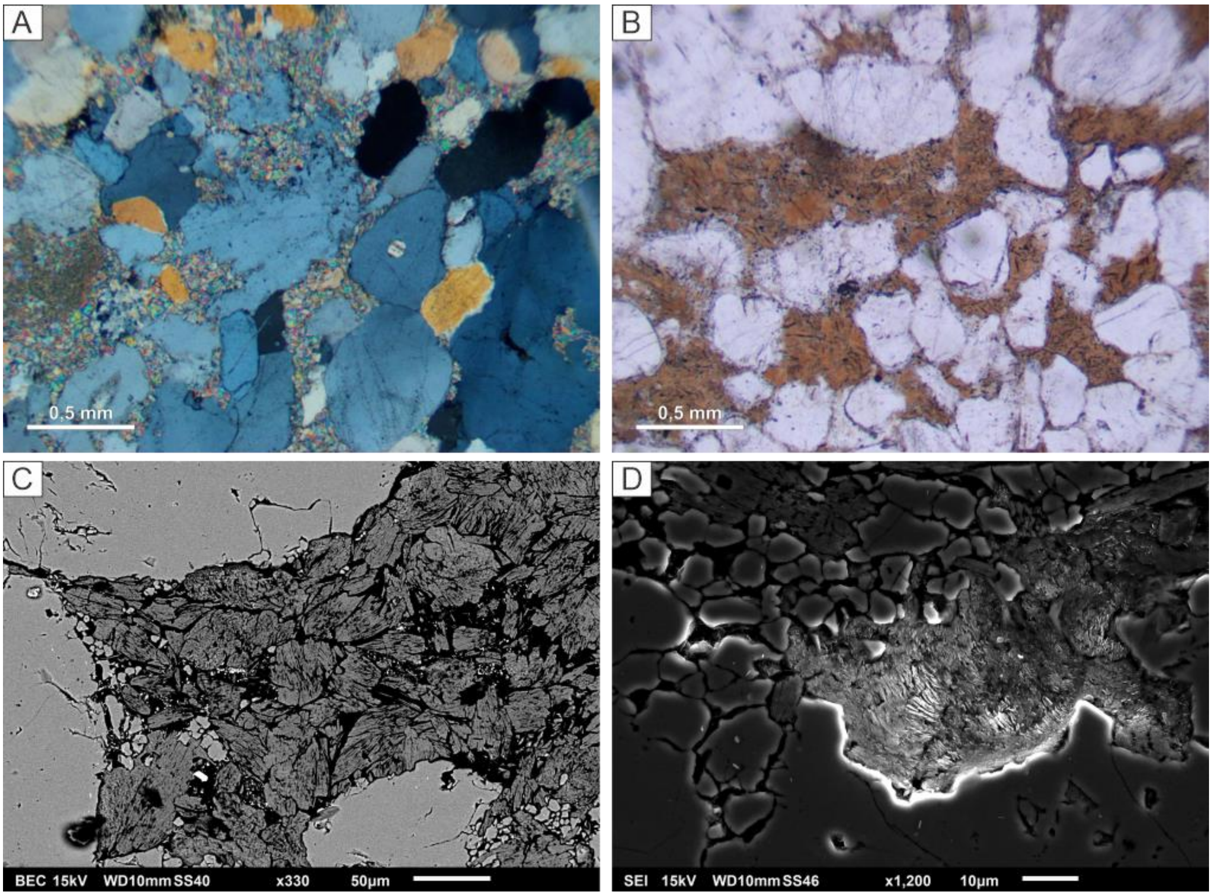

Fig. 6. A) Thin section (at crossed nicols) of quartz grains evolved by fine-grained phyllosilicate matrix from sample A34. Metamorphic corrosion of quartz is visible at the center; B) Thin section (at parallel nicols) of brownish euhedral pyrophyllite matrix from sample A40; C) and D) SEM images of sample IG013-A40, showing pyrophyllite matrix consuming quartz through anchi-metamorphism reaction. Quartz boundaries appear cracked and corroded. Kaolinite with typical booklet pattern also occurs, as a product of pyrophyllite weathering.

A clayey layer was also identified, with a thickness of around 30 cm (sample A35). XRD analysis detected the presence of kaolinite and illite, which explains the high percentage of aluminum and potassium identified by XRF (Table 1). Quartz and pyrophyllite were also recognized. This layer occurs limiting an upper altered metasandstone from a lower unweathered one, suggesting that this impermeable clay level could play a sealant role, holding the percolating water and, thus, the weathering in superficial levels. However, this layer was observed only at the southern conduit of the cave, so its lateral continuity could not be confirmed.

Weathered rock assume friable aspect and has the porosity strongly increased comparing to fresh one. Sometimes depositional structures, such as bedding planes, are totally effaced. Colour is diverse. In the example of Fig. 4E, there are two strata with advanced weathering contrasting in colors, limited by a N342/25 fracture plane filled with fibrous quartz. Upper strata is mottled white and brown, while lower one is homogenous brownish. Although this well marked bound, the upper color overpass the quartz vein and stain the lower strata at some points. This suggests that impermeable quartz vein restrain the weathering that comes from surface, which is exceeded only when it is thin or discontinuous. Therefore, the white mottled aspect could derive from kaolinization of pyrophyllite matrix – through processes described below – which is more advanced in the upper strata.

%	SiO_2	Al_2O_3	K_2O	TiO_2	Fe_2O_3	CaO	P_2O_5	Na_2O	MgO	MnO
A35	70.01	24.75	3.73	0.68	0.40	0.00	0.10	0.12	0.06	0.00
A36	86.97	12.04	0.22	0.49	0.13	0,01	0.07	0.00	0.00	0.00
A37	86.98	12.51	0.01	0.24	0.11	62ppm	0.02	0.00	0.00	0.00

Table 1. Whole-rock chemical composition obtained by XRF.

Host rock weathering is a fundamental stage of karstification in siliciclastic terrains, compassed by the concept of primokarst, in which *in situ* chemical alteration decrease rock strength and leaves the grains loose to posterior mechanical removal (Rodet, 1996; Quinif, 1999). Classical literature address two models for this process: the arenisation (Martini, 1979; 1982; Jennings, 1983) and the phantomization (Quinif, 2010; Hardt, 2011). Wray and Sauro (2017) proposed a differentiation between them. The arenisation occurs in mono-mineral quartz sandstone or quartzite, in which grains, overgrowth, and/or silica cement would be dissolved. On the other hand, phantomization requires more soluble fraction, such as clay matrix or feldspar, which suffer incongruent dissolution and leave residual less soluble quartz grains in place.

Considering the identified lithology and the models discussed above, it is more likely that chemical attack act mainly over aluminous phyllosilicate matrix, instead of quartz grains. The Fig. 6D evidences the occurrence of kaolinite with typical booklet patterns, interpreted as a product of pyrophyllite weathering, main process that lead to grains dissociation and, thus, rock strength decrease. Deep quartz grains corrosions are assumed as a product of anchi-metamorphism reaction, rather than surface-conditions solution.

This hypothesis are in agreement with authors that studied the presence of siliciclastic caves, dolines, sinkholes, and speleothems evolving the weathering of rock minerals other than quartz, in the State of Paraná, southern Brazil. Melo & Giannini (2007) and Melo *et al*. (2015) argues that karst features developed in Furnas Formation sandstone resulted from dissolution of mesodiagenetic well-crystalized kaolinite and illite cement, which precipitates in their microcrystalline form. Similarly, Pontes *et al*. (2022) registered dissolution of kaolinite cement at the Furnas Formation and iron oxides cement of Vila Velha sandstone, over phantomization processes that lead to karstification. Although all of these authors registered corrosion features on quartz grains and quartz cement, they argued that it plays a secondary role in rock weathering.

In turn, these processes need specific conditions to occur. Solubility of aluminum and silica tend to increase under acidic conditions (Dutra, 2013; Mason, 1966), which may be favored by the presence of organic compounds (Huang & Keller, 1970; Eberl & Hower, 1975), especially oxalic acid ($H_2C_2O_4$), originated from organic matter dispersed in water (Chin & Mills, 1991; Ganor & Lasaga, 1994). The study area perfectly fits these conditions, where water has acidic character (pH = 4-5, according to Auler *et al*. (2020)) and amber colour, due to organic matter dissolved, similar to the Venezuelan *Tepuis* sandstone karst systems (Mecchia *et al*., 2014).

Thus, evidences here suggest that weathering acts mainly at the pyrophyllite matrix. Congruent dissolution of pyrophyllite would leach both Si and Al. Water analysis were not carried in this work, but in very similar context Mecchia *op. cit.* found extremely low amounts of aluminum in cave waters. Therefore, it is more probably that incongruent dissolution acts over pyrophyllite, immobilizing Al in neoformed kaolinite and releasing Si into the solution, through the hydroxylation-desilication reaction described by Hemley *et* al. (1980) and Hurst & Kunkle (1985):

$$Al_2Si_4O_{10}(OH)_2 + 5H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2H_4SiO_4 \qquad \textbf{(2)}$$

In addition, neoformed kaolinte dissolution can also occurs, enhancing the porosity and contributing to rock phantomization. The alteration of kaolinite in acidic medium occur according to Chin and Mills (1991) reaction:

$$Al_2Si_2O_5(OH)_4 + 6H^{+} \rightarrow 2Al3^{+} + 2H_4SiO_4 + 2H_2O \qquad \textbf{(3)}$$

Therefore, it is evident that weathering on aluminous phyllosilicate matrix (pyrophyllite and kaolinite) plays a fundamental role in rock phantomization, probably more efficient than that carried in quartz grains. Under these conditions, data presented here are in agreement with Melo *et al*. (2015) when arguing that dissolution of kaolinite is much faster than quartz.

4.3. Clastic Deposits, Diamonds and Mine

Recent clastic deposits have also been identified within the cave. These deposits can be distinguished from Proterozoic metasandstone through discordant contact between them and, sometimes, it is possible to identify the paleoconduit morphology where they were deposited (Fig. 7A). The grain size also differs, with the clastic sediments being pebblier than the metasandstones (Fig. 7B), similar to those described by Lima et al. (2022) and Sampaio et al. (1994).

The high degree of weathering allowed miners to excavate the cave rock. Sometimes, existing conduits and galleries were widened, as shown in Fig. 7C, where the floor, smoothed and carved by the water flow, contrasts with the excavated walls and ceiling, which are irregular and rectified. In other cases, small passages were artificially created (Fig. 7D), connecting larger conduits and allowing access to gravel deposits. It is also assumed that miners also explored coarser facies of metasandstone in search of diamonds.

Where fresh rock occurs, in the southernmost zone of the cave, records of detonation were observed (Fig. 7E). Stone walls were also registered (Fig, 7F). Once the interior of the cavity was emptied, several points were subject to the roof collapsing, putting the miners at risk. Therefore, it was necessary to support the ceiling with block pillars.

Based on what has been presented, an evolution model can be proposed for the Canal da Fumaça Cave (Fig. 8), which goes from phases of natural karstic processes to human action during diamond mining cycles. Initially, the brittle deformation of metasandstones created subvertical fracture planes that, together with bedding planes, acted as preferential water flow surfaces and, so, as weathering fronts. Thus, mechanical processes, removed loose grains, creating subterranean conduits and superficial channels. These voids were thus filled by diamond-rich sediments, originating from the dismantling of Proterozoic rocks from the Tombador Formation. Finally, miners extracted these sediments and emptied the spaces again, in addition to excavating the altered rock, widening existing conduits and creating new ones.

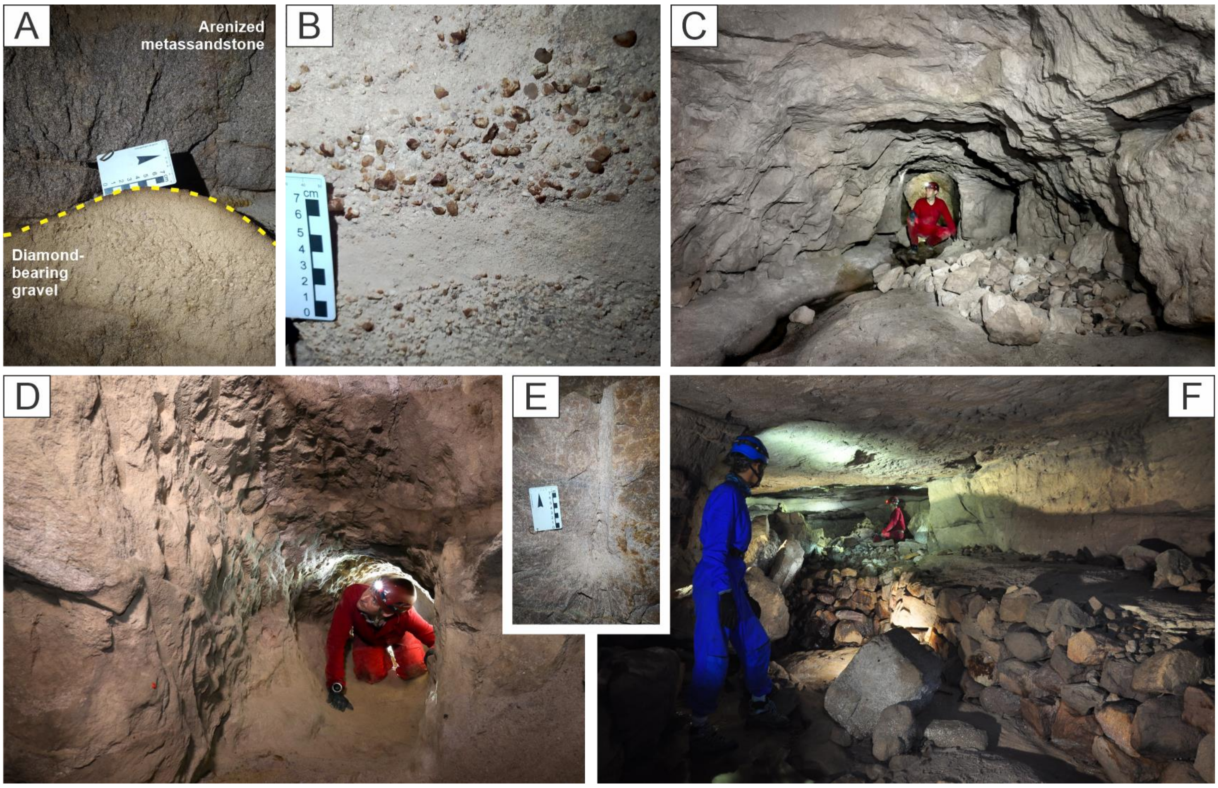

Fig. 7. A) Clastic diamond-bearing gravel filling paleo-conduit in phantomized metasandstone; B) Detail of banded clastic gravel deposits in the cave wall. These deposits were explored by the miners and its removal lead to the emptying of cave galleries; C) Contrast between natural and anthropic features: cave floor smoothed and carved by the water flow *vs.* ceiling and walls with straight morphology and signs of excavation. D) Artificial passage opened in the weathered metasandstone (chisel marks at the left side); E) Detonation record in a fresh rock wall; F) Stonewall built inside a cave gallery. Photos C and D by Cristina Alves de Macedo.

5. CONCLUSIONS

In this paper, we studied a siliciclastic karst system developed in metasandstone of the Tombador Formation, strongly affected by diamond miner activity that covered Chapada Diamantina during 19th and 20th centuries.

Karst processes recognized are in consonance with those consolidated in literature. Structural is the main conditioning factor for the cave development. Fractures planes act as weathering fronts and the bedding planes dip, in turn, guide the water flow. Thereby, phantomization processes occurs by quartz and, especially, phylossilicate matrix (kaolinite and pyrophyllite) dissolution. Mechanical processes (piping), thus, remove loose grains and enlarge voids.

We can conclude that natural processes originated the cave, which is recorded in a diversity of features, such as: structured galleries oriented with regional lineaments, fluvial erosion records, and paleoconduits filled by clastic deposits. However, there is no doubt that anthropic work deeply affected and modified the cave. New galleries were excavated in weathered rocks, existing ones were enlarged, including detonation of fresh rock, and most of sediments were removed.

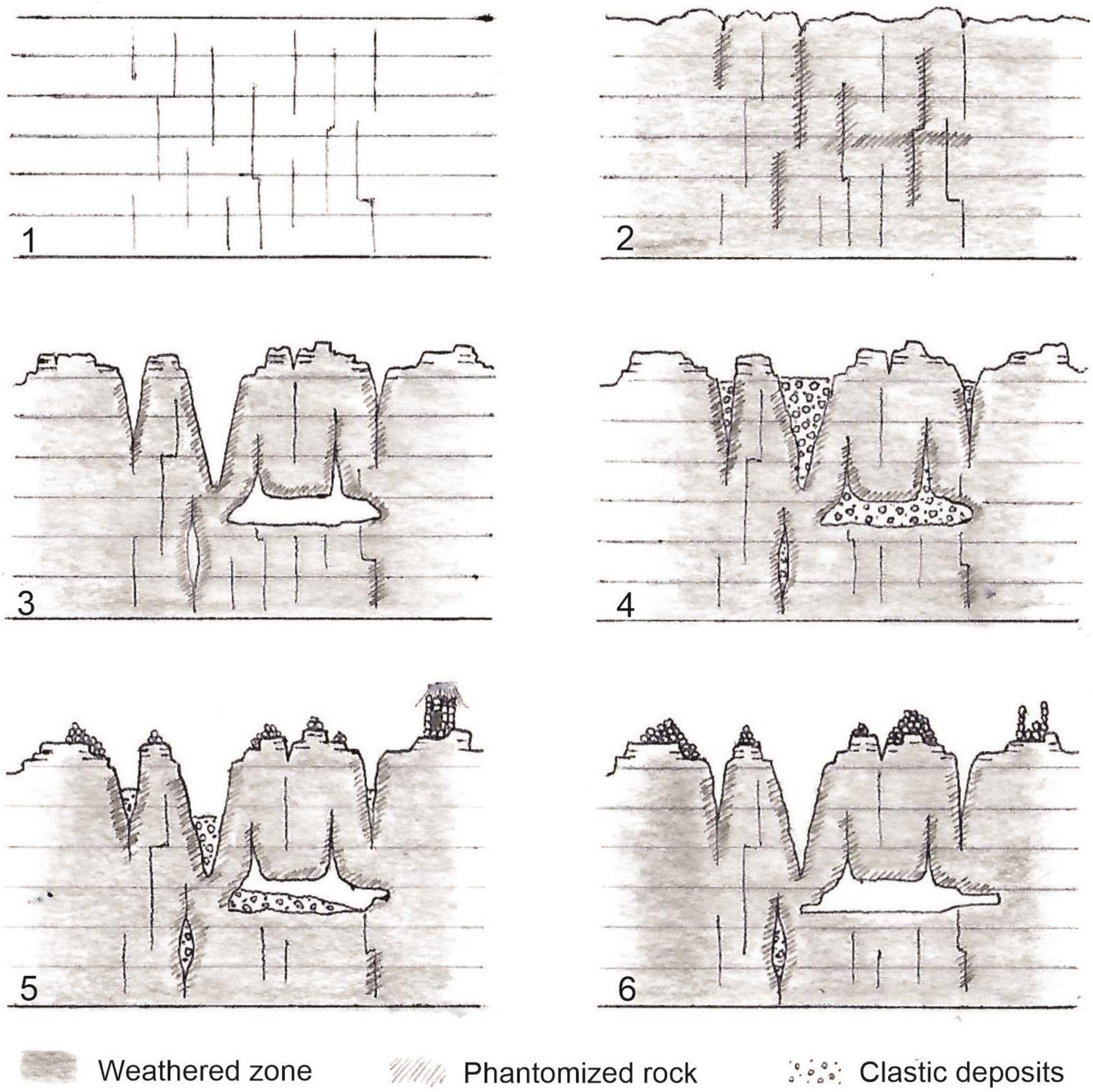

Fig. 8. Geological and anthropogenic evolution of Canal da Fumaça Cave. A) NNE deformation corridor, related to sinistral shear strain, fractures the metasandstone; B) Phantomization processes act mainly at subvertical fractures and subhorizontal bedding planes; C) Mechanical processes of piping remove loose grains, creating surface (channels) and subterranean (caves) conduits. The ruiniform relief also develops at this stage; D) Sandy and gravelly diamond-bearing sediments, weathering products of metaconglomerates, fill opened conduits; E) Miners remove sediments, emptying the galleries, in addition to excavate the weathered rock, creating artificial conduits; F) Current arrangement of Canal da Fumaça Cave, recording karstic processes, as well as anthropic modifications.

It is also important to highlight that if, on the one hand, cave mining allow the access to locals of scientific relevance, once inaccessible, on the other, it can also suppress, omit or decontextualize natural aspects of the cavity. Future studies are needed to expand the knowledge to other mined caves in Igatu Village.

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CAPÍTULO 4
CONCLUSÕES

Nesse trabalho de mestrado foram desenvolvidas pesquisas acerca de cavernas e relevos cársticos situados na Chapada Diamantina, região central do Estado da Bahia.

O primeiro produto da pesquisa foi uma revisão bibliográfica, publicada em formato de nota técnica na Revista Brasileira de Geomorfologia, acerca do patrimônio espeleológico e cárstico da Chapada Diamantina, tanto para rochas carbonáticas quanto para rochas siliciclásticas. Esse trabalho reuniu informações a respeito do meio físico e também acerca de formas de uso, manejo e valorização desses ambientes. Confirmou-se o postulado em que a Chapada Diamantina abriga um patrimônio espeleológico valioso e diversificado. No entanto, nota-se que há um grande acúmulo de conhecimento para sistemas cársticos desenvolvidos em litologias carbonáticas. Por outro lado, cavernas em rochas siliciclásticas, que também são de riqueza singular e guardam registros importantes da evolução geológica e geomorfológica da região, foram objeto de estudo de poucos trabalhos científicos, sendo menos conhecidas e valorizadas.

Tendo isso em vista, optou-se por desenvolver uma investigação geoespeleológica para o carste em rochas siliciclásticas Mesoproterozoicas da Formação Tombador na Vila de Igatu, município de Andaraí. Assim, selecionou-se para apresentar como estudo de caso o sistema da Gruta do Canal da Fumaça, para o qual foram aplicadas análises estruturais, químicas e petrográficas, com objetivo de compreender os processos que influenciaram na carstificação. Sugere-se que a dissolução tenha agido principalmente sobre os filossilicatos (pirofilita e caulinita) da matriz dos metarenitos, caracterizando o processo de fantomização, seguido pela remoção mecânica dos grãos desagregados de quartzo por *piping*. Também foi observado que o impacto da atividade de garimpo de diamante, ocorridas durante os séculos XIX e XX, trouxe profundos impactos à cavidade, deixando marcas como escavações e detonações de condutos, ampliando as dimensões da caverna.

Considera-se que essa pesquisa contribui para o avanço da compreensão do carste em rochas siliciclásticas na Chapada Diamantina, esperando incentivar o desenvolvimento de novos estudos e o aprofundamento dos conhecimentos. Futuros trabalhos deverão expandir essa pesquisa para os demais sistemas cársticos na Vila de Igatu e para a Serra do Sincorá.

APÊNDICE A

JUSTIFICATIVA DA PARTICIPAÇÃO DOS CO-AUTORES

O Prof. Dr. Ricardo Galeno Fraga de Araújo Pereira é o orientador desse projeto, portanto, consta como co-autor em ambos os artigos. O Msc. Carlos Gleidson Campos da Purificação, diplomado neste mesmo Programa de Pós-Graduação, foi responsável pela elaboração de toda a cartografia do artigo 1, auxiliando na compreensão da distribuição de cavernas cadastradas e das respectivas litologias na Chapada Diamantina. Por sua vez, estudante de graduação em Geologia, nessa mesma Universidade, Leonardo Fortes Vieira atuou como bolsista de iniciação científica no projeto que resultou no artigo 2, auxiliando nas atividades de campo, coleta de amostras e também na coleta, tratamento e interpretação dos dados.

ANEXO A – REGRAS DE FORMATAÇÃO DA REVISTA 1

Revista Brasileira de Geomorfologia

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Como parte do processo de submissão, os autores são obrigados a verificar a conformidade da submissão em relação a todos os itens listados a seguir. As submissões que não estiverem de acordo com as normas serão devolvidas aos autores.

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- Serão aceitas submissões nos idiomas português, espanhol e inglês. Para as submissões em português e espanhol, é obrigatória a tradução para o inglês após a avaliação e aceite final pela Revista, a fim de possibilitar a publicação bilíngue do manuscrito nos padrões de qualidade da RBGeomorfologia. A publicação do artigo ocorrerá somente após a apresentação do texto em inglês. Submissões originalmente em inglês não necessitam de traduções adicionais. A qualidade da redação do texto em inglês deve atender aos padrões estabelecidos; caso contrário, a submissão será imediatamente rejeitada.

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- O autor correspondente tem que cadastrar todos os autores do artigo (no sistema da revista) com seus respectivos vínculos institucionais e o número ORCID no processo de submissão do artigo.

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- No caso de estudos realizados sem recursos financeiros institucionais e/ou privados, os autores devem declarar que a pesquisa não recebeu financiamento para a sua realização.

- É obrigatório o envio de uma carta de apresentação (cover letter), inserido como arquivo complementar em formato .pdf (modelo da carta de apresentação para download).

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ARATTANO, M.; FRANZI, L. On the evaluation of debris flows dynamics by means of mathematical models. **Natural Hazards and Earth System Science**, v. 3, n. 6, p. 539–544, 2003. DOI: 10.5194/nhess-3-539-2003

Para livro:

HUGGET, R. J. **Fundamentals of Geomorphology**. 2ª Ed. Londres: Taylor and Francis, 2007. 458p.

Para capítulo de livro:

CASTRO, S. S. Micromorfologia de Solos Aplicada ao Diagnóstico de Erosão. In: GUERRA, A. J. T.; SILVA, A. S; BOTELHO, R. G. M. (Ed.). **Erosão e Conservação dos solos: Conceitos, temas e aplicações**. 1ª Ed. Rio de Janeiro: Bertrand Brasil, 1999. p. 127-163.

Para trabalhos em anais de eventos:

NOVO, E. M. L. M.; BARBOSA, C. C. F.; FREITAS, R. M.; MELACK, J.; SHIMABUKURO, Y. E.; PEREIRA FILHO, W. Distribuição sazonal de fitoplâncton no Lago Grande de Curuai em resposta ao pulso de inundação do Rio Amazonas a partir da análise de imagens MODIS. In: XII Simpósio Brasileiro de Sensoriamento Remoto (SBSR), 12., 2005, Goiânia. **Anais...** São José dos Campos: INPE. 2005. p. 3175-3182. ISBN 85-17-00018-8.

Para dissertações e/ou teses:

MONTANHER, O. C. **Padrões espaço-temporais do transporte de sedimentos suspensos dos rios amazônicos de águas brancas: relações com o clima e mudanças na cobertura do solo**. Tese (Doutorado em Geografia) - Programa de Pós-Graduação em Geografia, Universidade Estadual de Maringá, Maringá. 2016. 253p.

Para relatório técnico, manual:

IPT. **Ocupação de encostas**. São Paulo: IPT, 1991. 216p. Publicação IPT n. 1831.

Para documento cartográfico:

IBGE. **Estado de Roraima - Geologia**. Rio de Janeiro: IBGE, 2005. Escala 1:250.000.

Para programas de computador (software):

QGIS Development Team. **QGIS Geographic Information System (versão 3.10)**. 2021. Disponível em: <http://qgis.osgeo.org>.

Esri Inc. **ArcMap (versão 10.5.1)**. Redlands, Estados Unidos, 2016.

R Core Team. **R: A Language and Environment for Statistical Computing**. Vienna, Áustria, 2020. Disponível em: <http://www.R-project.org/>.

Diretrizes para Autores

Os manuscritos enviados à Revista Brasileira de Geomorfologia deverão estar formatados segundo o documento modelo (template) disponível em: https://github.com/revbrgeomorfologia/template/raw/main/rbg-template.docx. As submissões devem ser feitas em formato .docx (Microsoft Word). Manuscritos que não estiverem formatados de acordo com este modelo serão rejeitados na triagem editorial. As figuras e tabelas deverão estar inseridas ao longo do texto e não ao final do documento na forma de anexos.

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Artigos

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ANEXO B – REGRAS DE FORMATAÇÃO DA REVISTA 2

International Journal of Speleology

Submission Guidelines for

International Journal of Speleology (IJS)

http://scholarcommons.usf.edu/ijs/

Note to Contributors

1. Papers should be submitted online at http://scholarcommons.usf.edu/ijs/ through the "Submit Article" link. Texts should be submitted as Word documents. Documents (select type from the dropdown list) should be typed with 1.5 line spacing, have continuous numbered lines (preferably using Times New Roman 12 pt font), and **should contain all figures, tables, or plates** at their desired location within the manuscript. For the review process, all figures or/and plates should be of low resolution to keep the final file at reasonable size.

2. Figures, plates, and tables should be sent at full resolution ***only after the review process is completed and paper accepted***, and then in separate files (e.g. Fig1.jpg or Fig1.tiff, Table1.doc or Table1.xls). Complex formulas must be submitted as separate ***.tiff*** or ***.jpg files*** and must be written using Bookman Old Style, 9.5 point font. To do so highlight "Supplemental files" while submitting your revised manuscript, then upload your supplemental files and their short description. For long tables MS Excel should preferably be used (e.g., Tab1.xls). Submission of a paper will be taken to imply that it is unpublished and is not being considered for publication elsewhere.

3. Papers should preferably be written in English. Authors using a language other than their own are requested to have their manuscripts checked for linguistic correctness before submission. SI system units should be used. Dates should be in the form "5 February 1975", 21.6ºC with no spaces (and not 21,6 ºC or 21.6 ºC), distances as 200 m (not 200m). Complex formulas and equations should be inserted in the text but after the review process is completed, these must also be sent separately as high-resolution jpg/tiff files.

4. Papers should be headed by a title, the full name(s), business address(es) and e-mail address(es) of the author(s), plus full details of posts held by the author(s) if appropriate. If a paper has more than one author, the name of the person to whom correspondence and proofs should be sent must be followed by *****. To ensure proper attribution of publications and citations to the correct authors, IJS requires that all authors provide their **ORCID ID** (https://orcid.org) at the time of manuscript submission in the author's affiliation line.

5. Abstract should be short (less than 300 words) and summarizes the contents of the paper. Authors should provide five keywords after the abstract. Keywords are separated by a **;**. Articles can be structured in 3 orders of headings: e.g., **GEOLOGY**, **Lithology**, *Mineralogical characteristics*. **Article titles/subtitles and subheadings should use sentence case format**, which means only the first word and proper nouns should be capitalized. See recent issues for examples.

6. Each paper will be subject to editorial review by three referees. The Editorial Staff reserves the rights to refuse any manuscript submitted, whether by invitation or otherwise, and to make suggestions and modifications before publication.

7. **Authorship statement**. IJS requires that all authors listed in a paper should meet the criteria for authorship and such, the contribution of each author must be described in terms of conception, design, data collection, analysis, interpretation, drafting and/or critical revision. The author statement should be placed in the manuscript immediately following the Acknowledgement section. • *Example of authorship statement:* VJP, CAH, and DM designed and directed the study. OAD performed the measurements, JA carried out the simulations. OAD, PBO, HJ analyzed the data. CAN wrote the paper with input from all authors.

8. Any change in authors and/or contributors after initial submission must be approved by all authors. This applies to adding, deleting, or changing of order to the authors, or contributions being attributed differently. Any alterations must be explained to the editor, who may contact any of the authors and/or contributors to ascertain whether they have agreed to any alteration.

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✣ **Article:** Osborne, R.A.L., 2002. Cave breakdown by vadose weathering. International Journal of Speleology, 31, 37-53. Richards, D.A., Dorale, J.A., 2003. Uranium-series chronology and environmental applications of speleothems. Reviews in Mineralogy and Geochemistry, 52, 407-460. Dumitru, O.A., Austermann, J., Polyak, V.J., Fornós, J.J., Asmerom, Y., Ginés, J., Ginés, A., Onac, B.P., 2019. Constraints on global mean sea level during Pliocene warmth. Nature, 574, 233-236.

✣ **Book with personal author:** Palmer, A.N., 2007. Cave geology. Cave Books, Dayton, 454 p.

✣ **Book or report from an organization:** IPCC, 2014. Climate change 2014: Synthesis report. Contribution of working groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, 151 p.

✣ **Book with personal author:** Hildreth-Werker, V., Werker, J.C. (Eds.), 2006. Cave conservation and restoration. National Speleological Society, Huntsville, 600 p.

✣ **Book as part of a series:** Dougherty, H.P., 1985. Caves and karst of Kentucky. Kentucky Geological Survey, Lexington, KY, Special Publication, 196 p.

✣ **Chapter:** Palmer, A.N., Palmer, M.V., 2000a. Speleogenesis of the Black Hills maze caves, South Dakota, USA. In: Klimchouk, A., Ford, D.C., Palmer, A.N., Dreybrodt, W. (Eds.), Speleogenesis. Evolution of karst aquifers. National Speleological Society, Huntsville, p. 274-281. Tierney, J., 1985. Caves of northeastern Kentucky (with special emphasis on Carter Caves State Park). In: Dougherty, P.H. (Ed.), Caves and karst of Kentucky. Kentucky Geological Survey, Lexington, KY, p. 78-85.

✣ **Proceedings - with and without editor(s):** Jakopin, P., 1981. Macrostereological evaluation of cave space. In: Kalisnik, M. (Ed.), Stereologica Iugoslavia, contemporary stereology. Proceedings of the 3rd European Symposium for Stereology, Ljubljana, 3, 621-628. Gede, M., Petters, C., Nagy, G., Nagy, A., Mészáros, J., Kovács, B., Egri C., 2013. Laser scanning survey in the Pál-völgy Cave, Budapest. In: Buchroithner, M.F. (Ed.), Proceedings of the 26th International Cartographic Conference. International Cartographic Association, Dresden, 905 p.

✣ **Unpublished Masters thesis or PhD dissertation:** Hubbard, J.D., 2017. 3D cave and ice block morphology from integrated geophysical methods: A case study at Scărişoara Ice Cave, Romania. Unpublished MS Thesis, University of South Florida, 98 p.

✤ **Maps** Dimitrescu, R., Patrulius, D., Popescu, I., 1971. Geological map of Romania, Rucăr Sheet. Scale 1: 50.000, Institutul de Geologie şi Geofizică, Bucureşti.

✤ **Web references:** Karst Information Portal. https://digital.lib.usf.edu/karst [accessed: June 27, 2017]. UNESCO. Caves of the Buda Thermal Karst System. http://whc.unesco.org/en/tentativelists/282/UNESCO [accessed: March 6, 2019].

✤ **Reference to a data set:** Dragusin, V., Onac, B.P., Staubwasser, M., Hoffmann, D.L., Assonov, S., 2018. Stable isotope and U-Th age data on last glacial speleothems from Ascunsa Cave (South Carpathians) and Tausoare Cave (East Carpathians), Romania. *PANGAEA*, https://doi.pangaea.de/10.1594/PANGAEA.892728.

✤ **Software:** Ludwig, K.R., 2012. User's manual for Isoplot 3.75: A geochronological toolkit for Microsoft Excel. Berkeley Geochronology Center Special Publication 5. (http://www.bgc.org/isoplot_etc/isoplot/isoplot3_75- 4_15manual.pdf). Reimer, P.J., Reimer, R., 2009. CALIBomb radiocarbon calibration. (http://calib.org/CALIBomb/)

10.References should be cited in the text in parentheses, e.g. "(Jones, 1961)" except when the author's name is part of the sentence, e.g. "Jones (1961) has shown that...". When reference is made more than once to the same author and year, a, b, c, etc. should be added to the date in the text and in the reference list. For two authors cite in the form (Palmer & Palmer, 2000a); for more than two authors (but less than ten) cite in the form (Klimchouk et al., 1995); for more than ten authors cite the first five and then add *et al.* Multiple citations are listed in chronological order and separated by **;** (e.g., White et al., 1988; Palmer, 2001).

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ANEXO C – COMPROVANTE DE ACEITE DO ARTIGO 1

Revista Brasileira de Geomorfologia

[RBGeomorfologia] Decisão editorial
2 mensagens

Romario Trentin via Revista Brasileira de Geomorfologia <pen-bounces@emnuvens.com.br> 31 de outubro de 2023 às 07:35
Responder a: Romario Trentin <romario.trentin@gmail.com>
Para: Raphael Parra <raphaelparra95@gmail.com>, Ricardo Galeno Fraga de Araujo Pereira <fraga.pereira@ufba.br>, Carlos Gleidson Campos da Purificação <carlos_purificacao@hotmail.com>

Raphael Parra, Ricardo Galeno Fraga de Araujo Pereira, Carlos Gleidson Campos da Purificação,

Foi tomada uma decisão sobre o artigo submetido à Revista Brasileira de Geomorfologia,
"Carste Carbonático e Siliciclástico na Chapada Diamantina, Bahia, Brazil".

A decisão é: Aceitar

A partir de agora o trabalho passará pelo processo de edição e será publicado na sequência.

Atenciosamente,
Editores da RBG

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