

19th INTERNATIONAL CONGRESS OF SPELEOLOGY

38º Congresso Brasileiro de Espeleologia

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

PROCEEDINGS

VOLUME V

Session 11: Artificial Caves
Session 12: Pseudokarst and Non-Traditional Karst
Session 13: Volcanic Caves
Session 14: Climatology and Monitoring
Session 15: Special Topics



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FOREWORD

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

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

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Session 11

ARTIFICIAL CAVES

Cavernas? O uso do termo nos relatórios técnicos sobre o caso da subsidência de solo em Maceió (AL)

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Resumo

O presenter trabalho compõe pesquisa exploratória qualitativa no campo da Geografia Humana. Tem por objetivo sucitar reflexões e ampliar discussões, sobre os desafios identificados, por pesquisadores fora da geoespeleologia quanto ao uso do termo ceverna. Isso porque no Relatório Síntese da CPRM/SGB e Relatório da CPI da Braskem, que tratam sobre a subsidência do solo urbano e Maceió (Al), usa o termo caverna para designar formação subterrânea resultante de extração de salgema, por técnicas de dissolução.

Abstract

This work is part of a qualitative exploratory research in the field of Human Geography. It aims to stimulate reflections and broaden discussions on the challenges identified by researchers outside geospeleology regarding the use of the term ceverna. This is because in the CPRM/SGB Synthesis Report and Braskem's CPI Report, which deal with urban soil subsidence and Maceió (Al), the term cave is used to designate an underground formation resulting from the extraction of salt

Resumen

Ce travail s'inscrit dans le cadre d'une recherche exploratoire qualitative dans le domaine de la géographie humaine. Il vise à stimuler la réflexion et à élargir les discussions sur les défis identifiés par les chercheurs en dehors de la géospéléologie concernant l'utilisation du terme ceverna. En effet, dans le rapport de synthèse CPRM/SGB et le rapport CPI de Braskem, qui traitent de l'affaissement des sols urbains et de Maceió (Al), le terme grotte est utilisé pour désigner une formation souterraine résultant de l'extraction du sel.

1. Introdução

A dialética como a ferramenta comunicativa para a busca do conhecimento. (MARX, 1976, SANTOS, 2000) a dialética devia ser "o princípio dinâmico do materialismo".

No dia 03 de março de 2018, um de tremor de terra de magnitude 2,4 da Escala Richter abalou os bairros Pinheiro, Bebedouro, Bom Parto e Mutange e outros bairros, localizados a mais de 5 km de distância, como o de Cruz das Almas no município de Maceió (AL).

Simultaneamente ao terremoto ocorreu um estrondo que foi percebido por todos que residiam no perímetro alcançado pela subsidência. (LETRAS AMBIENTAIS, 2019; CPRM, 2019; GALINDO, 2022; MPF, 2023; BRASKEM, 2023; MACEIÓ, 2023,). O afundamento do solo em uma região de 3,6 km² já atingiu, diretamente, 60.000 pessoas, obrigadas a deixar suas casas, a abandonar seu passado, e a encontrar novo endereço em uma cidade que já era caracterizada por um déficit habitacional de 27.000 moradias (BRASIL, 2024, p.8).

O afundamento do solo em uma região de 3,6 km² já atingiu, diretamente, 60.000 pessoas, obrigadas a deixar suas casas, a abandonar seu passado, e a encontrar novo endereço em uma cidade que já era caracterizada por um déficit habitacional de 27.000 moradias (BRASIL, 2024, p.8).

A hipótese inicial para o ocorrido, conforme descreveu o engenheiro Abel Galindo, era de que o terremoto poderia estar associado à reativação de falhas geológicas, provocadas pela excessiva extração de água na área da mineração (GALINDO, 2022, p. 39).

No decorrer das investigações, as hipóteses, apresentadas pela CPRM/SGB levou em consideração o contexto geológico e geomorfológico da região, associados a ocupação de forma desordenada, bem como o aproveitamento mineral em área urbana, desta forma chegaram a quatro hipóteses:

Hipótese 1: Características geotécnicas dos solos da região e forma de ocupação do bairro; Hipótese 2: Presença de vazios (cavidades, cavernas) no solo e subsolo da região decorrente de causas naturais ou de ações antrópicas; Hipótese 3: Estruturas/feições tectônicas ativas na região (falhas, descontinuidades, por exemplo); Hipótese 4: Explotação de água subterrânea (CPRM, 2019, p.11).

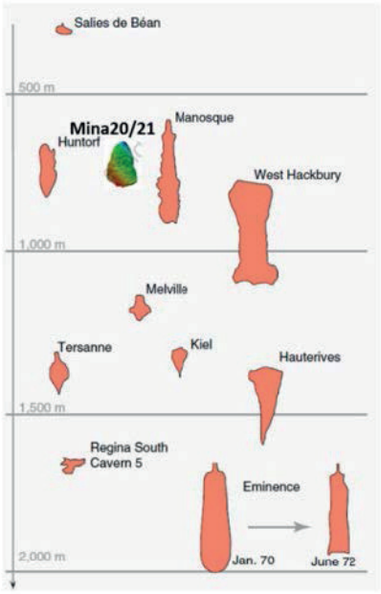
A partir de investigações por parte da CPRM/SGB "Estudos sobre a instabilidade do terreno nos bairros Pinheiros, Mutange, Bebedouro, em Maceió (Al): ação emergencial no bairro Pinheiros. Volume I, foi concluido no ano de 2019.

Nas considerações finais sobre a hipótese 2 apresentam a premissa de cavidades decorrentes de dissolução de rochas em superfície ou desabamento de minas na extração de sal-gema, como as minas 7 e 19. Em seguida no desenvolvimento cita-se a seguinte conclusão,

A sismologia mostrou sismos coincidentes com as minas de extração. A gravimetria demonstrou a existência de anomalias negativas de massas associadas com as cavernas produzidas pela extração de sal. O método geofísico audiomagnetotelúrico mostrou a existência de anomalias resistivas em profundidade que seriam geradas por cavidades

de mineração em desabamento (CPRM-SGB, 2019 p.11)

O relatório do SGB/CPM foi mencionado no Relatório da CPI da Braskem e o Caderno Técnico do Plano Diretor de Maceió, ambos no ano de 2024. No decorrer da análise desses três documentos, observamosa que palavra caverna foi utilizadas, variadas vezes para designar as cavidades subterrâneas resultantes de uma ação não natural, isso é em virtude da extração de salgema nas 35 minas da Braskem S.A. em Maceió.



Perfil de profundidade de cavernas salinas mineradas[27].

Figura 1: *Perfil de profundidade das "minas" "cavernas segundo CPI da Braskem. Fonte: Senado Federal, 2024, p.64.*

No Caderno Técnico do Plano Diretor de Maceió foi apontado a seguinte questão « do ponto de vista técnico, a susdidência do solo é um fenômeno geotécnico associado ao rebaixamento da superfície do terreno e geralmente ocorre após interferências humanas na retirada de suporte subterrâneo (MARTINELI op cit MACEIO, 2024). Continuam, em Maceió, o uso indiscriminado dos recursos naturais , percebidos pela extração irregular de sal-gema, criaram grandes cavernas no subsolo, reduzindo o nível do terreno. Essas cavidades, quando não estabilizadas adequadamente, podem colapsar provocando deformações significativas na superfície (MACEIÓ, 2024, p.20)

O termo caverna foi utilizado para designar feições nas área de subsidência, que resultou no afundamento do solo urbano de cinco bairros maceioenses. A extração de sal-gema em Maceió, teve início na década de 1970, e a subsidência do solo urbano resultou no deslocanto forçado de aproximadamente 60 mil pessoas e vem sendo considerado pelos atingidos, como o maior crime-sociambiental urbano do mundo.

Os estudos sobre cavernas apontam que em termos geomorfológicos as cavernas não estão isoladas da paisagem. Elas compõe um relevo muito próprio denominado de relevo cárstico. As cavernas constituem feições subterrâneas que fazem parte de um contexto geológico e ambiental que inclui desde as rochas nas quais se inserem como também seu entorno natural, integrando um sistema que abrange e depende de múltiplas variáveis ambientais e se estende por uma área que, em geral, extrapola em muito o entorno imediato da caverna (AULER e ZOGBI, 2011; AULER e PILÓ, 2019). Esses autores definem que as, cavernas constituem feições subterrâneas que fazem parte de um contexto geológico e ambiental que inclui desde as rochas nas quais se inserem como também seu entorno natural, integrando um sistema que abrange e depende de múltiplas variáveis ambientais e se estende por uma área que, em geral, extrapola em muito o entorno imediato da caverna. (AULER; PILÓ, 2019, .p.42).

As cavernas podem se formar em rochas carbonáticas e rochas não carboáticas. AULER (2019) destaca que dentre as rochas não carbonáticas em que ocorrem processos químicos e a consequente geração de um número expressivo de cavernas, citam-se gesso, sal, quartzito, arenito e formações ferríferas. O autor registra que cavernas em gesso e sal ainda não foram descritas no Brasil (AULER; PILÓ, 2019, .p.49).

O Serviço Geológico do Brasil, SGB classifica "O termo caverna (do latim cavus, buraco) designa qualquer cavidade natural em rocha com dimensões que permitam acesso a seres humanos. Pode ser de vários tipos, conforme topografia, comprimento e forma. O órgão ressalta que as cavernas se formam principalmente por dissolução das rochas. Por isso, são muito mais comuns em zonas de rochas carbonáticas, como mármores e calcários. Embora a calcita, mineral que forma os calcários e mármores, seja um carbonato de cálcio pouco solúvel em água, se essa água absorver pequenas quantidades de dióxido de carbono formará ácido carbônico (SGB, 2014).

De acordo com Miranda (2015) em termos legais, "entende-se por cavidade natural subterrânea todo e qualquer espaço subterrâneo acessível ao ser humano, com ou sem abertura identificada, popularmente conhecido como caverna, gruta, lapa, toca, abismo, furna ou buraco, incluindo seu ambiente, conteúdo mineral e hídrico, a fauna a flora ali encontrados e o corpo rochoso onde os mesmos se inserem, desde que tenham sido formados por processos naturais, independentes de suas dimensões ou tipo de rocha encaixante (art. 1º, parágrafo único do Decreto 99.556/90).

Para esse autor, já para finalidades jurídicas, as cavidades naturais subterrâneas e suas áreas de influência são considerados espaços territoriais especialmente protegidos, cujo regime jurídico depende da avaliação de seu grau de relevância, sendo vedada a utilização que comprometa a integridade dos atributos que justifiquem essa proteção (MIRANDA e CHIODI, 2015, p.58).

De acordo com a Sociedade Brasileira de Espeleologia, as Cavernas são encontradas em todas as partes do mundo, mas apenas uma pequena parte delas já foi explorada, catalogada e mapeada por espeleólogos. Ressaltam ainda que o Brasil é pioneiro no cadastro e gerenciamento de cavernas na América Latina.

Considerando o estudos de Auler (2019), e dados disponíveis sobre cavernas pela da Sociedade Brasileira de Espeleologia, assim como do CECAV bem como o que define o decreto 6640/2008, porquê designar cavernas de sal na área da exploração de salgema ? O uso desse termo caverna para designar formações diferentes não pode gerar conflitos de interpretação equivocada para a sociedade civil leiga sobre o assunto?

2. Materiais e métodos

Este trabalho trata de uma pesquisa exploratória, sob o método materialista dialético e das múltiplas combinações no campo da cieência Geográfica. A análise documental « Relatório Síntese da CPRM/SGB » (CPRM/SGB, 2019); Relatório Final da CPI da Braskem (SENADO FEDERAL, 2024), Caderno Técnico do Plano Diretor de Maceió (MACEIÓ, 2024).

Realizando o comando de pesquisa pelo "Ctrl F" na ferramenta do Word Windows 10 ou pelo PDF, identificamos no relatório técnico da CPRM – Companhia de Pesquisa de Recursos Minerais, sobre a instabilidade do solo em bairros em Maceió(AL), que o termo cavernas foi mencionado 07 (sete) .vezes, no Relatório da CPI – Braskem do Senado Federal, No respectivo relatório que possui 1335 (hum mil trezentas e trinta e cinco) páginas, o termo caverna apareceu por 87 (oitenta e sete), em diferentes momentos. No Caderno Técnico do Plano Diretor de Maceió, a palavra caverna apareceu por 02(dua)s vezes.

Por se tratar de documentos de órgãos públicos e que servem de base para outras pesquisas, procuramos identificar nos dados disponíveis

pela SBE e no CECAV, por meio do Cadastro Nacional de Cavernas sobre a existência de cavernas para a área das minas de sal-gema em Maceió.

Dessa forma nossa inquietação surge, na medida que desconhecíamos informações sobre a existência de cavernas, no município de Maceió, portanto por que o termo foi utilizado tantas vezes em documentos de diferentes instituições públicas e esferas governamentais?

Para tanto realizamos pesquisas no Cadastro Nacional de Cavernas que é o principal bancos de informações de cavernas da Sociedade Brasileira de Espeleologia disponível no sitio eletrônico: https://sbecnc.org.br/Regions.aspx, e no banco de informações do Cadastro Nacional de Informações Espeleológicas do CECA- ICMBio - CANIE disponível no sítio eletrônico: https://canie2.sisicmbio.icmbio.gov.br/relatorio

Ministério do Meio Ambiente
Instituto Chico Mendes de Conservação da Biodiversidade
Diretoria de pesquisa, avaliação e monitoramento da biodiversidade
Centro nacional de pesquisa e conservação de cavernas
Rodovia BR-450, km 8,5 - Via EPIA, Parque Nacional de Brasília - CEP: 70635-800
Brasília - DF
Telefone: (61) 2028-9792 | Email: cecav.sede@icmbio.gov.br

CANIE ICMBio-CECAV

ICMBio MMA

Cavernas por UFs

(Brasília, DF 18/12/2024)

Nome	Total do estado	Porcentagem do total
AL	30	0.11 %
Total	30	100 %

***Figura 2**: Fonte: MMA, 2024.*

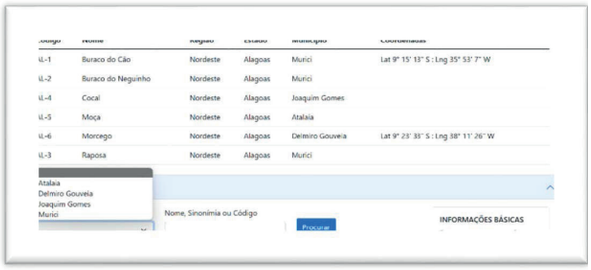


***Figura 3:** Cavernas do Estado de Alagoas – CNC-SBE 2024. Fonte: https://sbecnc.org.br/Regions.aspx#AL consulta em 18/12/2024.*

3. Resultados

Ao analisarmos o banco de dados do Cadastro Nacional de Cavernas(CNC) da Sociedade Brasileira de Espeleologia, há um cadastro de 9216 cavernas cadastradas. Ao realizarmos o filtro por regiões, em números absolutos a Região Sul (768), Centro-Oeste (1.234), Nordeste (1.579), Norte (1851) e Sudeste (3.784).

Quando se realiza um recorte para a região nordeste, mas especificamente para o estado de Alagoas, identifica-se cavernas nas cidades de Murici (3), Atalaia, Delmiro Gouveia, Joaquim Gomes, com uma caverna para cada um desses municípios e totalizando 06 cavernas registradas no CNC, no estado.

Diante dos dados, não há registros oficiais de cavernas no município de Maceió, cuja informação é de importante relevância para tomada de decisões dos órgãos ambientais de gestão e fiscalização, e planejamentos públicos e de empreendimentos privados.

No final de 2021 e início de 2022, a comunidade espeleológica brasileira e internacional, assim como vários setores sociedade civil organizada, manifestaram preocupação com a publicação do Decreto Presidencial 10.935. Isso porque apresenta ameaças significativas na destruição das cavidades naturais brasileiras.

A Sociedade Brasileira de Espeleologia manifestou preocupação, vários textos de entidades diversas foram publicados na edição do SBE Notícias nº 427. A seguir uma passagem da manifestação da diretoria da instituição.

> O Decreto n° 99.556/1990, que versava sobre a proteção das cavidades naturais subterrâneas existentes em território nacional. O verbo no passado (versava) não está equivocado, pois o novo decreto em vigor com toda certeza não trata sobre a proteção das cavernas brasileiras, pelo contrário, representa uma grande ameaça de destruição das mesmas e do patrimônio natural e cultural a elas associados. Tal constatação é consenso junto a grande parte da comunidade espeleológica brasileira e mesmo de outras áreas do conhecimento que estuda e/ou que trabalha com as cavernas no Brasil, visão compartilhada também por nossos pares fora do país. O Decreto no. 10.935/2022 constitui um retrocesso na área ambiental, mais um promovido pelo atual Governo Federa (SBE, 2022, p.1).

A definição de cavernas no Decreto 10.935, no "Parágrafo único. Considera-se cavidade natural subterrânea o espaço subterrâneo acessível pelo ser humano, com ou sem abertura identificada, conhecido como caverna, gruta, lapa, toca, abismo, furna ou buraco, incluídos o seu ambiente, o conteúdo mineral e hídrico, a fauna e a flora presentes e o corpo rochoso onde se inserem, desde que tenham sido formados por processos naturais, independentemente de suas dimensões ou tipo de rocha encaixante.

A autora Trajano (2022) sobre o Decreto 10.935/2022, que foi a falta de transparência e equívocos conceituais.

> Os problemas dos Decretos no 6.640/2008 e 10.935/2022, I. Total falta de transparência: os decretos foram elaborados dentro do Ministério de Minas e Energia (MME), sem ampla consulta da comunidade de espeleólogos, especialistas no tema e Ministério do Meio Ambiente (MMA), ao contrário do esperado em um país efetivamente democrático. Como consequência, temos decretos eivados de equívocos conceituais e metodológicos, que não cumprem os objetivos da Conservação. (TRAJANO, 2022, p.14)

Identificamos ainda com essa pesquisa que há diferenciação técnica no que se chama de caverna na área de subsidência de solo resultante da extração de sal-gema em Maceió, e para as cavidades naturais subterrâneas tratadas pela comunidade espeleológica.

4. Discussion

Na nossa pesquisa percebemos que há diferenciação técnica no que se chama de caverna na área de subsidência de solo resultante da extração de sal-gema, para as cavidades naturais suberrâneas tratadas pela comunidade espeleológica.

Nesse sentido, quando nos deparamos com o uso de termos cavernas nos relatórios técnicos sobre o caso subsidÇência de solo em Maceió, encontramo-nos em conflitos sobre a abordagem e de possíveis riscos futuros.

Isso porque ao se tratar da legislação vigente e de que o Brasil, principalmente a partir de 2016, vem sofrendo constantes ameaças para o desmonte da legislação ambiental, para atender interesses da mais -valia, o uso do termo caverna sem uma ampla discussão pode levar futuramente a naturalização de algo que não é natural.

5. Conclusion

> Quanto mais um país é aberto, mais desordem é criada, e mais necessita de regulação, isto é o Estado. (SANTOS, 2000, p.40)

Dessa forma, as nossas reflexões visam trazer reflexões sobre uma possível utilização indiscriminada, do termo caverna, buscando "naturalizar", uma produção pela ação antrópica, nessa era Antropogênica, que foi a produção de cavidades no subsolo da cidade de Maceió, decorrente da extração de salgema pela empresa Braskem.

Conforme dados do CNC – SBE e CANIE, não há registro de cavernas em Maceió, e o mapa produzido em 2024, para áreas de potenciais espeleológicos o município maceioense também não encontra como área de potencial.

Ressaltamos que legislação ambiental brasileira para proteção as cavidades naturais, mas acima de tudo nas investidas de desmonte dessa legislação na última década para atender interesses exclusivamente econômicos, como foi o caso da tentativa de aprovação do Decreto 10.935/2022, que embora fora suspenso pelo Superior Tribunal Federal, marcou graves ameaças ao patrimônio espeleológico.

No caso do decreto avançar, será que precedentes podem ser abertos para novas mudanças para o tratamento sobre as cavidades, uma vez que há teóricos que afirmam que repetir um termo por várias vezes, pode ser aceito para algo que não o era inicialmente? Por que o uso do termo cavernas para discriminar minas produzidas pela ação antrópica da mineração?

Reportando ao geógrafo Milton Santos (2000), esse destaca que as normas participam do processo de produção da ordem privada que amplia o poder de alguns atores (...). O autor enfatiza que a produção de normas é incessante, porque a mais-valia é doravante, esta sempre querendo mais, exigindo mais.

A mais valia se torna universal e é um paradoxo do mundo atual. É um produto ideológico, impalpável, ela está sempre fugindo, mas para frente. Isso faz com que no domínio da norma nada seja permanente, porque as empresas mudam os regulamentos para se adaptarem ao ambiente movediço. As normas que são boas num dado momento deixam de sê-lo no momento seguinte.(SANTOS, 2000, p.40).

No contexto em que o neoliberalismo "se esforça cada vez mais para atender seus interesses de acumulação capitalista, no qual os recursos naturais, em especial os minerais, dos países da periferia do sistema encontram-se na berlinda, constante são as ameaças ao desmonte das instituições democráticas brasileiras. A legislação ambiental fica a mercê do "passar a boiada", com um peso maior entre os anos 2016 a 2022, não por acaso quando tivemos dois grandes crimes socioambientais, em territórios diferentes, a saber em Maceio (AL) no ano de 2018 e em Brumadinho (MG, no ano de 2019.

Sobre o Decreto 10.935/2022, conforme informou a Sociedade Brasileira de Espeleologia,

> A decisão monocrática do então Ministro do Supremo Tribunal Federal (STF) Ricardo Lewandowski, do dia 24 de janeiro de 2022, que por meio da medida cautelar pleiteada na Arguição de Descumprimento de Preceito Fundamental 935 – Distrito Federal (ADPF 935/DF) suspendeu, ad referendum do Plenário, até julgamento final, a eficácia dos arts. 4º, I, II, III e IV e 6º do Decreto 10.935/2022, de modo a propiciar a imediata retomada dos efeitos do então revogado art. 3º do Decreto 99.556/1990, com a redação dada pelo Decreto 6.640/2008, nos termos do art. 5º, § 1°, da Lei 9.882/1999". Na mesma decisão foi apensada a ADPF 937/DF ajuizada pelo Partido Verde, por se tratar, simultaneamente, de "impugnação da validade constitucional do Decreto 10.935/2022"(SBE, 2022, p.1).

A atuação da sociedade espeleologica e sociedade civil surtiu efeito para supensão do decreto. No entanto, mesmo com atuação da sociedade civil brasileira para garantir a democracia e o respeito às prerrogativas da Constituição Federal de 1988, "o passar a boiada" continua sendo na pauta dos setores conservadores neoliberais.

Assim, devemos nós intelectuais e sociedade civil organizada nos não nos preocupar com utilizações terminológicas "aparentemente equivocadas" em documentos publicados por órgãos oficiais brasileiros?"

Fica nossa consideração. Que possamos ampliar o diálogo.

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Historical artificial caves in Brazil: from a fashion to an art and architectural proposal (or vice versa)

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Abstract

This study investigates the presence of artificial caves in several Brazilian cities, built at the end of the 19th and beginning of the 20th centuries, influenced by the Romantic style of the European Belle Époque. These structures attempt to mimic natural caves and were common elements in gardens and squares, serving as spaces for leisure and contemplation of nature. Their characteristics, construction materials, and historical context. Most of the caves were built in concrete or reinforced concrete and decorated with elements that imitated stalactites, stalagmites, and rocks. Many of them had artificial waterfalls and lakes, creating a bucolic and inviting atmosphere. The article highlights the importance of these constructions as historical and cultural heritage, evidencing the influence of European aesthetics on Brazilian landscaping. However, it warns of the loss of many of these caves due to urban reforms, abandonment, and lack of preservation. It is concluded that artificial caves represent a unique form of art and architecture, allowing visitors a unique experience of immersion in a simulated natural environment. The preservation of these constructions is fundamental for understanding Brazilian history and culture.

Resumo

Este estudo investiga a presença de cavidades artificiais em diversas cidades brasileiras, construídas no fim do século XIX e início do XX e influenciadas pelo estilo romântico da Belle Époque europeia. Essas estruturas tentam imitar grutas naturais e foram elementos comuns em jardins e praças, servindo como espaços de lazer e contemplação da natureza além de suas características, materiais de construção e contexto histórico. As grutas eram, na maioria, construídas em cimento ou concreto armado e decoradas com elementos que imitavam estalactites, estalagmites e rochas. Muitas delas possuíam cascatas e lagos artificiais, criando um ambiente bucólico e convidativo. O artigo destaca a importância dessas construções como patrimônio histórico e cultural, evidenciando a grande influência da estética europeia no paisagismo brasileiro. No entanto, alertamos para a perda de muitas dessas grutas devido a reformas urbanas, abandono e falta de preservação. Conclui-se que as cavernas artificiais representam uma forma singular de arte e arquitetura, que permitia aos visitantes uma experiência única de imersão em um ambiente natural simulado. A preservação dessas construções é fundamental para a compreensão da história e da cultura brasileira.

1. Introduction

The representation of nature is present in many art expressions. Especially in graphical and painted artworks, themes like mountains, rivers, waterfalls and seas were portrayed in various artistic moments throughout human history. Architecture and urbanism took part in many of such tendencies of landscaping, they seeked to imprison or approach certain natural elements as a way to delight urban populations or for private areas, focused on leisure and idleness. The representation of artificial cavities in those environments also went through history and, in accordance to Laura Stagon (PRIMOCANALE, 2024) the representation of artificial grottos in the city of Genova, Italy "*wanted to give an idea of a greater adherence with nature*" (authoral translation) in mannerist gardens in the 16th and 17th century.

For decades, caves continued to be represented in open spaces and to adorn gardens and squares in the 19th and 20th centuries. The attempt to copy nature produced numerous artificial grottos that varied in size and internal area, but always maintained aesthetic contents that imitated stalactites, stalagmites, waterfalls and rocks. In Brazil, during this period – politically, the country transitioned between the Empire and the Republic – it was the European Romanticism or the *Belle Époque* that stimulated the creation (through the inaugural use of reinforced concrete) of a series of objects for the urbanization of squares and palace gardens, which composed a natural environment produced by the human hand. This trend, which spread throughout the country in various public and private spaces, seems to have followed the fashion brought from Europe through rocailles, executed by landscapers who, in Brazil, came to be called "cascateiros" or "those who produce fake waterfalls". The city of Rio de Janeiro was the focus of this "fashion" in the 19th century as it was the administrative center of Brazil, from where the Imperial Family, its court and politicians, tried to Europeanize technological and cultural achievements to implement the innovations in the capital of the Empire (BORGES, 2005), even though they lived in a country whose main economy was agriculture.

The need to create public spaces was also an issue that had to be addressed in Brazil, since the hygienist principles advised for a life that reconciled human beings with nature. However, deprived of public transportation or given the difficulty to access preserved natural areas, far from cities, the solution was to imitate nature, this artifice turns natural anomalies – such as caves or waterfalls – into commonplaces. This was the reason why public squares or even gardens of mansions and palaces in several cities with large financial circulation were the

sites of construction of interesting artificial caves that imitated nature and adopted the foreign tradition of landscaping (FARIA, *et al.*, 2022).

In Rio de Janeiro, from 1876 onwards, artificial caves were used as a simulacrum of nature and allowed visitors to explore an almost aphotic environment, adorned with stalactites, stalagmites, running water and a high point from which they could appreciate the rest of the region, as a viewpoint of the square. The largest cave, the grotto in "Praça de Santana" (or current Praça da República) is 123 meters long that can be walked through two floors, between lakes and large cement blocks, which imitates the granite boulders of the region. According FARIA *et al.* (2022), the four artificial caves studied

> are great leisure options and even scientific, architectural and historical attractions and are one of the few types of Art that allow visitors to be inserted in their internal spaces.

This work aims to highlight the existence of a series of historical artificial cavities throughout the Brazilian territory. The caves demonstrate the artistic and cultural influence exerted by the period known as the *Belle-époque*, which occurred between the end of the 19th century and the first decade of the 20th century, and also express a curiosity about the underground, a fact that connects the history of landscaping with Speleology. This article also aims to describe differences and similarities between the many artificial cavities throughout the Brazilian territory that goes far beyond those that were presented at the International Speleology Congress in France in 2022 (FARIA, *et al.*, 2022).

2. Materials and Methods

Methodologically, the research based itself in searches through historical databases from national, regional or municipal sources, as well as content of books, magazines and newspapers of the period. Some of the caves presented below that still exist today were visited by the authors. Those in more distant states were examined using current images available on tourism websites and videos or even on Google Maps.

It is also worth noting that, in this text, only those cavities that allow or allowed internal visits and have or had architectural relevance in gardens are considered "artificial caves". This excludes other constructions with religious appeal, very common in Brazil, and which treat as "grottes" only small shelters for altars to saints of Catholic devotion.

3. Results

After our first publication in 2022, another important artificial cavity was found in the city of Rio de Janeiro (UTM - 676932; 7459669, 23 K). It's located in a listed historical heritage site in the neighborhood of Alto Boa Vista, it is privately owned, an attempt to visit was frustrated due to the lack of responsible parties. The summer palace of the Baron of Itamaraty was built in the area, which later gave way to the White and Itamaraty hotels between 1903 and 1917 (CASA SENHORIAL, n.d.). Documents from the early 20th century praise the gardens of the space – the ''Eden of Brazil'' (LLOYD, 1913) – where names such as Dom Pedro II (former emperor of Brazil) and Theodore Roosevelt (former president of the USA) passed through. The cave is a construction with the same characteristics of other artificial caves in the city of Rio: has alternating entrances, is well lit, has stalactite structures, iron bars and is fronted by the passage of an artificial canal or river. This description was made possible thanks to a video (https://www. youtube.com/watch?v=FugD_IMFJvM) in which a person, who is probably responsible for the renovation that has been underway for the past three years, states that the cave was the work of Auguste Glaziou (1833-1906), the same French who created the grottos in Praça da República and Quinta da Boa Vista (FARIA, et al., 2022). This information could not be confirmed, since neither historical documentation nor old photos were found, only a newspaper report of the "very interesting and picturesque cave" (Fig. 1) from 1903 that describes the garden of the Hotel Whyte (JORNAL DO BRASIL, 1903). In the place where the cave was located, there is a bandstand with characteristics of a *rocaille* construction.

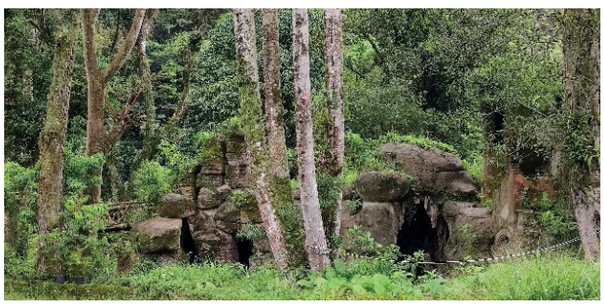


Figure 1: *cave of Palacete do Barão do Itamaraty.*

Two other caves analyzed in this study also resort to the same style. One of them is in the largest brazilian city, São Paulo – capital of the state of São Paulo (SP) – and can be freely visited in Jardim da Luz, the first "public garden" opened in the capital of the state, which offers a huge green space in a historic part of the metropolis. The park was once the "Botanical Garden" and today offers its visitors an excellent infrastructure of paths, an artificial lake, a theater and a couple of leisure areas. The cave was built in 1879 during the regency of Laurindo Abelardo de Brito (1828-1885) and functioned as a "reservoir for distributing 38 cubic meters of water" (JORNAL A TARDE, 1879). Another newspaper describes the cavity as follows:

> A laborious artificial grotto, at the top there is a tank, which one climbs up a grass-covered hill, and makes a pleasant meandering journey through two snake-like paths (CORREIO PAULISTANO, 1879).

In the same way the caves in Rio de Janeiro, the Jardim da Luz cave has a waterfall that, when it was operational, was the source of water that circulated throughout the park, supplying aquariums. Inside, you can see that iron bars were used to provide structure to the cement used in the walls, ceiling and formations, such as stalactites and stalagmites. The external landscape consists of bridges and benches that imitates rustic trunks and branches, in which leaves, vines and even knots can be seen in the wood. The Jardim da Luz cave is also the highest point in the square and visitors are allowed to climb to its top to admire the park (Fig. 2). The cavity is small, about 12 m, and consists only of an entrance and an exit, besides the open part for the waterfall.

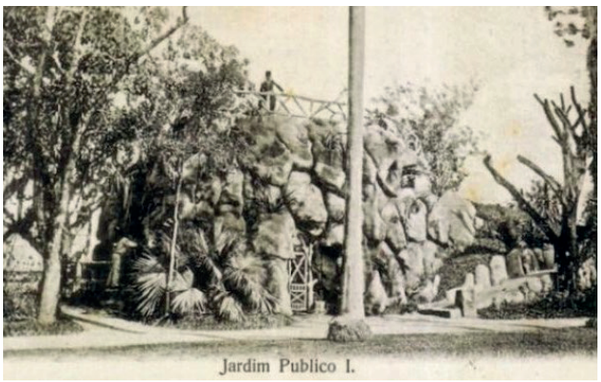


Figura 2: *Grotto with lookout on Jardim da Luz (postcard Laemmert & C., n .d.).*

The other artificial cave built at the end of the 19th century is attributed to the French landscaper Paul Villon (1841-1905). During the construction of the artificial grottos in Rio de Janeiro, he was Glaziou's right-hand man and primarily responsible for the design of parks and squares in Belo Horizonte, a city planned and built to be the new capital of the state of Minas Gerais (MG). Using French influence in the construction of open spaces, Paul Villon is responsible for the design of the Praça Municipal, the Praça da Liberdade and the gardens of the Palácio dos Governadores (or Palácio da Liberdade), the latter being the place from which state governors make their dispatches. Despite the numerous changes and modern projects that changed the layout of the squares, constructions in the *rocaille* style left by the French architect can still be seen in the gardens of the Palace, including the interesting, yet tiny, grotto of the Palácio da Liberdade (Fig. 3).

This artificial cavity is also built in reinforced concrete and once again a steel structure for structural maintenance can be seen, since above it the cave supports a rustic bandstand with a railing and benches that imitate twisted trunks and branches. The view is completed by a small artificial lake, while on the right side of the lake is an orchid greenhouse where one of the former governors of the state, João Pinheiro (1860-1908) like to spend some time (Fig. 3).

The artificial cave in the garden of the Palácio da Liberdade has been wrongly attributed to another artist, a Portuguese rock mason who lived in the south of the state of Minas Gerais, where he left his mark as a great master as a "master *waterfaller*" (or *cascateiro*: ''who makes waterfalls'') in the squares and public plazas of many cities. Francisco da Silva Reis - or Chico Cascateiro as he came to well know - left his works in the cities of Caxambu and Águas de Lindóia, among others. He imitated masterfully details that would goes unnoticed by the untrained eye, such as the wood ear fungi, knots and stalks of bamboo and thorns from trees in the region, such as 'barriguda' (*Ceiba Speciosa*), a common botanical species in the region.



Figura 3: *grotto of the Palácio da Liberdade (BH-MG) and its rustic bandstand in 1909 (*left*) e atual (*right*).*

Not far from there, back to the state of São Paulo (SP), a grotto in the city of Pindamonhangaba, in Praça Monsenhor Marcondes it's one of the most interesting artificial cavities in Brazil (Fig. 4). It is approximately 25 meters long in two parallel corridors. The cave, today closed to the public, also shows a water source and it was built in two phases, the first in 1900 and the second in 1972. This cave has an interesting detail: "the monkey man", as it is known by the locals, a cement sculpture of an Australopithecus, handling a bone as a tool, in an almost aphotic part of the construction. It was not possible to find documentation or old images of the Pindamonhangaba cave in newspapers and historical documents, but the inauguration plaque dated from 1900 leaves no doubt about its antiquity. The most curious details of this cave, which also used cement, rebar and bricks for its construction, is the attempt to imitate live animals such as frogs, rabbits, lizards and snakes, in addition to featuring cave formations made of cement from cloth that was molded with cement.

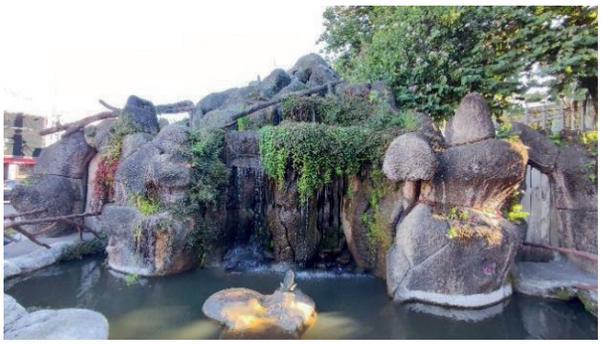


Figura 4: *artificial grottos of Pindamonhangaba (SP).*

Another cave, even further from the southeastern region of Brazil, can be found in Baronesa Park, in the city of Pelotas, state of Rio Grande do Sul (RS), close to the border with Uruguay. The impossibility of traveling to that city did not allow the authors to visit this cave, but from descriptions in an excellent video (https://www.youtube.com/watch?v=w92j7aIrRnM&t=3s) some insinuations could be made. Inside the cave, a date gives an idea of the period of its construction, 1883 (Fig. 5). The cave, unlike the others previously mentioned, does not have reinforced concrete and the bricks, in many visible places, form a structure similar to an igloo that was half-filled and covered with cement. In this apparent mass, numerous quartz crystals were placed (RIBEIRO *et al.*, 2023), torn out over time, and a few metal structures give a hint about the existence of a water source or waterfall.



Figura 5: *internal image of the cave in Baronesa park, showing the brick structure and date (in the background).*

*I*n the capital of the state of Espírito Santo (ES), the city of Vitória has a curious artificial cavern with no construction date established. The cavern located in Praça João Clímaco is undoubtedly the smallest of the caverns visited for this work, however, curious details made this cavern a complex work of architecture. The cavern is no more than 5 meters deep and is mixed with the stairs that give access to the highest part of the square (Fig. 6).



Figura 6: *grotto on plaza João Clímaco em Vitória (ES).*

The ornaments that imitate a real cave are scattered together with representations of a dragon, frogs, birds and snakes in cement or white plaster; two skylights, one on each side, provide natural light throughout the day, however, the cave had electric artificial lighting at some point. The cave is now closed with bars and its interior seems, even locked, to be a space and shelter for homeless people. The inhabitants of the houses in the surrounding area do not know the history of the place and resent the abandonment and contempt of the public administration. No type of documentation has been found that attests the date of construction of this cave, but the square, which was once called 'Largo de São Brás', underwent large transformations in 1910, when gained the bandstand and stairs that seem to be from the same date as the cave (LORDELLO, 2022).

In the northern region of Brazil, in the state of Pará (PA), the capital city Belém has a curious 19th-century cave in one of its squares. This is another cave that was not visited for this project, but it's considered a cave that illustrates the trend of building artificial grottos for public use. The cave also appears to have been made of reinforced concrete, allows access to the ceiling and is the source of an artificial waterfall that distributes water throughout the space (Fig. 7). It was built during the government of Antônio José de Lemos (1843-1913), "mayor" of Belém in 1900. Lemos describes the construction of the cave as follows:

> the construction services of waterfalls, streams and caves, directed by Mr. José de Castro Figueiredo, architect of the Intendancy... near a third lake in front of the cave, continuing more voluminous until the large central lake, where the two wide avenues intersect (BELÉM, 1902).

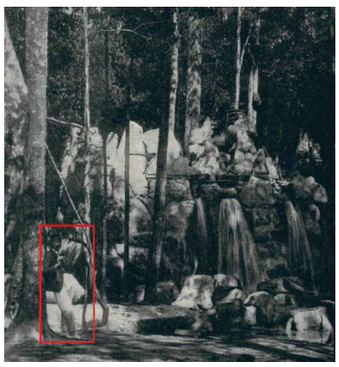


Figure 7: *cave of Rodrigues Alves Forest in Belém, 1902; emphasis on human scale (LEMOS, 1902).*

Annibal Amorim, during his trip across Brazil in 1909, thus portrays the city of Belém and his visit to the forest:

> Anyone who walks through the modern part of the capital of Pará has the feeling of being in a European city... One of the beautiful things about Belém is the Rodrigues Alves Forest, with its monuments, its bridges, its caves and its white waterfalls (AMORIM, 1909).

Unfortunately, not all of the historic caves built in the late 19th or early 20th centuries remained intact to this day. A large number of them were removed due to the expansion of urban areas, changes in aesthetic trends in landscaping and urban planning, or due to abandonment and neglect. This happened in Porto Alegre, the capital of Rio Grande do Sul (RS). A cave was built in 1881, along with other romantic ornaments, as one of the projects commissioned by the city government to the Italian set designer Oreste Colliva (NOVIDADE, 1923). The few images of the cavity that exists shows that it had a kind of arch that harmonized with other structures in the square, such as rustic bridges and water channels. Stalactites and runoffs were made to look like those of a natural cave, which is why it must have been criticized as being an "improvised cave" (NOVIDADE, 1923). The square underwent renovations in 1925 and the cave ceased to be one of the area's attractions (Fig. 8).



Figure 8: *demolition of the cave that existed in Praça XV de Novembro in Porto Alegre (1925).*

Besides Porto Alegre, two other cities in the interior of the state of São Paulo (SP) had their caves removed. Campinas and Ribeirão Preto, separated by a little over 220 km, had public squares adorned with artificial grottoes. In Campinas, further south, the place where the grotto existed was known, since its inauguration in 1876, as Jardim or Passeio Público de Campinas. The only images found of this grotto date from 1910 to 1920 (Fig. 9). The cave was also known as "cave of lovers" (MONICA & AMBRIZI, 1988).

> The Public Garden, nickname by which it came to be called Passeio Público after it was officially named Praça Imprensa Fluminense, at the beginning of this century was offered to the people as a pleasant and picturesque square. In the corner between Conceição street and Augusto César street, it had an artificial grotto, server at its top by a terrace and cement benches (MARIANO, 1979).



Figure 9: *image of the Campinas cave in which you can see the rocailles that imitate trunks on the bridge.*

In Ribeirão Preto, in Praça 13 de Maio, an artificial cave or arch (Fig. 10), similar to the grotto in Porto Alegre, represented a karst feature. It was located next to the Igreja Matriz de São Sebastião and also formed part of an English garden with other aesthetic elements. It was probably built in the early 20th century and the date of its demolition has not been found.



Figure 10: *cave in the 13th of Praça 13 de Maio, in Ribeirão Preto (SP).*

The city of Juiz de Fora (MG), in the historic Praça Halfeld, elements built using the rocaille technique reveal the presence of yet another artificial cave that was removed. No further information was found other than a photograph (Fig. 11) on a postcard and the lines in the newspaper 'O Pharol' which state that a music band played inside the cave on the day the square was inaugurated in 1901 (O Pharol, 1901).



Figure 11: *photo of Praça Halfeld in Juiz de Fora showing an artificial cave near what used to be a public library.*

Finally, another artificial cave was recorded in the city of Florianópolis, capital of the state of Santa Catarina (SC), in Praça XV de Novembro (Fig. 12) and has also been demolished. Like others, it was a cavity that allowed access and was the highest point of the square and supported a bandstand, all made in rocaille crafts. Little has been found about this cavity in terms of historical documentation or journalistic facts that support information about its construction and fate. However, the IHGSC (2009) registration of the following image reveals the date of the photograph as being 1900.



Figure 12: *Rocaille style cave with cement stone blocks and rustic bandstand (IHGSC, 2009).*

4. Final considerations

The large number of artificial caves in Brazil shows that the romantic style that accompanied the European *Belle Époque* was a widespread trend in Brazil. Cities that had a large income movement in their population and that had contact with foreign countries valued having artifices in their gardens that imitated nature and allowed the contemplation of leisure spaces. The imitation of nature through the construction of

artificial caves showed a need for closeness to nature and curiosity about what the underground environment can present to us.

However, it is noteworthy that most of the artificial caves that exist in Brazil are freely accessible to the public, or even that those that receive visitors should be the target of policies that help in their preservation and maintenance for future generations, since we can understand that this type of artistic expression is one of the only ones that allows the observer to penetrate their interiors.

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Updating the typology classification of artificial cavities

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Abstract

After the adoption in 2013 at the international level of the typological classification of artificial cavities, originally proposed by the National Commission of Artificial Cavities of the Italian Speleological Society, new researches and studies from different parts of the world highlighted the need for updating it, and possibly adding new entries in the classification. Many of these studies derived from activities of the members of the Commission on Artificial Cavities of the International Union of Speleology, and have been presented in the four Congresses Hypogea, organized since 2015. The advancements in research on artificial cavities brought at the Italian level to discuss new possible additions to the classification, and to present in this contribution the revised classification, that has been already defined and accepted by the Italian Commission. The classification is illustrated through some text, and the two tables included in this article.

1. Introduction

Studies on artificial cavities go back to many years ago, with a variety of researches and surveys that have been published in many different sources, since the issue of artificial cavities cover a wide range of disciplines, from history to archaeology, from geology to architecture, from biology to hydraulics, and so on. Starting from some of the main references on the issue, these were essentially classical works, such as the underground drainageways in southern Etruria and northern Latium by JUDSON & KAHANE (1963), that on archaeology of water by TÖLLE-KASTENBEIN (1993), or monographies on the most interesting areas in the world, as the rupestrian environment of Cappadocia, in Turkey (BIXIO & CASTELLANI, 1995; RODLEY, 2006; BIXIO, 2012), or shelters in China (GOLANY, 1992).

Then, a wide literature is available as regards especially the hydraulic structures, including the ancient underground aqueducts and all the related works for water tapping, collection, transport and distribution (CASTELLANI & DRAGONI, 1991; CASTELLANI, 1995, 2000; LAUREANO, 2001; MAYS, 2010; PARISE, 2009, 2012; SEMSAR YAZDI & LABBAF KHANEIKI, 2010; PARISE et al., 2015b; ANGELAKIS et al., 2016; BIXIO et al., 2017; VALIPOUR et al., 2020).

Hydraulic works were, however, not the only underground works object of studies: many other underground structures and works were in the meantime the focus of specific studies, from defensive works in underground shelters (BIXIO & DE PASCALE, 2015) and other war works (TRIOLET & TRIOLET, 2011), to rupestrian settlements and dwellings in the Mediterranean area (CRESCENZI & CAPRARA, 2012; POLIMENO et al., 2019), to worship and cult sites (GALEAZZI et al., 2016), and to dovecots (GERMANIDOU, 2015; BIXIO et al., 2023).

Italy was among the most active country in studies about artificial cavities, and Italian scholars among the leading researchers, both as concerns speleological explorations and scientific studies. It was therefore not surprising that the first efforts to classify the high number of typologies came from Italy. This contribution summarizes the story of the classification, and the main international activities coming out of it, before presenting a proposal of its revision, that follows that recently published in Opera Ipogea journal by GALEAZZI & GERMANI (2023), following works within the dedicated Commission on Artificial Cavities of the Italian Speleological Society.

2. The typological classification of artificial cavities

The typological classification of artificial cavities was issued by the National Commission of Artificial Cavities of the Italian Speleological Society in the 1980s, and proposed to the international community at the III Symposium on underground quarries, held in Naples in 1991.

It was only many years later, however, and precisely at the 15th International Congress of Speleology, held in Kerrville (Texas, USA), on 19-26 July 2009, that this topic became matter of wider interest, also thanks to the activity of the renewed Commission on Artificial Cavities of the International Union of Speleology (UIS). The UIS Commission restarted its work after the congress at Kerrville, in the attempt to raise again the attention on the issue of artificial cavities. At this goal, it was again in Italy, namely in Turin, that the classification of artificial cavities was the object of a specific workshop, organized in May 2012, with its proceedings published in a special issue of the journal Opera Ipogea (PARISE, 2013). On that occasion, starting from the Italian classification (GALEAZZI, 2013), some adjustments were produced, both in the typological tree structure and in the terminology.

The further inclusion of new typologies of cavities led to the revised classification, that was presented at the 16th International Congress of Speleology, held in Brno (Czech Republic) in 2013 (PARISE et al., 2013), and since then adopted also at the international level.

Thereafter, the renewed enthusiasm of the UIS Commission on Artificial Cavities brought to the idea of organizing an international congress, specifically dedicated to Speleology in Artificial Cavities. The congress was entitled “Hypogea”, and the first one was organized in Rome, Italy, in 2015, producing a ponderous volume of proceedings (PARISE et al., 2015a), that was distributed to participants at the time of the congress. The success obtained at Rome made Hypogea the main activity in the

years to come for the UIS Commission on Artificial Cavities.

After Rome 2015, following the will by the UIS Commission on Artificial Cavities to keep organizing Hypogea every two years, other three congresses have been organized, allowing continuous exchange of experiences and researches about artificial cavities from different parts of the world. All of this was realized notwithstanding the worldwide difficulties related to the Covid pandemic, and to political problems in some countries.

In 2017, Hypogea was organized in the magnificent scenario of Cappadocia, Turkey (PARISE et al., 2017); the lower number of participants, with respect to the first edition in Rome, allowed to give more space to field trips, and to visit many different situations of artificial cavities. In May 2019, it was the turn of Dobrich, Bulgaria, where the third Hypogea congress was held, as usual with the production of an interesting volume of proceedings (ZHALOV et al., 2019).

Then, in 2020 the Covid pandemic stopped the activities of the UIS Commission on Artificial Cavities, as well as those of the entire world. However, once passed this very difficult time, we started again thinking about Hypogea, and came back to Italy, this time in its north-western sector. In Genoa, at the turn between September and October 2023, the fourth edition of Hypogea was successfully organized, giving new, and very much needed, breadth to the UIS Commission on Artificial Cavities. The congress proceedings (SAJ et al., 2023) were as always distributed at the Congress, a habit of which the Hypogea organizers have always been proud. At the time we write, the fifth Hypogea congress is planned to be held in Georgia in 2026; the decision to postpone one year the next congress was taken by the UIS Commission in order not to overlap this meeting with the 19th International Congress of Speleology in Belo Horizonte (Brasil).

All the four Hypogea so far organized have allowed a comparison among the countless studies carried out worldwide, at the same time highlighting the need for a further revision of the classification, updating it through the inclusion of new typologies. In this case, too, the journal Opera Ipogea has played a fundamental role, hosting tens of contributions discussing different typologies of artificial cavities, and the related acquisition methods (see, among the many valid contributions so far published, BIXIO & DE PASCALE, 2013; KLONER & ZISSU, 2013; TRIOLET & TRIOLET, 2013; GILLI et al., 2014; ZISSU & KLONER, 2014; YAMAÇ, 2019, 2021; BIXIO et al., 2021). To all of the above, the works about potential instability problems related to artificial cavities, with the opening of anthropogenic sinkholes at the surface (GUTIERREZ et al., 2014; PARISE, 2019, 2022) has to be added: in some countries, and particularly in Italy (VENNARI & PARISE, 2022), this subject has been the focus of many studies, of high interest also for civil protection issues, aimed at ensuring the private and public safety.

3. Revising the classification of artificial cavities1

The aim of the present contribution, deriving from the work by the Commission on Artificial Cavities of the Italian Speleological Society, is to propose a revision of the classification, updating denominations and introducing sub-classes for better detailing some typologies. Figure 1 shows the revised version of the classification, as accepted by the Italian Commission. At the same time, it was decided not to change the original numbering, as this would distort the previous documentation, possibly creating some misunderstandings in the future.

The new classification proposal, therefore, obeys to the following scheme: 1) all the main typologies, labeled by capital letters ranging from A to G, remain unchanged; 2) all the sub-typologies, indicated by numbers after the main label, e.g. A1, remain unchanged, too; 3) a new level is introduced by adding a lowercase letter after the main label and the number, e.g. A.1a; this is aimed at better specifying the function those structures had at the time of their construction, and also in the sub-sequent phases of re-use. The following tables illustrate the revised classification.

Table 1: *Revision and updating of the typological classification of artificial cavities (by the Commission on Artificial Cavities of the Italian Speleological Society) (continues).*

A ANCIENT NDERGROUND HYDRAULIC WORKS	A.1 – Water regulation and land reclamation works	A.1a – conduits for regulating the level of lakes and basins without natural outlets
		A.1b – conduits for the reclamation of marsh land; galleries for the regulation of streams in order to obtain land to be used for agricultural purposes, or to reduce water pressure (defence from flooding, protection from erosive effects)
		A.1c – channels created by covering water courses, to gain new spaces in urban areas (construction of roads, buildings, etc.)
	A.2 – Water tapping works	A.2a – tapping/collection channels to feed underground reservoirs (A.4a) or directly the aqueducts (A.3a)
		A.2b – tapping/collection channels to feed fountains, tanks or external channels, even free-flowing
	A.3 – Underground transport water works: aqueduct	A.3a – aqueduct
		A.3b – galleries carrying non drinkable water (white waters)
		A.3c – conduits to transport water producing power
		A.3d – qanāt, qanaq, karez, kārīz, foggara, rhettara
		A.3e – by-pass
	A.4 – Water storage works	A.4a – reservoirs
		A.4b – cisterns
		A.4c – tunnel cisterns
		A.4d – rock-cut cisterns
		A.4e – underground tanks
		A.4f – silos for liquids
		A.4g – small cavities to trap the wind, or other underground structures for the condensation of moisture to produce water
	A.5 – Hydraulic wells	A.5a – groundwater wells or cistern wells, artesian wells
		A.5b – withdrawing wells (from aqueduct or cisterns)

A ANCIENT NDERGROU-ND HYDRAULIC WORKS	A.6 – Distribution works	A.6a – castellum aquae
		A.6b – distributors
	A.7 – Sewers	
	A.8 – Navigable underground canals	
	A.9 – Ice houses, snow houses	
	A.10 – Hydraulic underground tunnels or ducts with unknown function	
B UNDERGROUND AND ROCK-CUT CIVILIAN SETTLEMENTS	B.1 – Permanent dwellings	B.1a – underground structures to mitigate adverse meteoric phenomena (ventiducts, sirocco rooms, wind towers)
	B.2 – Temporary dwellings	B.2a – seasonal or extemporary settlements
		B.2b – false caves and nymphaea
	B.3 – Underground factories	B.3a – underground oil mills to produce oil
		B.3b – underground grape-treading basins for wine production
		B.3c – other underground workplaces (not dedicated to oil and wine production)
		B.3d – ovens to cook the limestone rocks and produce quicklime
		B.3e – undergound conduits to draw outer air to be directed into furnaces in order to feed the flames
	B.4 – Underground or rock-cut warehouses, storages, cellars	
	B.5 – Underground silos, grain pits	
	B.6 – Underground or rock-cut stables for animals	
	B.7 – Underground or rock-cut structures for breeding and housing pigeons, bees and fishes	B.7a (former B.7) – rock-cut pigeon houses, dovecotes
		B.7b (former B.8) – rock-cut apiaries
		B.7c – fish tanks
	B.8 – Any other kind of underground civilian settlements	
C UNDERGROUND WORKS DEDICATED TO WORSHIP AND BURIALS	C.1 – Underground places sacred to celebrate cults	C.1a – underground or rock-cut buildings dedicated to sacred cerimonies and rituals, temples of any religion, mithraea and artificial cavities dedicated to cults
		C.1b – hypogea for hermitic, cenobitic and monastic life
		C.1c – underground places for carrying out esoteric cults and initiatory rites
	C.2 – Underground places for burials	C.2a – catacombs
		C.2b – rock-cut necropolises
		C.2c – isolated underground burials
		C.2d – crypts
		C.2e – funerary columbaria
		C.2f – putridarium
D UNDERGROUND OF-FENSIVE AND DEFEN-SIVE WAR WORKS	D.1 – Defensive works	D.1a – underground traps
		D.1b – trenches (covered or open air)
		D.1c – bastion fortifications
		D.1d – stone fortifications
		D.1e – forts
		D.1f – cave fortifications
	D.2 – Galleries and connecting passages	D.2a – tunnels for transit or movement of weapons and armed men
		D.2b – connecting tunnels inside the bastions and the fortifications
	D.3 – Mine and countermine	D.3a – mine tunnels
		D.3b – countermine tunnels
		D.3c – mine chamber and mine shaft
	D.4 – Underground firing points	
	D.5 – Underground military deposits, including those for chemicals, bacteriological substances, garbage, hazardous materials	
	D.6 – Underground shelters for soldiers	D.6a – military anti-aircraft shelters
		D.6b – military anti-atomic bunkers
		D.6c – military shelters and/with trenches, including underground hospitals
	D.7 – Underground shelters for civilians	D.7a – shelters
		D.7b – anti-aircraft shelters
		D.7c – anti N.B.C. (Nuclear – Bacteriological – Chemical) bunkers
	D.8 – ICBM Silo for inter-continental rockets (attack facility)	
	D.9 – Defensive and offensive complexes	D.9a – defensive complex of first class
		D.9b – defensive complex of second class
		D.9c – “water-earth” complex
E MINING WORKS	E.1 – Quarries	
	E.2 – Underground mines	
	E.3 – Suspended typology (before, non metalliferous mines)	
	E.4 – Mineral exploration	
	E.5 – Underground farming (e.g. mushroom patch)	
	E.6 – mine shaft (if isolated)	
	E.7 – mine descending way (if isolated)	
	E.8 – deposito of explosives (if isolated)	
	E.9 – gallery to carry out waters (if isolated)	

F **UNDERGROUND TRANSIT WAYS**	F.1 – Abandoned tunnels
	F.2 – Underground tunnels for pedestrians
	F.3 – Railway tunnels, tramways or funicular
	F.4 – Non-hydraulic (technical) wells, shafts
G **OTHER WORKS**	



Figure 1: *The revised typological classification of artificial cavities, as approved by the Commission on Artificial Cavities of the Italian Speleological Society (drawing by R. Bixio).*

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ERDSTÄLLE - mysterious underground structures in central and western Europe

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Abstract

"Unsolved puzzles" called Lambert Karner, the "Erdstallpfarrer", already in 1904 the many small underground structures which he and others had visited, surveyed and mapped by then in Austria, Germany and other nearby areas. A lot of scientific effort has been devoted since then to them and a lot of information collected. Do we now really know more? Yes and no.

History

In 1640 a peasant dug a hole in the ground near Reichersdorf in Upper Bavaria in order to find drinking water. He discovered an artificial underground structure which was known to nobody before. A vertical shaft led to a small system of passages which were linked by a porthole.

There are at least 700 other similar places known now in the area of Bavaria, Lower and Upper Austria and other parts of Austria, some are in Hungary and the Tschech Republik (they are known there as „lochy" and, far away, in parts of France. They are called „souterain amenagé.

The exploration of these structures started whenever they were found. This was the case in 1828 in Roggenstein near Munich in Upper Bavaria and in Mergenthau near Augsburg in Swabia in 1830. The engineers of the king came and mapped them immediately, but found nothing in them. They were as all the others more or less empty.

A milestone in the history of Erdstallexploration was the publication of „Künstliche Höhlen aus alter Zeit" (Artificial caves from former times) by the Austrian monk Lambert Karner. He started with his explorations in 1879 in Lower Austria and visited, surveyed and described hundreds of them in the following years. He initiated the taking of the first photographs through a young Viennese photographer, Mr Wrbata, whose pioneering work was also used in his book.

Features

What are „Erdställe"? There is still no final valid definition of "Erdstall", only descriptions of basic parts of it.

Erdställe have:

- passages, some are up to 1,70 m high, a lot of them measure only 1 m in height, which often force the visitor to crawl on hands and knees. The width is around 70 cm, so the passing of other persons is obviously not intended. They are not very long, 5 to 10 m is normal, and straight only for short parts, more winding. The ceiling of the profile is either round or ogival.
- portholes. These are the most astonishing and unique parts of Erdställe. Small holes lead often from the passages in different directions, most times either vertical or horizonal. One has to crawl or slip through them, when you want to get to the continuations, either on the same level or to level above or below. Because Erdställe have only one entrance you have to return the same way.
- chambers. Some Erdställe finish in chambers, but by far not all. In the chambers you sometimes find niches where you can sit on a step.
- niches/alcoves. You often find in Erdställen little niches along the walls. They are supposed to offer an approriate place for an oil lamp, but nobody definitely knows whether this is he real reason for them.
- You often find dry stone walls in Erdställen. It is thought that there are vertical shafts behind these walls which were excaveted to be able to transport the material to the surface. After this work was finished, they were filled up again.
- scratches on the walls are often found and can show the direction in which the Erdstall was dug out.
- In some Erdställe you can see air holes in the walls which guide to the surface and show that care was taken that there is enough air in the underground place.
- Sometimes structures which are found in the underground passage seem to have served for the lockage of the passages.
- In a few Erdställe several steps were dug in the floor and some have a circle structure. For what purpose?

The outline of the system of passages is never the same. We have not found two identical ones though there are general patterns. In France they distinguish two main types: Type Ségala and souterraines annulaies. The Souterrains annulaires are passages which lead back to its entrance. Herbert Wimmer distinguished 4 different main types, dependent on the area, where they are in Bavaria and Austria.

The entrances to the Erdställe are in very different places. There is a church in Lower Austria, Kleinzwettl, where the entrance is right in the middle of the old building. You can find in Ulrichschlag in Upper Austria underneath almost every house in the village an Erdstall, they are in „Hausbergen"/ „Mottes", man-made mountains from Middle Ages, under cemeteries and a lot of them are out in the fields or meadows.

Reasons

The fundamental question is, why they were built. Lambert Karner already denied in his book about Erdställe all ideas that people ever lived in them or that they had been prepared graves, that they served storage purposes or were hiding places for household goods or treasures in times of trouble. He thinks that Erdställe are „unsolved puzzles“ and a lot of people afterwards have the same opinion.

There have been two main theories put forward, the escape theory and the cult theory. Some people claim that Erdställe were built to serve as hiding places in time of war, but this argument is not very convincing and the archeological evidence doesn't confirm this idea. Under the expression „cult theory“ a lot of very different ideas can be meant. Have the portholes once served for rituals? For cleaning the soul from sins? Help a woman to give easier birth to a child? Are the passages and rooms in the Erdställe „empty graves“ for the souls of the dead until resurrection?

How old are the Erdställe? This question is not really answerable when you don't know why they were built. The first interpreters thought that they were from stone age times, later on people thought of the Romans or Celts, now the idea is that they are of Medieval origin.

The entrances to many „Erdställe“ were known for a long time. A lot of stories were told about them. One of the more popular ones dealt with the Schrazln, a little folk, once living in these underground chambers, helpful and friendly, until something negative happened and they disappeared for good.

The Present

The main organizations which deal with the exploration and preservation of the Erdställe are in France/Belgium the SFES, the Société Francaise d'Etude des Souterrains, and in Germany/Austria the Arbeitskreis für Erdstallforschung e.V. and the Interessengemeinschaft Erdstallforschung (IGEF).

There are a few Erdställe open to the public. In Bavaria you can visit in Saldenburg the cellar of a wirtshaus a short piece of an Erdstall, in Upper Austria a few objects are also accessible, i.e. in Münzkirchen and near Perg the Ratgöbluckn, in Lower Austria the Erdstallmuseum Althöflein.

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Figure 1: *Entry to the Erdstall of Kleinzwettl, Lower Austria.*

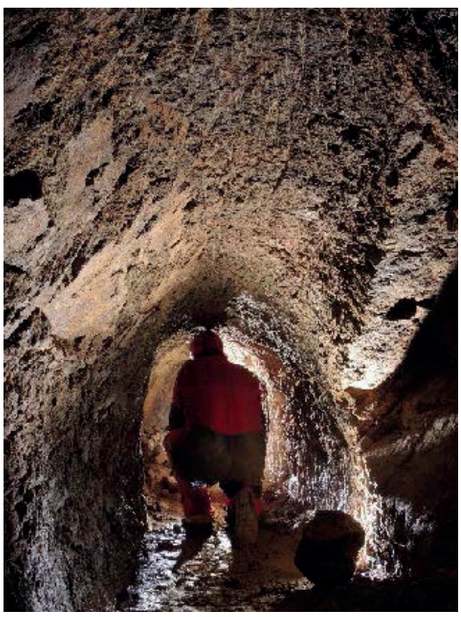


Figure 2: *Erdstall in Loitzendorf, Oberpfalz, Bavaria.*

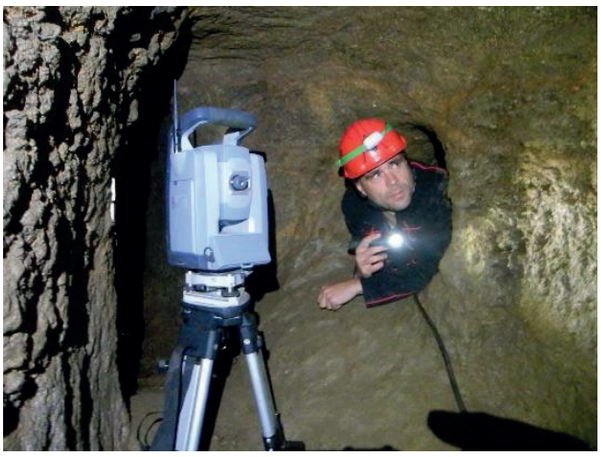


Figure 3: *Erdstall in Altnußdorf, Lower Bavaria with porthole.*



Figure 4: *Erdstall in Ulrichschlag, Lower Austria.*

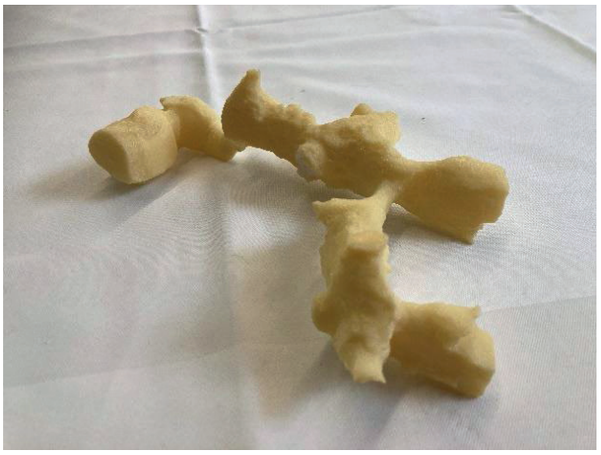


Figure 5: *3-D-Modell of an Erdstall.*

Session 12

PSEUDOKARST AND NON-TRADITIONAL KARST

Caracterização genética e morfológica das cavidades naturais graníticas do Município de Nova Venécia/ES

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Resumo

Este estudo apresenta a caracterização de cavidades naturais subterrâneas em litologia granítica no município de Nova Venécia, Espírito Santo, Brasil. A pesquisa de campo teve como objetivo identificar e descrever cavidades formadas por diferentes processos espeleogenéticos, destacando-se dois tipos principais: cavidades do tipo tafoni e cavidades formadas por depósito de tálus. A metodologia envolveu prospecção em campo com o uso de GPS para georreferenciamento, aplicação de fichas descritivas para registro morfológico e espeleometria para mensuração das dimensões internas. Foram identificadas quatro cavidades principais: Toca de Marte e Abrigo dos Olhos, associadas a processos de dissolução diferencial e intemperismo físico-químico; e Caverna do Tubarão e Caverna de Santa Rosa, formadas pelo acúmulo de blocos rochosos devido à ação gravitacional. Os resultados revelam a complexidade dos processos espeleogenéticos em granitos, desafiando a concepção tradicional de baixo potencial espeleológico para este tipo de rocha. Conclui-se que o mapeamento espeleológico em ambientes graníticos é essencial para ampliar o conhecimento sobre a diversidade morfológica e a dinâmica das cavidades naturais em litologias não carbonáticas.

Abstract

This research has as main objective to inventory, describe and analyse the physical aspects of the cavities in Nova Venécia, Espírito Santo, Brazil. The field research aimed to identify and describe cavities formed by speleogenetic processes as tafoni-type cavities and cavities formed by talus deposits. The methodology involved: bibliographic review, field work using GPS for georeferencing, the description of the physical aspects of the cavities. Four cavities were identified: Toca de Marte and Abrigo dos Olhos, associated with processes of differential dissolution and physico-chemical weathering; and Shark Cave and Santa Rosa Cave, formed by the accumulation of rock blocks due to gravitational action. The results reveal the complexity of speleogenetic processes in granites, challenging the traditional conception of low speleological potential for this type of rock. It is concluded that speleological mapping in granite environments is essential to expand knowledge about the morphological diversity and dynamics of natural cavities in non-carbonate lithologies.

1. Introdução

As cavidades naturais subterrâneas em rochas ígneas, especialmente em granitos, representam um campo emergente na espeleologia, desafiando modelos clássicos baseados na predominância de formações em litologias carbonáticas (PALMER, 2009; PILÓ & AULER, 2019). Embora o carste seja tradicionalmente associado a rochas solúveis, como calcários e dolomitos, processos espeleogenéticos em granitos têm revelado morfologias complexas e variadas, decorrentes de mecanismos físicos e químicos menos evidentes, mas igualmente significativos (LOWE, 1992; CHAVES, 2017).

No Brasil, a espeleologia em ambientes graníticos ainda é incipiente, com registros concentrados em estados como Rio de Janeiro (GONÇALVES et al., 2011), Paraíba (CHAVES, 2017) e São Paulo (ÁVILA, FERNANDES & MORITA, 2019). O Espírito Santo, apesar de sua extensa cobertura por intrusões graníticas, permanece subexplorado nesse aspecto, especialmente na região norte, considerada de baixo potencial espeleológico devido à predominância de rochas menos solúveis (CECAV, 2012). No entanto, recentes descobertas sugerem que tais classificações subestimam a diversidade morfológica e a complexidade dos processos de formação de cavidades em granitos.

A gênese dessas cavidades pode estar associada a dois principais tipos morfológicos: cavidades em tálus, formadas pelo acúmulo de blocos rochosos resultantes de processos gravitacionais, e cavidades do tipo tafone, desenvolvidas por mecanismos de intemperismo físico-químico e dissolução diferencial da matriz granítica (HARDT, 2003; WALDHERR et al., 2020). A compreensão da distribuição e das características dessas cavidades depende de estudos de campo sistemáticos, que permitam correlacionar fatores geológicos, geomorfológicos e climáticos aos processos espeleogenéticos.

Neste contexto, o presente trabalho tem como objetivo principal caracterizar as cavidades naturais subterrâneas em granito localizadas no município de Nova Venécia, noroeste do Espírito Santo (Figura 1). A pesquisa de campo concentrou-se na descrição morfológica e físico-ambiental das cavidades identificadas, visando ampliar o entendimento sobre a espeleogênese em ambientes graníticos e contribuir para a consolidação da espeleologia em litologias não carbonáticas no Brasil.

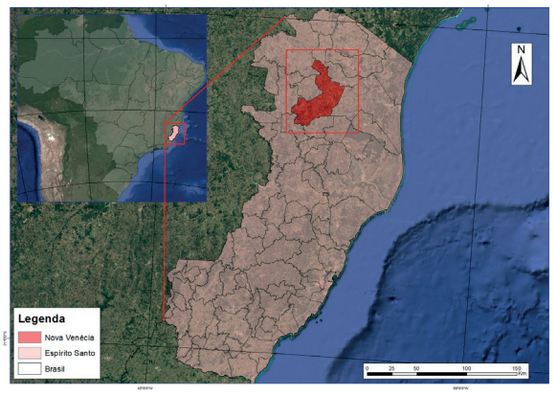


Figura 1: *Localização do município de Nova Venécia, Espírito Santo, Brasil.*

2. Materiais e Métodos

A pesquisa de campo foi conduzida no município de Nova Venécia, região noroeste do Espírito Santo, com o objetivo de identificar, descrever e mapear cavidades naturais subterrâneas em litologia granítica. O trabalho de campo baseou-se em uma abordagem metodológica integrada, envolvendo técnicas de geoprocessamento para a seleção de áreas de prospecção e métodos tradicionais de espeleometria para a caracterização físico-ambiental das cavidades.

2.1. Seleção das Áreas de Prospecção

Inicialmente, foi realizado o mapeamento do potencial espeleológico da região utilizando o software QGIS 3.10, com aplicação da técnica de álgebra de mapas. Foram consideradas variáveis geomorfológicas e geológicas, como litologia, estrutura, declividade e hidrografia, que, combinadas por meio de sobreposição de camadas temáticas, permitiram identificar áreas com maior potencial para a ocorrência de cavidades (CECAV, 2012; ÁVILA, FERNANDES & MORITA, 2019).

2.2. Prospecção em Campo

A prospecção de campo foi realizada em áreas previamente selecionadas, com o uso de GPS. O acesso às cavidades envolveu técnicas básicas de progressão em terreno acidentado, considerando medidas de segurança adequadas para ambientes espeleológicos.

Para cada cavidade identificada, foram aplicadas fichas descritivas padrão, adaptadas do modelo da British Cave Research Association (BRCA), contemplando informações sobre:

Características morfológicas externas: tipo de entrada, dimensões da boca, orientação e posição topográfica;

Aspectos internos: morfologia das galerias, presença de espeleotemas, depósitos sedimentares e evidências de processos de intemperismo;

2.3. Técnicas de Espeleometria e Registro Fotográfico

As dimensões das cavidades foram obtidas por meio de técnicas de espeleometria, utilizando trenas métricas, bússolas de precisão, permitindo o levantamento de perfis longitudinais e transversais das galerias. As medições consideraram os seguintes parâmetros:

Extensão total da cavidade;

Altura máxima e mínima;

Largura das passagens internas.

O registro fotográfico foi realizado com câmeras digitais, documentando tanto as feições morfológicas externas quanto as internas das cavidades, com ênfase em estruturas tafoniformes e depósitos de tálus.

3. Resultados

A pesquisa de campo realizada resultou na identificação e caracterização de quatro cavidades naturais subterrâneas em litologia granítica: Toca de Marte, Caverna do Tubarão, Caverna de Santa Rosa e Abrigo dos Olhos. Essas cavidades foram classificadas em dois tipos principais: cavidades formadas por depósito de tálus e cavidades do tipo tafoni, conforme critérios morfológicos e processos espeleogenéticos estabelecidos por autores como HARDT (2003) e WALDHERR et al. (2020).

3.1. Cavidades do Tipo Tafoni

O termo tafoni, plural de tafone, deriva do dialeto corso e significa «perfuração» ou «janela». Essas cavidades são formadas por processos de intemperismo físico-químico e dissolução diferencial da rocha granítica, resultando em cavidades pouco profundas com aparência de janelas ou alvéolos de dissolução, também conhecidos como honeycombs (VIDAL ROMANÍ & TWIDALE, 1998; WALDHERR et al., 2020).

3.1.1. Toca de Marte

A Toca de Marte (Figura 2) apresenta alvéolos de dissolução de tamanhos variados, de poucos centímetros até estruturas com mais de um metro de diâmetro. O processo espeleogenético predominante é a dissolução química associada à circulação de águas meteóricas e à variação da umidade, promovendo o intemperismo granular da superfície da rocha (CHAVES, 2017). O piso é irregular, com depósitos autóctones derivados da desagregação da rocha matriz. A ausência de fluxo hídrico interno sugere que o processo de dissolução ocorreu de forma predominantemente superficial.



Figura 2: *Feições morfológicas internas da cavidade Toca de Marte.*

3.1.2. Abrigo dos Olhos

O Abrigo dos Olhos também é uma cavidade do tipo tafoni, caracterizada por alvéolos de dissolução bem definidos. Sua formação está associada a processos de intemperismo físico-químico, com destaque para a decomposição esferoidal e o desenvolvimento de fraturas sub-horizontais que facilitam a infiltração de água e o posterior intemperismo físico-químico (VIDAL ROMANÍ e TWIDALE, 1998). O acesso restrito devido à inclinação da vertente contribuiu para a preservação das feições morfológicas internas.

3.2 Cavidades Formadas por Depósito de Tálus

As cavidades do tipo depósito de tálus são formadas pelo acúmulo de blocos rochosos resultantes do desplacamento gravitacional de porções da rocha matriz. Esse processo cria espaços vazios entre os blocos, que podem se conectar e formar cavidades de diferentes dimensões (PALMER, 2009; HARDT, 2003).

3.2. Caverna do Tubarão

A Caverna do Tubarão (Figura 3) é um exemplo clássico de cavidade em tálus, formada pelo deslocamento de um bloco rochoso de grande proporção que se separou da rocha matriz em um ambiente de alta declividade. O espaço resultante entre o bloco descolado e o substrato rochoso originou uma cavidade com desenvolvimento horizontal significativo. A morfologia interna é irregular, com blocos parcialmente instáveis e ausência de sinais de intemperismo químico ativo.



Figura 3: *Abismo da caverna do Tubarão.*

3.2.1. Caverna de Santa Rosa

A Caverna de Santa Rosa também se formou por depósito de tálus, localizada no sopé de uma vertente granítica. O acúmulo de blocos em uma área de menor declividade favoreceu a estabilidade da estrutura, permitindo o desenvolvimento de uma cavidade com galerias mais amplas e presença de um pequeno curso d'água perene, o que contribui para processos de sedimentação interna. Esse ambiente úmido favoreceu o desenvolvimento de pequenos espeleotemas do tipo coralóide, embora em escala reduzida.

4. Discussão

A caracterização das cavidades naturais subterrâneas em granito no município de Nova Venécia revelou a coexistência de dois tipos morfológicos principais: cavidades do tipo tafoni e cavidades formadas por depósito de tálus. A análise dos resultados de campo, em comparação com o referencial teórico, permite compreender as particularidades dos processos espeleogenéticos envolvidos.

4.1. Cavidades do Tipo Tafoni

As cavidades do tipo tafoni, representadas pela Toca de Marte e pelo Abrigo dos Olhos, estão associadas a processos de intemperismo físico-químico e dissolução diferencial da rocha granítica. Esses processos envolvem a interação da água meteórica com superfícies expostas da rocha, promovendo a desagregação mineral ao longo de fraturas e zonas de fraqueza (VIDAL ROMANÍ & TWIDALE, 1998; WALDHERR et al., 2020).

Observou-se que essas cavidades possuem alvéolos de dissolução de diferentes dimensões, evidenciando a atuação prolongada da água em ambientes com variação de umidade relativa. De acordo com WALDHERR et al. (2020), a morfologia tafoniforme tende a se desenvolver em ambientes áridos ou semiáridos, onde o intemperismo químico é mais eficiente em promover a desagregação granular da rocha. No entanto, os resultados desta pesquisa demonstram que tais cavidades também podem ocorrer em ambientes de clima tropical, desafiando modelos tradicionais de formação.

Outro aspecto relevante é a influência da declividade do terreno

na formação dos tafoni. As cavidades analisadas localizam-se em encostas íngremes, o que favorece o escoamento superficial da água e, consequentemente, a concentração de processos erosivos localizados (CHAVES, 2017). Isso sugere que, além da composição mineralógica da rocha, fatores geomorfológicos desempenham um papel crucial na espeleogênese em granitos.

4.2. Cavidades Formadas por Depósito de Tálus

As cavidades do tipo depósito de tálus, representadas pela Caverna do Tubarão e pela Caverna de Santa Rosa, são formadas a partir do acúmulo de blocos rochosos desprendidos da rocha matriz devido à ação gravitacional. Esse processo resulta em espaços vazios interconectados entre os blocos, criando cavidades de morfologia irregular (PALMER, 2009; HARDT, 2003).

Ao contrário das cavidades do tipo tafoni, as cavidades em tálus não dependem diretamente de processos de dissolução química para sua formação. O desplacamento de blocos ocorre devido a processos mecânicos, como o colapso de vertentes e o alívio de pressão litostática, associados a eventos de instabilidade geomorfológica (FINLAYSON, 1983, apud ÁVILA; FERNANDES; MORITA, 2019).

A presença de espeleotemas do tipo coralóide e pequenos cursos d'água na Caverna de Santa Rosa indica que, embora a gênese da cavidade seja mecânica, processos secundários de deposição química podem ocorrer em ambientes úmidos (MOCHIUTTI, 2020). Esse aspecto destaca a complexidade da dinâmica interna das cavidades em tálus, onde fatores abióticos e bióticos interagem para modificar o ambiente ao longo do tempo.

4.3. Comparação com Estudos Anteriores

Os resultados obtidos neste estudo estão em consonância com pesquisas realizadas em outras regiões do Brasil, como no Rio de Janeiro (GONÇALVES et al., 2011), Paraíba (CHAVES, 2017) e São Paulo (ÁVILA; FERNANDES; MORITA, 2019). No entanto, observa-se que as cavidades graníticas do Espírito Santo apresentam peculiaridades, como a coexistência de processos espeleogenéticos distintos em uma mesma área geográfica.

Além disso, enquanto o Centro Nacional de Pesquisa e Conservação de Cavernas (CECAV, 2012) classifica os granitos como de baixo potencial espeleológico, os achados desta pesquisa demonstram que essa classificação pode subestimar a real capacidade dessas rochas de abrigar cavidades significativas. Isso reforça a necessidade de revisões nos critérios de avaliação do potencial espeleológico em litologias não carbonáticas.

5. Conclusão

O presente estudo permitiu a caracterização de quatro cavidades naturais subterrâneas em litologia granítica no município de Nova Venécia (ES), evidenciando a diversidade morfológica e os diferentes processos espeleogenéticos associados a esse tipo de rocha. As cavidades identificadas foram classificadas em dois tipos principais: **tafoni**, formados por processos de intemperismo físico-químico e dissolução diferencial da rocha, e cavidades de **depósito de tálus**, resultantes do acúmulo de blocos rochosos devido a processos gravitacionais.

Os resultados demonstraram que, embora o granito seja tradicionalmente considerado de baixo potencial espeleológico, ele pode abrigar cavidades de relevância geomorfológica e ambiental, desafiando modelos clássicos de espeleogênese centrados em litologias carbonáticas. A presença de cavidades com diferentes formas e processos formativos em uma área geográfica relativamente restrita destaca a importância de estudos de campo detalhados para o reconhecimento do potencial espeleológico de rochas ígneas.

Além de contribuir para o avanço do conhecimento científico sobre a espeleogênese em granitos, este trabalho reforça a necessidade de revisões nos critérios de avaliação do potencial espeleológico em contextos graníticos, especialmente em regiões ainda subexploradas do Brasil. Recomenda-se a continuidade das pesquisas na região, com ênfase em análises mais detalhadas da dinâmica interna dessas cavidades e de sua relação com os processos geomorfológicos locais.

Agradecimentos

Este trabalho foi desenvolvido através do Instituto Federal do Espírito Santo (IFES) - Campus Nova Venécia, no âmbito do Curso de Licenciatura em Geografia. Agradecemos à Coordenadoria do Curso de Licenciatura em Geografia do IFES - Campus Nova Venécia pelo apoio institucional e pela viabilização das atividades de pesquisa. Nosso reconhecimento ao Pedro Paulo, que desempenhou um papel fundamental na condução das atividades de campo e prospecção das cavidades naturais. Agradeço, de forma especial, à Professora Manuela Corrêa Pereira pelo suporte técnico-científico, orientação e dedicação ao longo de todas as etapas deste trabalho.

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Caracterização de Cavidade em Quartzitos e Rochas Ferríferas - Itapanhoacanga, MG

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Resumo

A formação de cavidades acontece em rochas de durezas variadas, como carbonáticas, quartzíticas, ricas em ferro entre outras, desde que o processo dominante seja o de carstificação, uma ação conjugada de processos geoquímicos e hidrodinâmicos. Este estudo investigou cavidades que podem ter se desenvolvido em rochas ricas em ferro na região do distrito de Itapanhoacanga, Minas Gerais. Durante o levantamento, foram identificadas e contextualizadas, do ponto de vista paisagístico, treze cavidades na área de estudo, sendo apenas uma delas caracterizada com maior detalhe, por se desenvolver no contato entre o quartzito e a canga laterítica. Foi identificado o processo de carstificação com desenvolvimento paralelo ao acamamento do quartzito e característicos de rochas ferruginosas, onde a dissolução aconte especialmente na banda silicosa, além de fluxos hídricos temporários. Os resultados obtidos foram comparados aos estudos desenvolvidos acerca destas litologias. Conclui-se que a cavidade estudada reflete padrões típicos de formações em rochas ricas em ferro e apresenta similaridade com cavernas do Quadrilátero Ferrífero e da Serra de Carajás.

Abstract

Cavity formation occurs in rocks of varying hardness, such as carbonate, quartzite, iron-rich rocks, among others, as long as the dominant process is karstification, a combined action of geochemical and hydrodynamic processes. This study investigated cavities that may have developed in iron-rich rocks in the Itapanhoacanga district, Minas Gerais. During the survey, thirteen cavities in the study area were identified and contextualized from a landscape point of view, and only one of them, developed in the contact between quartzite and lateritic canga, was characterized in greater detail. The karstification process was identified as developing parallel to the bedding of quartzite and characteristic of ferruginous rocks, where dissolution occurs especially in the siliceous band, in addition to temporary water flows. The results obtained were compared to studies developed on these lithologies. It was concluded that the studied cavity reflects typical patterns of formations in iron-rich rocks and presents similarities with caves in the Quadrilátero Ferrífero and the Serra de Carajás.

1. Introdução

A formação de paisagens cársticas é resultado da ação da água ao longo das zonas de descontinuidade rochosa, que gradualmente promove sua alteração a partir de processos geoquímicos. Enquanto a rocha é parcialmente alterada, o fluxo de água percorre o maciço, vindo dos pontos de introdução em direção às restituições, removendo o material particulado e gerando um vazio, nenhum material permanece como um produto do processo de carstificação (DUBOIS et al., 2014).

Embora o carste mais conhecido esteja associado a rochas carbonáticas, como calcário e dolomito, a formação cárstica também ocorre em outras litologias como quartzito, arenito e rochas ricas em ferro, resultado do processo de carstificação (JENNINGS, 1985; HENRIQUES, 2016).

Estas rochas produzem ambientes cársticos e suas morfologias características, como as cavernas, kamenitzas e lapiáz, porém, o que pode variar é o tempo de formação, devido à resistência dos minerais, e a dimenção das morfologias. Além disto, fatores naturais podem potencializar o processo, como a estrutura da rocha, a tectônica, o clima, o solo e a vegetação, entre outros (VASCONCELOS, 2014).

De acordo com AULER et al. (2022) as formações ferríferas geram algumas das formas de relevo mais antigas da Terra. A Formação Ferrífera Bandada (BIF) formada no Proterozoico sofre intemperismo constante em razão da interação entre processos químicos e biológicos, que possibilitam a mobilização maciça dos principais minerais sílica e ferro, o que gera material ferroso pobre em sílica, portanto mais friáveis, e na parte superficial a canga. Ou seja, ocorre alteração geoquímica, e posteriormente diversos processos, dentre eles hidrodinâmica, gerando a carstificação. Já CABRAL et al. (2016) aponta que uma parte significativa das cavernas do corpo de minério de Carajás ocorrem em formações ferríferas bandadas, em jaspilitos. Nesta pesquisa observou-se feições características dos processos de dissolução, que aconteciam especialmente na banda silicosa. O processo de carstificação pode ser observado nesta área, a partir da dissolução e posterior lixiviação dos minerais, e erosão dos resíduos, gerando cavidades. Posteriormente, ocorre a precipitação de goethita em suas paredes, aumentando o teor de ferro. Da mesma forma, este trabalho teve como objetivo identificar, topografar e caracterizar uma cavidade mista desenvolvida em quartzitos e em rochas ricas em ferro, com ênfase na identificação de evidências

do processo de carstificação nessas rochas.

A área de estudo está localizada em Itapanhoacanga, distrito de Alvorada de Minas, Minas Gerais (Fig. 1). O distrito de Itapanhoacanga, inserido na borda leste da Serra do Espinhaço Meridional, compreende as unidades do Embasamento, Grupo Serra da Serpentina, Grupo Guinda e Coberturas Aluvionares (Fig. 2). As rochas que constituem a área são essencialmente rochas graníticas, quartzitos, filitos e itabiritos. A geologia estrutural apresenta falhas e dobras, que juntamente com as medidas de foliação e acamamento, evidenciam os movimentos compressivos decorrentes da formação do Orógeno Araçuaí.

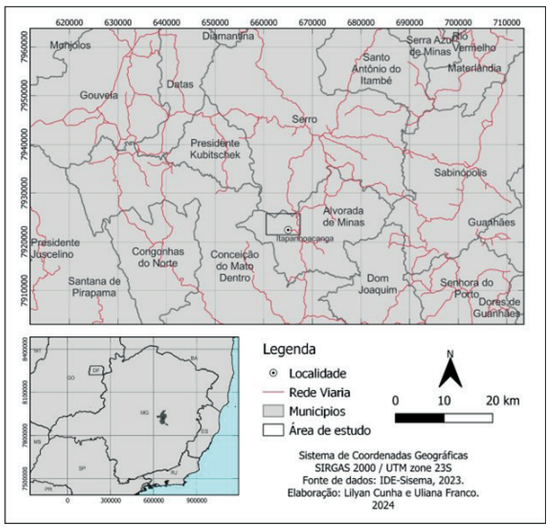


Figura 1: *Mapa de localizada área de estudo. Fonte de dados: IDE-Sisema, 2024.*

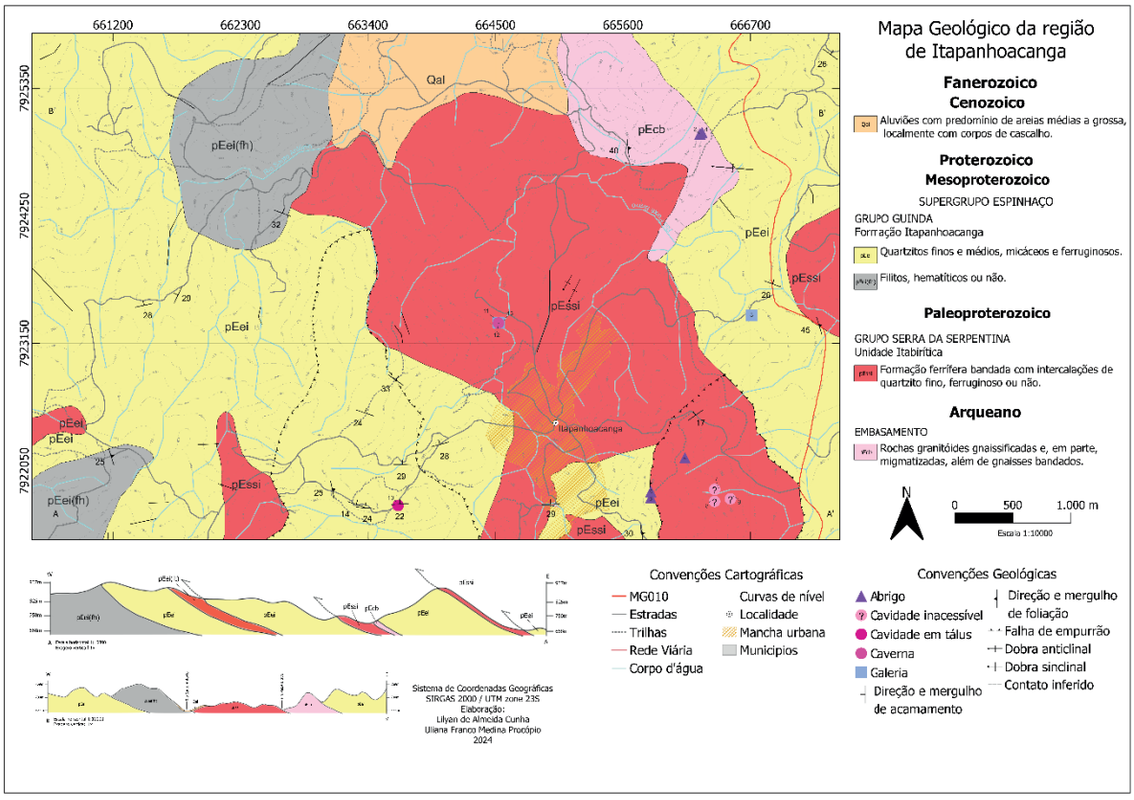


Figura 2: *Mapa geológico da área de estudo, Itapanhoacanga - MG. Fonte de dados: IDE-Sisema, 2023.*

2. Materiais e Métodos

A realização da pesquisa envolveu três etapas principais, a primeira consistiu na aquisição de dados, abrangendo atividades de escritório e a segunda os trabalhos de campo. A terceira etapa compreendeu a interpretação e integração dos dados.

Em escritório, procedeu-se o planejamento, a delimitação da área de interesse e estudos bibliográficos. Foram utilizadas técnicas de geoprocessamento para definir os limites da região de estudo. Posteriormente, foi realizada uma consulta ao banco de dados do Centro Nacional de Pesquisa e Conservação de Cavernas (CECAV), visando identificar a presença de cavidades na área selecionada.

Em campo, foram realizadas averiguações das cavidades identificadas no CECAV para a possibilidade de estudá-las. Para a pesquisa na cavidade, fez-se a topografia para o entendimento da sua formação, onde foram tomadas medidas de suas direções de desenvolvimento e realizada a confecção de planta baixa no local. Para o desenvolvimento dessa etapa, utilizou-se um GPS, bússola, escala, caderneta de campo,

lupa, caneta magnética, trena elétrica, prancheta, papel milimetrado, fita adesiva e equipamentos de proteção individual. Além disso, utilizaram-se mapas elaborados na etapa de escritório e celulares para marcação dos pontos no aplicativo Avenza Maps.

A partir dos dados coletados fez-se o tratamento e a integração dos dados, que envolveu técnicas de geoprocessamento apoiadas aos estudos bibliográficos promovendo a confecção de mapas de localização, vias de acesso, mapa hipsométrico e geológico a partir da utilização do software QGis®. A utilização do mapa geológico 1:100.000 da Folha Serro - SE.23-Z-B-IV, dados de sensoriamento remoto, informações do banco de dados CECAV e IDE-Sisema, e bibliografias, que associadas ao trabalho de campo foram fundamentais para compreender o contexto geológico do ambiente onde as cavidades estavam inseridas.

O reconhecimento das cavidades indicadas pelo CECAV, e o estudo da cavidade encontrada, assim como as medidas levantadas na sua topografia para a criação da planta baixa, auxiliaram na descrição e compreensão da sua formação.

3. Resultados

Durante o trabalho de campo, foi realizada a prospecção buscando as cavidades informadas nos dados fornecidos pelo CECAV (Fig. 3). No entanto, foram identificadas algumas divergências em relação às informações disponibilizadas, destacando-se que cavidades caracterizadas como caverna, tratavam-se na verdadde de galeria artificial, ponto 3, ou abrigo de tálus, pontos 4 e 6, por exemplo.

Nº	Coordenadas UTM – 23K	Tipo de cavidade encontrada	Classificação CECAV	Fonte
1	666283.48 E – 7924967.46 S	Abrigo em tálus	Abrigo	CECAV
2	666264.51 E – 7924956.55 S	Abrigo em tálus	Abrigo	CECAV
3	666711.46 E – 7923388.47 S	Galeria artificial	Caverna	CECAV
4	666134.53 E – 7922161.53 S	Abrigo em tálus	Caverna	CECAV
5	665840.44 E – 7921868.48 S	Abrigo em tálus	Abrigo	CECAV
6	665839.48 E – 7921819.46 S	Abrigo em tálus	Caverna	CECAV
7	666391.46 E – 7921889.17 S	Caverna inacessível	Abrigo	CECAV
8	666390.54 E – 7921785.46 S	Caverna inacessível	Caverna	CECAV
9	666527.46 E – 7921807.49 S	Caverna inacessível	Caverna	CECAV
10	663659.50 E - 7921750.51 S	Abrigo em tálus	Abrigo	CECAV
11	664523.82 E – 7923330.12 S	Galeria artificial	Não se aplica	Autores
12	664525.8 E – 7923324.33 S	Caverna	Não se aplica	Autores
13	664532.09 E – 7923323.17 S	Galeria artificial	Não se aplica	Autores

Figura 3: *Cavidades, abrigos e galerias artificiais encontradas na área de estudo. Ponto 12 – cavidade estudada neste trabalho.*

A cavidade estudada desenvolveu-se entre o contato da canga laterítica e o quartzito da Formação Itapanhoacanga, conforme observado seu interior (Fig. 4).

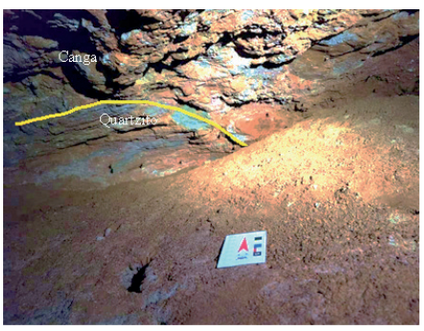


Figura 4: *Contato entre a canga e o quartzito no interior da cavidade. Fonte : Acervo pessoal, 2023.*

A entrada da cavidade apresenta abertura com orientação W-E, mas o seu desenvolvimento é evidenciado pela direção dos degraus, NW-SE (Fig. 5).



Figura 5: *Entrada da cavidade de estudo. Fonte : Acervo pessoal, 2023.*

O piso é recoberto por material alterado e blocos de canga. As paredes e teto formam um arco de canga, que apresenta matriz ferruginosa e clastos arredondados de quartzo e formação ferrífera bandada (Fig. 6).

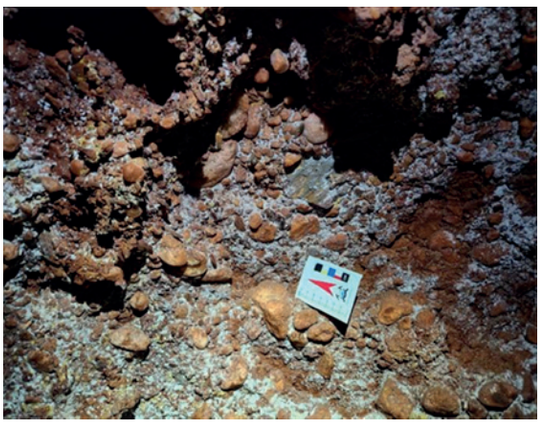


Figura 6: *Parede de canga com clastos de quartzo e formação ferrífera bandada. Fonte : Acervo pessoal, 2023.*

Em dois pontos do teto, foram observados espeleotemas do tipo coraloides, entre outros, formados pela precipitação química nas paredes e teto da cavidade. O ferro é mobilizado pela ação do intemperismo, e posterior transporte das águas percolantes, que novamente se depositam, formando os espeleotemas (MAURITY, 1995). (Fig. 7).



Figura 7: *Coraloides ferruginosos no teto da cavidade. Fonte: Acervo pessoal, 2023.*

Do ponto de vista paisagístico observa-se um relevo bastante dissecado, com variações altimétricas de aproximadamente 400 metros altitude (Fig. 8). As áreas mais elevadas, destacadas pelas tonalidades em marrom e vermelho, correspondem às serras, enquanto as áreas em azul e verde indicam vales e zonas de menor altitude.

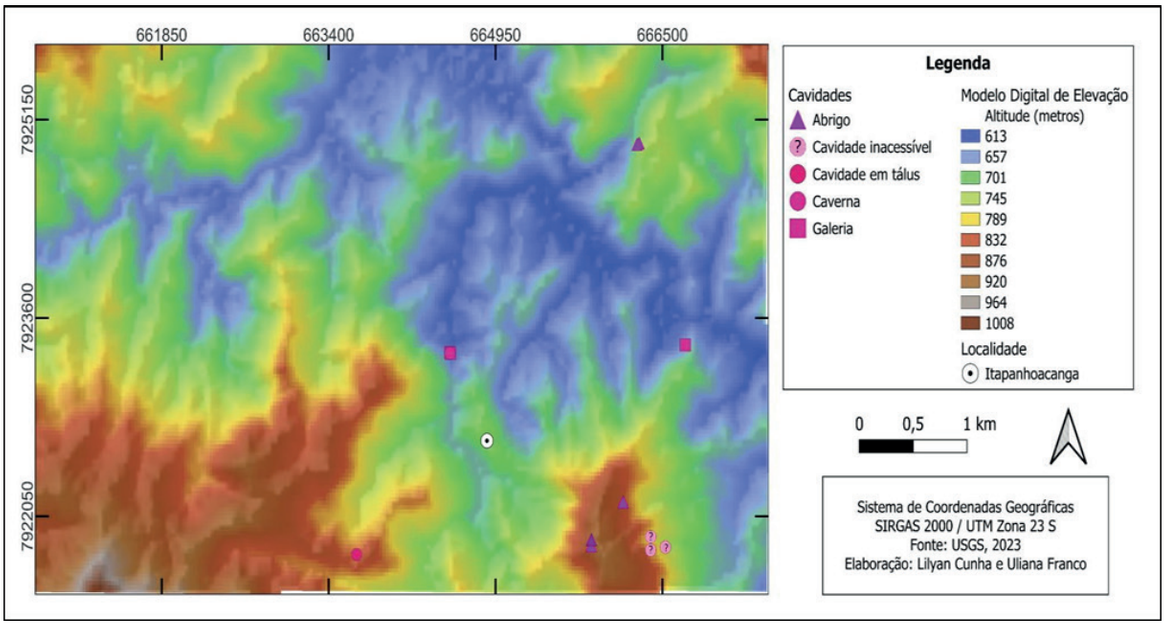


Figura 8: *Mapa hipsométrico da área de estudo. Fonte de dados: USGS, 2023.*

A partir do mapa hipsométrico é possível observar que as cavidades descritas na figura 2 estão distribuídas em altitude superior a 700 metros (Fig. 8), e as galerias artificiais estão dispostas na base das serras, próximas às drenagens. As cavidades da porção sudeste da área, caracterizadas pelo CECAV como abrigo, se encontram em cotas mais altas e distantes da drenagem, enquanto as determinadas como cavernas se encontram, assim como as galerias, na base de serras. O estudo da cavidade forneceu informações importantes, como seu desenvolvimento paralelo ao acamamento do quartzito, a presença de fluxo de água temporário e a importância do contato entre as diferentes litologias na sua formação, além de marcar a maior presença de cavidades em quartzito mais ao nordeste, e em rochas ricas em ferro mais para sudoeste. Essas características reforçam a complexidade destes processos em diferentes tipos de rochas.

4. Discussão

A cavidade estudada desenvolveu-se no contato entre a canga laterítica e o quartzito da Formação Itapanhoacanga, em conformidade com a geologia local (Fig. 2). Essas formações ferríferas encontram-se sobrepostas aos quartzitos da mesma unidade, que também abrigam as cavidades 04 a 09 catalogadas pelo CECAV. O desenvolvimento da cavidade, evidenciado pela direção dos degraus, apresenta orientação NW-SE e ocorre de forma lateralizada de acordo com o plano de acamamento do quartzito. Essa direção indica o regime de fluxo da água no interior da cavidade, que, quando comparado ao mapa hipsométrico (Fig. 8), está em concordância com a direção das drenagens no entorno da cavidade e com o nível de base local, indicando tratar-se de uma cavidade do tipo surgência. A cavidade é revestida por canga lateritica em forma de arco, com sua parte inferior revestida por clastos arredondados, de tamanhos de pequeno a médio, indicando se tratar de sedimentos cristalizados juntamente com os oxihidróxidos de ferro mobilizados e precipitados na forma de minério de hematita. Pode-se dizer que esta canga é um paleoteto (pela configuração atual da forma), visto que a rocha alterada foi quase totalmente removida, seja o quartzito ou a formação ferrífera bandada (Figura 6).

Pode-se observar na cavidade estágios de alteração da rocha

proposta por RODET (2014) na teoria do primorcarste, a isoalterita e aloalterita, demonstrando a importância das fases geoquímicas também para rochas mais resistentes. Segundo CABRAL et al. (2016), a formação dessas cavidades ocorre inicialmente a partir das bandas silicosas, devido à maior suscetibilidade do quartzo à lixiviação, seguida por um aumento da alteração intempérica, em menor escala, das bandas de minerais opacos. Observou-se a alteração das rochas mais permeáveis, quartzito, em contato com uma camada menos permeável, que atuou como um selo, neste caso, a canga laterítica. Segundo CABRAL et al. (2016), esse tipo de cavidade pode ser associado àquelas descritas na Serra de Carajás, onde o fluxo de drenagem direcionado ao longo do contato com a camada impermeável também favorece o desenvolvimento da cavidade após a alteração da rocha. Observa-se formas de dissolução e redeposição, como os espelotemas, e oxidações ao longo da cavidade.

O controle hidrológico e hidrogeológico desempenha um papel fundamental no desenvolvimento dessas formações. A infiltração, percolação e oscilação do lençol freático contribuem para a alteração geoquímica das rochas e a posterior remoção mecânica, sendo fatores determinantes na evolução de cavernas em canga.

Atualmente, observa-se na cavidade a presença de canais internos temporários, de A1 para A3 e de B1 para B3 (Fig. 9), que representam um resquício da fase singenética, já inexistente, conforme ilustrado na topografia da cavidade Além disso, fatores como rearranjos estruturais e abatimentos, de acordo com CABRAL et al. (2016), também influenciam a formação dessas cavidades, já que a alteração das rochas associada aos processos hídricos promovem o desprendimentos de blocos de rochas, clastos e sedimentos, como pode ser identificado a partir da topografia da cavidade (Fig. 9).

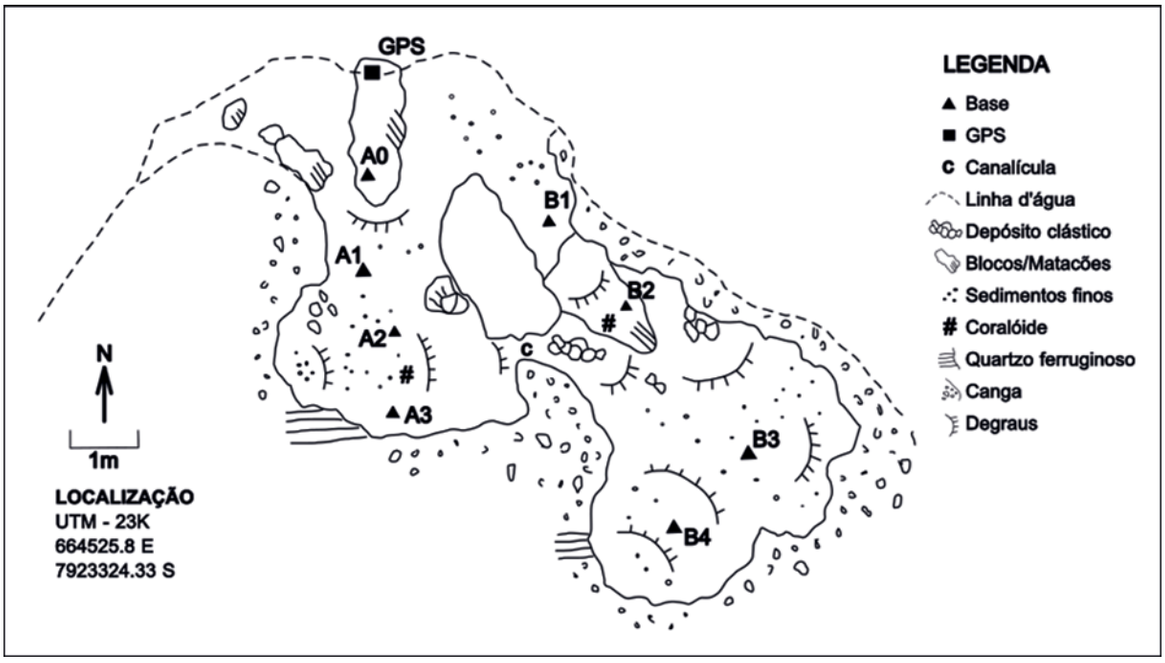


Figura 9: *Planta baixa da cavidade formada em rocha quartzítica e canga, na região de Itapanhoacanga - MG. Fonte : Acervo pessoal, 2023.*

As características das paredes e do teto da cavidade, como matriz ferruginosa e clastos arredondados de quartzo e formação ferrífera bandada, evidenciam o predomínio de eventos de remoção mecânica no processo de formação da cavidade, característicos da fase hidrodinâmica da carstificação. Na região de estudo, as cavernas 07, 08 e 09 foram identificadas próximas a cursos d'água, mas não puderam ser acessadas devido à vegetação densa e limitações de terreno.

Com base nos dados obtidos e na literatura, conclui-se que a cavidade analisada apresenta características condizentes com os processos de carstificação, e demonstram similaridades com formações observadas em contextos análogos.

5. Conclusão

Realizou-se prospecção de 13 cavidades (cavernas, abrigos e galerias artificiais) indicadas pelo CECAV, e observou-se discordância, pois algumas cavernas eram na verdade abrigos, ou galerias artificiais.

A cavidade estudada se desenvolveu no contato entre a canga laterítica e o quartzito da Formação Itapanhoacanga, refletindo a influência dos fatores litológicos, estruturais, hidrogeológicos e estratigráficos em sua formação e evolução. Além disso, observou-se que a cavidade apresenta uma direção de desenvolvimento preferencial paralela ao acamamento do quartzito, presença de canga laterítica em forma de arco e a matriz ferruginosa associada com clastos arredondados de quartzo no lado interno e formação ferrífera bandada, com ausência de preenchimento, indicando que a cavidade passou por processos de dissolução, remoção mecânica e redeposição de materiais. O arranjo da canga laterítica sugere que esta pode representar um paleoteto, resultado da remoção progressiva da rocha alterada, seja quartzito ou formação ferrífera bandada.

Dessa forma, pode-se notar que mesmo estando associada à rochas mais resistentes, a cavidade estudada é formada pelo processo de carstificação, com especificidades das formações ferruginosas, e seu estudo contribui para a compreensão dos mecanismos de carstificação em canga laterítica, e quartzito.

O principal aspecto relacionado a formação e evolução desta cavidade está na carstificação de rochas muito antigas, promovido por um contato entre duas rochas de durezas diferentes, o que causa um intemperismo e erosão diferenciais, e que portanto, são influenciados por fatores litológicos, estruturais, hidrogeológicos e estratigráficos, que atuam de maneira integrada, porém com intensidades variáveis.

Agradecimentos

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Arched shapes in granulary disintegrating rocks and how to measure their degree of weathering?

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Abstract

There are a relatively large number of rocks that disintegrate granularly. Arched shapes are often found in these rocks, not only on ceilings but also on walls or supporting pillars. These shapes are the result of the granular rocks "striving" for stability. Arched shapes are more resistant to erosion. Where the perfection of the shapes is disturbed, e.g. by sudden changes in the profile of corridors due to sudden rock falls, the development towards arched shapes starts again. However, different places weather at different rates, depending on how they gain stability. The rate of weathering, and therefore to some extent the state of development of the vault, can be measured using a field flexible pull-off test. In this paper, we demonstrate the application of this method to weathering coarse crystalline salts from natural caves in the Iranian salt karst.

1. Granularly disintegrating rocks – environment suitable for evolution of caves with arched shapes

Granular disintegration of rocks, including cemented sediments, is a type of physical weathering in which rocks disintegrate without significant changes in their mineralogical or chemical composition (Gregory and Goudie 2011). It is a mechanical breakdown into individual mineral grains, sometimes through intermediate stages in the form of segments such as detached layers, scales, etc. This kind of

disintegration is due to the nature of rocks/materials and the pressures (or better stresses) applied in the weathering material (Gregory and Goudie 2011). The stresses on the grains from the inter-granular space may be of different origins. The most common are crystallization stresses of salts during evaporation, cryosuction during freezing, hydric and hydrig dilatation or slaking, and stresses due to temperature changes in a diurnal or annual cycle (e.g., Wedekind et al. 2013). Granular disintegration refers to various types of rocks ranging from sedimentary rocks (sandstone, locked sands, loess, cemented residual sediments on salt diapirs, etc.) to igneous and metamorphic granitoid-type rocks (granite, gneiss, etc.) to various volcanic sedimentary rocks (e.g, tuffs) (Turkington and Paradise 2005). Most of the above-mentioned rocks have received a great deal of attention both in a geotechnical sense and from scientists in various disciplines. In fact, these rocks have been used for millennia as building materials and, in addition, in nature they create aesthetic shapes/monuments and entire landscapes that are used as tourist destinations.

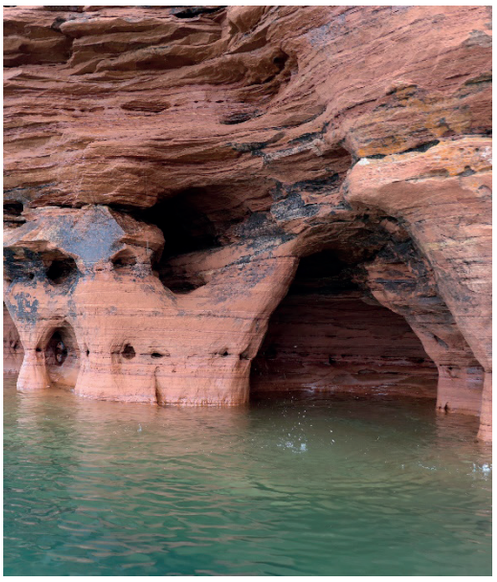


Figure 1: *Arched cavities – sea caves – with pillars on the castal sandstone cliffs, Bayfield Peninsula, Lake Superior, USA (Photo by M. Filippi).*

Experts from the ranks of geomorphologists, geotechnical engineers or conservators (in the case of architectural monuments) address the origin, evolution, and destruction of natural shapes, the mechanical properties of rocks under different conditions and their susceptibility to weathering and erosion. Rocks that undergo granular disintegration have similar weathering behavior and therefore produce similar weathering forms, landforms and entire characteristic landscapes (Young et al. 2009). Perhaps the best known and most widespread granular rock is sandstone and its stronger alternative, quartzite. As is well known,

these are the rocks in which various cavities and caves commonly form, including multi-kilometer systems with large underground domes (Auler and Sauro 2019). Another granular rock, although with a much smaller range of occurrence, is rock salt exposed in salt diapirs (Bruthans 2000).

A common feature of caves in granularly disintegrated rocks are the arched (vaulted) shapes (Figs. 1 and 2). They develop mainly on the ceilings of corridors and domes, but also on walls or supporting pillars. The perfection of the shapes and the similarity in different locations, as well as the exact mechanism of their formation, was long unknown. Only recently have works been published that have shed clear light on the issue. The explanation of the fundamental principle of stabilizing effect of gravity-induced stress on rocks with granular disintegration was presented by (Bruthans et al. 2014). Later, this principle was used to explain the weathering pattern of artificially created arched cavities (tombs) in the 2000-year-old rock city of Petra in Jordan (Rihosek et al. 2016). The formation of perfect rock arches (not only) in Arches National Park, Utah, USA, was explained and simulated for the first time by erosion of natural material (Rihosek et al. 2019). Finally, a new weathering form, called arcades, so far the best field evidence for stress-controlled-weathering was characterized and its origin explained by physical modelling and successfully simulated by novel numerical modelling of stress-controlled weathering (Filippi et al. 2018; Safonov et al. 2020). This principle has a major impact on considerations regarding the formation of some caves in granularly disintegrating rocks, as has been shown by the application of the arcade principle for the explanation of the origin of arched sea caves (Filippi et al. 2024).



Figure 2: *Square- versus arched- cave profiles in the interior/entrance parts of the quartzite/sandstone Berlin Cave, Mbombela (Nespruit) Area, South Africa (Photo by M. Filippi).*

2. Evolution of arched shapes – desire of the rock for stabilization

Arched shapes (profiles) in cavities and caves can be developed from the very beginning, for example in the case of arcade forms (Filippi et al. 2018). Sometimes, however, they do not arise immediately with the origin of the proto-cavity, but develop gradually, only with the long-term development of the cave (by simple enlarging), "driven" by the need of weathered granular rock to create stable forms (i.e. negative feedback between stress and erosion rate; Bruthans et al. 2014). However, irregular and angular (unstable) profiles of cave passages and domes in granularly disintegrating rocks are typical mainly of suddenly formed spaces (Fig. 2). Examples include spaces formed after the collapse of large blocks, the collapse of ceilings, the bursting of water into the rock environment, or or just the gradual detachment of a part of the rock from the main massif (see Filippi et al. 2021). After such events, the shapes of the walls, ceilings and related forms change and thus their stability. Usually, this is soon followed by an accelerated evolution of the exposed rock with the aim of regaining long-term stability. This development is reflected primarily in the rate of erosion in various places of the cave profile. That is, after an event that disrupts a certain "uniformity" in erosion resistance, the rock is strongly selectively attacked by erosion agents and reshaping occurs. The time over which this development takes place depends on the nature of the rock, the strength and duration of the effect of weathering (forming) agents (flowing water, crystallization of minerals from internal rock moisture, dissolution of any intergranular cement, etc.). The rate of the development will be different for quartzites and different for rock salt, for example.

Of course, other factors may enter the process of development of the shapes of corridors and cavities (primary sedimentary structures, consolidated tectonic features, ferruginization, silicification, etc.), but here we are now considering only development in homogeneous parts of massifs.

This process, or let's say the "development of arched shapes" in rock cavities and caves, can be detected to a certain extent by the difference in weathering on the supporting and ballast parts of rock walls. It can therefore be approximated in a certain way that a high difference in weathering on different parts of the cave space surface indicates ongoing development, and conversely, a similar degree of weathering on most of the surface of the shape indicates a certain maturity and potentially long-term stability. Can this be measured exactly?

3. Field methods to measure the rock strength

There are several methodologies for measuring rock surface strength on rock exposures in situ. Proxy measurements are used in the field, especially various tests connected to rock hardness (Schmidt hammer and Equotip methods; Viles et al. 2011). Schmidt hammer of various subtypes is the most widely used and shows often relatively tight correlation with unconfined compressive strength, and it is considered micro destructive (Viles et al. 2011; Přikryl and Snížek 2023). For firmer rocks the Schmidt hammer gives a strong correlation with weathering damage, demonstrated by Schmidt-hammer exposure-age dating calibrated by cosmogenic dating (Winkler and Matthews 2020). However, rock shape formation especially

degrades the tensile strength or material cohesion, which finally results in detachment of material by low-force erosion factors. Such material would not survive the impact of even L type of Schmidt hammer (lower impact energy than most common N type), its surface is often uneven, which is problematic for other hardness testers like Equotip to be used (Viles et al. 2011). In addition, a relatively large area is required to obtain a single value using the Schmidt hammer (it is obtained by averaging 20 measurements in a square grid) and this is a very limiting factor.

Field drilling resistance is another method commonly used for the rock surface and shallow subsurface strength evaluation (e.g. Pamplona et al. 2007; Cnudde et al. 2009). A drilling resistance hammer drill is used for this measurements. The hammer drill is designed to measure the strength of bricks and mortar. The device consists of an accumulator drilling machine equipped with a controller for a constant number of rotations of the drill, a spring to maintain constant pressure, and a masonry drill bit 5 mm in

diameter. After drilling, the depth of the drilled hole, which is inversely proportional to the sandstone strength, was measured with a sliding gauge/caliper.

The disadvantage of the drilling resistance method is its relatively low resolution, but also the need for charged batteries and a drill (considerable volume and weight). In addition, the measurement is point-based (on the drill tip area of 4–5 mm), so the measured value can be distorted by local inhomogeneities.

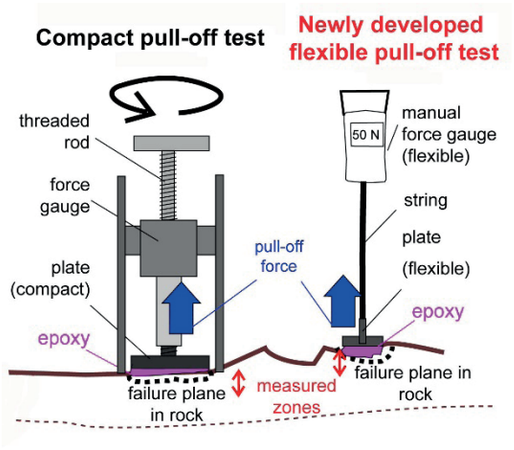


Figure 3: Comparison of the classic compact pull-off test method with the newly used flexible pull-off test method. The main advantages are: lower weight of the device and the glued units and simpler operations on the rock surface.

4. Tensile strength – a proper method for in situ measurement?

The third method, used to test the adhesion or strength of glues, paints, ceramic surfaces, concrete, asphalt and even rocks under laboratory conditions, called a pull-off test (Ramos et al. 2012). The method measures tensional stress (in fact shear stresses). This method uses professional compact pull-off test instruments. Unfortunately, these instruments are designed for even surfaces and work in limited ranges. They are (by nature) very inflexible for use on different materials and geometries of natural surfaces so they are not appropriate for most of the field measurements, let alone on the often richly shaped weathering forms of granularly disintegrating rocks. In addition, the device and the certified tear-off (steel) bodies are too heavy to transport in the field.

Therefore, a simple version of this method called “flexible pull-off test», which reflects the tensile strength of surfaces was applied: an aluminum T profile (square metal plates with grips, surface area 2 × 2 cm; weight 3 g) are glued by epoxy to the rock surface (Bruthans et al. 2012). After hardening, tensile force was applied by a forcemeter attached to the metal plate perpendicular to the rock surface until a failure of the rock beneath the epoxy. The maximum (pull off) force and failure area were measured. The ratio of the force and the area was reported as tensile strength (kPa).

The strong advantage of this method is that it can be used on a small surface (1–4 cm^2) and that it is relatively rapid (50 measurements/day). It imitates the weathering stresses (rock face retreat), since applying the tensile stress perpendicular to the rock surface is similar as if expansive stresses would occur in pore space in a shallow rock subsurface caused by crystallization of salts, ice or growth of endolithic organisms, etc. So, unlike the most used methods (Schmidt hammer, Equotip), this method measures the resistance of the rock to stresses which needs to be overcome by weathering to detach the material from the rock surface.

5. Example from the ventilated parts of caves in the Iranian salt karst: granular weathering and tensile strength

The southern and south-western part of the Zagros Mts. represents an area with the largest number of piercing salt diapirs in the world. Dozens of diapirs present a variability of well-developed karst phenomena, including countless salt caves. Characterization of the karst phenomena and notes on the speleogenesis were presented e.g. by Bruthans et al. (2002, 2010). Caves in salt karst develop very quickly (e.g., Bruthans et al., 2024). Especially in the entrance- and ventilated- parts of salt caves, several stages/types of ceilings can be seen displaying different rates of rock disintegration. In the newly created spaces after collapses of ceilings, there are angular shapes of passages and clear detachments (cracks) of larger portion of rock material (Fig. 4). In contrast, in longer evolve spaces, perfectly arched ceiling shapes are typical. In deeper, unventilated parts of large caves, the situation is different; we will not discuss these situations here. Our measurements come from entrance- and well-ventilated parts of caves. A photo documentation was carried out with time intervals of several years, measurements of the rate of grain/fragments fall out from cave ceiling were made by collecting and weighing material, as well as detailed measurements of temperature and humidity, as well as tensile strength measurements.

It was found, that during nights, when air relative humidity (RH) cross the threshold >75 %, the humidity is entering the salt caves and is wetting dry rock and slightly diluting the percolating brine in ceiling of the caves, which is otherwise just saturated with respect of halite. This causes dissolution of salt cement. During day, the RH is <75% and brine partly dries up and precipitates halite.

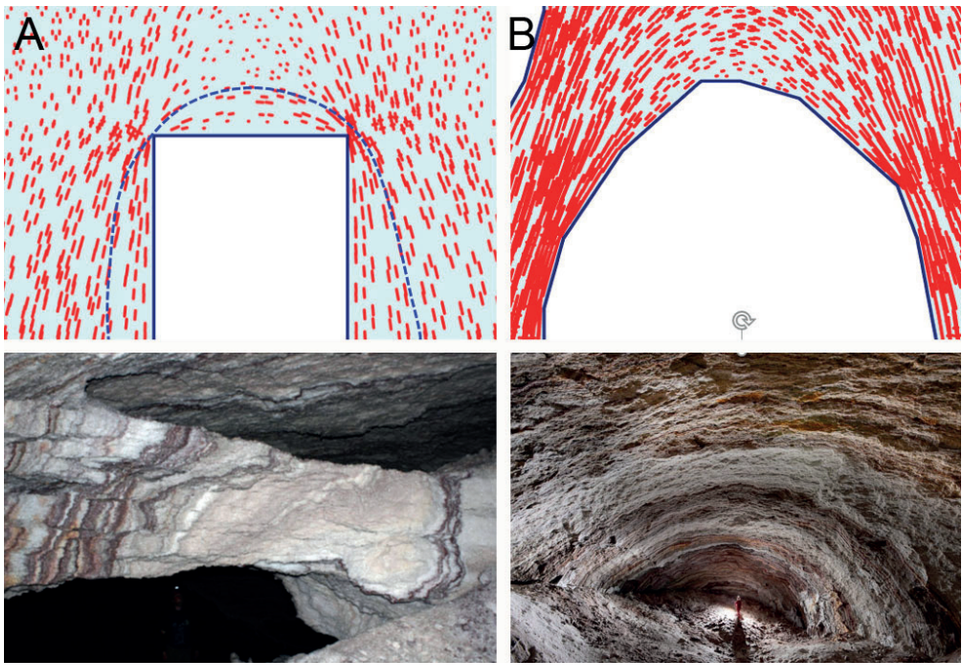


Figure 4: *Rectangular- (column A) versus arched- (column B) shape of the profile in a salt cave. The first row shows the directions and density of the stress lines around shapes (using the PLAXIS model). The second row shows an example from the 3N Cave, Namakdan salt diapir, Qeshm Island, Iran. (Photos by J. Bruthans - left and P. Crochet - right).*

Therefore, cave walls and ceilings can weather by repeated dissolution and crystallization by halite. In "unstable" rectangular parts of caves (e.g., those after rock collapses), which are not under a protection of the gravity-induced stress produced by arched shapes, the weathering may proceed significantly the rock disintegrates. It often falls not only in grains but especially in larger fragments and blocks. On the contrary, in places where there are vaults, the ceiling appears significantly more solid. The salt surface at various weathered locations was therefore tested using the flexible pull-of (tensile strength) method. It was found that in the places of arches on "unweathered" salt, detachments/failure occur at significantly higher forces. Additionally, detached rock plates were torn off across salt grains (detached surface was straight). This indicates high strength (Fig. 5A).

In contrast, on "weathered" surfaces, failure along salt grains contacts occurred (detached surface was rough, Fig. 5B). We can conclude that intergranulary-weathered salt behaves as a weak sandstone or a highly weathered granite (also granular material), for instance. Load-bearing parts are stabilized by gravity-induced stress (load of overburden and arched shape), ballast (material not loaded or in tension) is rapidly wasted. This is the principle that creates and maintains the arched ceilings in rock salt and also in other granularly disintegrating rocks.

In the case of ventilated caves in salt, air moisture is a very significant erosion factor. In other rocks, it can be the crystallization of salts from internal moisture, disintegration due to calcite dissolution or pyrite decomposition and other factors.

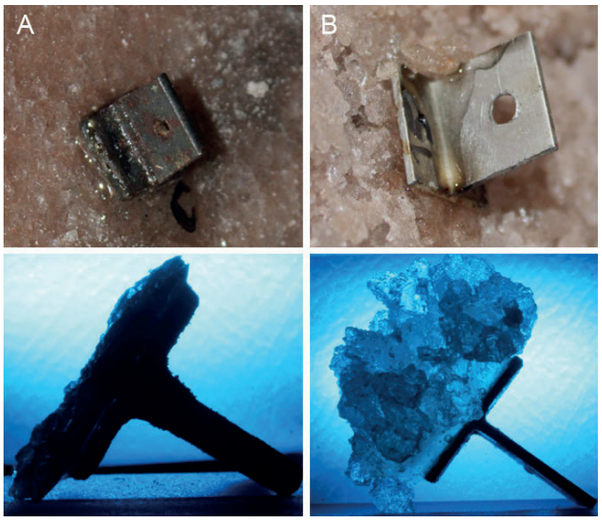


Figure 5 : *Results of the flexible pull-off (tensile strenght) test used on the rock salt on: A – a slightly weathered surfaces showed detachment/failure at a significantly higher forces and with detached rock plates torn off across salt grains (detached surface is straight); B – a strongly weathered surfaces showed detachments/failure at a smaller forces and with failure along salt grains contacts (detached surface was rough) (Photos by J. Bruthans).*

Acknowledgments

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Speleogenesis in Quaternary clastic sequences along the active front of South-Eastern Alps, a case study from Castel Sotterra Cave (Veneto, Italy)

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Abstract

The Castel Sotterra Cave, extending ~ 7 km in length and ~ 125 m in depth, is the longest cave in the Montello Hill and the fourth longest conglomerate cave in the world. The Montello hill is an isolated low plateau composed of conglomerate beds alternating with sandstone and siltstone layers, bordered by a fault system belonging to the most advanced deformation front of the Venetian Pre-Alps. The landscape is shaped by the erosive power of the Piave River and by extensive karst processes characterized by sinkholes, karst valleys, underground cave systems and springs. Speleogenesis within Castel Sotterra is dictated by variability in lithology, which is influenced by the contrasting mechanical properties of the conglomerate matrix and clasts, and fracture networks. As a result of the rapid tectonic uplift, at least three main lithologically controlled cave levels were formed. Castel Sotterra Cave is an example of a remarkably rapid landscape evolution, where Pleistocene fluvial deposits have undergone diagenesis, uplift and karstification within a short geological time frame, and the interplay between fluvial incision and tectonic uplift by the active thrust system has significantly influenced groundwater flow and karst development.

1. Introduction

The karst potential of conglomerate outcrops is poorly explored, yet conglomerates are found on every continent due to erosion of active margins and orogenic belts. Few studies investigate “non-traditional” conglomerate caves around the world and their speleogenesis (Lapaire et al., 2007; Finch and Pistole, 2011; Lipar and Ferk, 2011; Dunkley et al., 2017), reflecting an interplay between dissolution and mechanical erosion, often controlled by inception horizons in well-defined carbonate-bearing portions of the terrigenous bedrock. The Montello Hill is considered a “classic karst” of conglomerate (Ferrarese and Sauro, 2005), due to the presence of the state of the art of sinkholes, karst valleys, karst springs and hundreds of caves in such a small area.

The Montello Hill is a low-elevation WSW-ENE elongated plateau, ~ 13 km long and ~ 5 km wide, which belongs to the subalpine hills, a series of ridges emerging from the Venetian fluvial plain by tectonic scarps due to thrusting by the most advanced fault system in the region (Figure 1A) (Zanferrari et al., 1982; Ferrarese et al., 1998). The Montello hill represents an emerging tectonic pop-up, bounded on the SE escarpment by the main branch of the Montello thrust system and on the NW slope by the Piave river, which cuts the hill on the NE side, creating the Nervesa water gap (Figure 1B). The SW side is characterized by an abandoned dry valley, where the Piave River flowed until ~ 27 Kyr (Mozzi et al., 2015), and a series of seven-order erosional fluvial terraces (Figure 1B). At the top of the hill, two planation plateaus occurred at different elevations (Figure 1B).

The substrate of the subalpine hills is represented by molasse-type terrigenous sequences that show a gradual filling of the Alpine foreland since the Late Oligocene (Massari et al., 1986). The substrate of the outer hills, such as the Montello Hill, consists of two conglomerate formations: (1) the Montello Conglomerate, dated as Late Miocene (Dal Piaz, 1941; Martinis, 1955), and (2) the Conegliano Unit, dated as Pliocene-Middle Pleistocene (see Avigliano et al., 2008; Caputo et al., 2010). Since previous work on the Montello karst system (Ferrarese et al., 1998) and tectonic studies (Benedetti et al., 2000; Picotti et al., 2022), it has been assumed that the Montello Hill is composed entirely of Montello conglomerate, but there is no clear evidence and the borehole stratigraphy (see Mancin et al., 2007) across the hill contradicts the current interpretation.

Therefore, new speleological investigations in the largest cave of Montello, the Castel Sotterra Cave, aim at proposing a renewed stratigraphic model in which the shallower unit is represented by the upper part of the Conegliano Unit. An attempt to determine the age of the substrate can lead to the discovery of the true nature of tectonically modulated karst processes, which represent the main driving factor in the evolution of the Montello landscape. In this work we present a speleogenetic model for conglomerate karst, integrated with a model of hydrostructural evolution in accordance with the tectono-stratigraphic setting of the Montello Hill.

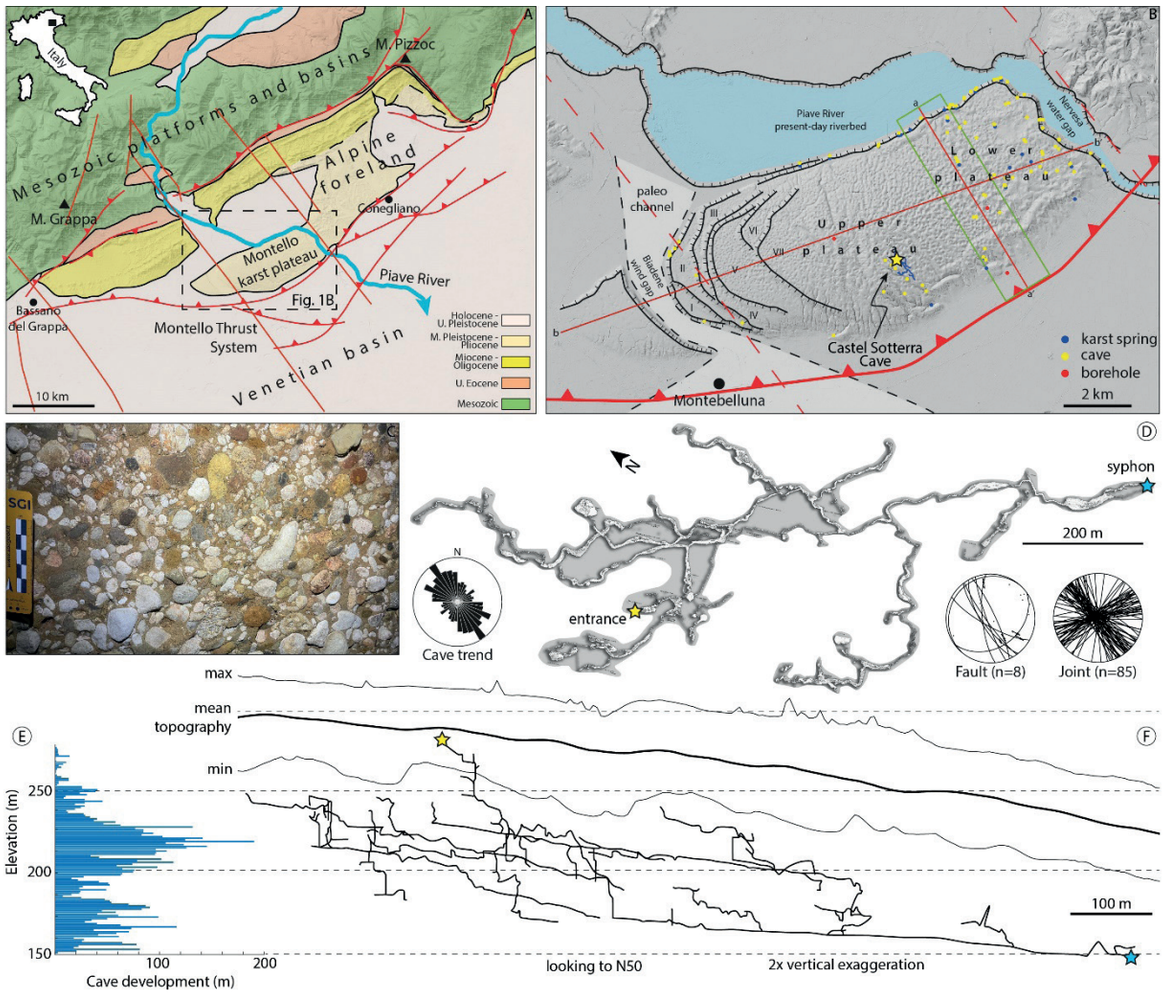


Figure 1: *(a) Simplified geological map of the southeastern Alpine foreland system showing the position of Mount Montello. (b) Main geomorphologic features of the Montello Hill, such as the location of caves and karst springs, and seven orders of fluvial terraces carved by the paleo-Piave river, a-a' and b-b' profile traces refer to Figure 3. (c) The typical conglomerate facies as seen from inside the Castel Sotterra cave. (d) Map of Castel Sotterra; directions of tectonic and morphologic structures are shown in stereonets. (e) Spatial distribution of karst channels on the vertical axis. (f) Cross section of Castel Sotterra cave, topography is represented in a range of elevations averaged over the surface area above the cave.*

2. Materials and methods

This work was done by combining traditional cave mapping and geological field surveys. The first comprehensive map of the cave was drawn in the 90's and the polygonal lines have recently been computerized on C-Survey software, allowing a three-dimensional observation of the cave in Loch software extension. In the last two years a new mapping project has been conceived to add newly explored passages and correct known errors present in the old map. The new map is the result of speleological surveys carried out with a modified Leica Disto-X laser telemeter and the Topodroid mobile application. The topographic analysis of the Montello hill is done in GIS environments with a 2m resolution LiDAR-based digital elevation model (provided by the Veneto Region online repository). Borehole stratigraphies are available on Videpi website and the ISPRA national borehole repository.

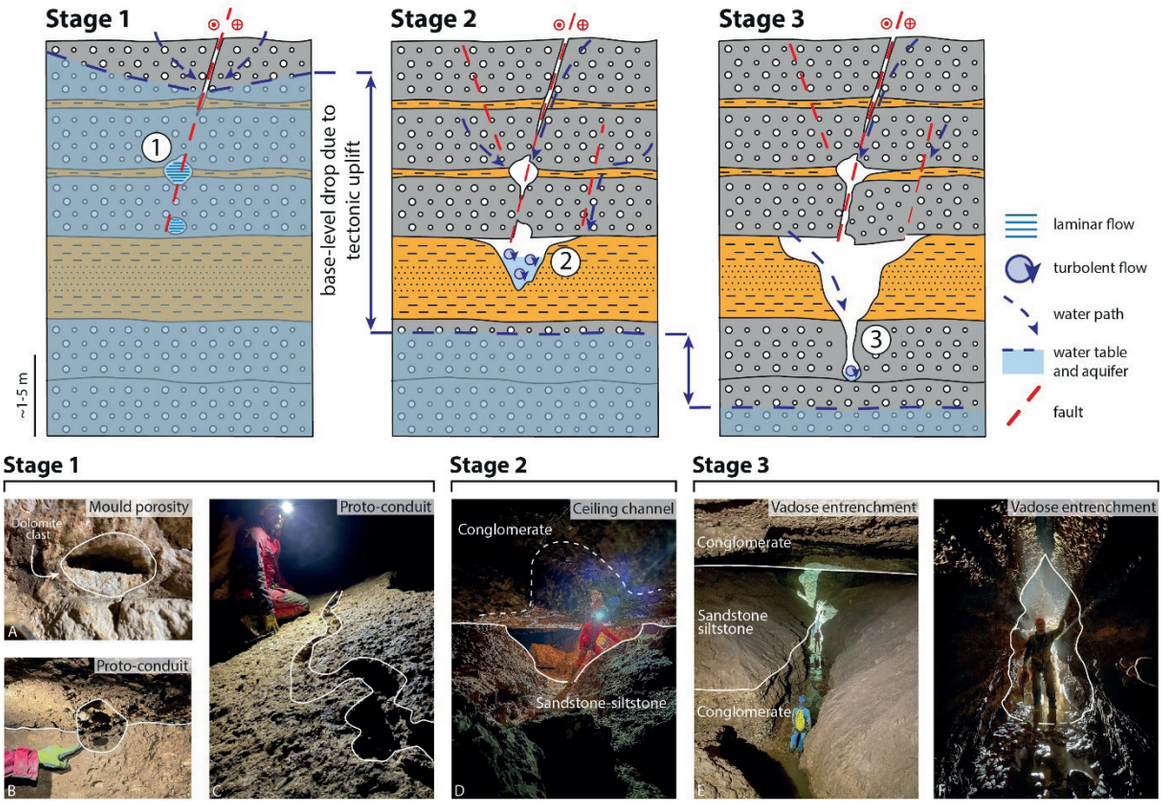


Figure 2: *Model of cave evolution in the conglomerate facies of the Montello Hill. The engine of karst evolution is represented by the lowering of the basement due to tectonic uplift, and the morphologies reflect the local stratigraphy.*

3. Results

The Castel Sotterra Cave extends for more than ~ 7 km below the upper plateau (Figure 1B), with the entrance at 275 m a.s.l. and the terminal syphon at the end of the active canyon 125 m lower (Figure 1D, F). The cave is mainly formed by several kilometers of vadose passages, such as meandering canyons, phreatic tubes, horizontal fissures following bedrock stratification, breakdown rooms and shafts connecting parts of vadose passages at different elevations.

Bedrock formation is characterized by the alternation of decametric to metric layers of polymictic matrix-dominated carbonatic conglomerates and centimetric to metric unconformable bodies of siltstone and sandstone. Vadose passages carved in fine-grained lenses are usually wider than deeper, because erosion spreads rapidly to the sides due to instability caused by erosion at the base of poorly consolidated silty walls. Canyons in conglomerate are generally narrow and 10 to 30 meters deep. Rooms created by ceiling collapses extend horizontally along weak discontinuities in the substrate, generally represented by centimeter-thick layers of fine-grained sediments. Bedrock stratigraphy exerts strong control over the development of cave passages. The occurrence of fine-grained lenses enhances formation of nearly-horizontal vadose canyons at several levels (Figure 1E-F). Different clusters of elevations characterized by the development of long passages occurred (Figure 1E). Since the first explorations, three main cave levels have been identified and named: (1) "*Superiori*" (upper passages), (2) "*Argilloni*" (mud passages), (3) "*Inferiori*" (lower passages). The other key factor that controls the karst development in this cave is the presence of an extensive network of fractures and faults (Figure 1D). The general azimuthal trend of the passages, striking NW-SE, is almost identical to the orientation of the fractures and strike-slip faults. In addition, conglomerate beds are often offset by vertical planes. Evidence of movement along the planes is represented by fault striae and calcite slickensides, and in rare cases by mud squeezed between blocks. Tectonic structures are also observed to control large gravitational collapses.

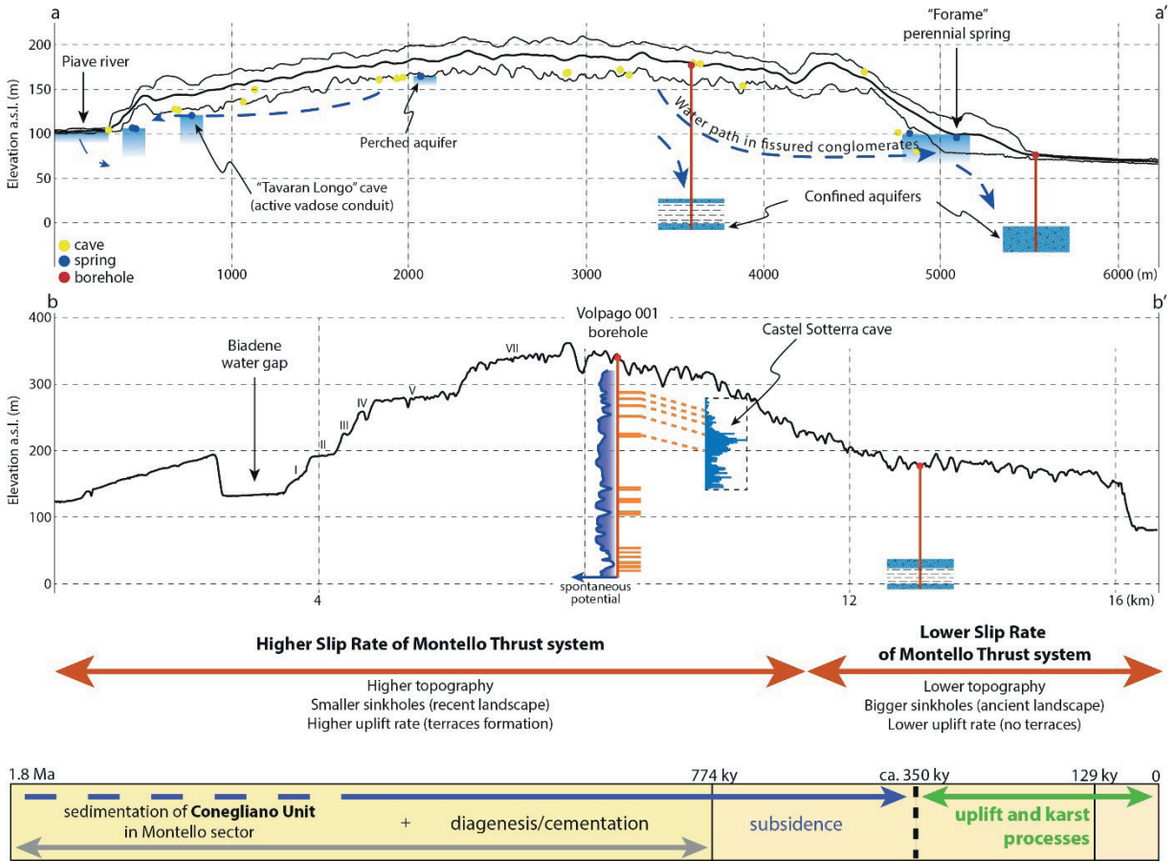


Figure 3: *a-a' swath profile across the lower Montello plateau showing the main hydrostructural features. b-b' topographic profile across the entire length of the Montello Hill, highlighting the fluvial terraces, the elevation difference between the higher and lower plateau, and the stratigraphy of the fine-grained sediment layers detected in the Volpago 001 borehole. the bottom panel shows the inferred geological evolution of the Montello hill since the Early Pleistocene.*

4. Discussion

We propose a simple speleogenetic model based on direct observations of cave morphology. The conceptual formation and evolution of cave morphologies can be resumed in a three-stage model (Figure 2). Initially, near or below the base of a conglomerate karstic aquifer, widespread dissolution promotes the development of secondary porosity in the silty carbonaceous matrix. In addition, dissolution is concentrated on limestone-dolostone pebbles (Figure 2 - Stage 1). Along inception horizons more prone to karstification and tectonic structures, fluid flow under phreatic conditions is able to form proto-pipes (Figure 2 - Stage 1), which are able to expand by exploiting muddy interlayers commonly found between massive conglomerate beds. As confirmed by fluvial terraces (Benedetti et al., 2000; Ferrarese and Sauro, 2005; Picotti et al., 2022), the entire Montello Hill structure was uplifted in the Quaternary by the Montello thrust system, leading to multiple base level drops. When phreatic conduits are formed in conglomerate beds just above arenaceous-silty beds, it can happen that the expansion of the conduits leads to the encounter of softer sediments, which in a short time form large cave passages, such as horizontally developed fissures or vadose canyons. Non-paragenetic ceiling channels formed by vertical vadose entrenchment are recurrent morphologies in Castel Sotterra (Figure 2 - Stage 2). Mechanical erosion is dominant at this stage, considering the reworking of soft arenite-siltstone beds by particles dispersed during floods. As the base level is continuously lowered, vadose entrenchment continues to the bottom of the stratigraphic sequence, cutting narrow canyons in the conglomerate beds (Figure 2 - Stage 3). Together with lithological variability in the local stratigraphy, a series of large vadose canyons and narrower fractures and tubes alternate vertically in Castel Sotterra. Even small variations in grain size lead to differential and gradual sculpturing of vertically oriented passages (Figure 2 - Stage 3, last image). In addition, gravitational collapse and fault activity are key mechanisms in speleogenesis. Huge sectors of the cave are completely filled by rockfall deposits, and conglomerate beds are often displaced along nearly vertical planes. The true extent of gravitational collapses is certainly underestimated by the low-resolution of traditional cave mapping in imaging three-dimensional spaces. Collapses and tectonic structures facilitate connections between cave levels, enhancing water circulation and dissolution. The concurrent interplay of gravitational and tectonic movement is difficult to distinguish, but fault striae coherent with the local stress field (stereonets in Figure 1D) are found along cave passages.

We believed that the tectonic uplift was not uniform, considering that it is directly related to the activity of the thrust system, as also highlighted by the uplift rates estimated for the terraces (Benedetti et al., 2000). Cave development along three main levels may reflect three phases of local water table stability due to tectonic quiescence or climatic stability of the paleo-Piave fluvial system, ultimately related to the Quaternary glacial cycle.

The present-day base level is poorly constrained by few boreholes (Figure 3, section a-a'). Borehole stratigraphy and aquifer analysis suggest that below the present fluvial plain elevation (~ 75 m on the

SW side of Montello Hill), several local aquifers are confined between low-permeability layers. Water entering Montello Hill through karst passages can follow three pathways (Figure 3) by: (1) reaching deep aquifers confined in highly porous conglomerate beds, (2) remaining near the surface and discharging at springs on the plateau, (3) feeding perennial springs typically found at the base of the Montello Hill escarpment. The stratigraphy of the Volpago 001 borehole confirms the presence of fine-grained beds along its entire length (Figure 3, section b-b'). At the present stage of geological exploration of the Montello structure, a clear correlation between fluvial terraces, fine-grained sediments and cave levels is lacking (Figure 3). Nevertheless, a stratigraphic control of erodibility on bedrock planation processes will certainly be a key point in evaluating the lithological control on landscape evolution, which could even lead to a rethinking of uplift rates. However, looking at the topography of Montello (Figure 3), the SW sector presents a higher relief with respect to the NE sector (Upper vs. Lower plateau in Figure 1B). This observation suggests a structural model where the southern part of Montello Hill is more uplifted than the northern part. Also considering the morphometry of sinkholes (Ferrarese and Sauro, 2005), a more stable and therefore older landscape is expected in the northern plateau, where larger sinkhole diameters and higher coalescence rates are found with respect to the surface at the same elevation in the southern sector.

The landscape evolution interpretation described above is consistent with the increase in modeled uplift rate towards the southern tip of the Montello Thrust (Benedetti et al., 2000) and a change in geometry just south of the Montello Hill (see Figure 1A-B). A contrasting interpretation of the tectono-stratigraphic evolution has shown that the northern plateau has been affected differently by erosion and weathering, as the Conegliano Unit unconformably overlaps the Montello Conglomerate, the latter inferred to outcrop on the upper plateau. Picotti et al. (2022) stated that the northern plateau is formed by less weathered younger conglomerate with respect to the southern plateau. However, considering the uniformity of the conglomerate sequences studied by speleological exploration and the borehole stratigraphy of Mancin et al. (2007), the entire Montello hill structure appears to be composed of the Conegliano Unit at least in the first few hundred meters of depth. The age of the substrate forming the Montello structure, inferred to be Messinian by Dal Piaz (1941) on the basis of gastropod association, must be revised in the light of more recent biostratigraphic correlations, since a single paleontological finding may not be representative of the entire conglomerate facies. These observations may lead to a renewed interest in the rate of uplift and convergence of the southeastern Alpine deformation front.

Assuming that the entire Montello Karst system developed within the Conegliano Unit sequences, whose sedimentation is constrained by the Villafranchian fauna described by Venzo (1977), correlated with the Calabrian stage (1.8-0.77 Ma), and that the onset of uplift is constrained to be ~ 350 Kyr by modeling of thrust activity (Benedetti et al., 2000), karst processes occurred in a very short time (Figure 3, bottom panel). Cave development is accelerated by (1) enhanced mechanical erosion, which is fundamental to the carving of deep vadose passages, (2) abrupt base-level drops due to thrusting, (3) conglomerate collapses, and (4) neotectonics.

5. Conclusion

The Castel Sotterra Cave is a remarkable example of rapid landscape evolution dominated by dissolution processes in a non-traditional conglomerate karst. The transition from the end of the deposition of continental Molasse-like fluvial conglomerates in the Pleistocene to uplift, karst dissolution, weathering and erosion has occurred in a very short time. The incision caused by the Piave river and the uplift caused by the active thrust system have significantly influenced the groundwater flow and the karst development. Geomorphic evolution and neotectonic processes are ongoing within the cave. Speleogenesis is initially dominated by dissolution of conglomerate matrix and carbonate pebbles, followed by mechanical erosion in hydrologically active cave passages and gravitational collapses. Deep entrenchments, structurally-controlled rock collapses and vertical movements induced by faulting are observed. The lowest level of the cave reaches a local water table, but the hydrologic connection to springs remains unresolved. Aquifer levels are documented at perennial springs, on the Montello Hill escarpment, and in boreholes. Elsewhere, rapid tectonic uplift and numerous fine-grained horizons acting as seals suggest a hydrostructural model of multiple confined and perched aquifers.

Acknowledgments

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The digital elevation model is taken from the Veneto repository (https://idt2.regione.veneto.it/idt/downloader/download). Volpago borehole stratigraphy is from the Videpi repository (https://www.videpi.com/videpi/videpi.asp). Water borehole stratigraphy from the ISPRA repository (https://www.isprambiente.gov.it/it/banche-dati/banche-dati--folder/suolo-e-territorio/dati-geognostici-e-geofisici). The software used in this work are: C-Survey (https://csurvey.it/site), TopoDroid (https://sites.google.com/site/speleoapps/home/topodroid), QGIS Desktop 3.34.3, ArcMap 10.8.2, Adobe Illustrator 2023, MATLAB R2022b with the packages Topotoolbox (https://topotoolbox.wordpress.com) and TAK (https://github.com/amforte/Topographic-Analysis-Kit).

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Caviadades naturais em granito: breve revisão de tipos

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Resumo

Cavidades naturais em embasamento (granitos, gnaisses) são relativamente pouco conhecidas e estudadas se comparadas a cavernas em outras litologias, especialmente em rochas carbonáticas. A partir de uma breve revisão sobre classificações de tipos de cavernas em granito elaboradas por diversos autores são apresentados três tipos considerados principais: cavidades estruturais, cavidades em matacões e tafoni. Aspectos das possíveis gêneses relacionadas a esses tipos são apresentados de forma sucinta. No Brasil, diversas expedições e estudos em cavidades graníticas foram realizadas principalmente a partir da década de 1990. Entretanto, o número de cavidades cadastradas no país é muito pouco representativo considerando-se o enorme potencial para essas ocorrências.

Abstract

Caves in granite are not well known compared to caves in other lithologies, especially limestone. A review of types and classifications made by various authors resulted in three main types: structural caves, boulder caves and tafoni. Aspects of genesis of these types are briefly presented. In Brazil, several expeditions and studies in granitic caves have been made, mainly since the 1990s. However, the number of registered caves in the country is very small considering the enormous potential for these occurrences.

1. Introdução

Cavidades naturais formadas em granito ainda são relativamente pouco conhecidas e estudadas se comparadas às cavernas inseridas em outras litologias, especialmente nas rochas carbonáticas. Talvez isso se deva à pouca dimensão dessas cavernas considerando as dimensões constatadas em outras litologias. A grande maioria das cavernas em granito apresentam pouco desenvolvimento linear, e um grau de maior dificuldade na identificaçao na fase de prospecção, no mapeamento e em sua valoração espeleológica. Estudos acadêmicos e os que visam o licenciamento ambiental em granitos vem se intensificando no país.

A referência à cavidade natural no chamado embasamento cristalino (granitos e gnaisses em geral) nesse artigo remete à ideia de cavernas que se formam em rochas duras e resistentes, menos propensas à dissolução. Portanto, pode-se estender essa referência a cavidades formadas em rochas ígneas da família dos granitos, granitoides (ex. tonalitos ou granodioritos), como também ao gnaisse, rocha metamórfica que pode ser formada a partir do metamorfismo e por por deformações sofridas por rochas graníticas.

Em geral, tende-se a pensar que cavernas nesse tipo de rocha ocorre somente como em depósito de talus de matacões. Conforme a presente revisão aponta, existem outros tipos de gênese de cavernas nesse embasamento.

Um ponto importante relacionado à formação, desenvolvimento e dimensão das cavidades em granitos ressaltado por TWIDALE & VIDAL ROMANÍ (2005) é que independente da solubilidade da rocha, outros fatores podem ser determinantes para o desenvolvimento do vazio subterrâneo. Dentre eles, a dimensão e conectividade das descontinuidades na rocha (p. ex. fraturas, falhas, estratificações), continuidade e velocidade da passagem de água, gradiente hidráulico e taxas de elevadas pluviosidades. Esses fatores, mesmo em rochas pouco solúveis como no caso de granitos e gnaisses, podem formar grandes sistemas de cavernas.

De forma mais intensa, a partir da década de 1970, expedições e estudos nestas cavernas foram relatadas em diversos países sendo possível citar apenas alguns deles: Estados Unidos - T.S.O.D Cave, New York (CARROL JR, 1977; ESCH, 1991), Austrália - Girraween National Park (FINLAYSON, 1982) Labertouche Cave em Melbourne (FINLAYSON, 1986), Suécia - Fennoscandian Shield (SJÖBERG, 1986), Espanha - Península Ibérica (VIDAL ROMANÍ & RODRIGUEZ, 2011), Alemanha - Fichtelgebirge Mountains (STRIEBEL, 2008), África do Sul (SCHEUERER et al. 2013); China (SONG et al., 2015) e no Brasil (SENA, 1996; HARDT, 2003; AULER, 2007; IGUAL, 2011, MOCHIUTTI & TOMAZZOLI, 2019; MAIA et al., 2022).

Considerando o enorme potencial para ocorrências de cavernas em granitos no Brasil o presente documento apresenta os principais tipos dessas feições baseado nas classificações tipológicas propostas por diversos autores.

2. Breve revisão de classificações de tipos de cavernas em granito

Diversas classificações tipológicas de cavidades naturais em granitos foram publicadas, principalmente a partir da década de 1980 (TWIDALE, 1982; SJÖBERG, 1986; FINLAYSON, 1986; TWIDALE & VIDAL ROMANÍ, 2005; VIDAL ROMANÍ & RODRIGUES, 2011), sendo que elas apresentam variações de organização e nomenclatura.

TWIDALE (1982), em seu livro dedicado a formas de relevo em grani-

tos, descreve três tipos de cavernas: aquelas associadas com "corestones and grus"[1], cavernas estruturais e tafoni. Essa mesma classificação é reapresentada com atualizações por TWIDALE & VIDAL ROMANÍ (2005) em livro dedicado a geologia formas de relevo em terrenos graníticos.

SJÖBERG (1986) investigou cavernas na Suécia, fez uma revisão de classificações tipológicas de cavernas em granito e propõe um sistema de classificação em duas categorias principais. A primeira são as cavernas em afloramentos *in situ*, subdividida em cavernas em fraturas e em outros tipos de cavernas que incluem processos fluviais, marinhos, glaciais, tafoni, dentre outros. A segunda categoria contempla cavernas formadas por matacões.

De forma resumida, a classificação de FINLAYSON (1986) que estudou cavernas na Austrália contempla duas classes de cavernas em granito: formadas em blocos e formadas em juntas. Cada classe se subdivide em duas, a primeira em blocos em pilha e blocos em canal. Ressalta-se que o termo bloco é aqui entendido também como matacão. A segunda classe se subdivide em juntas abertas e juntas fechadas. No Brasil, HARDT (2003) aplicou essa classificação para cavernas em São Paulo e Minas Gerais. A Figura 1 extraída do artigo de HARDT (2003) ilustra de forma esquemática a classificação de FINLAYSON (1986).

A classificação apresentada por VIDAL ROMANÍ & RODRIGUEZ (2011) contém três tipos principais: cavernas desenvolvidas ao longo de planos de fraturas principais, cavernas associadas a blocos residuais e tafoni.

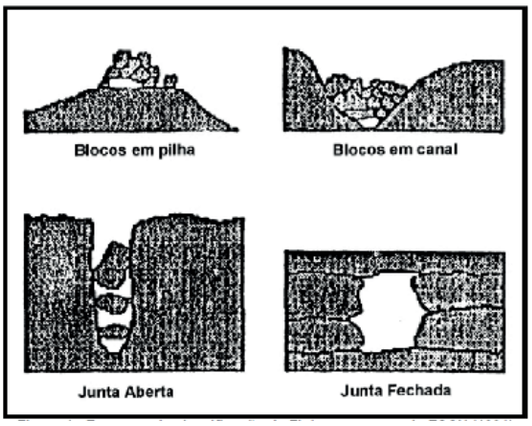


Figura 1: *Sistema de classificação de cavernas de FINLAYSON (1986). Extraído de HARDT (2003).*

3. Principais tipos de cavernas em granito

Para apresentação dos principais tipos de cavernas em granito optou-se por basear na classificação apresentada por TWIDALE (1982) e TWIDALE & VIDAL ROMANÍ (2005). Isso se deve ao caráter sintético de seus três tipos. Entretanto, conforme a revisão acima realizada, optou-se por denominar as cavernas desenvolvidas ao longo de planos de fraturas principais em caverna estrutural e as cavernas associadas a 'corestones and grus' simplesmente de cavidade em matacões (SJÖBERG, 1986).

Cavidade estrutural

O primeiro grupo corresponde às cavidades estruturais que se desenvolvem segundo planos de descontinuidades da rocha maciça tanto disposta de forma verticalizada quanto horizontalmente. Esse tipo se enquadra em cavernas formadas em afloramentos de rocha in situ de acordo com a classificação de SJÖBERG (1986).

Considera-se que as cavernas estruturais podem ser controladas por planos de fraturas, falhas, foliações e até mesmo por planos de bandamento gnaissico (Figura 2). A definição mais restrita de FINLAYSON (1986) in HARDT (2003) de cavernas de juntas, restringe a essa estrutura e as classifica em dois tipos: junta aberta e junta fechada (Figura 1).

VAQUEIRO & RODRIGUES (s/d) se referem ao fato que o alargamento de estruturas descontinuas na rocha pode ocorrer devido ao intemperismo relacionados à erosão química e física da rocha. TWIDALE (1982) descreve que o intemperismo em descontinuidades pode em alguns locais ser suficiente largo para conformar uma caverna. VIDAL ROMANÍ & RODRIGUEZ (2011) ressaltam o importante papel da lixiviação ao longo das descontinuidades no alargamento dessas estruturas.



Figura 2: *Cavidade natural condicionada por descontinuidades.*

Cavidade em matacões

As cavidades em depósito de blocos e matacões incluem as Cavernas de Talus e constituem outro tipo, caracterizado pelo empilhamento e intemperismo tanto dos blocos e matacões quanto do solo. Estas cavidades podem se localizar em várias posições na encosta, bem como no fundo de vales de drenagens (Blocos em canal - Figura 1). De maneira mais específica podem ser listadas dentro desta tipologia outros tipos mais específicos.

A seguir é apresentada uma sequência sucinta de processos para a gênese de cavidades a partir da formação de talus:

- Instabilização em taludes rochosos, resultando em processos gravitacionais como queda de blocos; ou ruptura e deslizamento planar ou em cunha;
- Depósito de matacões empilhados que se acumulam em geral na base de escarpas ou de encostas declivosas e podem se encontrar em várias posições tanto no terço superior, médio e inferior de vertentes
- Formação de "vazios" (lixiviação da matriz terrígena) entre matacões métricos ou decamétricos.

Outra possibilidade para formação desse tipo de pode ocorrer a partir da instabilização de blocos in situ, geradas a partir da sequência (Figura 3):



Figura 3: *Cavidade natural sob matacões arredondados de gnaisse posicionados na meia encosta de vertente.*

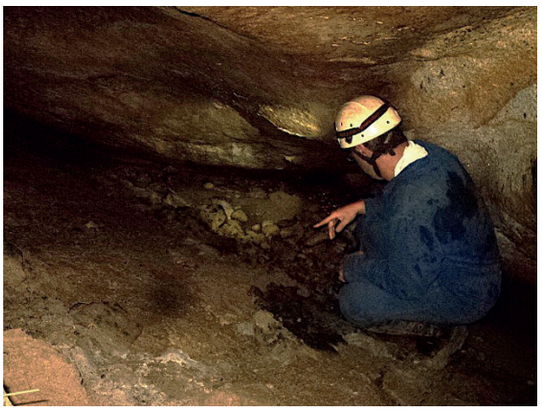


Figura 4: *Drenagem subterrânea em cavidade natural conformada por matacões graníticos em fundo de vale.*

- Intemperismo diferencial ao longo de planos de descontinuidades;
- Instabilização de blocos/matacões;
- Acomodação de blocos/matacões;
- Formação de "vazios".

Uma terceira sequência de processo de formação dessas cavidades pode estar associada à circulação de águas conforme a classificação 'Corestones and Grus' de TWIDALE (1982). Esse tipo de cavidade foi denominado ainda como "Blocos em Canal" (FINLAYSON, 1986).

- Relacionado à circulação de águas pluviais ou águas subterrâneas entre as rochas, no caso maciças, que de forma prévia apresentam fraturas, fissuras, falhas ou nos planos de estratificação (TWIDALE & VIDAL ROMANI, 2005)
- Intemperismo da rocha em contato com a água resultam no arredondamento de arestas rochosas;
- O produto do intemperismo rochoso ("grus" – areia e cascalho) pode ser removido pela circulação das águas ("descargas" de água subsuperficial ou drenagem subterrânea)
- As cavidades parecem se relacionar ao processo de piping da descarga dos sedimentos arenosos e cascalhos (grus). Segundo TWIDALE (1982) matacões e esses sedimentos grosseiros permanecem suficientemente rígidos para sustentar as cavidades, ou há um acomodamento de matacões ao ponto de conjuntamente permanecerem estáveis.
- Formação de caverna ou sistema de cavernas com drenagem subterrânea (Figura 4) apresentando sumidouro e ressurgência.

Tafone

O terceiro tipo de cavidade natural em granitos são tafoni (plural de tafone) que são vazios naturais que se desenvolvem em diversas litologias apresentando-se em formas côncava, convexa e alveolar. Os tafoni de dimensões centimétricas constituem a maioria, entretanto podem se desenvolver até algumas dezenas de metros suficientemente para serem adentradas por uma pessoa[2]. Em geral se situam em escarpa rochosa de inselbergs, frequentemente granito-gnáissica. Podem ocorrer também em rocha arenítica, em climas secos desérticos ou ao longo de falésias marinhas, de dimensões variadas até métricas, em geral formando "pequenas cavernas rasas", muitas vezes associadas em conjuntos alveolados («honeycombs»).

De acordo com TWIDALE (1982) e TWIDALE & VIDAL ROMANI (2005) a maioria dos tafoni se inicia a partir de planos de fraturas.

È importante ainda considerar que relacionado a este tipo de gênese as alterações sofridas principalmente pelos plagioclásios (feldspatos constituintes dos granitos) que resultam na formação de pequenos vazios nestas rochas.

Os tafoni constituem uma feição geomorfológica de gênese controversa, cujo intemperismo diferencial que leva a formação dessas cavidades pode estar relacionado a vários fatores que podem ser convergentes, aventando-se entre outras hipóteses:

Crescimento de cristais de soluções salinas de intemperismo em clivagens ou fissuras minerais acentuado por calor de insolação;

Ruptura localizada de capa superficial de intemperismo (silicificação, oxidação) expondo localizadamente a rocha com maior potencial de intemperismo onde se formam as cavidades;

Bolsões de concentração de minerais com granulação diferenciada, mais suscetível ao intemperismo; Desgaste por abrasão eólica (corrosão).

4. Estudos de cavernas em granito no Brasil

No Brasil, expedições e pesquisas em cavidades de Granito, Granitóides e Gnaisse foram realizadas no sul de Minas Gerais (SENA, 1995; HARDT, 1996), em Bertioga (ZAMPAULO et al., 2005) e Ubatuba (IGUAL et al., 2011) em São Paulo. Na Bahia, tafoni foram cadastrados por AULER (2007).

Em 2011, um Boletim Informativo do Grupo Pierre Martin de Espeleologia - GPME sediado em São Paulo foi inteiramente dedicado às cavernas em granito. Vários artigos sobre o tema se encontram nesse boletim incluindo texto de pesquisadores de fora do país.

No Boletim, a Gruta do Riacho Subterrâneo em Itu (SP) se destaca como a maior caverna de granito da América do Sul uma vez que o mapeamento na época já havia alcançado cerca de 1.400 m de desenvolvimento linear e despertou o interesse multidisciplinar atraindo a atenção devido aos seusaspectos mineralógicos, biológicos, arqueológicos (IGUAL, 2011).

MARTINS (2011) atribui a formação dos vazios subterrânos da Gruta do Riacho Subterrâneo à erosão vertical de frações mais finas liberadas de matacões residuais resultantes da erosão de maciço rochoso. Essa descrição aliada ao nome da caverna, além da presença de sumidouro e ressurgência sugere que a Gruta do Riacho Subterrâneo se enquadra no tipo de caverna associada a 'Corestones and Grus' de TWIDALE (1982).

MOCHIUTTI & TOMAZZOLI (2019) exploraram, mapearam cavernas na Ilha Santa Catarina (Estado homônimo). Os autores relatam que 33 cavidades naturais localizadas no setor centro norte da Ilha são associadas a aglomerações de matacões e exibem morfologia labirintica complexa relacionada a disposição caótica dessas frações. Metade das cavernas apresentam mais de 100 m de desenvolvimento linear com destaque para o Sistema de Cavernas da Água Corrente, com 1026 m. Outras cavidades no setor sul da ilha relacionam a cavernas formadas

por erosão marinha (SILVA, 2018 in MOCHIUTTI & TOMAZZOLI, 2019).

MAIA et al. (2022) elaboraram trabalho de cunho genético e morfoestrutural de Tafoni de dimensões métricas a decamétricas em diferentes áreas no Brasil, tanto em clima semi-árido de estados como Ceará, Paraíba e Bahia quanto em clima tropical úmido do Rio de Janeiro. Os autores atribuem a origem dos Tafoni ao intemperismo químico em planos de descontinuidade na rocha como "...fraturas, falhas, veios, diques, sets de junta onde se instalam microambientes de maior umidade".

O Anuário Estatístico do Patrimônio Espeleológico Brasileiro de 2022 do CENTRO NACIONAL DE PESQUISA E CONSERVAÇÃO DE CAVERNAS – CECAV (2022) disponibilizou informações, incluindo a localização geográfica, de 23.378 cavidades naturais subterrâneas no Brasil. O Anuário apresenta um gráfico relacionando as cavidades naturais com quinze classes de rocha definidas no Mapa das Áreas de Ocorrência de Cavernas do Brasil (CECAV, 2018). Segundo o documento, 509 cavidades se localizam em classe de rocha definida como granitoides que corresponde aproximadamente a 2,2% do total de cavernas cadastradas. Considerando outras três classes que contemplam associação de rocha granitoide com rochas carbonáticas (97), vulcânicas (13) e siliciclásticas (7) o número absoluto aumenta para 626 cavidades, e representa cerca de 2,7% do total.

5. Considerações finais

O número de cavernas em granito (e gnaisses) cadastradas no Brasil é relativamente muito pouco considerando-se o potencial para ocorrências espeleológicas nestas rochas no pais. Como exemplos, a Província Geológica da Mantiqueira de extensão regional, localizada a leste do Craton do São Francisco se estende desde o estado do Rio Grande do Sul até a Bahia, abrangendo partes dos estados de Santa Catarina, Paraná, São Paulo, Rio de Janeiro, o sul e leste de Minas Gerais e o Espírito Santo. A Província Geológica do Borborema abrange parcialmente os estados do Ceará, Rio Grande do Norte, Paraíba, Pernambuco e Alagoas no nordeste Brasileiro.

O presente trabalho pretendeu revisar os principais tipos de cavernas que se formam no chamado embasamento cristalino (gnaisses e granitos) com o objetivo de otimizar trabalhos espeleológicos desde a fase de prospecção, identificação, descrição das feições nesse tipo de rocha.

Notas

1 | Corestones – grosso modo se refere a matacão (ões) arredondado (s), Grus – se refere sedimento grosseiro composto predominantemente por areia e cascalho, esse termo é discutido emdetalhe por MIGON & THOMAS (2002).

2 | MAIA et al. (2022) ressaltam que segundo a classificação do CECAV as cavidades em tafoni estudadas por eles no Brasil se enquadram como abrigos. Aqui serão tratadas como cavidades naturais.

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Piping erosion and its impact on landscape morphology at the Dead Sea Basin, Israel

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Abstract

Piping erosion refers to sub-surface erosion in poorly consolidated soils by mechanical grain transport with minor dissolution contribution. This study investigates Holocene piping systems in the Late Pleistocene Lisan Formation along the western Dead Sea Basin. Through field observations, high-resolution topographic analysis, and 14C dating, we demonstrate that piping activity created complex pseudo-karst landscapes with extensive cave networks up to ~1.5 km long. Surface runoff penetrates the subsurface primarily along pre-existing fractures, which develop into major cave systems. 14C-Dating reveals that most speleogenesis occurred within the last ~1300 years, with erosion rates of 2.8-19.6 mm/year. The subsurface erosion fundamentally controls landscape development, forming distinctive morphologies including orthogonal drainage patterns, piping badlands, and butte and mesa landforms. This research provides insights into how piping processes influence landscape evolution in poorly consolidated sediments under arid conditions.

1. Introduction

Piping erosion involves sub-surface hydraulic erosion in poorly consolidated sediments through mechanical grain transport, with minor or no karst activity (BERNATEK-JAKIEL & POESEN 2018). This process creates elongated voids with water inlets and outlets, occurring worldwide across various climate zones and soil types. When these features reach sufficient scale to resemble karst landscapes, they are classified as pseudokarst (HALLIDAY 2007).

In Israel, piping erosion landscapes exist in semi to hyper-arid regions, particularly in the Late Pleistocene Lisan Formation along the Dead Sea Basin (Fig. 1). The formation, dated to 70-14 Ka BP, was deposited in Lake Lisan at the deepest part of the Dead Sea Rift (KAUFMAN 1971).

The Lisan Formation unconformably overlies older unit, associated with Lake Samara. According to Waldmann et al (2009), the Samara Formation is ~135 to 75 ka old. The lithology of the Samara Formation varies depending on the location on the lake shore, onshore, or offshore. It consists of alternations between alluvial material including sands and conglomerates, and lacustrine material including silt or clay laminea alternating with aragonite or calcite.

The study area experiences a hyper-arid climate with annual precipitation ranging from 40-90 mm and average temperatures of 25°C.

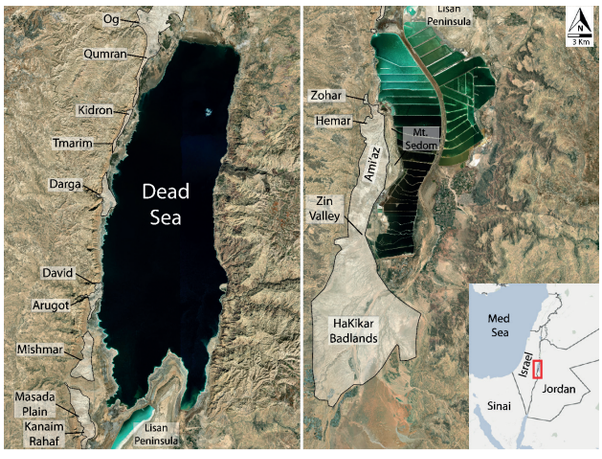


Figure 1: *Regional map showing study areas along the Dead Sea Basin. The left panel shows the northern side of the Dead Sea, while the right panel shows the southern side of the Dead Sea. Major outcrops of the Lisan Formation are marked with white patches. These patches form the Western Dead Sea Lisan Platform. Names of the places appear next to them.*

2. Materials and methods

We investigated piping landforms in four main regions: HaKikar area, Ami'az Plain, Masada Plain, and the Western Dead Sea Lisan Platform (WDSLP). Field surveys combined foot traverses, aerial photography, and 0.5 m/pixel Digital Elevation Models from airborne LiDAR. Cave mapping employed standard speleological techniques using Leica Distance Meters and DistoX systems (TRIMMIS 2018).

Fracture measurements were recorded using smartphone applications, excluding those associated with local stress along vertical cliffs free faces. Organic material for ^{14}C dating was collected using sterilized tools and analyzed at the Alfred Wegener Institute following MOLLENHAUER et al. (2021) protocols.

3. Results

The HaKikar region exhibits extensive piping erosion, with nearly 100 large caves and thousands of smaller cavities. Cave systems typically display curvilinear branchwork patterns, with passages ranging from narrow channels to large galleries. Surface features include numerous sinkholes forming distinctive 'egg carton' morphology. Notable examples include the Viatnami Cave (171 m long, 16.3 m deep) which demonstrates characteristic morphological transitions between the Lisan and Samra Formations.

The Ami'az Plain features complex fracture-controlled piping systems creating orthogonal drainage patterns. The Kemah Cave (274 m long, 22.5 m deep) and Peretz Cave (80 m long, 11.2 m deep) exemplify contrasting development patterns: Kemah follows linear fracture-controlled passages, while Peretz shows meandering channels through collapse materials (Fig. 2).

The Masada Plain demonstrates unique butte-and-mesa landforms resulting from piping erosion interacting with surface channels. Caves here develop primarily along N to NNW oriented fractures, perpendicular to main streams and ridges. The Masada Plain Cave (40 m long) illustrates a typical piping structure with linear channels following fracture systems beneath local water divides.

The Western Dead Sea Lisan Platform (WDSLP) exhibits a varied piping morphology across several zones. In the Nahal Zohar area, notable caves include Metzad Zohar (33 m), Ashman Zohar (33.6 m), and Shfanei Zohar (67 m), each showing distinct developmental stages. The Nahal Kidron region contains the extensive Marzev Kidron system (479 m long), featuring complex dendritic patterns and multiple evolution phases, with 14C dating of branches stuck in the cave ceiling, indicating speleogenesis within the last ~1300 years (Fig. 3). The organic material was collected from a fissure in the cave ceiling, at a location high above the active flood level in the cave. Based on field relations, the fissure represents the initial path along which the cave developed.

The Qumran area demonstrates intricate relationships between natural piping processes and archaeological features, particularly evident in several piping systems with interconnected sinkholes.

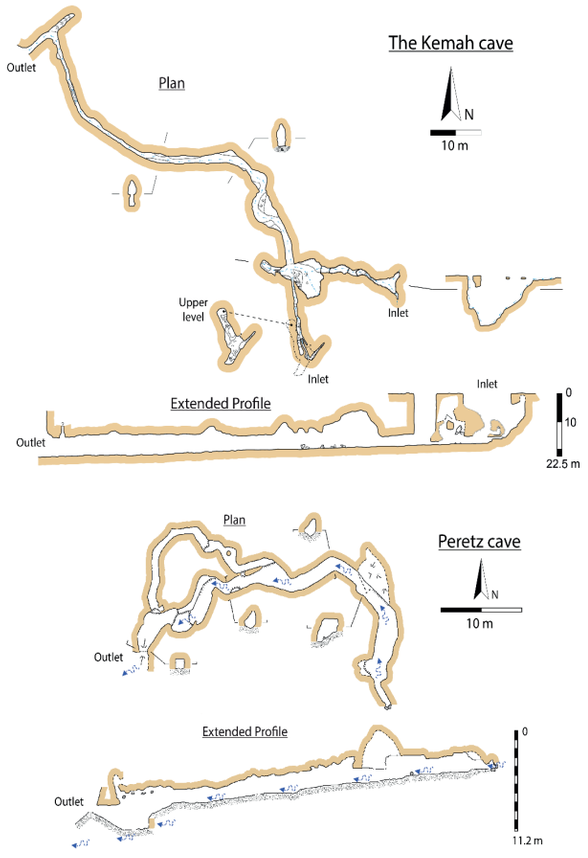


Figure 2: *Representative cave morphologies showing Linear fracture--controlled passage (Kemah Cave), and meandering channel in collapse material (Peretz Cave).*

4. Discussion

Piping erosion significantly influences landscape evolution through the interplay of surface and subsurface processes. Cave morphology varies based on host material: linear passages follow fractures in bedrock, while meandering channels develop in collapsed materials. Cross-sectional shapes reflect stability conditions, with bedrock passages showing higher, more stable profiles.

14C dating reveals relatively recent development, with most speleogenesis occurring within the last ~1300 years. Erosion rates vary significantly (2.8-19.6 mm/year) depending on local conditions and stream order. Higher-order streams (2nd-3rd) can erode coarser materials, while lower-order channels remain confined to finer sediments.

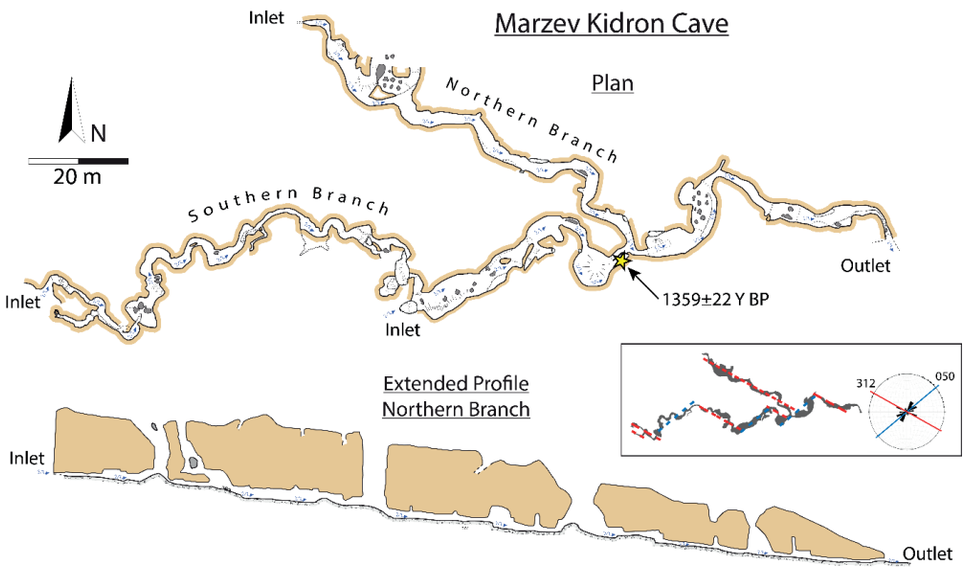


Figure 3: *Plan and profile of the Marzev Kidron Cave. The cave forms a ~0.5 km long underground dendrite channel, which originally developed along cracks (shaded model with crack directions). Location of organic material sample collection for dating with yellow star. BP calibrated age on the figure.*

5. Conclusion

This study demonstrates how piping erosion fundamentally shapes the Dead Sea Basin landscape through complex surface-subsurface interactions. The process creates distinctive pseudo-karst features controlled by pre-existing fracture systems. Recent development ages and variable erosion rates indicate a dynamic landscape evolution continuing until today. These findings enhance our understanding of how subsurface erosion influences arid landscape development in poorly consolidated sediments worldwide.

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A Gruta Quartzítica Lapa Santa: Caracterização, Gênese e Contribuições para o Estudo do Carste Siliciclástico

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Resumo

A gruta Lapa Santa, situada em Felício dos Santos, Minas Gerais, é reconhecida como a maior cavidade quartzíticas da região do Complexo Arqueológico Serra Negra. Este estudo visa compreender sua gênese e evolução, destacando as características que influenciam o processo de carstificação nesta rocha, e que moldaram suas morfologias. A pesquisa incluiu análises topográficas e morfológicas, evidenciando o papel das estruturas geológicas na formação de condutos e galerias. Os resultados ampliam o entendimento sobre sistemas cársticos em rochas siliciclásticas, reforçando sua relevância científica e ambiental.

Abstract

The Lapa Santa cave, located in Felício dos Santos, Minas Gerais, is the largest quartzitic cavity in the Serra Negra Archaeological Complex. This study explores its genesis and evolution, focusing on the interplay between geochemical and hydrodynamic processes, karstification, shaping its morphologies. Topographic and geochemical analyses highlighted the role of geological structures in forming conduits and galleries. The findings expand the understanding of karst systems in siliciclastic rocks, emphasizing their scientific and environmental importance.

1. Introdução

A região de Felício dos Santos em Minas Gerais, conhecida por seus vastos sítios arqueológicos estudados pelo Laboratório de Arqueologia da Paisagem - LAEP da UFVJM, não tem seu território ligado a espeleologia. Nos últimos anos, o laboratório de Análise de Paleoambientes Espinhaço - LAPE, juntamente com o LAEP, tem se dedicado a prospectar as grutas de região, já tendo encontrado mais de 7 grutas, entre elas, a mais famosa, e visitada para fins religiosos, a Lapa Santa. A Lapa Santa está localizada no município de Felício dos Santos, Minas Gerais (Fig. 1) e destaca-se como a maior cavidade desenvolvida em quartzitos da região do Complexo Arqueológico Serra Negra. Sua importância científica reside na contribuição para o entendimento de processos cársticos em litologias siliciclásticas, um tema ainda pouco explorado na Carstologia brasileira.

Tradicionalmente, os estudos sobre carste foram amplamente direcionados a litologias solúveis, como calcários e evaporitos, devido à predominância da dissolução química como processo formador dessas paisagens (FORD & WILLIAMS, 2007; JENNINGS, 1985; BOGLI, 1980). Durante muito tempo, ambientes cársticos foram compreendidos apenas como resultado da solubilização intensa desses materiais, restringindo-se a regiões carbonáticas. Entretanto, pesquisas recentes mostram que cavidades também podem se formar em rochas de baixa solubilidade, como os quartzitos, porém, com tempo de formação bem mais lento. Por outro lado, por sua resistência, as morfologias nessas cavidades são preservadas por um período muito maior que nas rochas carbonáticas, muito solúveis (RODET, 2014; QUINIF, 2014; VASCONCELOS, et al., 2019). Essa nova abordagem amplia o conceito de carste e reconhece que a interação entre processos químicos e mecânicos pode ser determinante na evolução dessas paisagens.

A Lapa Santa está inserida na Serra do Espinhaço Meridional (SdEM), no contexto geológico e estratigráfico da Formação Capelinha. Castro (2014) descreve a Formação Capelinha dividida por duas unidades litológicas principais. A unidade inferior é predominantemente metapsamítica, formada por mica xistos, xistos quartzosos e quartzitos, que podem ser puros ou micáceos, e apresenta também a presença de magmatismo básico. Já a unidade superior é majoritariamente metapelítica, composta por xistos ricos em alumínio, que contêm granada e, em alguns casos, também estaurolita e/ou cianita. O autor observa que a unidade inferior alterna entre quartzitos puros e micáceos, além de incluir rochas metamáficas. A Lapa Santa é formada por quartzitos micáceos, que fazem parte da unidade inferior da Formação Capelinha.

Este trabalho aborda a gênese e a caracterização da Lapa Santa, destacando as principais morfologias cársticas observadas e os processos responsáveis por sua formação. Além disso, discute-se a relevância da gruta para a ciência.

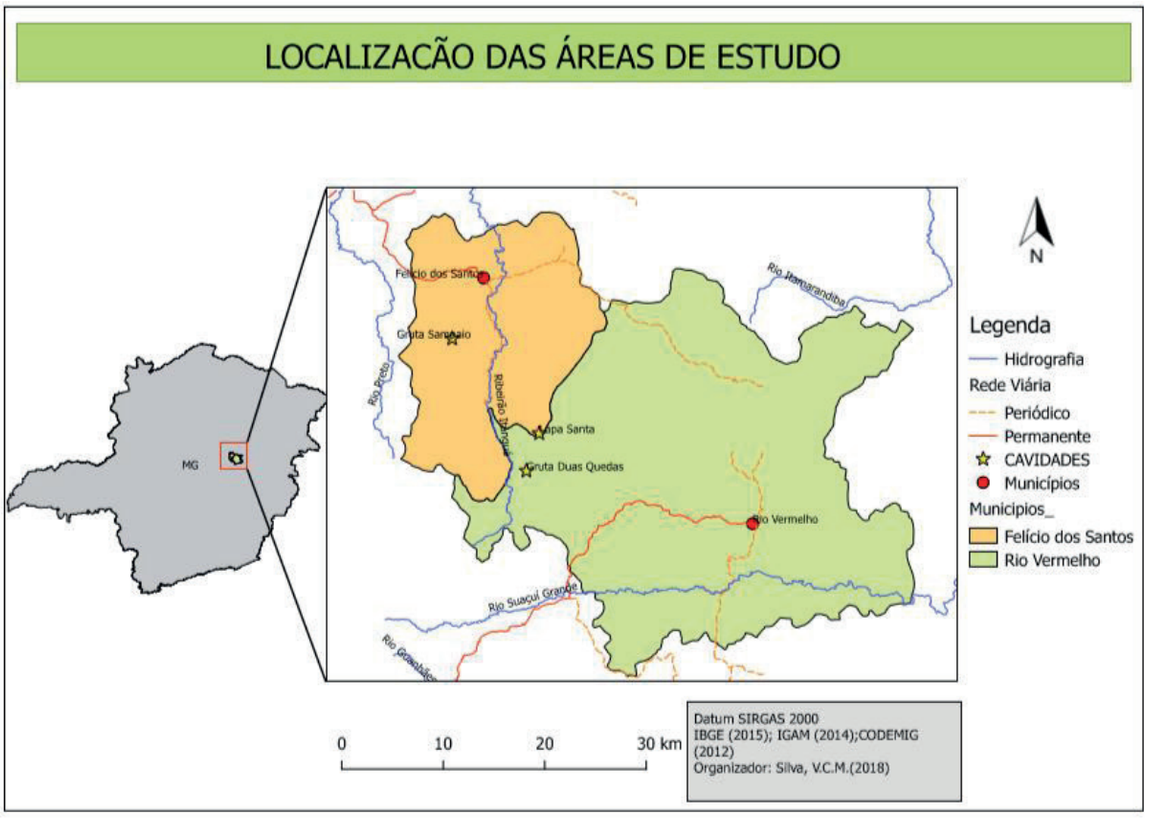


Figura 1: *Localização da Gruta Lapa Santa, Felício dos Santos - MG.*

2. Materiais e Métodos

O estudo da Gruta Lapa Santa foi realizado por meio de uma abordagem interdisciplinar, combinando métodos de campo, análises laboratoriais e ferramentas de modelagem. A seguir, detalham-se os principais procedimentos adotados:

1. Levantamento Topográfico

Para mapear a organização espacial da gruta, foram realizadas expedições de campo com o auxílio de equipamentos de medição, como trenas manuais e bússolas. As medidas obtidas foram simultaneamente transferidas para o papel milimetrado e então, a partir do tratamento dos dados, realizou-se a confecção do mapa topográfico em papel milimetrado. As visadas topográficas registradas foram digitalizadas e realizados os contornos das visadas. Posteriormente foram integradas no software Corel Draw, para a elaboração do mapa em planta da cavidade.

2. Observação de Morfologias Cársticas

Durante o trabalho de campo, foram realizadas observações diretas das morfologias presentes na gruta, como alvéolos, sifões e condutos. Essas estruturas foram fotografadas e descritas em detalhes, com o objetivo de identificar as principais feições relacionadas aos processos de carstificação.

3. Revisão Bibliográfica e Modelagem Conceitual

Os dados coletados em campo foram complementados por uma extensa revisão bibliográfica sobre carste siliciclástico. Modelos teóricos, como o proposto por Bogli (1980), Jennings (1985), Ford & Williams (2007), Rodet (2014), Quinif (2014), e foram utilizados para interpretar os processos de gênese e evolução da gruta.

Essa combinação de métodos permitiu uma análise integrada da Gruta Lapa Santa, abrangendo desde a identificação de processos geoquímicos até a interpretação de sua dinâmica hidrológica e morfológica.

3. Resultados

A Lapa Santa é uma relíquia do relevo da região, pois ela se encontra no topo da montanha, alta vertente, mostrando uma possível inversão de relevo na área (Fig. 2). Hoje, a dinâmica hídrica é associada a eventos de chuva, temporária, especialmente nos meses de verão.



Figura 2: *Entrada da Lapa Santa na alta vertente do Córrego Indaiá.*

Trata-se de uma cavidade com morfologias complexas e variadas, formada majoritariamente por salões na forma de alvéolos, um grande salão logo na entrada com 19m de largura e 16m de comprimento (Fig. 3), seguido por um outro salão pouco menor com 7,8 m de comprimento, e mais 3 salões menores, além de diversas formações alveolonares ao longo da gruta.



Figura 3: *Salão de entrada em forma alveolonar.*

Foram também identificados, condutos e sifões, além de depósitos ferruginosos associados a processos de oxidação. O quartzito ferruginoso tem o intemperismo mais acelerado que o quartzito puro. Nele, o ferro tende a oxidar e alterar a estrutura da rocha (Fig. 4), visto, vários desplacamentos ao longo da cavidade. No geral observa-se uma grande alternância do quartzito com lentes de filito. Estes apresentam a coloração prateada, aspecto brilhante, devido à presença da sericita, com partes avermelhadas devido ao intemperismo. A granulação varia de fina a grossa na maior parte da rocha, com minerais micáceos. O quartzito apresenta forte grau de deformação, com textura foliada devido à presença de minerais micáceos ferruginosos em aglomerados, como pórfiros de tamanho areia muito grossa.



Figura 4: *Precipitação de óxido de ferro e manganês ao longo das paredes da Lapa Santa.*

Ao longo de toda cavidade nota-se a rocha bastante alterada, devido suas características, discutidas anteriormente, e que possibilitaram uma alteração mais facilitada do que em um quartzito puro, potencializando assim a carstificação da cavidade. Em todos os salões existem muitos domos (Fig. 5), alguns deles muito profundos, podendo indicar que estes salões alveolonares estiveram imersos em água, que é um dos elementos que é uma das hipóteses para explicar os sedimentos (ou alterita, não há consenso) o bandamento entre finas camadas brancas arenosas e pretas, possivelmente de matéria orgânica (Fig. 6).



Figura 5: *Domo de teto na cavidade Lapa Santa – Felício dos Santos - MG.*



Figura 6: *Preenchimento (ou alterita) com bandamento branco arenoso e preto, no fundo de uma das galerias da Lapa Santa, Felício dos Santos – MG.*

Outro ponto marcante é o desnível em cachoeira, do ponto 7 para o ponto 8, com declividade de -46° indicando uma mudança no nível de base, além de ser responsável pela captura de diversos fluxos de drenagem.

A partir desse ponto, a gruta prossegue seu desenvolvimento em direção NE-SW, apresentando um desnível mais suave até sua saída. O percurso é caracterizado por um coletor tubular ladeado por condutos repletos de alvéolos. O piso da galeria encontra-se recoberto por uma grande quantidade de sedimentos, variando desde areia fina até grandes clastos, atravessados por um curso de água intermitente.

Na porção final da galeria, observa-se um rebaixamento acentuado do teto, seguido por uma inflexão em direção ao noroeste, onde a água escoa por um conduto estreito, cuja dimensão permite apenas a passagem rastejante de uma pessoa (Fig. 7). Posteriormente, a gruta se abre em um salão mais amplo, porém ainda de altura reduzida, impossibilitando a postura ereta completa. Esse ambiente é predominantemente preenchido por sedimentos finos, estendendo-se até a restituição seca da cavidade, situada em um terreno íngreme, abaixo do qual corre o Córrego do Indaiá.



Figura 7: *Conduto diminuto, ligação entre o final da galeria.*

E o próximo salão.

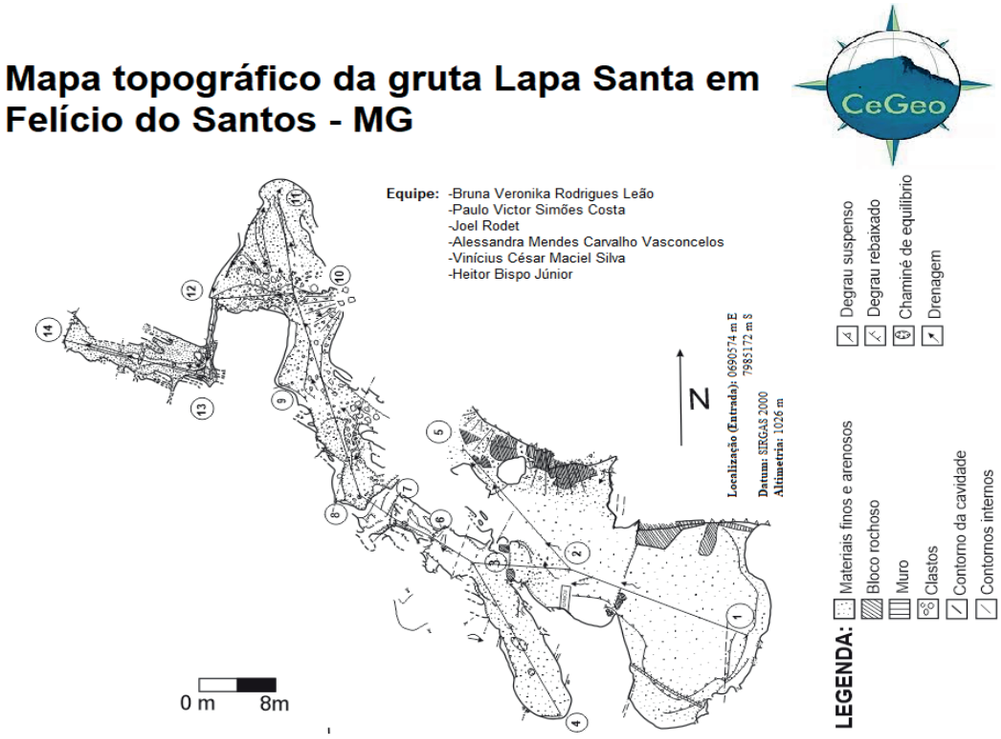


Figura 8: *Mapa em planta da cavidade Lapa Santa- Felício dos Santos – MG.*

4. Discussões

Os resultados da pesquisa indicam uma intensa atuação de processos geoquímicos na cavidade. Observa-se que, em diversos pontos as rochas apresentam desplacamento e um aspecto enrugado, resultante da ação prolongada da água e da característica do quartzito micáceo, com muitas lentes de filito, com o ferro muito oxidado alterando a estrutura da rocha. Esse padrão sugere que a carstificação foi o principal processo responsável pela formação da gruta, em detrimento de um controle estrutural imposto pela tectônica. No entanto, a tectônica pode ter desempenhado um papel fundamental na percolação da água pelo maciço rochoso, com sua influência sendo mais significativa em litologias menos permeáveis e menos expressiva em rochas mais permeáveis.

Adicionalmente, verifica-se que, desde a região da cachoeira até a saída, a gruta está preenchida por sedimentos, atingindo seu ponto máximo no ponto 11 da topografia (Fig. 8 e 6), onde o conduto pretérito se encontra completamente obstruído até quase o teto. Esse preenchimento sedimentar sugere que essa porção mais baixa da cavidade esteve fechada em algum momento, permitindo a acumulação de sedimento, ou a segunda

hipótese, promovendo a alteração da rocha (paredes) em contato com a água, e gerando alterita. O sedimento identificado apresenta características semelhantes ao encontrado em outras cavidades, como a Gruta Monte Cristo em Diamantina – MG, sendo composto por areia fina a média, intercalada por finas camadas de material negro.

A distância entre o topo do depósito sedimentar e o teto da cavidade pode ser interpretada à luz do conceito de primocarste, conforme descrito por Rodet (2014). Segundo esse modelo, a aloalterita presente na cavidade passou por um processo de ressecamento, resultando na formação de pequenos espaços que possibilitaram o início da dinâmica paragenética. Evidências de mudanças na dinâmica hídrica também são observadas, como indicado pelo rebaixamento do nível de base local. A drenagem atual incide sobre os sedimentos pré-existentes, promovendo sua incisão até a base e desviando-se para noroeste, onde se estabelece um novo conduto através da rocha (Fig. 7). Esse novo canal permitiu a mobilização parcial dos sedimentos para galerias subsequentes (Fig. 9), as quais apresentam domos e alvéolos de diferentes dimensões em suas laterais, reforçando a interpretação de que essas estruturas estiveram completamente submersas em algum momento.



Figura 9: *Salão final da gruta, de altura reduzida, preenchido por sedimentos finos. Felício dos Santos – MG.*

Do ponto de vista científico, os resultados deste estudo contribuem significativamente para a carstologia ao demonstrar que litologias tradicionalmente consideradas pouco propensas à carstificação, podem desenvolver sistemas cársticos expressivos, com características próprias ao meio em que se desenvolveram. Esses resultados ampliam a compreensão dos processos cársticos em ambientes siliciclásticos e podem ser aplicados a outras regiões do mundo, onde esse tipo de carste ainda é pouco investigado.

5. Conclusão

A Gruta Lapa Santa é um exemplo de carstificação em substrato quartzítico, demonstrando que o carste pode se devolver em rochas diferentes daquelas carbonatadas. Porém, apesar do processo ser o mesmo, a carstificação, cada litologia, ambiente, podem ter maior ou menor facilidade para os processos geoquímicos e hidrodinâmicos. Além disto, a mesma rocha, com diferenças mineralógicas, pode também ter variações no seu processo de carstificação, no desenvolvimento de suas morfologias e na velocidade de evolução do processo. Tal fato, pode ser demonstrado na Lapa Santa, com características peculiares em seu quartzito, que lhe confere um intemperismo mais intenso do que em outros mais outros mais puros.

Seu preenchimento (sedimento, ou alterita) também é um elemento importante que está sendo estudado em conjunto com outras cavidades da região, visto que não há um consenso sobre sua origem. Portanto, a Lapa santa é uma gruta com importantes registros espeleológicos e paisagísticos, que deverá continuar a ser estudada.

Agradecimentos

Agradecemos ao valioso apoio do Laboratório de Arqueologia e Estudo da Paisagem (LAEP-UFVJM), cuja participação na primeira expedição de campo foi crucial para a realização desta pesquisa. Agradecemos também a toda ajuda dispendida pelo Sr. Heitor Bispo e seu filho Heitor Bispo Jr. no caminhamento e conhecimento das cavidades e sítios arqueológicos da região de Felício dos Santos.

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Mineral composition of non-carbonate speleothems from non-karst caves of the polish outer carpathians

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Abstract

In siliciclastic-clayey, flysch rocks of the Outer Carpathians numerous non-karst caves occur. Most them are genetically related to gravitational slope deformations. The speleothems and similar forms are not frequent in these caves, but they represent diversity of shapes and mineralogical composition. Based on morphological and macroscopic features, the following non-carbonate speleothems were distinguished: (A) stalactites and flowstones, (B) soft and earthy coatings, (C) hardened coralloidal forms, and (D) gypsum incrustations and coatings. These formations were characterized using powder X-ray diffractometry (PXRD), optical microscopy, electron microscopy (SEM-EDS), electron microprobe (EPMA), and Raman microspectroscopy. All the speleothems were found to contain variable amount of sandstone-derived detrital material – chiefly quartz, feldspars, phyllosilicates, as well as titanium oxides, zircon etc. Organic admixtures are common. However, the bulk mass of the speleothems consists of authigenic minerals. Mineral phases in dripstones, flowstones (A) and earthy coatings (B) appear to be the most diverse in terms of their micromorphology, chemistry and structural ordering. Among these poorly ordered minerals, several following types have been distinguished: (i) nearly amorphous Al-Si-P compounds with Al/(Si+P) molar ratios of ca. 2–3, always containing some Ca and Mn; (ii) aluminum phosphates with Al/P molar ratios of ca. 1–2, and traces of Ca, Fe, Mn, Mg, K; (iii) phosphate-free aluminum oxides containing Si with lower (ca. 2–3) and higher (ca. 4–6 ca.) Al/Si molar ratios; (iv) phosphate-free allophanes (Al/Si ca. 1) and possibly imogolite; and (v) manganese oxides with major Al and Si admixtures. Hardened coralloidal forms (C) are predominated by amorphous opal-type silica containing minor Al, Ca, Na, Mg, P and Fe impurities. In gypsum crusts (D) calcium sulfate crystals are accompanied by calcite admixtures. The observed variation in the mineral composition of non-carbonate speleothems indicates variable crystallization conditions, which are mainly influenced by the lithology of the sandstones, chemistry and pH of circulating water as well as the presence of organic guano-like sediments.

1. Introduction:

The Outer Carpathians are Alpine orogen formed of Upper Jurasic--Lower Miocene flysch rocks: sandstone, sandstone-siltstone-claystone, siltstone-claystone, and sandstone-conglomerate series. These rocks are strongly folded and faulted, forming several lithostratigraphic-tectonic units that thrust each other toward the north. The following units are distinguished in this region (from the south): Magura Unit, Dukla Unit (and its equivalents), Silesian Unit, Sub-Silesian Unit and Skole Unit, as well as folded Miocene units adjacent to the northern margin of the orogen, such as Zgłobice Unit (LEXA et al. 2000).

In the geomorphological terms the Outer Carpathians, called in Poland the Beskidy and Bieszczady Mountains and their Foothills, represent medium high mountains divided into many ranges, which stand from several tens metres to 800 m above the river valleys. They are characterised by steep slopes often modified and shaped by gravitational mass movements. And the gravitational processes are responsible for the development of numerous underground empties in the Late Pleistocene and Holocene, which are often accessible for people and thus recognised as caves (MARGIELEWSKI & URBAN 2017, 2024). Up to now ca 1700 caves of the total length ranging 30 km have been documented in the Polish Outer Carpathians. Their shapes are very diverse and sizes range from several metres up to more than 2 km (GĄDEK 2023).

The secondary mineral or mineral-clastic formations are relatively rare and small in these caves, however they represent many different types, which are conditioned at least partly by petrographic composition of the host rocks. Regarding the petrographic environment two principal groups of these formations can be distinguished: (1) typical carbonate speleothems which occur in caves formed within sandstones characterised by calcareous or dolomitic cement and (2) formations of various mineral and clastic composition that are associated with sandstones of differentiated cement: siliceous, argillaceous, siliceous-argillaceous or siliceous-argillaceous-carbonaceous. Initial research of both groups of formations was conducted at the begining of the 21st century (URBAN et al. 2007a, b), and the study of carbonate speleothems (1) was continued in order to determination of their age, structure and reconstruction of minerological alternations (URBAN et al. 2015).

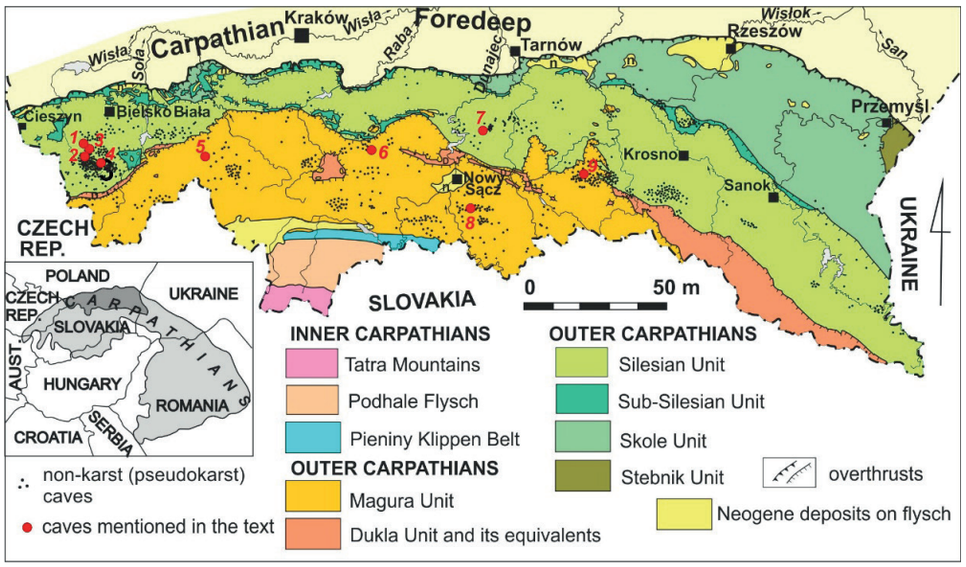


Figure 1: *Situation of non-karst caves in the Polish Outer Carpathians against the generalised geological map of this region (after MARGIELEWSKI & URBAN 2024). Caves mentioned in the text: 1 - Jaskinia Wiślańska, 2 - Jaskinia Dująca, 3 - Jaskinia Salmopolska, 4 - Jaskinia w Kościelcu, 5 - Oblica, 6 - Jaskinia Zbójecka w Łopieniu, 7 - Diabla Dziura w Bukowcu, 8 - Jaskinia Złatniańska, 9 - Jaskinia Mroczna.*

The initial study of the secondary formations associated with non-carbonate or poorly carbonate sandstones enabled the following division of them (URBAN et al. 2007a, 2012): (A) – non-carbonate, moderately hard, small stalactites and tooth-like forms (Fig. 2A); (B) – non-carbonate, soft, crenulated and ribbed sheets or coatings (Fig. 2B); (C) – non-carbonate, very hard coatings and small coralloids (Fig. 3A); (D) – white crusts and coatings of microcrystalline gypsum and calcite (Fig. 3B); (E) – crusts of sparry and glassy gypsum crystals; (F) – agglomerations of very small carbonate coralloids; (G) – blankets of carbonate moonmilk; (H) – typical, but small carbonate dripstones, flowstones and helictites.

The occurrence of these types of secondary formations is connected with three kinds of host rocks: sandstones of Godula Beds (Silesian Unit, Upper Cretaceous), Magura Beds (Magura Unit, Eocene) and Ciężkowice Beds (Silesian Unit, Palaeocene-Eocene).

The initial study proved that specimens representing types (A) and (B) are composed of opal, clay minerals (illite, kaolinite, chlorites) with an admixture of clastic partings from host rocks (quartz, feldspar). Opal developed within the speleothems. Also chlorites could have been formed due to alterations of micas. Non-crystalline silica plus clastic partings are also the principal components of non-carbonate hard coralloids (C) (Fig. 3A), whereas instable siliceous mineral – cristobalite has been recognised within the carbonate-gypsum coatings (D) (Fig. 3B) (URBAN et al. 2007a, 2012).

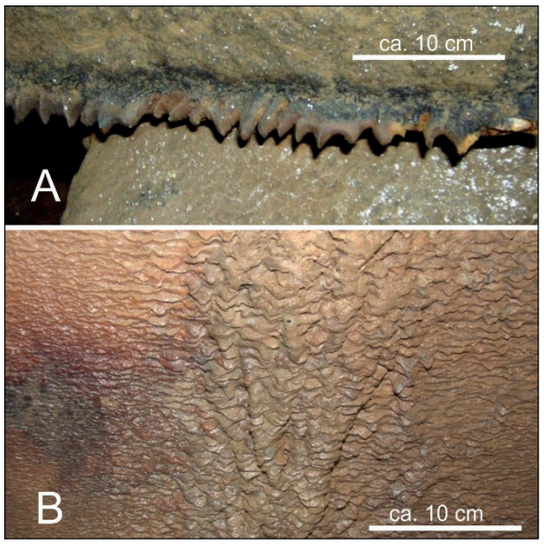


Figure 2: *Secondary formations in the Jaskinia Zbójecka na Łopieniu cave: A – tooth-like moderately hard stalactites (A). B – soft crenulated sheet (B) (Photo J. Urban).*

In turn, GRADZIŃSKI et al. (2010) studied in one cave developed within the Magura Beds, soft secondary sheets, composed of clastic material originated exclusively from the host rocks: grains of quartz, mica, feldspar and clay minerals. These sheets were formed owing to trapping and binding of clastic grains by microbial activity, therefore such formations can be called “siliciclastic microstromatolites”, while containing no new mineral phases, they cannot be considered to be speleothems.

Consequently, the problem of origin, mineralogical modification (alteration stages) and present-day detailed composition and structure is still unresolved and open. This paper is the next step in recognition and understanding of complex and sophisticated problem of nature of secondary formations in caves developed in siliciclastic-clayey rocks.

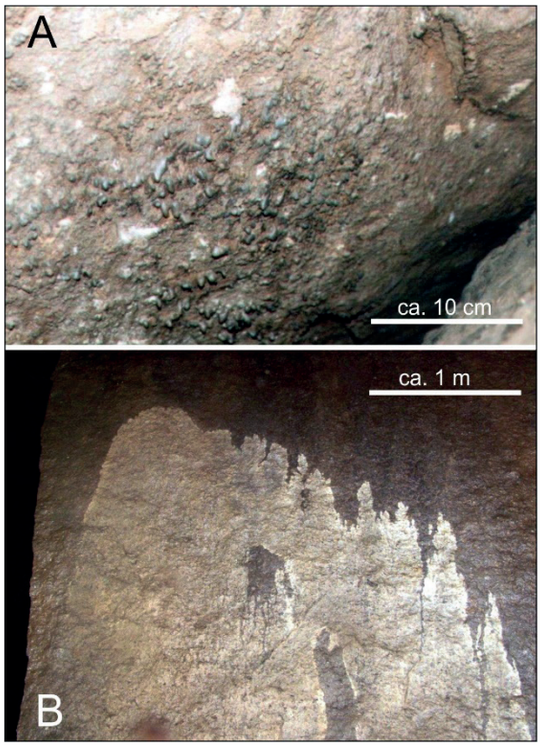


Figure 3: *Various formations in non-karst caves of the Outer Carpathians: A – hard coralloids (type C) from Diabla Dziura na Bukowcu cave; B – carbonate-gypsum coatings (D) in Jaskinia Miecharska cave (Photo J. Urban).*

2. Materials and methods

The samples were collected from the following caves (Fig. 1): Jaskinia Wiślańska, Jaskinia Zbójecka w Łopieniu, Jaskinia Dująca, Oblica, Jaskinia Złatniańska, Jaskinia w Kościelcu, Jaskinia Salmopolska, Jaskinia Mroczna and Diabla Dziura w Bukowcu. Based on morphological and macroscopic features several non-carbonate mineral speleothem types have been distinguished (terminology follows HILL & FORTI, 1997). These speleothems include: (A) draperies, stalactites and flowstones (the caves: Wiślańska, Zbójecka, Dująca, Oblica, Złatniańska); (B) soft and earthy coatings (Zbójecka, w Kościelcu, Salmopolska); (C) hardened coralloidal forms (Mroczna and Diabla Dziura), and (D) gypsum incrustations, crusts and coatings (Wiślańska and Miecharska).

Microscopic analysis was carried out using an Olympus BX-51 polarizing microscope. Thin sections were cut perpendicular or along to the speleothem surface. The key laboratory studies comprised analyses of the samples based on the following methods: X-ray powder diffraction (XRPD), scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDS), electron microprobe (EPMA), and Raman micro-spectroscopy (RS). The XRPD studies were carried out using a Rigaku SmartLab 9 kW diffractometer equipped with a reflective graphite monochromator. The diffraction data were collected using Cu-Kα radiation. The micromorphology, microstructure and elemental composition of the speleothems were studied using a FEI 200 Quanta FEG scanning electron microscope with an EDS/EDAX spectrometer. Quantitative micro-area chemical analyses were conducted using a JEOL SuperProbe JXA-8230 electron microprobe equipped with five WDS spectrometers. The molecular characteristics of the speleo-thems' components were determined using Raman micro-spectroscopy. The spectra were recorded with a Thermo Scientific DXR Raman Microscope with a 900 grooves/mm grating and a charge- coupled device (CCD) detector.

A 532-nm diode laser was the excitation source.

3. Results

Mineral composition of all the speleothems includes grains of detrital material inherited from the parent sandstones. It is mainly quartz, potassium feldspars and sodium-rich plagioclases. Micas (mainly muscovite, less frequently biotite) and other phyllosilicates (kaolinite, chlorite, illite) are also common. Various accessory minerals: Ti oxides, zircon, monazite, etc. were encountered, as well. No correlation was found between the speleothem type and the amount and composition of those grains.

The bulk mass of all the speleothems consists of, usually low-crystalline, authigenic minerals. Raman microspectro- scopy also evidenced admixtures of organic matter in most of the samples (see ADAMOVIČ et al., 2022).

Dripstones and flowstones (type A) are composed of cryptocrystalline isotropic mineral mass often forming parallel or concentric laminae of more or less diversified colors (Fig. 4A). In some samples, small quasi-nodular accumulations of flaky crystallites of unidentified sodium, magnesium and calcium silicates, showing Si/(Na+Ca+Mg) molar ratios of ca. 3-3.5, occasionally appear. XRPD patterns of the speleothems (Fig. 5A) usually reveal only a few extremely broadened diffraction bands at ca. 3.4, 2.2 and 1.5 Å, i.e. at the positions reported previously for amorphous hydrated Al hydroxy-phosphates – evansite and bolivarite (GARCÍA-GUINEA et al., 1995) as well as similar to those of allophane (OHASHI et al., 2002, SATO et al., 2024).

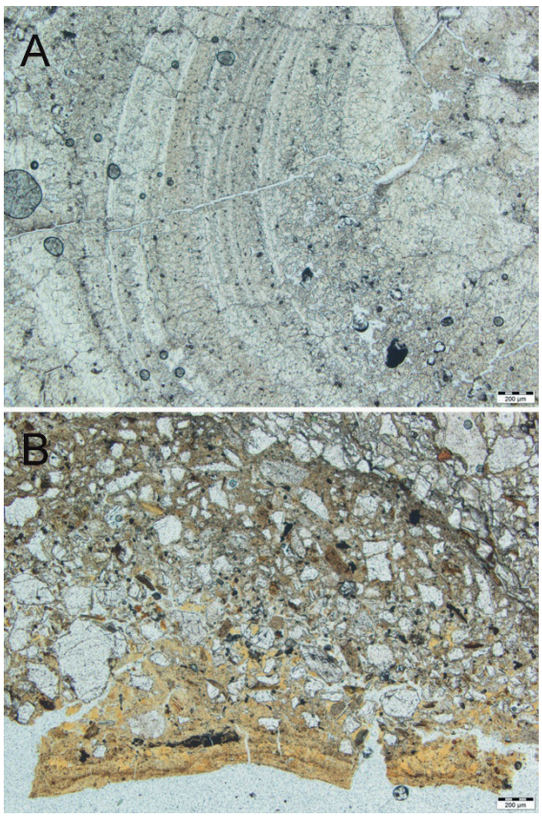


Figure 4: *Sections of some speleothems (optical microscope). A – a dripstone composed of cryptocrystalline mass forming laminae (Jaskinia Wiślańska cave), B – poorly crystalline earthy coating with weakly developed lamination (Jaskinia Salmopolska cave) (Photo M. Marszałek).*

The peaks of crystalline phases visible in the diffractograms, originate exclusively from the sandstones, and include quartz, feldspars, and phyllosilicates (mica/illite, kaolinite, chlorite).

Soft earthy coatings (type B) are also extremely-poorly crystalline as evidenced by their XRPD patterns (Fig. 5B), which, unlike for type A speleothems, reveal an additional intense very broad peak at ca. 12-14 Å. This feature might be attributed to allophane and/or imogolite (THILL, 2016). However, the presence of the latter has not been reported in any speleothems, so far (ONAC & FORTI, 2011a). The soft coatings are similar to type A speleothems under the microscope, but their lamination is usually weakly developed and in thinner coatings on the sandstone surface

is completely absent. The inner parts of such coatings are rich in quartz and other detrital grains, which disappear in the outermost zones (Fig. 4B). The A and B types of the spe-leothems appear to be the most diverse in terms of their micromorphology and chemistry (Fig. 6A). Among mineral phases present in type A and type B speleothems, several following types have been distinguished based on XRPD patterns, SEM observations and EDS/WDS analyses: (i) nearly amorphous Al-Si-P compounds with Al/(Si+P) molar ratios of ca. 2–3 (Fig. 6B), always containing some Ca and Mn; (ii) aluminum phosphates with Al/P molar ratios of ca. 1–2, and traces of Ca, Fe, Mn, Mg, K; (iii) phosphate-free aluminum oxides containing Si with lower (ca. 2–3) and higher (ca. 4–6 ca.) Al/Si molar ratios; (iv) phosphate-free allophanes (Al/Si ca. 1) and possibly imogolite (Fig. 6C), (v) Al-rich manganese oxides (Fig. 6D), probably vernadite-like phyllomanganates, sometimes containing traces of Zn, Ni, Cr, and Co; and (vi) Na-Ca-Mg (phyllo)silicates.

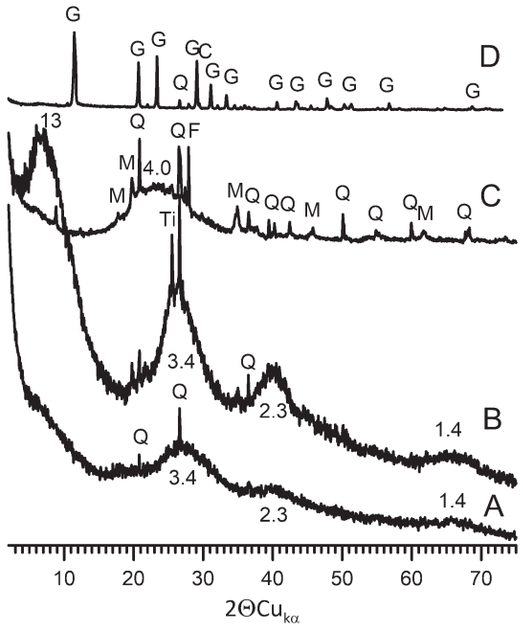


Figure 5: XRPD patterns of selected speleothems. A - Jaskinia Zbójecka cave (type A), B - Jaskinia w Kościelcu cave (type B), C - Jaskinia Mroczna cave (type C), D - Jaskinia Miecharska cave (type D). Q - quartz, M - mica-like phyllosilicate, G - gypsum, C - calcite, F - feldspar, Ti - Ti oxide. The numbers denote positions of broad diffraction bands [Å].

Hardened coralloidal forms (type C) are predominated by X-ray amorphous opal-type silica (Fig. 6E) containing minor Al (Al/Si 0.1-0.2), as well as traces of Ca, Na, Mg, P, and Fe. XRPD patterns of the coralloids reveal very broad diffraction band at ca. 4 Å, typical for opal-A (KÄMPF et al., 2000) accompanied with sharp reflections of quartz and feldspars (Fig. 5C).

In gypsum crusts and incrustations (type D, Fig. 3B) calcium sulfate (Fig. 5D) is accompanied by calcium carbonate admixtures (chiefly calcite, occasionally aragonite). The largest gypsum crystals reach several millimeters in size. However smaller, anhedral crystals (usually below 0.5 mm), resembling desert roses are much more common (Fig. 6F). Within these speleothems, rare disseminated tiny barite crystals (several micrometers in size) and accumulations of very fine-crystalline acicular iron oxyhydroxides (probably goethite) were also found.

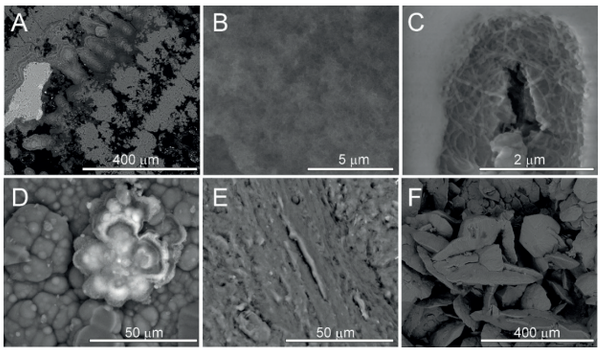


Figure 6 : *Selected speleothems in BSE images. A – D - the most diverse in micromorphology and chemistry A and B types of the speleothems: A - quartz (bright) and various Al-Si-P compounds (Jaskinia Wiślańska), B - nearly amorphous Al-Si-P compounds (Jaskinia Wiślańska), C - phosphate-free allophanes (Al/Si ca. 1) and possibly imogolite (Jaskinia Salmopolska), D - Al-rich manganese oxides (Jaskinia Wiślańska). E - opal-type silica with minor Al in hardened coralloidal forms (Jaskinia Mroczna), F – small anhedral gypsum crystals (type D) (Jaskinia Miecharska) (Photo G. Rzepa, M. Marszałek).*

4. Discussion

The majority of the studied non-carbonate speleothems occur in the caves developed within the Godula Beds, to a lesser extent in the Magura Beds and the Ciężkowice Beds. They are mainly hard sandstones with silica or silica-clay cement. This causes the aeration zone waters to be usually characterized by very low mineralization (often below 100 mg/L), including low calcium and bicarbonate concen-trations (ZAWIERUCHA et al., 2005). Acidic conditions can therefore often develop – ground waters and dripwaters in the caves usually show low pH (even below pH 5). In some cases pH 3 were measured (MOTYKA & ZAWIERUCHA 2001). Low pH prevents precipitation of calcium carbonate and at the same time promotes weathering of aluminosilicate minerals in the sandstones and leaching of aluminum. Indeed, Al concentrations as high as 10-12 mg/L were reported in dripwaters of some caves. Silica concentrations in these waters are also relatively high, reaching > 10 mg/L.

Such conditions favor formation of poorly-crysalline 'cation- free' aluminosilicates such as allophane and imogolite (PARFITT, 2009). The occurence of phosphates in many caves results from the presence of bat guano, the decom-position of which leads to the release of phosphate ion (AUDRA et al., 2019 ; ADAMOVIČ et al., 2022). In the Jaskinia Zbójecka cave, where the largest colony of bats in the Beskid Mts. is located, phosphate concentration in dripwater is high enough to allow the precipitation of aluminum phosphates of the evan-site/bolivarite type. When the phosphate concentration is lower, the PO_4^{3-} anion may substitute the silicate anion in allophanes and/or can be surface-adsorbed, which is facili-tated by their very high specific surface areas and the positive surface charge at low pH values (THENG et al., 1982; PARFITT, 2009).

Gypsum probably precipitated from acidic solutions originated from pyrite oxidation present in the sandstones (ALEXANDROWICZ et al., 2014) and/or decaying guano that reacted with Ca-containg dripwater (AUDRA et al., 2019).

5. Conclusions

The non-carbonate speleothems in the pseudokarst caves of the Polish Outer Carpathians are highly variable. Their origin seems to be affected by lithology of the host sandstones, geochemistry of ground waters as well as biogeochemical processes related to guano deposits. In the caves formed in the Godula Beds, the speleothems reflect water conditions: as stalactites and flowstones appear to precipitate from water flowing down the cave walls whereas crusts and coatings are probably related to capillary and formerly condensation water seeping through the sandstones. The details of these processes, as well as mineral composition of the speleothems, are not yet fully understood, therefore further research is required, including dripwater analysis and advanced methods of solid state characterization as transmission electron microscopy and infrared spectroscopy.

Acknowledgments

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Karren and caves in granite islands of Seychelles

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Abstract

This text guides you in drafting your complete paper for the 19th ICS Scientific Conference proceedings. Please submit your finalized paper in *.doc, *.odt, or preferably *.docx format. The paper should be 6 pages long, including all figures, photos, and tables. The summary should be no longer than 200 words. Keywords are not permitted. The abstract should be written in a single column. If your paper is in English, an abstract in French is recommended but not required. If your paper is in a language other than English, an abstract in English (with the English title at the beginning) is mandatory. Use Calibri 9 pt font.

Résumé

Lapiés et grottes dans les îles granitiques des Seychelles. La partie nord-est des Seychelles comporte les plus grandes îles du pays, formées de granite, et d'une multitude d'ilots associés. Ces îles présentent un développement exceptionnel de lapiés d'écoulement et constituent un cas d'école à l'échelle mondiale. Les formes sont ici présentées du haut des reliefs jusqu'à la côte et sous le niveau marin. Les grottes associées sont avant tout des grottes d'interstices, mais il y a également des grottes marines. On sait aujourd'hui que certaines de ces grottes ont servi d'habitat.

1. Introduction

First permanent occupation of Seychelles was made by the Frenchs and started in 1770, following pirates' activity after 1630. In 1811, British took over the island and in 1635, they abolished slavery. In 1976, Seychelles became an independent republic.

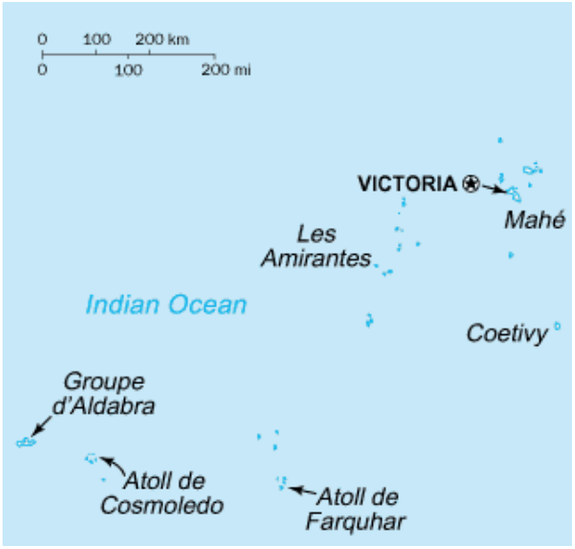


Figure 1: *The Seychelles Islands. The studied ones are Mahé and these to the northeast of it, called Inner Islands. https://commons.wikimedia.org/wiki/File:Se-map.gif.*



Figure 2: *Close up map on granite islands. https://www.justseychelles.com/seychelles-map.*

Most location names in Seychelles are French and local creole language is derived from it.

Seychelles are comprised of several archipelagos (Fig. 1). Only the islands called inner islands are made up of granite.

They display an exceptional pervasive development of karren and show many caves of various, though limited, size between boulders. Karren are even present in the sea under present day sea level. Marine caves are present in some locations.

This paper is aimed at showing the distribution of karren and caves in the islands, from island tops down to sea shore and under the sea.

2. Geology of Seychelles

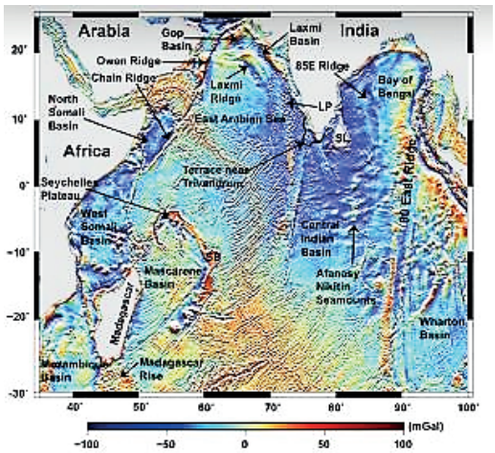


Figure 3: *The Seychelles Plateau, a remnant of India Plate left behind during the rifting of Gondwana and north-eastward motion of India. Free Air Gravity Anomalies in the Indian Ocean (Sandwell & Smith, 2009), in Ross .*

The Seychelles Plateau (Fig. 3) is the higher elevation part of Mascarene Plateau that lies 1.5 to 3 km above the adjacent sea floor. The Plateau is a part of India that was left behind after its break off the Gondwana supercontinent, during the motion of Indian Plate towards the North-east.

Seychelles granites show two groups of dates: 670 to 725 MA on Mahé Island and broadly 700 to 600 MA for mahé and Praslin, both groups being Precambrian. Doleritic dikes were emplaced around 620 MA during the Precambrian and in the Early Tertiary. Silhouette and North Islands are made up of alkaline igneous complexes emplaced during the 67 to 61 MA period and may be contemporaneous of Tertiary dolerites (ROSS. 2024)

Dark rocks are also present as inclusions in Mahé granites.

Triassic and Jurassic sediments are reported to exist only in the Southwestern part of the Mascarene Plateau.

At around 96 to 84 MA, rifting started between Madagascar and Seychelles while separation of Seychelles and India started in the Late Cretaceous and Lower Tertiary (PLUMMER,1995, cited by ROSS, 2024).

The Seychelles are presently subsiding at a slow rate of less than 2.5 cm per 1000 years (HOWELL, 2000, cited by ROSS, 2024).

Seychelles landscape is heavily controlled by fracturing with a variety of directions.



Figure 4: *intensive fracturing in the southern tip of Félicité Island (East of La Digue).*



Figure 5: *fracture-controlled rocky capes along the southeastern coast of La Digue and along the northern tip of the island. The NE and SW coastlines also are controlled by the same directions, the mountain ranges as well. © 2024 Airbus. Data SIO, NOAA, US Navy, NGA, GEBCO, CNES. 7 May 2023, Google Earth.*

Seychelles islands follow overall NW-SE trends and main ones show steep slopes. Mahé culminates at Morne Seychellois (905 m), Praslin at Mont Azore (367 m) and La Digue at Nid d'Aigle (337 m). Silhouette Island is different, more rounded, probably due to its different geological nature and it culminates at Mont Dauban (751 m).

3. Climate of Seychelles

The climate of Seychelles is considered as tropical though the islands are close to the equator. Victoria, the capital city is at a 4°40' South latitude, on Mahé Island. There, annual rainfall depth amounts 2365 mm, which is a high value, with 200 days of rain a year. Contrast is high between wettest and driest months. Temperature varies only to a variable amount. Mean annual value is 28.2 °C.

There are 2530 hours of sunshine per year (6.9 hours/day).

Trade winds from SE are stronger from June to September.

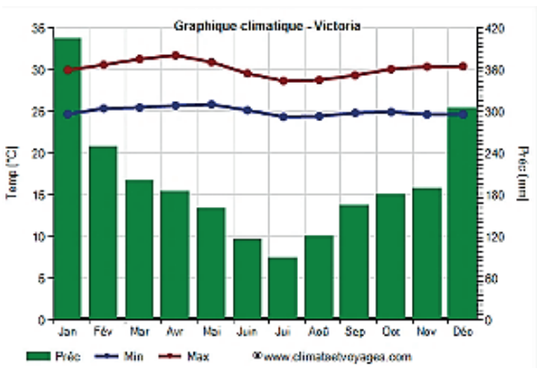


Figure 6: *Rainfall depth and temperature at Victoria.*

4. Spatial and altitudinal distribution of karren

We observed in the field the distribution of granite landscapes from mountain tops to seashore in Mahé, Praslin and La Digue Islands and we have added images from other sources including valuable information from sea divers.

All granite Seychelles islands are extremely rocky, with cliffs, rocky floor areas, and boulders in extreme abundance. Mahé, especially, that is much more elevated in its central northern part (905 m a.s.l.), shows an abundance of rocky surfaces (Fig. 7 to 9).

Mountain tops

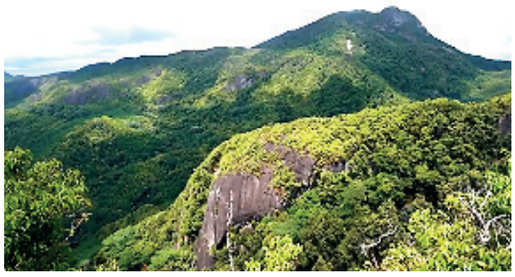


Figure 7: *Morne Blanc (675 m) in the front shows high cliffs with rillenkarren. Morne Seychellois (905 m) in the back. NW side of Mahé. https://www.youtube.com/watch?v=j5Im25bbr04.*



Figure 8: *Hilltop above Victoria, showing areas of bare granite and, to the right, karren. https://www.youtube.com/watch?v=zqvMi2WZi5c.*



Figure 9: *Granite cliffs with karren SW side of Mahé. Mont Plaisir area.*

Higher areas in Seychelles are more prone to cultivation, in granite arena areas. In the early days of occupation by Europeans, plantations were commonly located in such areas. Arenisation generates a reddish acidic soil containing remnant boulders of unweathered rock. Such boulders are sometimes separated from weathered granite by a fracture which prevents capillary water to weather the top boulder (Fig. 10). The latter is subject to formation of karren (Fig. 11).



Figure 10: *Boulder separated from substratum by a fracture. Nid d'Aigle, top of La Digue, 333 m a.s.l.*



Figure 11: *Rillenkarren on a boulder near Nid d'Aigle.*

Mountain slopes

Slopes are often steep and include cliffs which are often carved by karren (Fig. 13) with some pinnacles (Fig. 13).



Figure 12: *Cliffs at various elevations in front of Mahé airport showing low angle fractures, karren and pinnacles on top.*



Figure 13: *Slopes, cliffs with karren and pinnacles. Mahé E.*



Figure 14: *Low slopes and rocky floors. Mahé SW coast.*



Figure 15: *Slopes with boulders and karren. NW Praslin.*



Figure 16: *Rock flow with rotated boulders. NE La Digue.*



Figure 17: *Disseminated boulders with karren. SW La Digue.*

Slopes show a variety of features from large bare rock surfaces (Fig.14), isolated boulders with some larger ones (Fig. 15), rock flows which are angular to carved by runnels (Fig. 16-17). Large isolated boulders show a variety of morphologies, from gently sloping top surfaces giving way to wall runnels to runnels starting from the top of boulder (Fig. 17). Rundkarren are present on some boulders which are denudated from soil. Some several metre large boulders show a peripheral overhang in their lower part, with bare rock devoid of runnels, a likely capillarity effect.

Inselbergs

Inselbergs are rare because flat areas are rare also. One such area is located along the western coast of La Digue, where the Giant Rock Monolith (Fig. 18) is lying in the Union Estate.



Figure 18: *The Giant Rock Monolith. Google Earth, view of 7/5/2023 by Airbus.*

It shows an eastern side wall almost smooth (Fig. 19) and a western one with a lot of karren (Fig. 20-21-22).



Figure 19: *The northern side, with scarcer karren.*

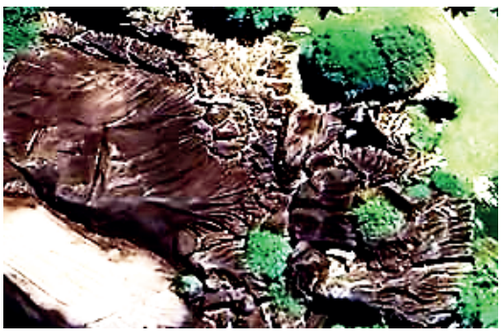


Figure 20: *seen from above, the fan-shaped beginning of karren on the top of monolith (centre of the view).*

The monolith shows an interesting variety of karren forms, from rillenkarren to more abundant hortonian rinnenkarren located downward of bare rock surfaces. Wall runnels are well developed on high subvertical surfaces (Fig. 21), either downstream of bare rock surfaces or from the top of isolated boulders (Fig. 22). Steep runnels often start at sharp angles of the rock wall with downward slope increase.

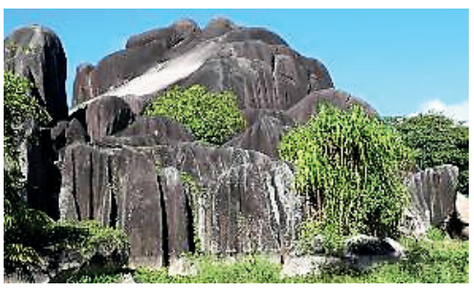


Figure 21: *The northeastern side of Giant Rock Monolith.*

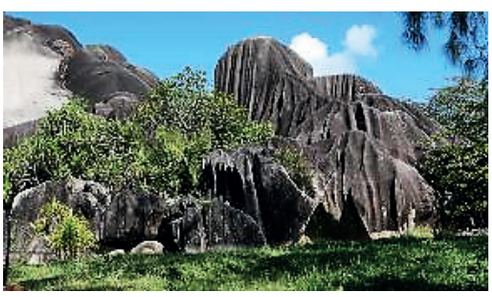


Figure 22: *The eastern side, with developed karren originating from tops of boulders.*

Shorelines

Along shore features are easy to spot, because they are washed by sea water (to a variable degree) and because vegetation is much scarcer than elsewhere. They are rather spectacular and participate in the touristic attractivity. Many landforms are present, though rinnenkarren are dominant.



Figure 23: *Massive rounded rocks (right) and boulders with karren (centre).*



Figure 24: *Boulders with runnels, vertical ones due to gravity flow, others oblique due to rock heterogeneity.*



Figure 25: *Runnels a few metres from the beach.*

Underwater karren

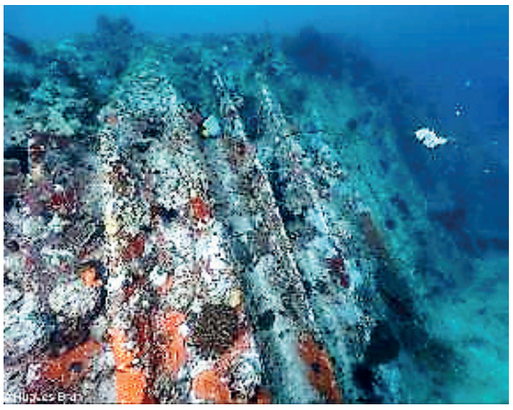


Figure 26: *Submerged karren, Ave Maria area, N. of La Digue. Hughes Brun. https://www.plongeur.com/forums/topic/68814-compte-rendu--seychelles-d%C3%A9cembre-2021/.*

Drowned features formed under aerial conditions are now submerged, due to post-glacial sea level rise. They are mentioned at several locations. Based on Mason-Parker & Walton's book (2015): at Channel Rock between Praslin and La Digue, where runnels are associated with "numerous channels and ledges" (sea bed at 25-30 m), near South Marianne Island (sea bed at -25 m), where "granite pinnacles rise from the sandy substrate, forming cathedral-like structures and creating precipitous ravines and narrow gullies".

STEINHAUER-BURKART (2024) shows (p.54-55) unlocated impressive pinnacles with runnels on the sides, that are likely located either in Ave Maria area or in South Marianne's.

5. Caves

Three types of caves are recognised in Seychelles granitic islands.

Talus caves

Talus caves are pervasively spread from mountain tops to underwater realm, as granite boulders of small to very large size are present in most parts of the islands. However, they are easier to spot near the shore, where vegetation is less pervasive (Fig. 27a & b).





Figure 27, a & b: *Two examples of talus caves. La Digue.*

DE COMARMOND et al (22024) have listed a number of caves that were inhabited by slaves between 1770 and 1837. They are located near summits, high on the slopes, because most of plantations were located in such areas. On Mahé Island: Montany Brile (500 m a.s.l.) at Au Cap (South Mahé) with man-built walls under a gigantic boulder; Castor Cave, underneath a rock high on Castor Mountain to the West of Anse aux Pins, where maroon slaves' bones and skeletons were observed. In the same area, Camp Marron Cave is located near the top of a mountain: in this large cavity, skeletons, hair and teeth were found, that were probably belonging to maroon slaves. Dan Galla, located around 350 m a.s.l. on Le Niole Mountain close to morne Seychellois was occupied by Ethiopian slaves freed in 1868 by the British from Arab boats after being rescued along the African coast.

On Silhouette Island: caves at Jardin Marron Mountain, near La Passe, are large enough to shed several persons; possible stones of a fireplace were observed inside, as well as a nearby spring; slaves likely lived there in the early 1800's.

Presently, these caves are often difficult to reach due to dense bushy

vegetation and remoteness.

A few talus caves are used to shed Virgin's statues. Some are crossed through during walking tours, as to the South of Grande Anse on La Digue.

Submarine talus caves

They are present between boulders under the sea, as it was reported by divers. MASON-PARKER & WALTON (2015) report: a swim-through at Brissare Rocks (photo, p. 63), at a 5 m depth in Mahé; small caves at Grouper Point, L'Îlot and Shark Bank (at ca 30 m). Around Silhouette Island, at Anse Mondon, "numerous giant boulders provide a seascape of intricate swim-throughs and passages".

Coastal marine caves



Figure 28: *Lavantir Cave on Marianne Island. © Odile de Comarnod.*

Such caves are poorly known. On Marianne Island, Trou Lavantir is a cave at sea level, with a several meter large and high opening that is accessible at low tide only. The cave is said to develop "deeply" underneath the island (DE COMERMOND & GILLIEAUX, 2024, p. 7-8).

Lavantir is the creole name for L'Aventure, a maroon slave who used to live inside during several years; Trou for Cave. Other caves are still undocumented and might be not numerous.

6. Conclusion

This paper gives an overview of caves occurrence and distribution in granitic islands. Coastal caves may be large but seem to be scarce. The bulk of caves is represented by talus caves which are numerous and located in many places. However, due to high density of vegetation, they are difficult to reach and their prospection is difficult as well.

Studies on human presence show that a number of them, and probably more than published, were used as living places in the olden days by slaves located near plantations near mountain tops.

This study highlights the interest of prospecting granitic areas, not to find large caves, but to better understand distribution of caves in such rocks, under tropical conditions. The pervasiveness of karren is extremely noticeable and it can probably be explained by the saline air and rains in an insular area.

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Silicilcastic cave or diamond mine? The case of Canal da Fumaça, Igatu Village, Chapada Diamantina - Bahia, Brazil

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Abstract

The Igatu Village is a remanescent of the diamond mining period that covered the Chapada Diamantina, center of Bahia state, northeast of Brazil, during the XIX and XX centuries. Caves and other geological features, developed in Mesoproterozoic siliciclastic rocks, acted as traps for diamond-bearing sediments and, therefore, were severely impacted by mine activity. The Canal da Fumaça Cave, probably the first and richest mine in Igatu, was so modified that raises the doubt: is it trully a cave or an artificial diamond mine? Aiming to answer this question, we developed speleological and geological analysis, in order to recognize natural and anthropogenic factor that may have influenced the system development.

Résumé

A Vila de Igatu é remanescente do período de mineração de diamantes que recobriu a Chapada Diamantina, região central do estado da Bahia, nordeste do Brasil, durante os séculos XIX e XX. Cavernas e outras feições geológicas, desenvolvidas em rochas siliciclasticas mesoproterozoicas, agiram como armadilhas para os sedimentos diamantíferos e, assim, foram severamente impactadas pela atividad mineira. O Canal da Fumaça, possivelmente o primeiro e mais rico garimpo em Igatu, foi tão modificado que levanta a dúvida: se trata realmente de uma caverna ou de uma mina artificial de diamante? Para responder a essa pergunta, foram desenvolvidas análises espeleológicas e geológicas, visando reconhecer os fatores naturais e antropogênicos que podem ter influenciado no desenvolvimento desse sistema.

1. Introduction

The diamond rush in Chapada Diamantina (Bahia, Brazil) during the XIX and XX centuries, attracted thousands of people in search for wealth, leading to a populational boom followed by profound social and ambiental issues. The Igatu Village, at the east part, emerged during this period and, today, preserves the building and living history of the mining era.

The Canal da Fumaça was the richest and, possibly, the first mine site in Igatu (PEREIRA, 1937). Together with eleven other cavities (according to national databases, such as the CANIE and CNC), it composes the knowed subterranean heritage of Igatu. Significant cave occurrences were recognized in the last years, involving one of the longest caves of South America in siliciclastic lithologies (AULER & SAURO, 2019), and other systems with a great diversity of chemical and clastic deposits (PARRA et al., 2023a, 2023b). The rich subterranean biodiversity is also highlighted and the area is considered a biodiversity´s hotspot (GALLÃO, BICHUETTE, 2015).

This karst features are hosted in Mesoproterozoic rocks of Tombador Formation, Chapada Diamatina Group. They are constituted by metasandstones and metaconglomerates, mainly (BONFIM & PEDREIRA, 1990; PEDREIRA, 1994). Those resistent lithologies result in a montainous relief, knowed as Sincorá Ridge (LIMA & NOLASCO, 2015).

Diamond deposits come from the conglomerates erosion, whose sandy to pebbly sediments are deposited as colluvium and alluvium, often filling fractures or ‘’channels’’, as called by miners (NOLASCO et al., 2001), and in some cases, inside the caves.

Due to it, caves were significant targets to miners prospect, leading to heavily mischaracterization of this environments. In this context, the Canal da Fumaça was one of the most affected cavities, raising doubts even whether it is a natural cave, or an artificial mine. In order to answer this question, this study introduces geological and speleological data, aiming to identify the main natural or anthropogenic processes that led to its development.

2. Materials and methods

Work development involved field campaigns and laboratory analysis. Cave survey and geological assesment were carried out. Morphological aspects were described inside the cave and surroundings, looking for identify and diferentiate natural features, crated by karst processes, from those artificials, resulted of human impact during mining activity. Host rock and clastic deposits were described, searching for structural, lithological, and stratigraphic guidances of cave development. Structural measurements of fractures and bedding planes were carried, following strike-dip notation.

Fresh and weathered rock were collected (samples A34, A35, A36, A37,

A38, and A40) and sent to laboratory analysis. Thin and polished sections were prepared, aiming the microscopic assessment. Weathered samples were impregnated with a hardener resin and blue dye, allowing the observation of the porosity evolution at optical microscope. Furthermore, polished and carbon-metalized sections were described at scanning electronic microscope (SEM), equipped with a detector for energy dispersive X-ray spectroscopy (EDS). Whole rock chemical compositions – mayor and minor elements – were obtained by X-ray fluorescence (XRF).

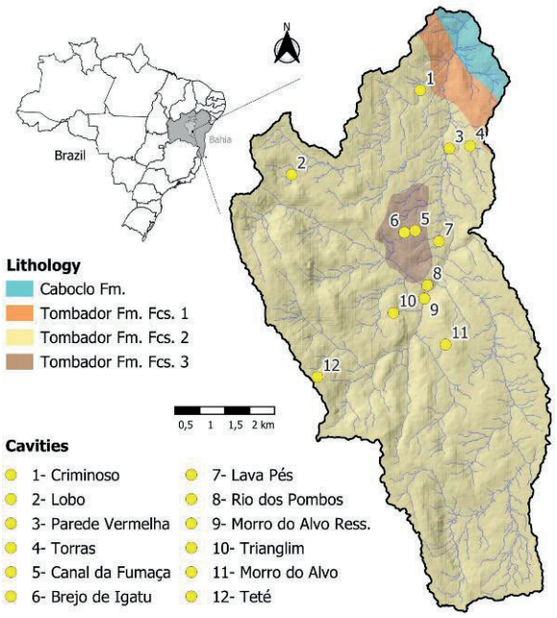


Figure 1: *Lithological map of the Coisa Boa River basin and location of caves registered in Igatu Village.*

3. Results

Cave survey covered, to date, 644m in linear development and 624m in horizontal projection, such as 29m in vertical range. However, mapping was not completed yet, and this values must increase, specially for secondary conduits. With the speleometry data, distance between extremes was measured as 172m and the overall slope calculated as 17% or 9.6º, with dip from SSW to NNE. Conduits are straight and main elongations follow the NNE-SSW, ENE-WSW and NNW-SSE directions. Passage connectivity is high (around 90 connections), resulting in a network pattern at floor plan map (Fig. 2A).

The structural measurement indicates a close correlation between cave morphology and structures (see diagrams in Fig. 2A). Subvertical fracture planes occur parallel both to the primary (NNE-SSW) and secondaries (ENE-WSW and NNW-SSE) orientations of cave elongation. This planes occur in some cases as dense fracturing zones with cataclastic aspect, guiding the block falling from the ceiling and contributing to larger galleries development (Fig. 2B). Sub-horizontal fractures were also identified, at times, filled by quartz veins.

At the surface relief, fracture planes mark fissures and channels that reach up to 15m in depth and 8m wide, creating a ruiniform relief (Fig. 2C) and, in some cases, connecting the surface with underground conduits (Fig. 2D). Bedding planes show N dip trend, with gentle angles close to 10º, conducting water flow in that direction.

The predominant lithology of host rock is sandy, composed by quartz and rare feldspar grains at an advanced level of alteration. Textural maturity is low and the grains are surrounded by a phyllosillicate matrix (pyrophyllite and kaolinite), which occurs as fine-grained aggregates in the cave rock facies (sample A34, Fig. 3A) and as brownish masses of well-crystalized pyrophyllite in upper cave strata. Quartz grains often occur corroded at the boundaries and, in some cases, in the whole grain, where they appear replaced by pyrophyllite. XRF analysis indicate, to samples A36, A37 and A38, the predominance of silica (80-87%), and aluminum (12-18%), varying according to grain/matrix proportion (Table 1).

A clayey layer was also identified (sample A35), with a thickness varying from 10 to 20 cm (Fig. 2E). XRF pointed to higher amounts of aluminum and potassium, indicating the presence of clay minerals (e.g. kaolinite, illite). This stratum occurs boundaring a lower fresh rock sandy facies (A34) and an upper weathered one (A36).

wt%	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	< 0.01	0.02	0.00	0.00	0.00
A38	80.97	18.33	0.02	0.48	0.15	0.00	0.00	0.00	0.00	0.00

Table 1: *Whole-rock chemical compositions (mayor and minor elements) obtained by XRF analysis.*

Fresh rocks are cohesive and low porous, while weathered rock assume friable aspect, has depositional structures partial or tottaly effaced, and the porosity increased comparing to fresh one. Thin section of sample A36 impregnated with hardener resin and blue dye, showed the intra and intergranular secondary porosity enhancing (Fig. 3B). Intergranular pores are spread through the matrix and, in some cases, at the quartz grain contacts or overgrowth cement.

SEM images highlight the corrosion and crack of quartz grains boundaries, such as the presence of pyrophyllite filling the voids between grains (Fig. 3C). Frequently, this pyrophyllite occur replaced by kaolinite with booklet pattern (Fig. 3D).

Clastic deposits are rarely preserved inside the cavity. They constitute coarse-grained sediments, with pebble levels and discordances with the host rock, in some cases preserving the paleoconduit morphologies (Fig. 4A).

Cave passages and galleries morphology varies from natural to anthropogenic origin, predominanting the artificial ones (Fig. 4B). The floor is smoothed, possibly due to high energy floods wear, although often carved by a linear perennial water flow. On the other hand, passages in weathered and friable rock seems to be excavated, sometimes in a low arch format and, in other times, rectified from fractures and bedding planes (Fig. 4C). Fresh rock were also impacted, with marks of gunpowder detonations (Fig. 4D). Stone buildings, walls and pillars are present all over the cavity.

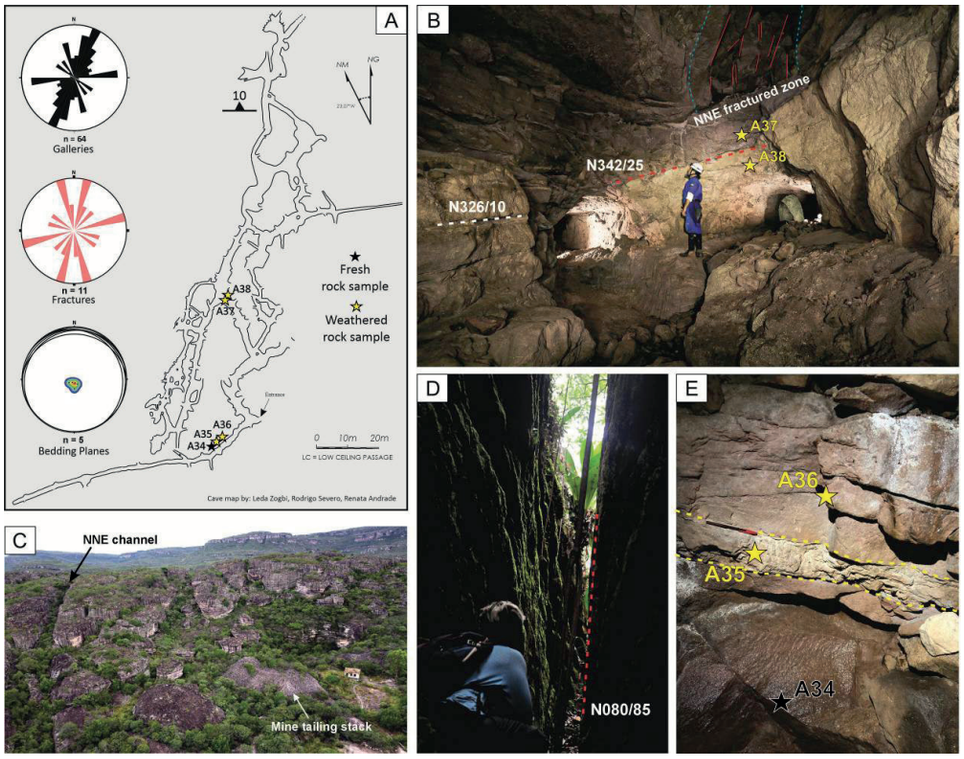


Figure 2: *A) Floor plan map of the Canal da Fumaça positioning the rock samples collected and rose diagrams of galleries, fractures and bedding dip direction. B) Largest gallery of the cavity, where subvertical fractures planes guide the block falling. C) Ruiniform relief above the cavity. D) Deep fissures (channels) that connect surface to underground. E) Clay layer limiting upper altered and lower fresh metasandstone strata. Stars represents the rock samples collected, yellow for weathered rock and black for fresh rock.*

4. Discussion

The correlation between structures measured in the field and the elongation direction of the cave conduits suggests the structural as a important factor guiding its development. Subvertical fractures planes were recognized setting the water percolation and block falling, evidencing that they act as weathering and mechanical erosion fronts, similiar with described by MELO et al. (2007) and SAURO (2014).

As the meteoric waters infiltrate mainly through this planes, minerals are more exposed to chemical weathering, leading to a higher rock alteration, which is notable by the friable rocks at the fractures walls.

Furthermore, bedding planes dip conducts the water flow to N, contributing to the cave N to NNE-SSW elongation. Water flows along the bedding dip tend to be fast (AULER et al., 2020), which increases the erosion potential and, thus, the enlargement of galleries and channels. Similarity between bedding inclination (~10o) and overall calculated cave slope (9,6o) reinforce this correlation.

Lithology was also identified as a guiding factor for the cave formation. The presence of the clayey layer limiting an upper altered sandy facies from a lower unweathered one (Fig. 2E), suggests that this impermeable stratum could play a sealant role, holding the percolation of meteoric water and, thus, retaining weathering in superficial levels.

In turn, constrast in matrix crystallization degree can also contribute to limit stratigraphic development of the cave. Low-crystalline pyrophillite of the cave facies (A34) are more susceptible to weathering in comparision to well crystallized pyrophyllite of cave upper strata (A40).

Petrographic analysis demonstrated that the occurrence of pyrophyllite is due to the regional anchi-metamorphism that affected the east Chapada Diamantina (VARAJÃO & GOMES, 1997; BATTILANI et al., 1999; SOUZA, 2017). Therefore, lithology can be defined as metasandstone. Phyrophyllite formation is given by the anchi-metamorphism reaction of deposicional kaolinite and quartz, through the HEMLEY et al. (1980) equation:

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

This reaction explains the quartz corrosion and cracks (Fig. 3A and 3D). Although these features are not products of weathering processes, this minerals weakness sites increase the microporosity and act as starting points for chemical attack.

On the other hand, the pyrophyllite shows alteration stains, where neoformed kaolinite occurs, interpreted as a product of recent chemical weathering. Incongruent dissolution of pyrophyllite and neoformation of kaolinte is ruled by the hydroxylation-desilication reaction, described by HEMLEY et al. (1980) and HURST & KUNKLE (1985):

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

Thus, it suggests that weathering transformation that affect the rock occurs mainly on aluminous phyllosilicate matrix, instead of quartz grains. The acid water pH (4-5), common in the study area (AULER et al., 2020), corroborates with this hypothesis, once aluminousilicates have considerably higher solubility than quartz in acid medium.

This chemical attack over the metasandstone matrix dissociates the quartz grains and reduces the rock strength. This process can be classified as phantomization, and represents an important mechanism to siliciclastic rocks karstification (QUINIF, 2010; HARDT, 2011; WRAY & SAURO, 2017). With the cohesion decrease, grains are susceptible to mechanical erosion, which takes place through water flow, in piping process, leading to the conduit opening.

On the other hand, several anthropogenic modifications are notable in the cave interior. In search of diamonds, miners removed most of the clastic deposits, emptying the galleries once filled by them. In addition, due to friable aspect of the predominant rocks in the cave, miners were allowed to excavate, enlarging existing conduits and creating new ones. This process possibly obliterated natural features of the cave, such as speleogens and speleothems, and certainly increase considerably the conduits area and volume.

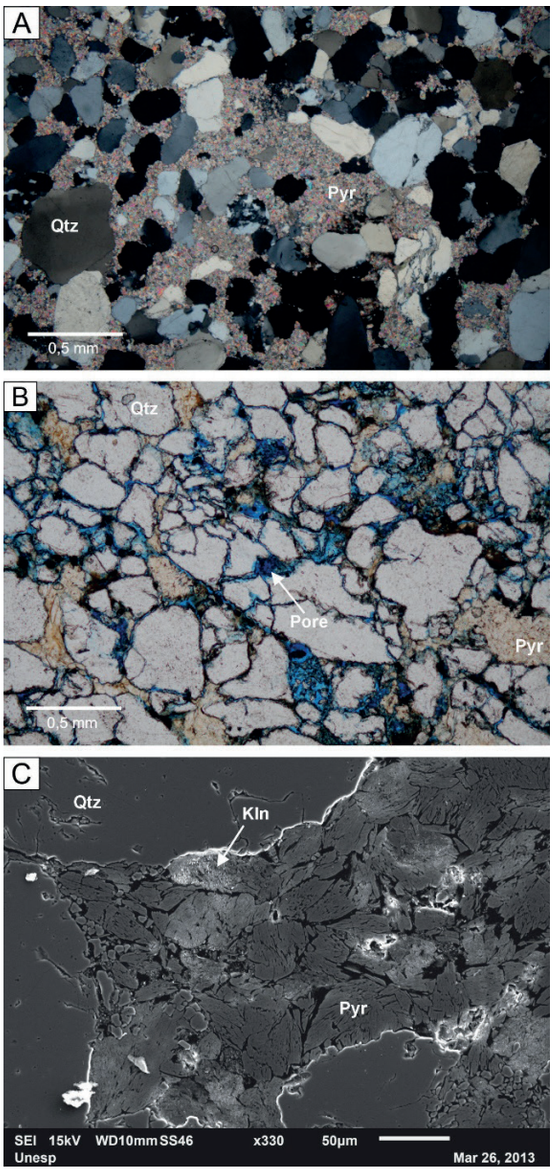


Figure 3: *A) Thin section (at crossed nicols) of fresh sample A34, evidencing the imature texture, with the fine-grained phyllosilicate matrix surrounding poor sorted grains, some of then corroded by anchi-metamorphism reaction. B) Thin section (at parallel nicols) of weathered rock sample A36 impregnated with resin and dye, highlighting intra and intergranular porosity. Cracks and corrosions increase the microporosity, and the metamorphic reaction sites act as preferential weathering targets. C) SEM image from sample A40, showing pyrophyllite matrix and consumed quartz grains boudaries. Neoformed kaolinite with booklet pattern occurs replacing initial weathered pyrophyllite, increasing the porosity where the reaction is advanced.*

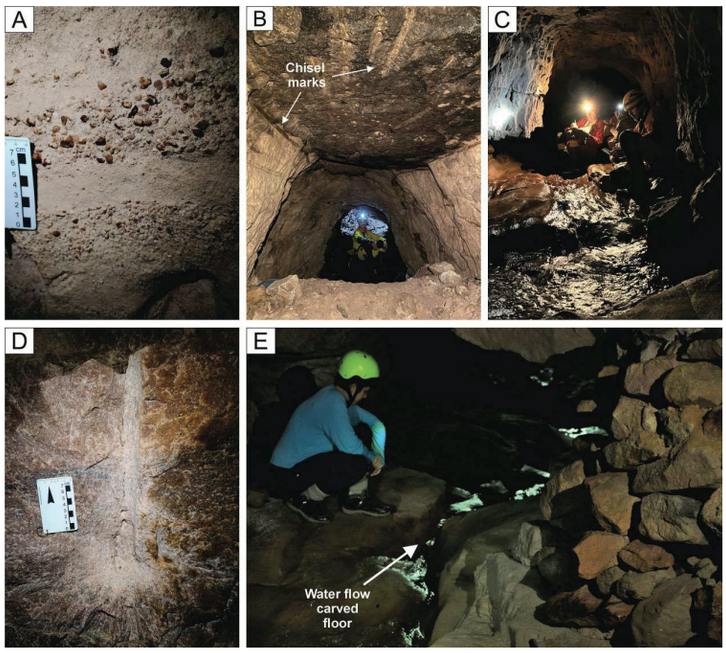


Figure 4: *A) Clastic diamond-bearing gravel explored by the miners. B) Excavated passage, with morphology varying from straight to arch. Note the chisel marks. C) Contrast between water eroded floor and excavated ceiling and walls. D) Gunpowder detonation in fresh rock. E) Water flow carved floor and stonewall built inside cave gallery.*

5. Conclusion

This work aimed to present and discuss studies developed at the Canal da Fumaça Cave, a siliciclastic karst system hosted in metasandstone rocks of the Tombador Formation, which was strongly affected by diamond miner activity that ruled the Chapada Diamantina during 19th and 20th centuries.

Natural processes of karstification were recognized, which are in consonance with those consolidated in literature. Structural and lithology are important factors guiding the cave development, conditioning the chemical weathering that leads to the metasandstone matrix dissolution, in a process of phantomization. Thus, mechanical piping removed loose grains and enlarged voids, creating conduits, channels and galleries. Later, fluvial sedimentation processes filled the cave conduits with diamond-rich deposits.

Contrasting with these natural processes, anthropogenic modifications by mine activity took place and left several marks in the cave system. Existing conduits were enlarged, new galleries were excavated in weathered rocks, fresh rocks were detonated with gunpowder, and most of clastic sediments were removed. Main impact of the modifications were the increase of the conduits area and volume.

Thus, the Canal da Fumaça were originally a cave and then transformed in a mine. So, it can be classified as a mined cave, in consonance with the descriptions of Onac (2019).

This research can be a contribution both to karst system in non-carbonate rocks literature and to the study of mined caves, which are common in the Chapada Diamantina and other regions of the Espinhaço Ridge. Future studies at this system must evolve water analysis, aiming to better understand the mobility of elements. Furthermore, researches should be expanded to other cave systems in Igatu Village, providing a complete view of this speleological and historical region and also supporting advances in the implementation of the Serra do Sincorá Geopark Project as a UNESCO territory.

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Na brecha aperta: identificando a ação da água nas cavernas basais

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Resumo

No presente projeto, vinculado ao curso de pós-graduação em Espeleologia ministrado pela Universidade de Passo Fundo-RS, a equipe do espeleogrupo Salamanca do Jarau realizou levantamento de cavidades localizadas na região da encosta da Serra Geral, abrangendo municípios da mesorregião nordeste do Rio Grande do Sul. Foram visitadas seis cavernas previamente registradas no CANIE (Cadastro Nacional de Informações Espeleológicas) , e identificadas outras sete cavidades por meio de metodologia oportunística, em colaboração com as comunidades locais. Nas atividades de campo, procurou-se levantar dados gerais das cavidades, entre os quais: município de localização, georreferenciamento (latitude, longitude), altitude, litotipo, espeleotemas, ação de águas, fauna, presença de sítios arqueológicos, ocupação recente e observações sobre a preservação/possíveis agentes de causadores de impacto. Estas informações estão apresentadas e compiladas no presente artigo. Outrossim, ao longo do diagnóstico de campo, foi possível observar a ação das águas nas cavidades basais: espaços de surgência e ressurgência, espeleotemas em formação, antigos dutos, reservas hídricas e gotejamento perene na boca. A sistematização destas informações, em consonância com as características do Sistema Aquífero Serra Geral, aventa-se uma hipótese acerca da gênese de tais cavidades. Sugere-se que estas cavidades estariam em um ciclo contínuo que envolve a drenagem, confinamento de águas meteóricas em zonas de fragilidade entre um derrame basáltico e outros, percolação continua pelas brechas, expansão das cavidades, formação de dutos e finalmente exposição destas em eventos contínuos de desmonte dos vales.

Abstratc

NA BRECHA APERTA: IDENTIFYING THE ACTION OF WATER IN BASALT CAVER. In this project, linked to the postgraduate course in Speleology taught by the University of Passo Fundo-RS, the team from the Salamanca do Jarau speleogroup carried out a survey of cavities located in the region of the Serra Geral slope, covering municipalities in the northeastern mesoregion of Rio Grande do Sul. Six caves previously registered in CANIE (National Registry of Speleological Information) were visited, as well as another seven cavities were identified through opportunistic methodology, establishing contact with local communities. In field activities, we sought to collect general data from the cavities, including: municipality of location, georeferencing (latitude, longitude), altitude, lithotype, speleothems, water action, fauna, presence of archaeological sites, recent occupation and observations on preservation/possible impact-causing agents. This information is presented and compiled in this article. Furthermore, throughout the field diagnosis, it was possible to observe the action of water in the basalt caver: spaces of emergence and resurgence, speleothems in formation, old ducts, water reserves and perennial dripping in the mouth. Through the systematization of this information, considering the characteristics of the Serra Geral Aquifer System, a hypothesis is put forward about the formation of such cavities: these would be in a continuous cycle that involves drainage, confinement of meteoric waters in zones of fragility between a basaltic spill and on the other, continuous percolation through the breccias, expansion of the cavities, formation of ducts and finally exposure of these in continuous events of valley collapse.

1. Introdução

A Serra Geral, localizada no nordeste do Rio Grande do Sul, é uma região de grande relevância para a espeleologia, abrigando uma rica diversidade de cavidades naturais associadas a formações basálticas, ainda desconhecida. Essas cavernas não apresentam apenas interesse geológico, mas também biológico e histórico cultural, o que as coloca no centro de estudos voltados para a conservação ambiental e ao entendimento dos processos de gênese de cavidades que se formam nesta litologia.

Apesar da importância dessas formações, muitos aspectos relacionados à gênese e evolução das cavernas permanecem pouco explorados, especialmente no que diz respeito à interação entre a geologia local e a dinâmica hidrológica. Neste contexto, o presente estudo, teve como objetivo realizar um levantamento espeleológico detalhado de cavernas na encosta da Serra Geral, coletando dados essenciais sobre os processos das águas no ciclo dinâmico de formação das cavidades.

2. Materiais e Métodos

A equipe visitou 13 cavidades localizadas na mesorregião nordeste do Rio Grande do Sul, todas em áreas com litologia basáltica (Figure 1). Dentre essas, seis cavernas já estavam cadastradas no Cadastro Nacional de Informações Espeleológicas (CANIE), enquanto outras sete foram identificadas durante o presente projeto, por meio de entrevistas com moradores locais.

Durante as atividades de campo, foram coletados dados detalhados sobre a localização e características de cada cavidade, incluindo: número de registro (quando aplicável), nomenclatura, localidade, município, latitude, longitude, altitude e litotipo. Além disso, foram avaliados aspectos espeleológicos e ambientais, como a presença de espeleotemas, a ação das águas subterrâneas (surgências, ressurgências e dutos antigos), registros de fauna, evidências de sítios arqueológicos e vestígios de ocupação humana recente.

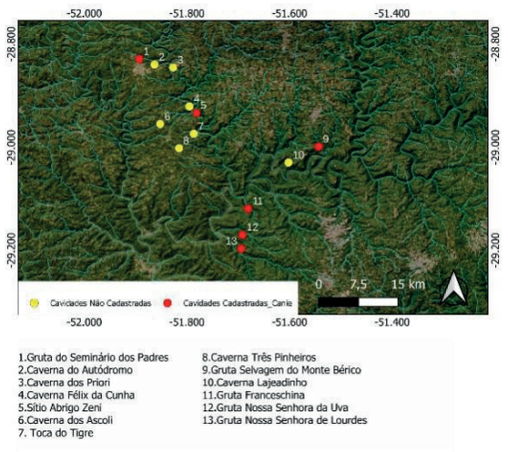


Figure 1: *location of the studied cavities.*

3. Resultados

A Figure 2 ilustra algumas das cavidades estudadas e as informações gerais sobre as 13 cavidades se encontram sistematizadas na Tabela 1, com uma descrição detalhada de suas características principais. Além disso, apresentamos os dados sobre a ação das águas nas cavidades para identificar padrões de erosão e formação de espeleotemas, bem como sua influência na gênese da cavidade.



Figure 2: *From left to right: Caverna Lajeadinho, Gruta N.Srª da Uva, Gruta Selvagem, Caverna dos Priori, Caverna Autódromo, Caverna Ascoli, Caverna Toca do Tigre, Gruta do Seminário.*

Cavidade	Nº Canie	Município	Latitude	Longitude	Altitude	Litotipo	Espeleotemas	Águas	Fauna	Sítios Arqueológicos	Ocupação recente	Obs. preservação
Gruta Seminário dos Padres	006226.00030.43.09407	Guaporé/RS	-28,828572	-51,892796	490	Fácies Gramado a 700 m transição com Fácies Caxias	Coralóides	Duto ativo orientado de fora para dentro, presença de queda d'água na boca (perene)	Morcegos, presença de guano, aracnídeos, grilos (troglófilos)	Não	Sim, capela com culto à Nossa Senhora de Lourdes onde ocorrem missas. Uso religioso	Visitada e com presença de pichações e escavações no bloco testemunho
Caverna do Autódromo		Guaporé/RS	-28.839525	-51.863025	370	Fácies Gramado (Rocha Ígnea, vulcânica, Litotipo Basalto)	Coralóides	Gotejamento interno nas fissuras, presença de queda d'água na boca (perene)	Morcegos, presença de guano, aracnídeos, grilos (troglófilos)	Sim, lítico em superfície. Tradição Umbu/Humaitá. Não cadastrado	Sim, altar com culto à Nossa Senhora Aparecida. Uso religioso. Uso turístico, presença de escadaria de pedra	Visitada pela comunidade
Caverna dos Priori		Vista Alegre do Prata/RS	-28.845225	-51.826931	450	Fácies Gramado a 300 m transição com Fácies Caxias	Sim – coraloides, travertinos, cortina	Gotejamento interno nas fissuras, presença de queda d'água na boca (perene)	Tamanduá mirim, graxaim, morcegos com presença de guano, aranhas, grilos (troglófilos)	Sim, lítico em superfície. Tradição Umbu/Humaitá. Sítio dos Priori, cadastrado, escavado pela UPF, 2024.	Construção de muro de pedras bloqueando a zona afótica	Visitada pela comunidade
Caverna Félix da Cunha		Guaporé/RS	-28.920520	-51.795057	450	Fácies Gramado (Rocha Ígnea, vulcânica, Litotipo Basalto)	Sim – cones pendentes (inferior a 10 cm), coralóides, deposito do tipo talus, estalagmite circular	Gotejamento interno nas fissuras, presença de queda d'água na boca (perene)	Morcegos, presença de guano	Sim, líticos em superfície (05 peças identificadas). Tradição Umbu/Humaitá. Não cadastrado	Não	Visitada eventualmente pela comunidade
Sítio Abrigo Zeni	023320.00001.43.07864	Fagundes Varela/RS	-28,933379	-51,781447	200	Fácies Gramado (Rocha Ígnea, vulcânica, Litotipo Basalto)	Sim – coralóides	Gotejamento interno nas fissuras, na base de calha de drenagem recebe águas externas, presença de queda d'água na boca (perene)	Veado, cachorro doméstico	Sim (escavado – UNISC) – caçador-coletor, Tradição Umbu e cerâmico, Tradição Taquara	Sim, muro de pedras	Impactada pela construção da PCH Linha Emília e gravemente impactado pela enchente de 2023 que recobriu a cavidade de lama
Caverna dos Ascoli		Dois Lajeados /RS	-28.954656	-51.852244	600	Fácies Gramado a 119 m transição com Fácies Caxias	Sim – coraloides, cortina	Gotejamento interno nas fissuras, pequeno fluxo de drenagem ativo, presença de queda d'água na boca (perene)	Morcegos, presença de guano, urubus, fezes de bovinos no primeiro salão	Sim, líticos em superfície . Tradição Umbu/Humaitá. Não cadastrado	Sim, manejo de gado, presença de muros de pedra (isolamento da zona afótica)	Visitada eventualmente pela comunidade
Toca do Tigre		Dois Lajeados/RS	-28.973713	-51.786654	350	Fácies Gramado (Rocha Ígnea, vulcânica, Litotipo Basalto)	Sim – coralóides, carbonatos no piso	Gotejamento interno nas fissuras, presença de queda d'água na boca (sazonal)	Tamanduá mirim, urubu, dentes molares de herbívoros, mandíbulas e vértebras não identificadas	Não	Sim, vias de escalada esportiva	Visitada eventualmente pela comunidade, algumas pichações

Caverna Três Pinheiros		Dois Lajeados/RS	-29.001721	-51.815404	500	Fácies Gramado a 113 m transição com Fácies Caxias	Sim – coraloides	Gotejamento interno nas fissuras, presença de queda d'água na boca (perene)	Morcegos, presença de guano, aracnídeos, opilião azul (troglófilos), esterco bovino	Sim, lítico em superfície. Tradição Umbu/Humaitá. Não cadastrado	Construção de muro de pedras na boca (bloqueando a zona afótica), manejo de gado	Utilizado para manejo de gado
Gruta Selvagem	006255.00046.43.22806	Veranópolis/RS	-28,998375	-51,543195	400	Fácies Gramado a 534 m transição com Fácies Caxias	Sim – Coralóides, estalagmites, cortinas, coluna	Gotejamento interno nas fissuras, lago eventual formado pelas precipitações que inundaram a caverna em evento recente (2024), presença de queda d'água na boca (perene)	Morcegos, presença de guano, mariposas, aranhas, grilos (troglófilos)	Sim. Sítio arqueológico Caverna Indígena de Veranópolis, material resgatado emergencialmente pela CUME Projetos, 2024	Sim, uso turístico.	Visitada pela comunidade. Entorno impactado devido aos eventos de inundações e desmoronamentos ocorridos no RS em 2024
Caverna Lajeadinho		Veranópolis/RS	-29,029434	-51.602052	500	Fácies Gramado a 147 m transição com Fácies Caxias	Sim – Coralóides	Gotejamento interno nas fissuras, lago perene, presença de queda d'água na boca (perene)	Morcegos, presença de guano, aranhas, grilos (troglófilos)	Não identificado	Visitação e uso turístico	Antigo proprietário realizou escavações na parte interna, removeu blocos da entrada e aplanou parte do salão.
Grutas Franceschina	019709.00002.43.12385	Monte Belo do Sul/RS	-29,118971	-51,680691	230	Fácies Gramado (Rocha Ígnea, vulcânica, Litotipo Basalto)	Não	Presença de queda d'água na boca (perene)	Morcegos, presença de guano, aranhas e grilos	Não identificado	Sim, uso religioso. Pichações nas paredes.	Visitada pela comunidade
Gruta N. Sra da Uva	019711.00001.43.17251	Santa Tereza/RS	-29,169678	-51,691706	400	Fácies Gramado a 572 m transição com Fácies Caxias	Coraloides, tubular, estalactites, estalagmites, dente de cachorro	Gotejamento interno nas fissuras, lago perene e duto ativo de drenagem, presença de queda d'água na boca (perene)	Morcegos, presença de guano, mariposas, aranhas, grilos (troglófilos) e identificação de troglóbio nas águas do lago perene	Não identificado	Sim, capela com culto à Nossa Senhora da Uva onde ocorrem missas. Uso religioso. Escadaria de pedra e estrutura de visitação na entrada (deck, bancos e banheiros)	Visitada pela comunidade, intervenções no subsolo
Gruta N. Sra de Lourdes	019716.00002.43.17251	Santa Tereza/RS	-29,196339	-51,694128	400	Fácies Gramado (Rocha Ígnea, vulcânica, Litotipo Basalto)	Sim – coraloides e colunas de coraloides, canalículos	Gotejamento interno nas fissuras, presença de queda d'água na boca (sazonal)	Morcegos, presença de guano	Não identificado	Sim, capela com culto à Nossa Senhora de Lourdes onde ocorrem missas. Uso religioso. Escadaria de acesso e estrutura de visitação na entrada (deck, bancos e banheiros)	Visitada pela comunidade

Figure 3: *Cavities covered in the research.*

4. Discussão

Hipótese sobre a gênese das cavernas basais

As cavidades pesquisadas estão na Formação Serra Geral (FSG), composta por derrames vulcânicos com basaltos e andesitos na base e riolitos na parte superior (Waichel et.al. 2007). Segundo Haag et al. (2016), essas cavidades ocorrem no contato entre basaltos (fácies Gramado) e riolitos (fácies Caxias). A hipótese de Betella et al. (2016) sugere que essas cavidades se formaram devido ao contraste entre o riolito pouco alterado e a brecha vulcânica basáltica alterada. Espeleotemas silicosos e coralóides indicam que as cavidades estavam preenchidas por águas meteóricas antes da formação dos vales profundos. estes autores excluem imediatamente a formação da cavidade: dissolução da rocha, fraturamento do maciço, ação de águas correntes (subterrâneas ou superficiais), colapso do litotipo inferior ou ação antrópica.

A ação das águas nas cavernas basais: pensando eventos epigênicos

- Surgência e ressurgência: as cavidades em geral encontram-se

na encosta de vales bastante encaixados e íngremes, na parte superior dos declives, em áreas aplanadas é comum observar acúmulos de águas perenes denominadas "banhados". Tratam-se de águas coletadas através de cargas pluviais que podem ou não formar corpos hídricos vultosos e visíveis, entretanto, compõem elemento da drenagem local. Ao longo dos trabalhos de campo, percebeu-se que tais reservas hídricas de superfície estão, por vezes associados às cavidades em estudo. Na falésia da Toca do Tigre, ao lado desta, observam-se dutos de surgência que vem conduzindo a água da parte alta para a cota mais baixa, em meio as rochas basálticas, onde é evidente processo erosivo.

- Espeleotemas em formação: é possível evidenciar em diversos pontos associados às fraturas da rocha, onde há gotejamento de água constante, que os espeleotemas se encontram em plena formação. Em função dos eventos recentes de inundações, ocorridos em maio e abril de 2024 no Rio Grande do Sul, foi possível observar o carreamento de minerais, através de água bastante turva vertendo por meio de um "pinga" dentro de uma das cavidades (N.Sra. da Uva). Foi possível identificar a sujidade da água uma vez que no local se encontra um recipiente de vidro coletor, em geral a água é limpa, no entanto, estava barrenta após os eventos que causaram inclusive desmoronamentos na região da Serra.
- Antigos dutos: em algumas das cavidades (Gruta Selvagem, N. Sra. da Uva, Gruta do Seminário, Ascoli, Priori, Lajeadinho, Toca do Tigre, N.Sra. de Lourdes, Três Pinheiros) foi possível observar antigos dutos d'água com espeleotemas testemunhos, em todas as suas bordas, que indicam fluxo de água contínuo em momento pretérito. Nestes dutos também foi possível observar que o solo apresenta características de ondas causadas por fluxos de água.
- Reservas hídricas dentro das cavidades: nas cavidades Lajeadinho, Seminário e N. Sra. da Uva, observou-se a presença de lagos perenes dentro das cavidades em zonas afóticas. Esta última, possui um lago de boas proporções localizado ao final da cavidade, a lama no entorno deste demonstra fluxo hídrico. Nas superfícies destes lagos encontra-se uma camada de biofilme capaz de alimentar e dar suporte para crustáceos, da ordem amphipoda com troglomorfismo e despigmentação. Até o presente momento não há menção à fauna troglóbia nas cavernas basais, tratando-se de uma novidade. A presença de fauna aquática do tipo troglóbia indica uma continuidade milenar da presença de águas subterrâneas neste ambiente.
- Gotejamento e fluxos perenes na boca: As cavidades localizadas nas vertentes de vales encaixados e próximas às drenagens apresentam fluxos de água perenes na entrada. Em cavernas onde a boca tem uma inflexão para o interior, ocorre a deposição de material transportado que se acumula no piso e nivela a superfície. Nas cavidades sem essa característica, o chão exibe traçados antigos de fluxos de água, com blocos expostos e superfícies irregulares. Em 2024, um evento de chuvas intensas resultou no acúmulo de mais de 20 cm de sedimentos na Gruta Selvagem, em Veranópolis, demonstrando que o local canaliza um grande fluxo d'água e solo saturado.

Tais evidências levantam algumas reflexões sobre a participação das águas nos processos de formação destas cavidades:

Os derramamentos basais de espessura variada têm baixa permeabilidade, o que faz com que as águas pluviais se acumulem em áreas alagadas e, eventualmente, drenem para os vales em direção aos rios, funcionando como um aquífero livre (Goetten, 2017). A região é dominada pelo Sistema Aquífero Serra Geral (SARG), caracterizada como um sistema vulcânico fraturado e heterogêneo. Esse processo contínuo de transferência contribui para a formação constante de falésias e vales encaixados, especialmente acelerado durante eventos de intensa.

Observando os dutos abandonados e o perfil das bocas das cavidades estudadas, onde a ruptura é abrupta tanto no teto quanto no chão, levanta-se a possibilidade destas terem sido, no passado, áreas eclusas com acumulo e até mesmo fluxo de águas. Estas águas "confinadas" estariam, por sua vez, aumentando a extensão da cavidade, formando dutos e espeleotemas, bem como em atividade de drenagem via brechas nas rochas basálticas.

Em virtude do dinamismo contínuo nos vales encaixados supõem-se que desmoronamentos das sucessivas camadas basálticas expuseram estas reservas hídricas que estavam eclusas, formando grande parte das cavernas basais. Apesar de terem perdido tais reservas d'água, algumas cavidades ainda apresentam resquícios de lagos em seu interior.

sustentação das águas subterrâneas como elemento importante e marcador deste sistema hídrico, que perpassa as rochas basálticas percolando pelas brechas e formando reservas.

As cavernas basais tendem a estar entre as últimas camadas de derrame de lava, recebendo primordialmente as águas que drenam da superfície, estas podem ultrapassar até centenas de metros de desnível pelas fissuras dos derrames, com distintos volumes e velocidades antes de serem lançadas para o aquífero livre. Neste processo, erodem e desgastam as camadas de contatos entre derrames, gerando vãos preenchidos ou não por água, que hora se conectam e criam uma rede interligada de drenagem, esta denominada SASG, Sistema Aquífero Serra Geral.

Betela et al. (2016) Abordamos a possibilidade de águas meteóricas na formação das cavernas basais. Complementamos essa hipótese, destacando que as cavernas eram originalmente excluídas e expostas foram por desmoronamentos ao longo da formação dos vales encaixados. Além disso, a ação contínua das águas, drenando pelas brechas, forma espeleotemas, cria novos dutos e sustenta espécies típicas do sistema. Assim, as cavernas básicas atuam como elementos ativos dentro do Sistema Aquífero Serra Geral (SASG).



Figure 4: *1. network of underground water circulation ducts, 2. pillar bearing witness to the wear of the contact between the facies; 3. water percolation in the fracture; 4. coralloid spelothems of large proportions among the easy ones; 5. perennial lake with biofilm; 6. 7. crustaceans with troglomorphism; 8. 10. conical speleothems with active deposition; 9. drips; 11. canaliculi; 12. pipeline sediment deposition after 2024 climate events; 13. inspection of a flooded; 14. verification of abandoned conduit; 15. collapse after a large rainfall event exposing the cavity.*

5. Conclusão

A região da Serra Geral, associada aos litotipos basálticos, possuí grande potencial espeleológico. Em um estudo prospectivo oportunístico, foram identificadas cavidades ainda desconhecidas do ponto de vista acadêmico, algumas destas possuem sítios arqueológicos e raros exemplares faunísticos, o que as coloca dentro do potencial de máxima relevância para preservação. As discussões sobre sua gênese ainda são embrionárias, sobretudo, considerando fatores externos e condições que, se não são propriamente epigenéticas, também podem ser classificadas como orientações singenéticas. Os levantamentos de campo demonstraram que a ação das águas nas cavidades, tanto em tempos pretéritos como atualmente, não podem ser consideradas como eventos desprezíveis, revelando um amplo campo de pesquisa na busca por entender estas relações e à preservação das cavernas basais.

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Exploration and mapping of glacier caves of the Southern Patagonian Ice-sheet, Chile

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Abstract

The Ultima Patagonia 2023 speleological and scientific expedition took place over the months of January to March 2023, targeting glacial caves in temperate maritime glaciers of a little-known sector of the Southern Patagonian Ice sheet. Under the leadership of Centre Terre association, the logistically challenging but ultimately successful exploration of glacier in the Estero Calvo yielded new insights in the location of moulins and glacier margin cavities. The main findings from speleological exploration and survey of various englacial cavities in Glaciers HPS-31 and HPS-35 are described. The value of on-the-fly photogrammetric survey of one glacier margin cavity is demonstrated through the production of a detailed geomorphological map of the glacier bed, while another survey of the glacier surface to aid exploration, using airborne UAV imagery, allowed the identification of moulin-rich zones of the HPS-35 glacier. The survey also allowed rough estimates of annual glacier velocity by image correlation. Simple modelling of HPS-35 using Open Global Glacier Model provided bounds on ice thickness along this glacier's flowline as well as surface velocities in agreement with the field observations.

1. Introduction

The Southern Patagonian Ice sheet (SPI spans over 13 000 km^2 between 48-52 °S latitude and is situated at an altitude range of 800 – 2000 m above sea level (a.s.l.). Maritime glaciers in the Chilean Patagonia transfer precipitation accumulated on the SPI to the Pacific Ocean. Ice movement is governed by the balance of gravitational and friction forces acting on the glaciers themselves (BENN & EVANS, 2010). The temperature distribution in the ice depends on the accumulation and ablation regimes along the glacier flowline during the hydrological year. Most maritime Patagonian glaciers are temperate, meaning that the ice exists at the pressure melting point throughout, and any temperature signal penetrating through the ice is erased from one cold season to the next (CUFFEY & PATERSON, 2010). Extreme amounts of precipitation brought by dominant Westerlies drive ice accumulation rates which reach 14 m water-equivalent on the Andean ridge (SCHWIKOWSKI et al., 2006), values which are among the highest in the world. At the marine terminations on the western rim of the SPI, air temperatures are above melting point almost year-round; this setting is favourable for the development of many landforms linked with ice fusion and diagenesis (SCHAEFFER et al. 2019). Between 2000 and 2018, the SPI has lost an estimated 1750 km^2 corresponding to about 12.6% of its surface area (RIVERA, 2019).

In the ablation area of these glaciers, fracture networks in ice guide the development of hydrographic networks of supraglacial as well as englacial streams which route melt water (SHREVE et al., 1972). The organisation of subglacial conduits, especially those developed at the interface between glacier and bedrock modulate the flow velocity of many glaciers worldwide (HEWITT, 2013). Since the permeability of ice is extremely low, transport of melt water through a glacier to its outlet follows pre-existing fracture sets (LLIBOUTRY, 1996; GULLEY et al, 2009). The organisation of the sub- and englacial stream networks evolves throughout the hydrological year. During the melt season, increasing discharge enlarges the sub- and englacial conduits and evacuate melt water through an increasingly channelised network at the glacier base, acting somewhat like a lubricant and modulating glacier base velocity (MOON et al, 2014; CHURCH et al. 2020). Diurnal discharge peaks tend to occur at day's end (HUBBARD et al., 1995).

The exploration and assessment of englacial cave morphology in the SPI were carried out on land-terminating glaciers Tyndall, Petito Moreno, and Ameghino, among others (BADINO et al., 2001, PICCINI et al., 2013). The Ultima Patagonia 2019 project targeted the marine-terminating Tempanos glacier (MAIRE et al., 2022), but other marine-terminating glaciers where supraglacial streams and pseudo-karstic features could be seen from satellite imagery remained unexplored. For this reason, the Ultima Patagonia 2023 expedition to the glaciers of Estero Calvo targeted several glacier-contact caves.

2. Study site

Several maritime glaciers belonging to the SPI calve directly into the Estero Calvo or terminate near sea level. Of these, the Ultima Patagonia 2023 projected targeted glaciers HPS-31 and HPS-35 where zones of high moulin density were spotted from airborne or satellite imagery (Fig. 1). Both sites lie in the Bernardo O'Higgins National Park.

Glacier HPS-35, centred on 50°42' S 73°35' W had an area of 27 km^2 in 2016 according to Landsat TM/ETM+ observations (MEIER, 2018). The glacier calves directly into a narrow bight off the main Estero Calvo fjord. The glacier catchment has a median altitude of 815 m, but its accumulation area reaches an altitude of 1500 m. To the east, a rocky ridge separates it from neighbouring glacier HPS-34. To the west, the glacier skirts around a cirque into which several glacier margin streams flow. The general flow of ice is from south to north, reaching a sharp bend to the west at altitude 500 m, descending to sea level over a kilometre.

The glacier narrows considerably at this section, going from over 1 km in width to about 300 m.

Glacier HPS-31 has an area of 157 km2 with a median altitude of 1488 m a.s.l., and its accumulation area is mainly located above 2000 m asl. The glacier flows east to west, with a bifurcation at an elevation of 300 m asl. The northern terminus calves into a small bight on the northern shores of Estero Calvo. The southern branch, which was investigated for moulins and marginal caves, terminates about 10 m a.s.l.

Caves were investigated mainly on its western extremity. At the time of exploration, strongly developed melt water channels were visible on the glacier surface. Near its terminus, the glacier narrows from about 800 m to about 250 m. A set of splaying crevasses allows the exploration of glacier margin caves from which several englacial streams issued. The largest of those exhibited a discharge rate estimated at over several cubic metres per second at the time of exploration (mid-afternoon during the warm season), corresponding to a melt water pulse.

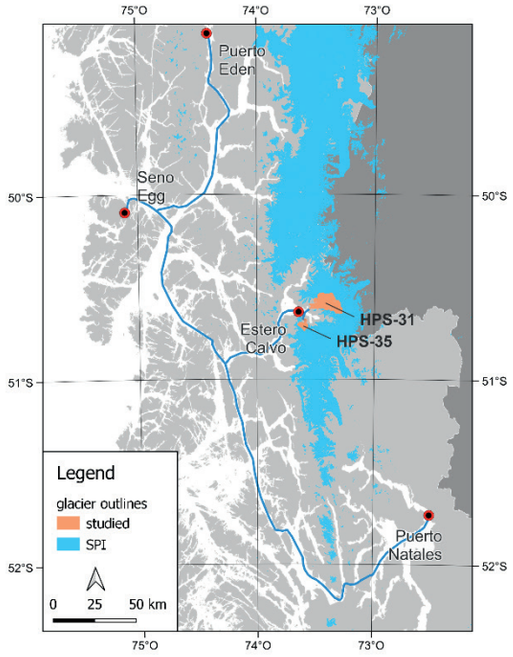


Figure 1: *Location map for the two glacier cave exploration sites and base camps from the Ultima-Patagonia 2023 expedition – glacier outlines from MEIER (2018).*

3. Materials and methods

Exploration of the moulins was carried out based on available satellite imagery prior to the expedition, which identified high moulin density zones on glaciers HPS31 and HPS35. Lightweight campsites on the border of HPS-35 allowed for multi-day explorations of its surface. Topographic surveys were carried out using paperless survey technique (HEEB, 2008), with a combination of DistoX2 and rugged phones. The topographic data were imported into a georeferenced Therion database, which contains all survey data from previous Ultima-Patagonia projects.

Lapis Lazuli cave was surveyed at high resolution using a photogrammetric approach and visual structure-from-motion to construct a 3D model using Agisoft Photoscan software. Using a Nikon-Z5 camera, with a 20 mm fixed focal length lens, and side-mounted Yongnuo-560-III flash equipped with polarising filters, a total of 1058 pictures were assembled into a photogrammetric model. Targets placed in the cave and surveyed independently using standard distoX2 speleological survey allowed the model to be scaled, oriented and georeferenced. The dense point cloud thus generated was refined using a filter to remove statistical outliers.

To facilitate exploration, HPS-35 was mapped by airborne photogrammetry using a Mavic Mini 2 drone in manual mode, following a pre-defined flight path over several sections of the glacier. A total of six flights with 1,077 photos, spanning four days of fair weather, allowed a significant portion of the glacier surface to be mapped. The photogrammetric resulted in an orthophoto and a Digital Elevation Model (DEM) at a vertical resolution of 4 cm per pixel and 20 cm per pixel respectively. The scan was georeferenced using targets on the surrounding fixed bedrock. Those were tagged and referenced using a Garmin field GPS. Mean residual error after georeferencing was 5 m, and the correlation between the two images was increased by matching pairs of reliable markers assumed immobile across the two images, e.g. bedrock and coastline features.

The comparison of available satellite imagery with the generated orthophoto allowed a rough estimate of glacier surface velocity field to be calculated by feature matching between the images. Google Earth imagery was dated to 22/02/2022, while our own was taken between 30/01/2023 and 01/02/2023. The time lapse between the two acquisitions is thus between 342 and 344 days. Salient features like moulin entrances, or crevasse network intersections were and plotted on a GIS software to calculate the displacement vector field.

Glacier thickness for HPS-35 at the exploration site was estimated using the Open Global Glacier Model (OGGM, MAUSSION, 2019.) The model resolves glacier dynamics based on a given glacier outline, a digital elevation model and climate data. Climatological parameters are interpolated along each flow line, with a model for the separation of solid and liquid fraction in precipitation, allowing for a monthly mass balance at each flow-line node (HUGONNET et al., 2021). Modelled glacier surface velocities were compared to the estimates derived from image analysis, while ice thickness allowed for a longitudinal bedrock topographic profile to be calculated.

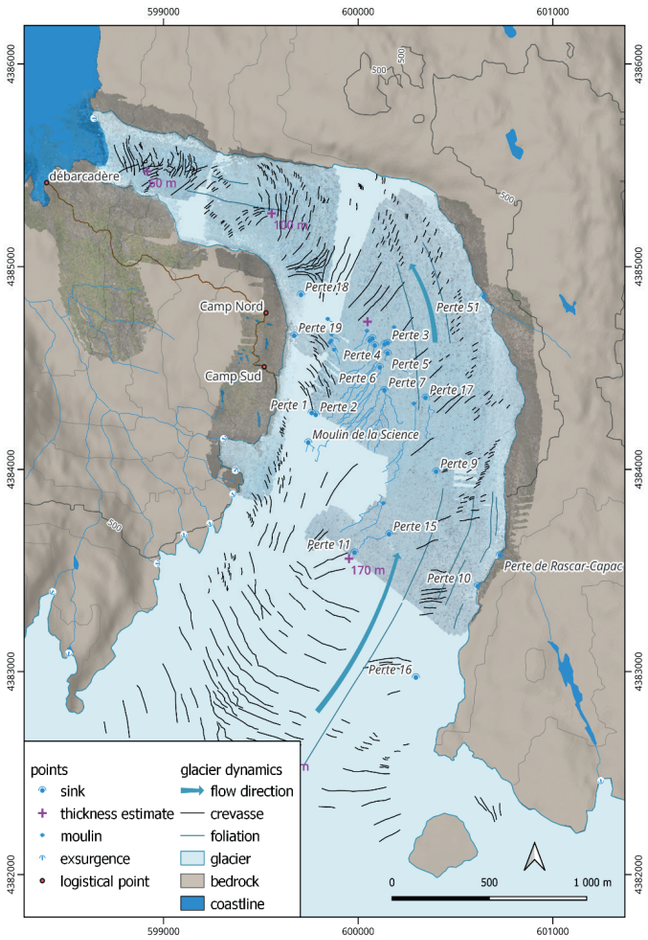


Figure 2: *Overview map of the ablation area of HPS35, highlighting the special distribution of crevasses, high moulin density zones and supraglacial hydrographic networks interpreted from drone-derived orthophotos.*

4. Results

The following description of the moulins follows is a synopsis of the main speleological results of the glacier cavity explorations during the UP2023 expedition. More detail can be found in the post-expedition report (CENTRE TERRE, 2024)

Moulins: On HPS-35, moulin development was favourable between 400 and 500 m a.s.l., and over 20 features were GPS-tagged, with the most promising descended and mapped. Of these, Moulin 7 was mapped to a depth of 75 m. The moulin continues to further depth but is unsafe due to high water conditions. In this region, the modelled ice thickness suggests that another 100 m of depth could be attained before reaching the bedrock. In the immediate vicinity of Moulin 7, other moulins were explored to depths reaching 50 m, but high-water levels or constrictions prevented the team from reaching bedrock. All moulins were found to open at the intersection of fracture planes visible as crevasses or topographic lows on the glacier surface. Downstream of active moulins, we identified moulins no longer fed by an active stream. On the side of HPS-35, three marginal cavities developed at the contact between glacier and bedrock were partially explored. Rascar-Capak sink (65 m deep), and Perte 51 (125 m deep) are related to surface melt water streams which meet HPS-35 and follow the glacier-bedrock interface (Fig. 2).

Crevasses: Together with the field observations, the drone flights allowed the identification of several sets of crevasses. Transverse crevasses, formed under extension are visible wherever the glacier accelerates in the longitudinal axis. They are well developed upstream of the high moulin density zone and they are oriented NW-SE, perpendicular to glacier flow. These extend several hundreds of metres horizontally and often exceed 10 m depth in the DEM. En échelon sets of smaller crevasses are visible at the glacier margin, particularly at the outer edge of the sharp westward bend of HPS-35, as well as around its western edge above the ice-free cirque, where many streams exit the ice mass. The most intense brittle deformation zone of glacier HPS-35 is near its terminus, where groups of crevasses intersect to generate a chaotic topography. The differential stress orientations from basal friction on steep topography as well as a narrowing of the valley combine to break apart the glacier surface in large polygonal blocks.

Glacier movement: the image correlation between the satellite image and the drone-flight orthophoto yielded a surface velocity field typical for a flowing glacier (i.e. with maximum displacement values near the centre of the glacier and lower values near the margins). The velocity estimates vary between 30 and 100 m per year at minimum for the 2022-2023 hydrological year, from the margin to its centre, respectively (Fig. 3). Results from OGGM yield flowline velocities ranging between 30 to 80 m per year in the study area, with an estimate of glacier thickness in the high moulin density zone of near 200 m.

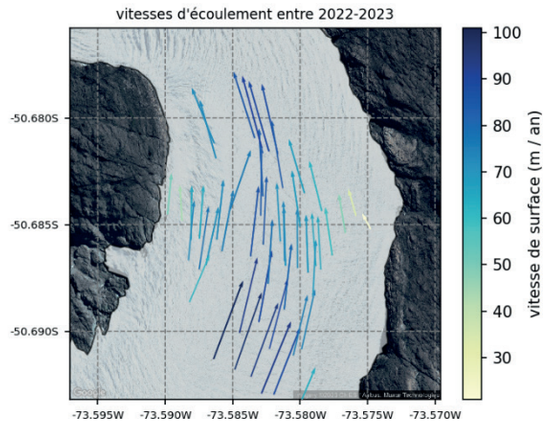


Figure 3: *Glacier displacement field calculated by feature tracking on repeated images (velocities given in m.y-1).*

Glacier bed caves: We use the example of the photogrammetric survey of Lapis Lazuli Cave. Located at the terminus of glacier HPS-31, the cave features two entrances: one is an open pit which is a surface melt water channel, feeding directly the upstream lake. The second is an 8 x 4 m portal at the southern rim of the glacier terminus. The cavity has a horizontal extent of 80 m and features the hallmarks of subglacial drainage: the floor of the cavity features deposits of glacial till and polished surfaces, while the ceiling is overprinted by decimetre-scale scallops. The lakes, whose depth reaches 2 m are dammed by till deposits. At its upstream extremity where the melt water channel allows a shaft of sunlight to penetrate the cave, the cave chamber measures near 20 m in diameter, with a ceiling height of 3 m.

The photogrammetric survey of Lapis Lazuli allowed the reconstruction of a point cloud consisting of about 2 108 points, containing colour information. The pairwise point registration of the model yielded a Root Mean Square error of 0.07 m on a set of 19 reference points. Gaps in the Structure From Motion reconstruction occur on the lake surfaces, as well as clean portions of the cave walls. Most of the cavity walls were coated with fine material which provided reference points for camera alignments and allowed the photogrammetric reconstruction to proceed. Ceiling and floor segmentation allowed digital elevation models of the cave to be quantitatively analysed. Calculation of topographic indicators: slope, hillshade, openness, etc. allowed a blended multiscale relief image to be used as a background image in a vector graphics software to aid the map drawing and the geomorphological interpretation.



Figure 4: *Plan view of the colourised point-cloud generated through the photogrammetric survey of Lapis Lazuli Cave.*

Despite being nearly planar, the cavity ceiling reveals the main glacier flow direction to the SW as strongly developed linear macro--features (Fig. 4), which result from a 5 m amplitude wavy pattern in the ceiling. Most of the cavity volume appears to be formed by erosion and transport of the till underlying the glacier, highlighting the role of subglacial melt water streams as actors in the development of glacial landscapes (ALLEY et al. 1997).

Subglacial deposits: Sedimentary deposits found in Lapis Lazuli Cave are a poorly sorted assemblage of coarse sand to boulder grade typical of glacial till. The accumulation of such materials allowed the formation of the two intermediate lakes (Fig. 5). Interesting deposits of unconsolidated coarse sand to pebble grade material organised in parallel stripes several cm-thick, separated by gaps ranging from 5 to 20 cm were found in the uppermost reaches of the cave (Fig. 6). These linear deposits exceed 2 m in longitudinal extent and directly overly both a fine grain matrix as well as boulders, so they appear to be the last deposit of the visible sequence. They are interpreted as material dropped out of the ice during scallop formation by ablation of the surrounding ice.

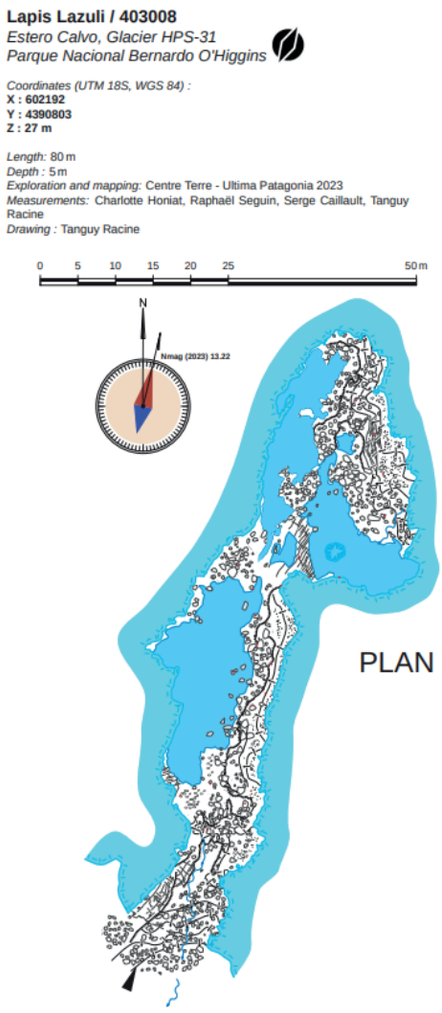


Figure 5: Detailed map of Lapis Lazuli cave.

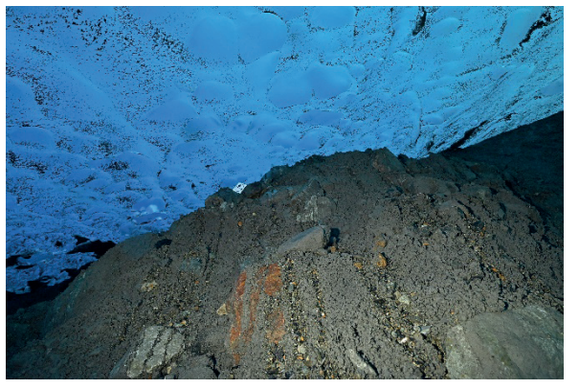


Figure 6: parallel deposits of coarse sand to pebble deposits found at the NE end of Lapis Lazuli Cave. The ceiling exhibits pervasive dm size scallops.

5. Conclusion

The UP2023 expedition successfully reached its objectives of exploring and documenting englacial and subglacial cavities in temperate glaciers in remote and logistically challenging settings. Over the course of ten days, the speleological and scientific team extended the geographical knowledge of glacier marginal caves and moulins in two maritime glaciers of the Southern Patagonian Ice sheet. The value of drone-based or on-the-fly photogrammetric acquisitions for building DEM or cave models was demonstrated through the detailed mapping and geomorphological interpretation of the cave models.

Acknowledgments

We gratefully thank the Centre Terre team and the many sponsors who supported the UP2023 expeditions, particularly the Ministerio de Bienes Nacionales de Chile, the Gobierno Regional de Magallanes y la Antárctica Chilena, Corporación Nacional Forestal, the Asociación Espeleológica de Patagonia, the French Embassy in Chile, the Fédération Française de Spéléologie and MC4, and many more.

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A rare cave developed in silcrete: Inferences for understanding soil silicification.

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Abstract

The PEA-1008 cave is a rare example hosted within a silcrete duricrust, located in western Bahia, Brazil. This study investigates its genesis, emphasizing the silicified lithotypes and their role in shaping the cave. The silcrete host rock, interpreted as a pedogenetic product, presents unique lithological characteristics, including massive chalcedony, laminated opal, and brecciated facies with silica cementation. The cave's formation is attributed to subsidence and collapse of underlying karst. The study highlights the significance of silcrete duricrusts as unique speleological settings and the importance of geological expertise in classifying caves host rocks and understanding cave genesis for the environmental licensing and conservation strategies.

Résumé

La grotte PEA-1008 est un exemple rare situé dans une croûte dure silcrétisée, dans l'ouest de Bahia, au Brésil. Cette étude examine sa genèse, en mettant l'accent sur les lithotypes silicifiés et leur rôle dans la formation de la cavité. La roche hôte silcrétisée, interprétée comme un produit pédogénétique, présente des caractéristiques lithologiques uniques, notamment de la calcédoine massive, de l'opale laminée et des faciès bréchiques avec cimentation de silice. La formation de la grotte est attribuée à l'affaissement et à l'effondrement du karst sous-jacent. L'étude souligne l'importance des croûtes dures silcrétisées en tant que cadres spéléologiques uniques et la nécessité de l'expertise géologique pour classifier les roches hôtes des grottes et comprendre leur genèse dans le cadre des stratégies de conservation et des licences environnementales.

1. Introduction

The PEA-1008 cave, located in western Bahia, lies approximately 60 km northwest of the municipality of Santa Maria da Vitória, Bahia, Brazil.

Regarding the geological context, the studied cave is situated within the São Francisco Craton, near the eastern boundary of the Tocantins Province (ALMEIDA, 1977). Crystalline basement rocks are observed in the drainage areas of the municipality of Correntina and the surroundings of the PEA-1008 cavity, represented by granitoid-gneissic rocks. These rocks belong to the Correntina Gneiss-Migmatite Complex (BAHIA, 2022), which is interpreted as an archean sialic basement, intensely metamorphosed and containing amphibolite fragments.

Overlying the Correntina Complex are the rocks of the Bambuí Group, an epicontinental marine pelite-carbonate sedimentary sequence of Neoproterozoic age (DARDENNE, 1981). In the region, carbonate rocks are characterized by horizontal bedding interbeded with clay-rich layers and marl. There is also occurrences of sedimentary breccias. This assemblage can be correlated with the basal unit of the Bambuí Group, specifically the Sete Lagoas Formation, particularly Facies 1 (BAHIA, 2022). Additionally, according to the Lithological Map of the State of Bahia, terrigenous rocks such as pelites and sandstones of the Serra da Saudade Formation crop out to the east of the cavity.

In the plateaus and elevated terrains, sands and sandy soils derived from the Urucuia Group are predominant. When exposed, the Urucuia Group is represented by continental siliciclastic sediments such as conglomerates, sandstones, and siltstones deposited during the Late Cretaceous in the homonymous sub-basin located in the central-northern portion of the Sanfranciscana Basin (CAMPOS & DARDENNE, 1997). However, in the area surrounding the cavity, this unit does not crop out, with only rare blocks of massive sandstone present.

The absence of significant compressive tectonic activity over the São Francisco Craton cover units has prevented deformation of the layers and the formation of structures commonly found in their deformed counterparts within the Tocantins Province. Nevertheless, the effects of crustal distension, amplified by material removal through erosion, allowed for the formation of vertical joint sets. These joints serve as the primary drivers of preferential dissolution in carbonate caves, with reticulated conduits evident in plan-view maps of the various cavities known in the region.

Geomorphologically, the area is characterized by a small, flat denudational plateau covered by quartzarenic neosols resulting from the erosion of Urucuia Group rocks. In the cave surroundings, a large suffosion doline, approximately 470 m in diameter, is present, where carbonate rocks, silicified rocks, and two small caves are exposed. These features will be described in the results of this study.

The preservation of cavities within pedological units is relatively rare, primarily represented by caves in calcretes and ferricretes. Records of caves in silcretes are extremely scarce worldwide, likely due to the rarity of speleogenesis in these lithologies or the misinterpretation and misclassification of such rocks.

Guided by the objective of understanding the factors influencing the genesis of the PEA-1008 cave, as well as the characteristics of the host rock, this study aims to provide a description of the cavity and its enclosing rock to propose an evolutionary speleogenesis model for this rare cavity.

2. Materials and Methods

Initially, a bibliographic review was conducted on cavities associated with the Urucuia Group in the vicinity of the municipalities of Correntina and Santa Maria da Vitória. After the cave identification process, a field campaign was carried out to perform speleotopographic survey. The survey used digital topography through DistoX and Topodroid application. Map final drawing digitalized in QGIS software.

Given the rarity of this cavity, it may be classified as of maximum relevance. In light of this, rock samples were collected from outcrops external to the cave, both in nearby areas and more distant locations where the same lithology as the cave host rock was exposed.

After selecting the samples of interest, 14 petrographic thin sections were prepared and described using a ZEISS AXIO petrographic microscope, with imaging conducted through the ZEISS ZEN software, version 3.7.

3. Results

The cave has a horizontal projection of 40 meters, consisting of interconnected chambers that result in a surface area of 368 m^2 (Fig. 1).

The entrance is discreet, located at the base of the slope between the substrate and the rocky outcrop at the hilltop. The walls and ceilings of the cavity are predominantly composed of exposed rock, which is locally weathered. Vadose and condensation water were observed, with a few dripping points and humidified walls. The floor is irregular, with many angular blocks of varying scales.

The host rock displays ochre, light brown, and bluish to gray tones in certain locations. Three predominant lithotypes can be identified (Fig. 2). The first and most common type exhibits a massive structure, mycro-crystalline to vitreous texture, and occasional bluish opal geodes (Fig. 2A). The second lithotype is characterized by irregular lamination, with intercalations of chalcedony (ochre) and opal (bluish-gray) (Fig. 2B). The third lithotype occurs as breccias, with decimetric clasts and large vugs partially filled with opal and quartz cement(Fig. 2 C,E and F).

According to the petrographic analysis (Fig. 3), the ochre material likely represents chalcedony (Fig. 3A), a product of carbonate or sandy--clayey soil silicification. The bluish-gray microcrystalline material, which fills vug edges, spaces within the breccia, or botryoidal precipitates, exhibits a fibro-radial internal texture and is interpreted as low-temperature opal (Fig. 3 A and B), cemented or precipitated under vadose conditions.

Finally, the presence of macrocrystalline quartz was confirmed as the final phase of crystallization, filling porosity in geodes and fractures (Fig. 3 B and D).

Inside the cave, a tubular feature was described, entirely silicified, with an empty interior or composed of unidentified disaggregated material (Fig. 2D). This feature was interpreted as a fossil root (rhizolith), possibly silicified during pedogenesis. Another biogenic feature identified in thin section resembles root bioturbation, with a vertical orientation that truncates the primary rock lamination and is partially filled with silica (Fig. 3C).



Figure 1: *Topographic map of PEA-1008 cavity.*

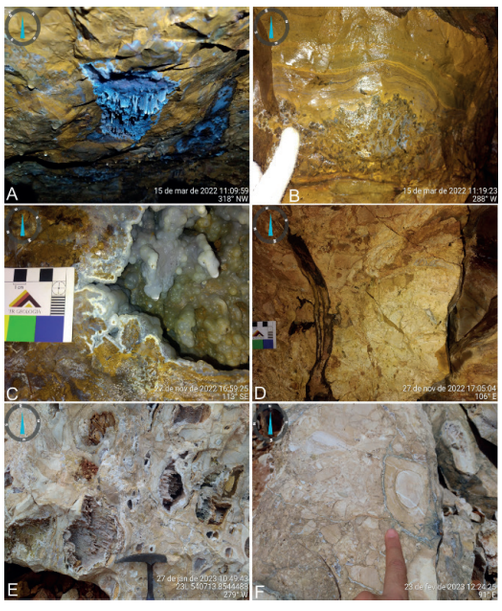


Figure 2: *A-D: Photos of the walls of the PEA-1008 cave. E-F: Photos of rock blocks external to the cave. A – Massive chalcedony lithotype with bluish opal cementation; B – Laminated lithotype with dendritic opal cementation; C – Botryoidal opal filling in geode; D – Tubular feature interpreted as a silicified root; E – Breccia lithotype with vadose cementation in vugs; F – Breccia lithotype resembling beige calcrete from the silicified Caatinga Formation.*

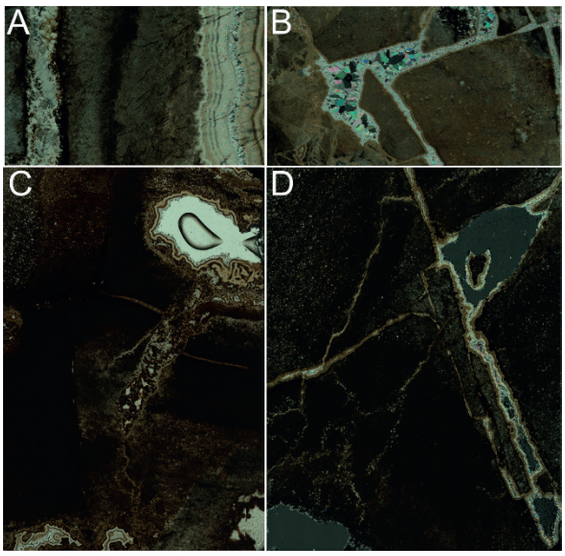


Figure 3: *Photomicrography of samples collected near the PEA-1008. A – Cross-polarized image of laminated lithotype indicating silicification to chalcedony (dark portions) of pre-existing material and cementation by opal and quartz (light portions); B – Breccia lithotype with phases of quartz cementation in spaces between clasts; C – Possible moldic pore of a root; D – Possible cementation of clayey-sandy material.*

4. Discussion

Since the classification of the rock can play a fundamental role in the cave's genesis, as well as enhance its rarity in the geological context, a brief discussion on the origin of the rock is presented in this study.

Silicified levels have previously been described in the Urucuia Group as the result of precipitation processes in a lacustrine environment influenced by desert conditions Basin (CAMPOS & DARDENNE, 1997 ; BARBOSA, 2016). However, in the case of this cavity, this hypothesis was excluded due to the silicified packages consistently being found overlying the carbonates of the Bambuí Group or atop small hills of meta-igneous rocks from the Correntina Complex.

A second possibility would associate the silicification with fault zones, which tend to silicify carbonates. Nevertheless, no evidence of deformed Bambuí Group carbonates has been observed throughout the region of the Urucuia Plateau, extending to the western margin of the São Francisco River.

On the other hand, the occurrence of brecciated facies, very similar to breccia facies of calcretes of the Caatinga Formation, drew attention to a genesis associated with pedogenetic processes or aquifer-related mechanisms.

These process results on duricrust evolution with time, which involves a group of elements with a tendency to cement the soil, resulting in 'caps' that stand out positively in the relief (NASH & MCLAREN, 2007). Precipitation typically occurs in arid to semi-arid climates, with seasonal fluctuations in vadose or phreatic water levels.

In this context, the common occurrence of calcretes in soils developed over carbonates in the state of Bahia, particularly in the region between Santa Maria da Vitória and the banks of the São Francisco River, encouraged us to investigate such occurrences near the cavity. In these areas, only siliceous duricrusts were identified. Silcretes are described as soil deposits hardened due to silica cementation (NASH & ULLYOT, 2007). One possible genesis is due to the silicification of calcretes (THIRY, 1999).

At least three elements are necessary for the formation of these deposits: a silica source, silica transport, and silica deposition (MILNES & THIRY, 1992 ; NASH & ULLYOT, 2007 ; DIXON & MCLAREN, 2009) . The identified silica source in the region is associated with colluvium and quartzarenic neosols derived from the sandstones of the Urucuia Group that cover the area.

The transport of colloidal or dissolved silica in water requires conditions of high pH (~10) (WHITE, 2020). Such conditions could have been achieved due to a combination of carbonate dissolution, which would enrich the water with Ca and Mg, followed by arid conditions that favored calcrete precipitation. Physical-chemical conditions of precipitation would reduce the water's pH, resulting in silica precipitation.

Silcrete deposition is associated with vertical migration, either by capillarity or illuviation, with the latter being more prominent due to evidence of silica precipitated in "stalactite-like" forms. Additionally, the factor of time plays a role in silica precipitation, as the fluid must lose its transport capacity to enable substitution and cementation. These factors were certainly controlled by lithotypes with extremely low permoporosity, such as the dioritic rocks and the carbonates of the Sete Lagoas Formation, which behave as sealant layers in comparisson to the soil.

Another interesting question concerns the genesis of the cave. No features suggesting silcrete dissolution were identified. This process could be explained by extremely aggressive waters with high pH, typically associated with hydrothermal fluids of alkaline magmatic origin, not observed in the geologycal records.

Furthermore, the features resembling speleothems were not formed in the cavern environment, as they occur exclusively in vugs or geodes of the host rock and were also identified in rock blocks outside the cave (Fig. 2 A, C and E).

The cavity exhibits considerable area and volume relative to its horizontal projection. Given the absence of evidence for dissolution or erosive processes, the features described in the cave are solely associated with subsidence or collapse.

The interpretation for the creation of the accommodation space can be explained by the dissolution of carbonates from the Sete Lagoas Formation that support the silcrete crust. This hypothesis is reinforced by the presence of a limestone cave (C2-07F) located 60 meters downstream from the entrance of the PEA-1008 cave.

Thus, the genesis of the cavity is attributed to subsidence resulting from the collapse of an underlying carbonate cave. This combination of factors, along with the rare lithotype, allowed us to interpret this cave as having a rare or unique genesis, with no previously documented records.

5. Conclusion

The PEA-1008 is a rare geological cave hosted within a silcrete duricrust, with a horizontal projection of 40 meters and colourful speleothem-like features occupying pore spaces, likely composed of opal.

The cave's genesis is attributed to subsidence and collapse, linked to underlying karst processes. This interpretation is reinforced by the absence of dissolution features within the silcrete and the unique lithological and structural context of the region.

This study underscores the importance of integrating geological expertise into speleological research to properly classify host rocks and understand cave genesis processes. Such knowledge is crucial not only for scientific purposes but also for environmental licensing and conservation efforts.

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Regional fractures as major controls on caves in sandstone: Insights from Serra de Itaqueri, São Paulo, Brazil

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Abstract

The Serra de Itaqueri (São Paulo state, Brazil) exhibits significant speleological potential regarding caves developed in sandstone. With only 20% of its slope surveyed, 16 cavities were known before this study, highlighting the area’s promise for new discoveries. Previous research has established a solid understanding of the factors controlling the formation and distribution of these caves. They are primarily located in steep slope areas at approximately 800 m elevation, where the Botucatu Formation sandstone outcrops, and are associated with NE and NW lineaments. These structural features influence the cliff formations where the caves are exposed and define the elongation directions of their chambers. Funded through a grant awarded to the EGRIC and EGJ groups, this initiative aimed to enhance cave exploration by integrating expertise and refining survey strategies. Priority areas, based on structural control, were selected, leading to the identification of four new cavities. The recent discovery expanded our knowledge on region’s caves morphologys and related process on their evolution, with the structural control being the one constand despite variations on genesis processeces and general cave characteristics.

Resumo

A Serra de Itaqueri tem grande potencial espeleológico no que diz respeito a cavernas em arenitos. Com apenas 20% de sua encosta prospectada, se tinha conhecimento de 16 cavidades até este estudo, o que indica uma área promissora para novas descobertas. Devido a seguidos estudos realizados na região, já se tem uma boa base dos fatores que controlam a formação e posicionamento das cavidades, sendo eles as áreas de encosta de grande declividade, com as cavidades aparecendo na cota de 800m, onde aflora o arenito da Formação Botucatu, e regiões cos lineamentos NE e NW, responsáveis pelos paredões em que as cavidades estão expostas que também são as direções de elongamento dos salões das cavidades. Tendo em vista a dificuldade de infraestrutura e técnica para a prospecção na Serra, os avanços neste sentido são lentos e são a razão deste projeto, que foi realizado devido a um edital concedido aos grupos EGRIC e EGJ, que se juntaram neste projeto, trocando experiências e alinhando conhecimentos, a prospectar a área após selecionar áreas prioritárias com base nos critérios descritos acima, atestando a utilidade da metodologia, identificando 4 novas cavidades na área, ampliando o conhecimento das cavidades na região, com destaque para o controle estrutural, que é a constante apesar da variação em outras caracteristicas das cavidades.

1. Introduction

Sandstone areas with cavities have significant potential for new cave discoveries, a trend that has been increasing annually with the growing number of studies on these formations. Moreover, understanding the main factors that control their formation or identifying common correlations between these factors and their spatial distribution facilitates targeted investigations and site selection for new prospecting efforts.

The Serra de Itaqueri, located in the western region of São Paulo State, Brazil, is a sandstone ridge composed of rocks from the Botucatu Formation, situated at the margin of the Paraná Basin. This region has been studied for decades by EGRIC (HARDT et al., 2011), which has made significant contributions to understanding the genesis, structural and stratigraphic controls (RIFFEL et al., 2022), and the slope types where caves are found in the Serra (figure 1).

Recently, the Serra de Itaqueri was classified as an independent speleological nucleus (PARRA et al., 2022) within the Rio Claro district of the Serra Geral speleological province (MARTINS et al.,1985). Until last year, 80% of its area remained unprospected, with only 16 known cavities before this study (CUNHA et al., 2022). The area presents significant logistical challenges due to dense vegetation, steep slopes, thorny undergrowth, and restricted access through private properties. Located in the Mata Atlântica rainforest, covered by agricultural areas and fragments of semideciduous seasonal forest (Nalon et al., 2020), with regions where the slope prevents land exploitation by humans.

The main objective of this initiative was to delineate priority areas for prospecting, conduct field investigations and expand our knowledge on the region’s cavities, focousing on the structural control of their morphology and postionin within the Serra de Itaqueri. Additionally, the project aimed to integrate EGRIC and EGJ groups by fostering experience

exchange, methodological alignment, and the establishment of long-term partnerships for future research endeavors.

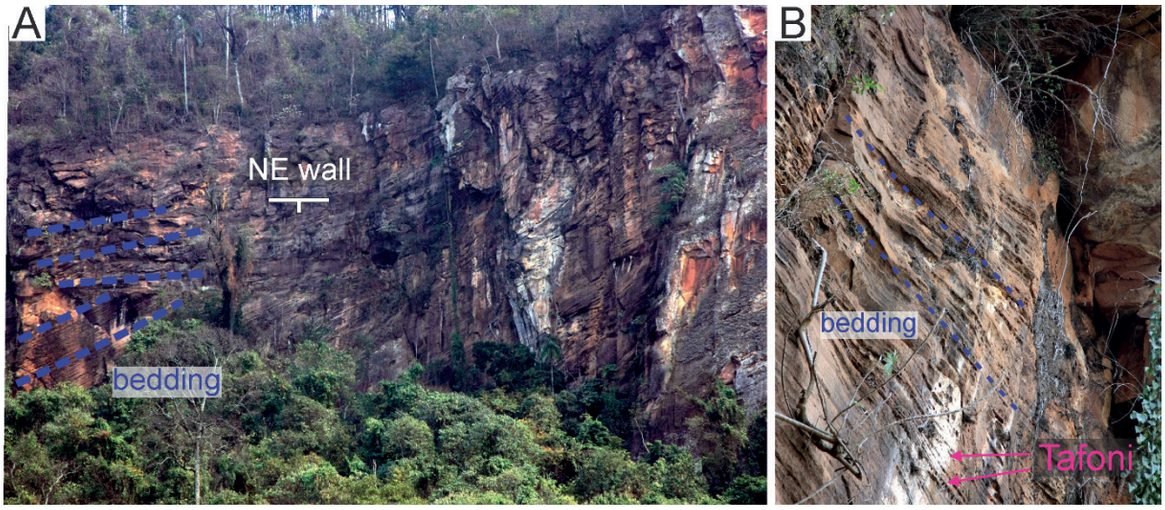


Figure 1: *A) General view of the Serra do Itaqueri slope, with NE and NW fractures controlling the orientations and visible stratigraphical markers of the sandstone; B) A closer look on the wall, with tafoni parallel to bedding.*

2. Materials and methods

The methodology applied in this study consisted of two main stages. The first stage involved pre-fieldwork analysis, including the review and identification of criteria to determine the most suitable areas for cave prospecting. This process resulted in the development of a potential areas map, integrating all relevant factors. The second stage comprised fieldwork, focusing on the prospection of the designated areas, as well as the identification, mapping and describing of newly discovered cavities.

The first part of the study builds upon the theoretical and cartographic framework developed by EGRIC, which has conducted research in the region for decades. Due to extensive investigations, the key factors controlling cave formation in the Serra de Itaqueri are now better understood, like the criteria used to determine the priority areas.

The cuesta relief of the Serra de Itaqueri results from the contact between basaltic flows of the Serra Geral Formation and the underlying sandstones of the Botucatu Formation. This lithological contact, where a resistant rock overlies a more friable substrate, promotes differential erosion, leading to the formation of steep vertical cliffs along the cuesta's cornice and front. It is within these sandstone cliffs, at an altitude of approximately 800 meters above sea level, that the formation and development of caves in sandstone occurs.

Based upon these knowledge, the two first criteria for prospecting new caves are defined: Botucatu Formation and High declivity areas

The irregular outline and abrupt elevation change at the cuesta's cornice create structural landscape variables that influence cave formation and the likelihood of their occurrence. Using information from the interpretation of lineaments from ALOS imagery at scales of 1:100,000,

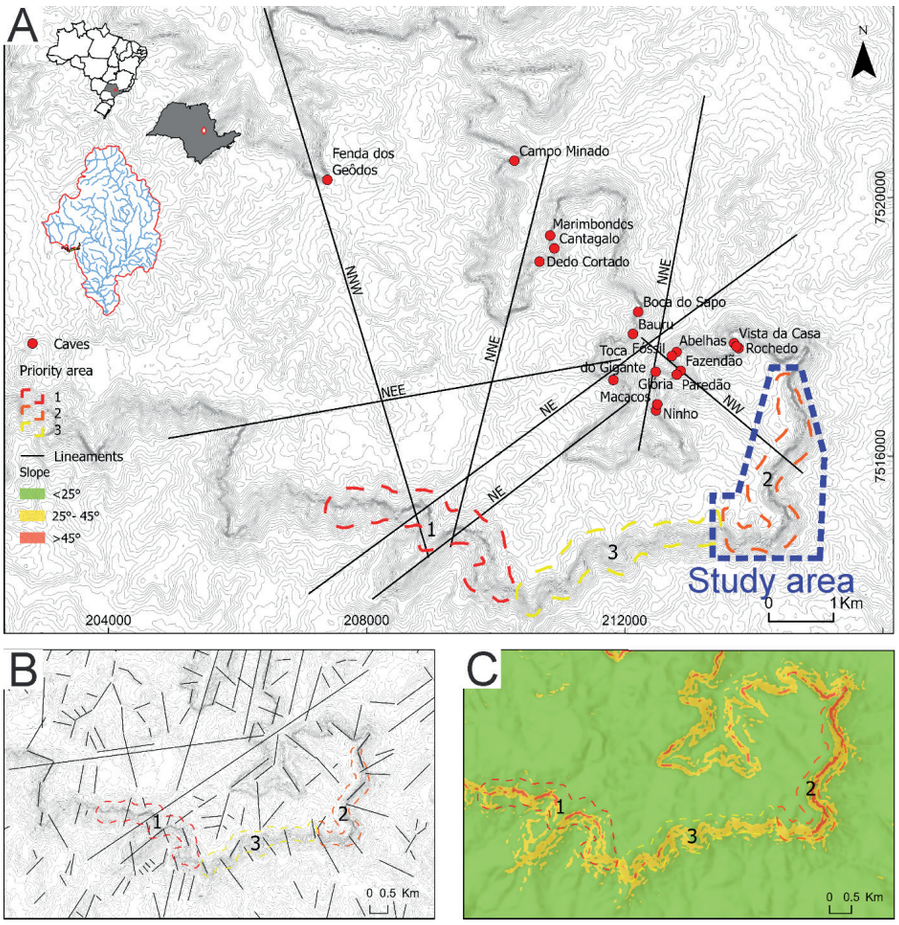


Figure 2: *Priority areas map, with major lineaments represented as well as topography and known caves ; 1 :100.000 lineaments as exemple from previous studies (RIFFEL et al., 2022) ; Slope declivity indicating areas 1 and 2 as the ones with the most exposed sandstone walls.*

3. Results

During fieldwork, significant logistical challenges were encountered in the Serra do Itaqueri, particularly in reaching the cliff face where the region's main known caves are located. In addition to dense and challenging vegetation, the area features steep slopes along the ascent of the Cuesta. These slopes, combined with the presence of numerous fallen blocks, unstable terrain, and deep ravines covered in vegetation, made traversing the landscape particularly difficult.

Despite these challenges, four new cavities were identified (figures 3 and 4), the largest of which has a horizontal projection of approximately 20 meters. All cavities were found under the expected conditions, around the 800m elevation mark, at the base of the sandstone cliff.

The first cavity (figure 3A), named Abrigo da Fenda (Crack Shelter), is located on a NE cliff and develops along a NW joint. It features numerous fallen blocks and a stepped, ascending gradient toward the interior, with a vertical conduit that narrows along the fracture. The cavity exhibits alveoli consistent with bedding planes. The unusual morphology for the region, indicates a crevice cave.

The second identified cavity (figure 3B), named Gruta Leito de Areia (Sand Bed), is situated within a highly pronounced block collapse zone with an amphitheater-like morphology and a small entrance at the top of the blocks. This is a single-chamber cave with an oval NE elongated floor plan and a dome-like ceiling with the soft curved shape marked only by NW joints crossing the cave. The substrate is entirely covered with soft sand and lacks any significant blocks. The current stage of the cave indicates a significant gravitational process, positioning the current cave on top of a boulder that was the original cave ceiling.

The third cavity (figure 4A), Gruta da Armadeira (Armed Spider cave), had already been mapped and is characterized by the intersection of a NE oriented fracture and cross-bedded stratification. This intersection results in zones of higher ceilings with block collapse features. The cave have both gravitational and weathering process with alveoli within the bedding.

The final cavity identified and mapped (figure 4B), Abrigo da Dissolução (Dissolution Shelter), is relatively small but exhibits distinct features such as alveoli, extensive rock weathering marks, and small speleothems. Unlike the other cavities, this one is N-S and E-W structured. The region have opal speleothems with the same morphology registered, which is a indicator of an old cave, despite being the smallest.

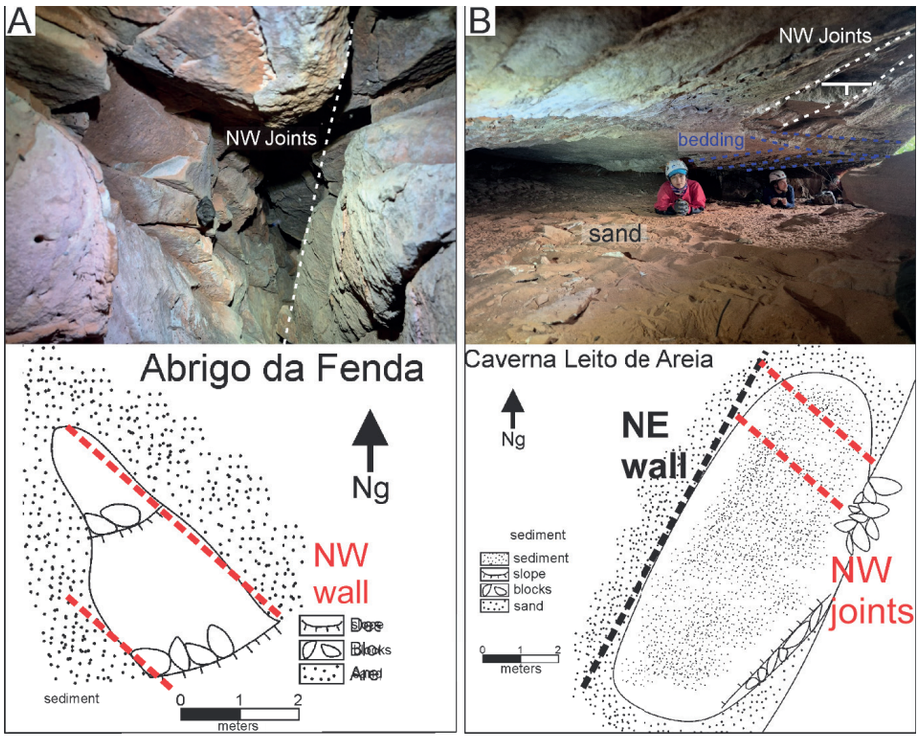


Figure 3: *New caves found at Serra do Itaquery and its most proeminent features and reespective map below. A) Gruta Leito de Areia (Sand bed Cave), with NW joints, visible bedding planes and sand sediment in a horizontal substract; B) Abrigo da Fenda (Crack Shelter) with a visible major NW joint at the cave ceiling, with unstable blocks and a small bat.*

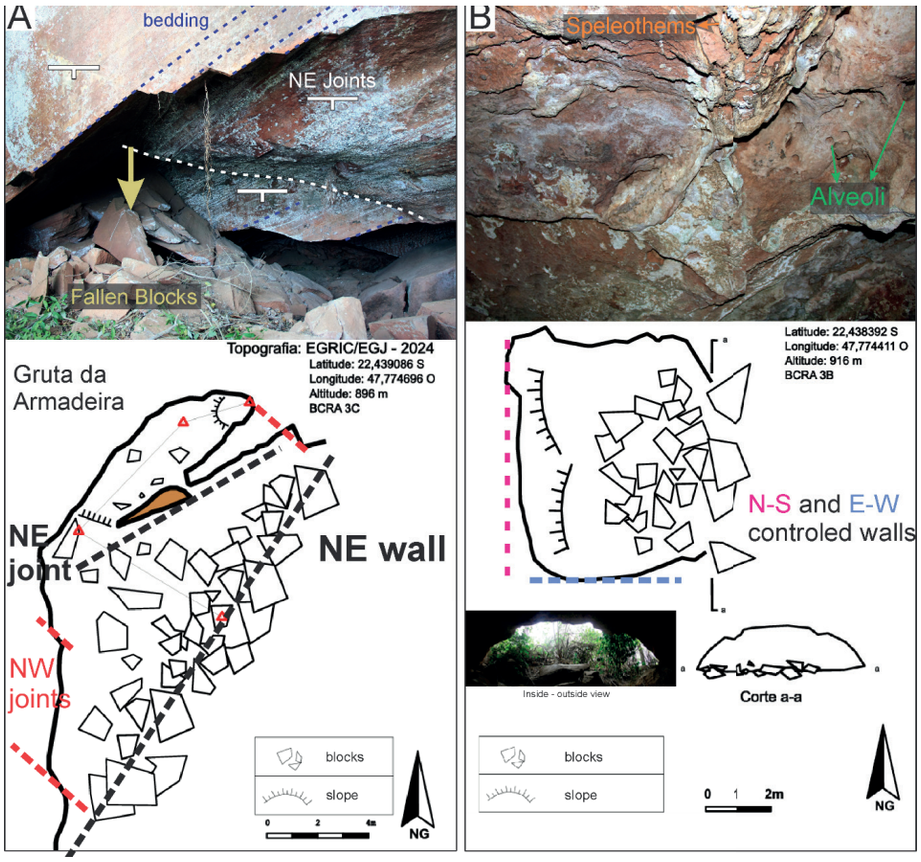


Figure 4: *New caves found at Serra do Itaquery and its most proeminent features and reespective map below. A) Gruta da Armadeira (Armed Spider cave) with the intersection of the inclined bedding and vertical NE joints resulting in fallen blocks, the maps; B) Abrigo da Dissolução (Dissolution Shleter) with speleothems (opal), alveoli and a whethered ceciling.*

4. Discussion

The extensive cliff faces to be surveyed presented several challenges related to the prospection activities. These difficulties included obtaining authorization to enter private rural properties, navigating dense forest in steep terrain, the high presence of venomous animals, and training inexperienced team members in fieldwork.

Regarding the results, the discovery of four new cavities represents a 25% increase in the total number of previously known caves, highlighting the area's significant potential for new findings. The method could still be further enhanced by integrating data through an image-processing software script instead of relying on manual analysis, as was the case in this study.

As for the caves themselves, they all exhibit a common characteristic observed in other caves in the region : a strong structural control, with NE and NW fractured walls as major trends for the caves placement within the landscape. The same directions are also the most common elongation trends for the cavities, and represent most of the identified joints. Besides the fractures, stratigraphic control also has a notable importance for the caves morphology where fracture intersections lead to block collapse, significant sediment accumulation inside the cavities, tafoni features, small conduits aligned with bedding planes, and opal speleothems.

From a social perspective, there was a positive integration among the groups, resulting on significant improvements in leveling and training of the involved team members. These advances have also contributed to safer field operations and facilitated progress in areas with limited access.

5. Conclusion

This study significantly advances the understanding of the Serra de Itaqueri, with particular emphasis on its eastern sector, a region characterized by extensive and dense vegetation. By expanding the scope of previously surveyed areas and integrating newly identified caves and rock shelters into the existing speleological inventory, this research substantially enhances local geological knowledge while contributing to the broader scientific discourse on karstic processes in sandstone formations.

NW and NE lineaments represents the major control for the caves placement and their development, regardless of the process responsible for their genesis.

This research validates the applicability of the criteria used for the systematic investigation of the region, demonstrating its efficacy in identifying and characterizing speleological features within the geological setting. Future efforts will focus on the exploration of Priority Area 1.

Lastly, the Ampliando Rotas grant, administered by the Brazilian Speleological Society (SBE), has had a considerable impact on the EGRIC and EGJ research groups, particularly in strengthening their collaborative efforts and improving infrastructure.

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Alluvium or Alterites in quartzite karst? The case of Monte Cristo Cave (Minas Gerais, Brazil)

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Abstract

The Monte Cristo Cave is a major cavity in the quartzites of the Diamantina region. It is an advanced sinkhole that surface erosion has partially isolated from its feeder basin. As a result, there are a large number of inherited forms. In particular, its western tributary, which is largely disconnected from its feeder, is surprisingly full, with an unusual rhythm that raises questions. For some, this is fluvial sedimentation, while for others it is alteration resulting from the evolution of the walls. A third proposal envisages a rearrangement of these elements through a long succession of flooding and submergence phases in an enclosed environment. The question remains wide open and will require further research.

Résumé

Alluvions ou altérite dans le karst des quartzites : le cas de la grotte du Monte Cristo (Minas Gerais, Brésil). La Grotte du Monte Cristo est une cavité majeure des quartzites de la région de Diamantina. Il s'agit d'une perte évoluée que l'érosion superficielle a partiellement isolée de son bassin d'alimentation. Les formes héritées sont donc très nombreuses. En particulier, son affluent occidental, largement décroché de son alimentation, offre un comblement surprenant, avec une rythmicité inhabituelle qui pose question. Pour certains, il s'agit d'une sédimentation fluviatile alors que pour d'autres, il s'agit d'altérites provenant de l'évolution des parois. Une troisième proposition envisage un réagencement de ces éléments par une longue succession de phases d'inondation et d'ennoiement dans un milieu clos. La question reste largement ouverte et nécessitera la poursuite des recherches.

Resumo

Aluvião ou intemperismo no carste de quartzito: o caso da gruta Monte Cristo (Minas Gerais, Brasil). A gruta de Monte Cristo é uma cavidade notável nos quartzitos da região de Diamantina. Trata-se de um sumidouro antigo que a erosão da superfície a isolou parcialmente de sua área de captação. Como resultado há um grande número de formas herdadas. Em particular, seu afluente ocidental, que está em grande parte desconectado de seu alimentador, está surpreendentemente cheio de sedimentos, com um ritmo incomum que levanta questões. Para alguns, isso é sedimentação fluvial, enquanto para outros é uma alteração resultante da alteração das paredes. Uma terceira proposta discute um rearranjo desses elementos por meio de uma longa sucessão de fases de inundação e submersão em um ambiente fechado. A questão continua sendo estudada, mas ainda permanece em aberto e exigirá mais pesquisas.

1. Introduction

The Serra do Espinhaço is a mountain range that begins in the vicinity of the Quadrilátero Ferrífero, near Belo Horizonte, in the state of Minas Gerais, and extends to the borders of the states of Bahia, Pernambuco, and Piauí, with a general N-S direction. In its southern area it is known as Serra do Espinhaço Meridional (SdEM), representing an orogenic belt that limits the southeast of the São Francisco Craton and extends for about 300 km to Chapada Diamantina in Bahia [AUGUSTIN et al., 2014]. One of its fundamental characteristics is the occurrence of quartzite outcrops, which form a set of mountains interspersed by relatively flat, sandy planation surfaces [SAADI, 1995], associated with a high-altitude tropical climate, important springs, and preserved vegetation. In this environment, an unconventional karst is formed, with morphologies mainly of exokarst, such as poljes, kamenitzas, and limestone pavements (lapias), as well as several cavities, such as the Lapa Santa and Furna do Crioulo caves in Felício dos Santos, and the Salitre, Tromba d'Anta, and Monte Cristo caves in Diamantina, both in the state of Minas Gerais.

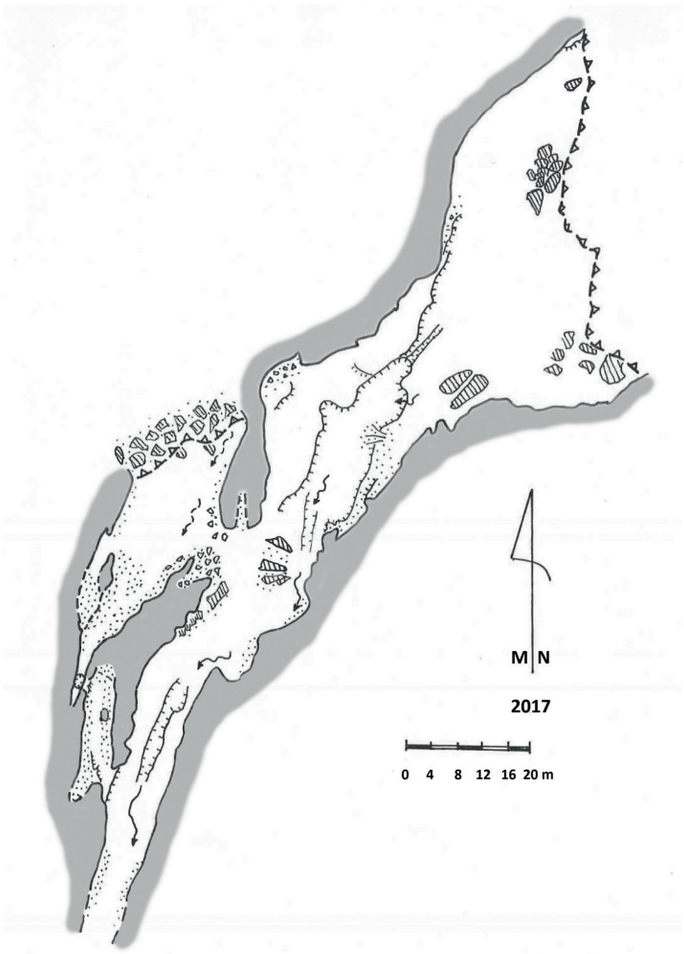


Figure 1: *Monte Cristo Cave survey.*

The formation of the karst environment, whether in classic, carbonate, or non-traditional lithologies, such as sandstones, itabirites, or quartzites, among others, has already been addressed by several authors [EK, 1987; YOUNG & YOUNG, 1992; WILLEMS 2002; RODET, 2014] and is associated with genetic processes rather than with rocks or simply with morphology. Regardless of the rock of origin, it is possible to form karst morphologies in isolation or as a set generating a karst system. Therefore, there needs to be a conjunction of geochemical processes, transforming the rock into saprolite, and hydrodynamic processes, eroding this newly formed particulate material, leaving empty spaces, forming small conduits to large chambers [VASCONCELOS, 2014].

2. Morphological context



Figure 2: *Tsingy on the little hill of Monte Cristo Cave.*



Figure 3: *deep weathering of the main gallery walls.*

South of the town of Diamantina, develops the Monte Cristo Cave (Fig. 1), a major cavity in this sector of the SdEM. It is located in a small quartzite massif with a spectacular surface morphology (Fig. 2). It is a sinkhole traversed by a small watercourse that has lost most of its catchment area due to a superficial piracy by enlargement of the local drained valley (Ribeirão do Inferno). This is particularly true of the western tributary, which has lost its catchment area and drainage, which is now limited to strictly local rainfall. Around 250 m of variable-section conduits have been explored in the cave, ranging from drains that force people to crawl to mega-galleries almost 10 m high and up to 20 m wide. It comprises a highly advanced main gallery 140 m long with a putting out of level of over 30 m. Its very wide entrance porch is the result of the coalescence of at least three axes of introduction, bringing the width to more than fifty metres. The gallery, with its heavily weathered walls (Fig. 3), gradually becomes narrower (around 25 m wide), and about a hundred metres from the entrance, it is only around ten metres wide. At this point, the slope accelerates, creating torrential erosion patterns on the ground. At the bottom, the slope decreases sharply, the drain is reduced to a few metres wide and the roof lowers, leaving no space for a human body (Fig. 4). However, a slight breeze underlines the probability that water will reach an exit point.



Figure 4: *low roof at the end of the main gallery.*

Fifteen metres or so before the final pinch, on the right wall, a small passage opens up 3 m above ground level, giving access to a parallel drain, heavily clogged with soft filling, extending for almost 70 m of drain. Upstream, a large boulder chute obstructs the gallery, leading to the outside. Phytolith soil samples were taken in this gallery [CHUENG et al., 2023]. The morphological contrast between the main gallery, which is very wide and high, and this secondary gallery is significant. The vault of the secondary gallery is criss-crossed with waffered joints, the result of weathering (Fig. 5).



Figure 5: *waffered joints on the roof of the secondary gallery.*

The dominant feature of this small tributary is the slight difference in level of around 3 m between the entrance porch and the junction passage, which remains suspended more than three metres above the main drain, whereas upstream, the two drains are at roughly the same altitude. This suspension indicates that the tributary was inactive for a long time before it joined the main drain, which had continued to develop and sink into the massif. This trepanation is at the origin of the incision allowing passage through the deposit filling in the drain (Fig. 6), which demonstrates its fossilisation, but also its water-soaked filling, facilitating alteration of the walls. This aqueous imbibition breathes according to the seasons and this respiration is inscribed in the contact with the vault (Fig. 7).



Figure 6: *perfect horizontal sediment complex with its white & black linear banded succession and on the top a black sequence with phytoliths.*

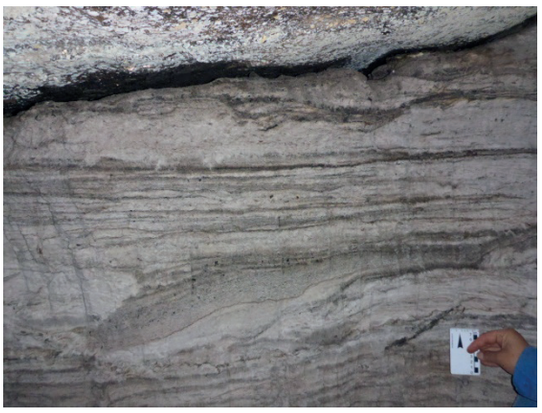


Figure 7: *perfect parallelism of the top of infill elements with the gallery roof, illustrating the sediment breathing due to the humidity variations.*

Upstream, this tributary gallery is closed off by an important scree. By squeezing between the boulders, you can reach a small suspended terrace on the outside, overlooking the slope facing the valley being drained: the tributary no longer receives water from upstream and the water that runs through the drain comes solely from the rain that falls on the small massif over the gallery.

3. Discussion

A particular question is the origin of the loose formations observed in the drains. There are two opposing analyses. If they are alluvial sediments, they are old because they predate the isolation of the gallery, which is the result of a long evolution of the valley slopes (Fig. 8). If it is the result of deep alteration of the quartzite bedrock, a very long phase must also be considered, especially as the physical isolation of the tributary, with no water supply, must have considerably reduced the effectiveness of this process.

Faced with these two concepts, the first considering it to be a sedimentary deposit, the second opting rather for alteration of the host rock, we were unable to reach a clear decision on this origin, since in certain caves in the region a similar distribution can be observed affecting the quartzite host rock (Fig. 9), in particular in cave CAV-0007 at Morro do Pilar [AULER et al., 2015_p.132 & 149].

If we lean towards a sedimentary origin, the systematic succession of a whitish layer topped by a highly repetitive blackish layer would seem to point towards an alternative white/black diet. There is nothing in the landscape to identify distinct sedimentary sources. We must therefore opt for extremely restrictive conditions of introduction, such as those found under cold, periglacial climatic conditions. To envisage such a constraint in a region with a current tropical climate is to take a problematic view of a very remote age. When was the last glacial period in the Serra do Espinhaço?



Figure 8: *deposit aspect in Monte Cristo Cave.*



Figure 9: *wall aspect in the CAV-0007 (after A. Coelho).*

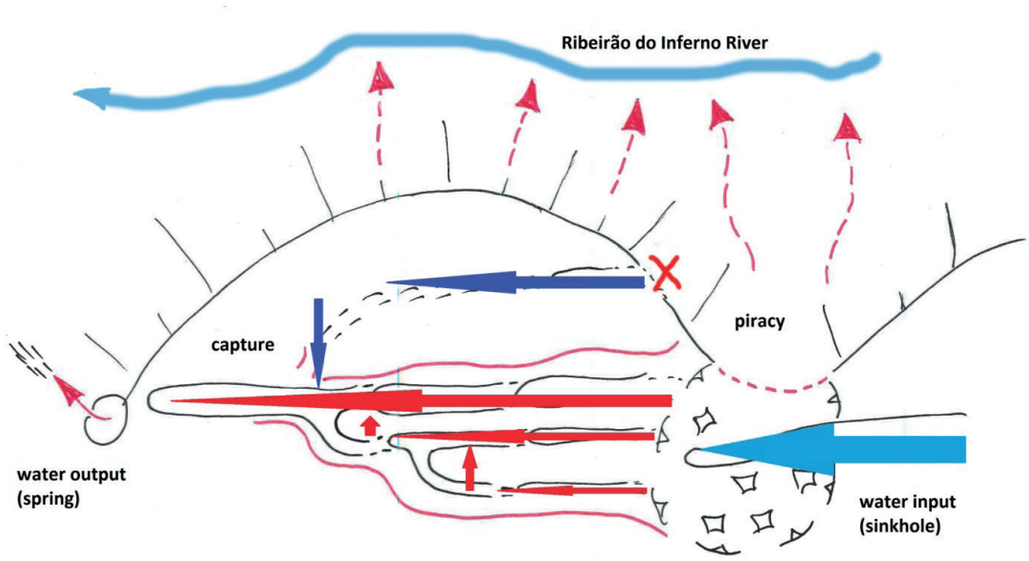


Figure 10: *the Monte Cristo Cave in its context.*

A third approach would be to take into account numerous and repetitive flooding phases, allowing a certain mineral redistribution affecting both the sedimentary deposits and the weathered walls. This dimension of successive phases seems credible in a context of blocked flows, reflected in the organisation of the fine-bedded filling of sandy products that join the vault.

It should be noted that a study of phytoliths collected in the tributary branch of Monte Cristo Cave [Chueng et al., 2023] assigns an age ranging from 4450 y to 550 y to these phytoliths. This latter dating would seem to indicate that the opening up and, consequently, emptying of this environment is historical. It is clear that this dating, which is far too modern, underlines a “biological pollution” of a sedimentary deposit that is obviously much older, for several reasons. Firstly, for geomorphological reasons: the gallery is isolated, suspended in a residual quartzite snag, isolated from an obvious upstream source (Fig. 10). It is difficult to imagine such a major change in such a short space of time in a quartzite

substrate. This suspension of several metres above the main drain highlights 1) the disconnection of the tributary, 2) its separate evolution, 3) its fossilisation, 4) and finally its trepanation by calibration of the main axis, generating the sudden emptying of the tributary. Secondly, quartzite karstification is a slow mechanism that extends over long periods, even in tropical climates with dry seasons.

4. Conclusion

The karstification of quartzite supports is an undeniable fact. Monte Cristo Cave is proof of this. Its complex, long-term evolution is comparable to that of carbonate supports. Certain phases can be identified:

1. the cavity is organised by the coalescence of at least 4 parallel axes, as the drainage sinks and therefore becomes more concentrated. We can see the slide of the water inlet and the over sinking of the bed releasing an 8 m high waterfall, which was abandoned in favour of another almost permanent one. The western gallery does not offer this significant gradient, which means that its evolution is separate and specific, disconnected from the main drainage. It may also be disconnected from its feeder basin (evolution of the relief).
2. the cavity undergoes a long phase of flooding and alteration. It is then filled in and has no functional outlet. This is why stratified fillings are found throughout the underground network, right down to the distal conduit.
3. the distal conduit opens up, allowing hydrodrainage throughout the cavity, with the exception of the western branch. The main cavity is largely free of its filling and captures the upstream part of the intermediate drain. A few stratified elements of the old backfill remain, protected by the morphology of the fast-flowing conduits. The west gallery is still not connected and therefore remains filled in and flooded, or even drowned, at least in its downstream section.
4. The calibration of the downstream part of the main drain, essentially by altering the intermediate wall, eventually causes the partition to give way and releases the liquids from the western gallery, partially clearing the backfill (mini-canyon). The result is the morphology we know today.

Our hypothesis is that the stratified sandy accumulations could illustrate the mineral redistribution of a sedimentary deposit or an alterite complex, induced by a long phase of oscillating flooding before an erosive phase opened up a trench in the sedimentary accumulation.

The question remains open, and new studies are being carried out, and their resolution may shed new light on the karst evolution of quartzite bedrock.

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Análise dimensional, morfológica e paisagística de cavernas siliciclásticas no setor noroeste da Serra do Lenehiro, São João del Rei - MG

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Resumo

Na Serra do Lenheiro, adjacente à cidade de São João del Rei – MG, três cavernas foram avaliadas por seus atributos dimensionais, morfológicos e contexto paisagístico. Foram executadas Topografias convencionais pela acurária *British Cave Research Association*, BCRA-4C, extraindo-se parâmetros espeleométricos. Classificaram-se os padrões morfológicos e planimétricos. Analisaram-se suas inserções paisagísticas, em função dos compartimentos serranos e de condicionantes lito-estruturais. A Gruta do Lajedo apresenta dimensões de destaque em topo serrano, dividida em zona proximal por tálus e distal ao longo de direção de mergulho do acamamento, em eixo de antiforme do topo da serra. A Gruta da Passagem, posiciona-se em compartimento intermediário de vertente serrana, com morfologia curvilínea escalonada por conduto de passagem em declive entre entradas, aproveitando os mergulhos subverticais do quartzito em flanco de antiforme. A Grutinha localiza-se em patamar intrasserrano, sob maciço individualizado, com características mistas entre acomodação de blocos e ampliação de condutos subjacentes em planimetria ramiforme, com porção de salão amplo com duas entradas e porção de condutos distais com piso predominante horizontal. Pelo constatado, há padrão de direção de desenvolvimento geral das cavernas em W-E, acima da altitude de 1.000 m, com maior maturidade para aquela localizada em setor de topo, associada a antiforme.

Abstract

In Serra do Lenheiro, adjacent to the city of São João del Rei – MG, three caves were evaluated for their dimensional, morphological and landscape context attributes. Conventional topographies were performed using the British Cave Research Association, BCRA-4C accuracy, extracting speleometric parameters. Morphological and planimetric patterns were classified. Their landscape insertions were analyzed according to the mountain compartments and litho-structural conditions. Gruta do Lajedo has prominent dimensions on the mountain top, divided into proximal zone by talus and distal zone along the bedding dip direction, on the antiform axis of the mountain top. Gruta da Passagem is located in an intermediate compartment of the mountain slope, with a curvilinear morphology stepped by passage conduit on slope between entrances, taking advantage of the subvertical dips of the quartzite on the antiform flank. The cave is located on an intra-mountainous level, under an individualized massif, with mixed characteristics between accommodation of blocks and expansion of underlying conduits in ramiform planimetry, with portion of large hall with two entrances and portion of distal conduits with a predominantly horizontal floor. Based on the findings, there is a general pattern of development direction of the caves in W-E, above the altitude of 1,000 m, with greater maturity for the one located in the top sector, associated with antiform.

1. Introdução

No Brasil, cavernas em litologia quartzítica, ou siliciclásticas, correspondem ao segundo tipo mais frequente, com 18% do total (CECAV, 2023). Seu potencial é representativo em função das extensos alinhamentos serranos e planálticos expostos, compostos por essa litologia. Uma delas é a Serra do Lenheiro, localizada na cidade de São João del Rei – MG, reconhecida por sua exploração colonial de ouro durante os séculos XVIII e XIX.

Conforme PASSARELLI (2023), o perímetro protetivo da Serra do Lenheiro apresenta 4.867 hectares, incluindo Parque Ecológico Municipal e conjunto de patrimônios natural, histórico e cultural, entre altitudes de 885 m e 1.218 m. É composta por complexo de elevações serranas quartzíticas compartimentadas.

Entre compartimentos do setor noroeste da Serra do Lenheiro, há patamar intrasserano, três cavernas inventariadas por PASSARELLI (2023) foram analisadas por seus atributos dimensionais, morfológicos e paisagísticos. O intuito é avançar nas análises ambientais e embasar o conhecimento em termos do patrimônio conhecido e padrões de ocorrência para futuras prospecções e descobertas espeleológicas.

As cavernas são denominadas de : Gruta do Lajedo, Grutinha e Gruta da Passagem, conforme a Figura 1.

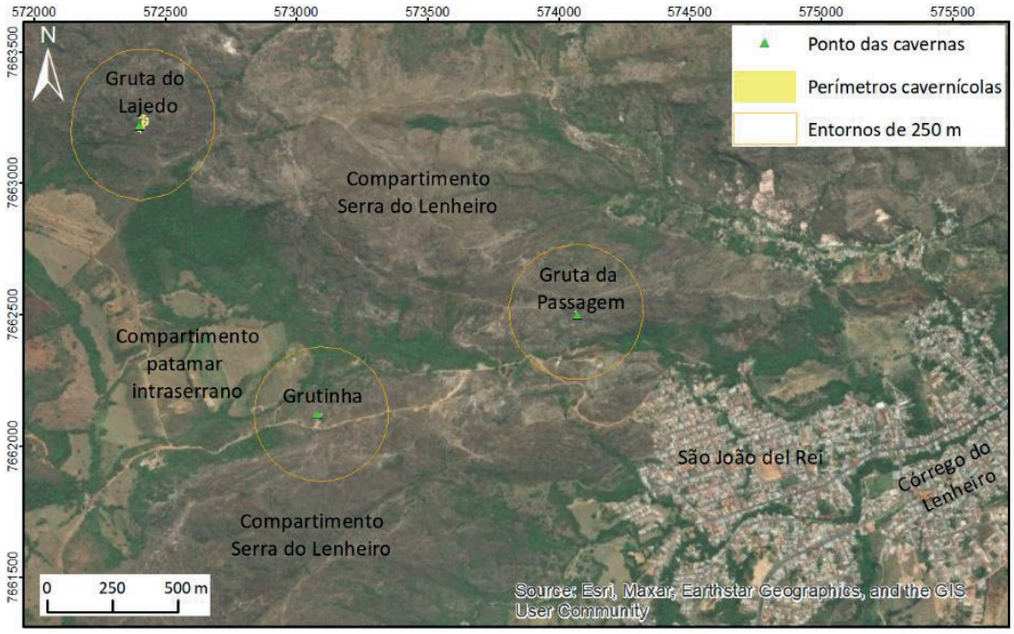


Figura 1: *Inserção das cavernas, em relação aos compartimentos de relevo e à cidade de São João del Rei.*

2. Métodos

Em 13 e 14/06/2024, as cavernas foram topografadas em campo pelo método convencional através de bússola digital magnética e trena a laser com clinômetro, atendendo aos critérios do nível de detalhe do *British Cave Research Association*, BCRA-4C. Os dados foram tratados através dos *softwares* Speleoliti 4.4 e AutoCAD®, chegando aos valores espeleométricos de desenvolvimento linear, projeção horizontal, desnível, área e volume.

Pesquisou-se bibliografia sobre espeleometria de outras cavernas do entorno (serras do Lenheiro e São José) para comparação de expressividade. Interpretação geomorfológica quanto à inserção na paisagem, registros fotográficos e medidas geológicas foram executadas para reconhecimento de controles lito-estruturais.

Com as topografias digitalizadas e concluídas, seus padrões planimétricos, de seções e perfis foram classificadas com base em PALMER (1991 *apud* AULER & PILÓ, 2011). Demais atributos geoespeleológicos como maturidade de atividade hídrica, de sedimentação clástica e química foram considerados. Espacializaram-se os perímetros das cavernas com delimitação de seus entornos de 250 m, conforme estipula a legislação brasileira ao patrimônio espeleológico.

Unificando as avaliações dimensionais, morfológicas e paisagisticas formou-se conclusão do contexto geral de ocorrência e comportamento das três cavernas na condição noroeste da Serra do Lenheiro.

3. Resultados

A Gruta do Lajedo, com 287,75 m de desenvolvimento linear e 3.277,56 m³ de volume, possui dimensões de destaque. Localiza-se em topo serrano, com morfologia de piso em declive para interior e planimetria curvilínea espongiforme. Apresenta amplos salões lenticulares, dividida em zona proximal em tálus e distal ao longo de direção de mergulho de quartzito (90°/50°). Inclui presença de claraboia em forma de dolina de abatimento não convencional.

Há atividade hídrica através de condensação constante e escoamentos intermitentes pluviais. Apresenta sedimentação clástica em suas porções distais expressiva, em pacote métrico com estratificação horizontal a cruzada. Há indícios de fase de acumulação, atualmente em processo de erosão e retrabalhamento. O conjunto e diversidade de coraloides é notável e disseminado em sua porção distal.

A Gruta da Passagem, com 39,46 m de desenvolvimento linear e 115,74 m³ de volume, apresenta planimetria curvilínea ramiforme. Posiciona-se em compartimento intermediário de flanco serrano sul, com morfologia escalonada por ampliação de canalículos, em passagem de declive para interior entre entradas, aproveitando os mergulhos na direção de camada do quartzito (194°/45°) em flanco de antiforme com vergência para W. Não apresenta atividade hídrica aparente ou depósitos clásticos ou químicos representativos.

A Grutinha, com 37,18 m de desenvolvimento linear e 191,12 m³ de volume, apresenta planimetria curvilínea ramiforme. Localiza-se em patamar intrasserrano, sob maciço residual individualizado (localmente denominado « Pedreira da Divisa »), com características mistas entre acomodação de blocos e ampliação de canalículos subjacentes em planimetria ramiforme, com porção de salão amplo principal com duas entradas e porção de condutos distais com piso predominante horizontal. Aparentemente acompanha borda sul de sinclinal na base do compartimento da Serra do Lenheiro. Não apresenta depósitos clásticos ou químicos representativos e sua atividade hídrica se restringe aos aportes pluviais sazonais ocasionais.

Tabela 1: *Principais atributos locacionais e espeleométricos das cavernas analisadas.*

NOME	LITOLOGIA	SIRGAS2000 UTM X	SIRGAS2000 UTM Y	ALT. (m)	PROJEÇÃO HORIZONTAL (m)	DESENVOLVIMENTO LINEAR (m)	DESNÍVEL (m)	ÁREA (m^2)	VOLUME (m^3)	DETALHE DE MAPEAMENTO	INSERÇÃO NO RELEVO	SERRA DE INSERÇÃO
GRUTA DO LAJEDO	Quartzito	572576	7663190	1.187,00	174,65	287,75	13,1	1.295,48	3.277,56	BCRA-4C	Topo serrano	LENHEIRO
GRUTA DA PASSAGEM	Quartzito	574071	7662497	1.077,52	33,98	39,46	8,09	52,37	115,74	BCRA-4C	Vertente serrana	LENHEIRO
GRUTINHA	Quartzito	573083	7662119	1.084,49	33,12	37,18	1,18	66,36	191,12	BCRA-4C	Patamar intrasserrano	LENHEIRO

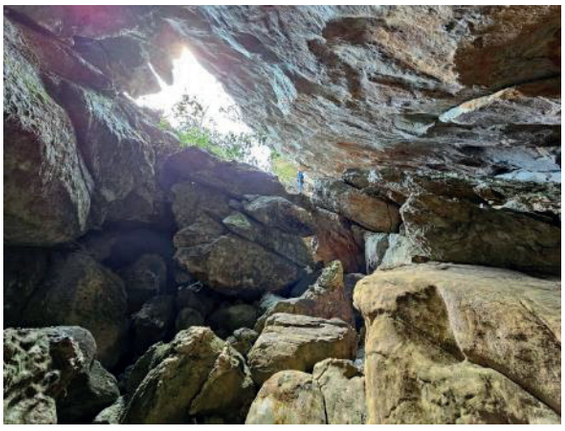


Foto1: *Porção proximal e pórtico de entrada da Gruta do Lajedo, cujo teto apresenta direção e mergulho 90°/50°.*



Foto 2: *Setor distal da Gruta do Lajedo de salão lenticular com teto baixo, acompanhando inclinação de acamamento.*



Foto 3: *Aspecto de seção interna da Gruta da Passagem, com mergulho de 194°/45°.*

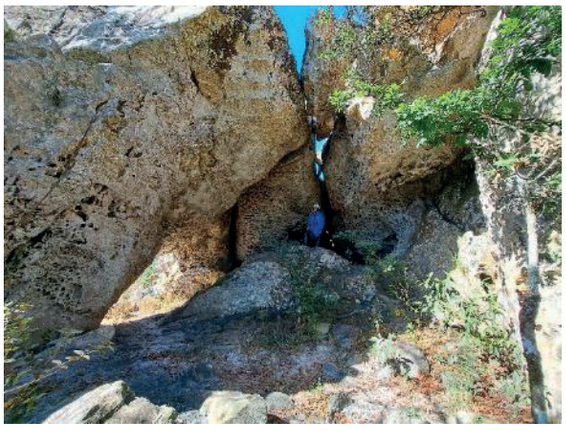


Foto 4: *Vista das entradas da Grutinha. O azimute principal de desenvolvimento é 100°.*

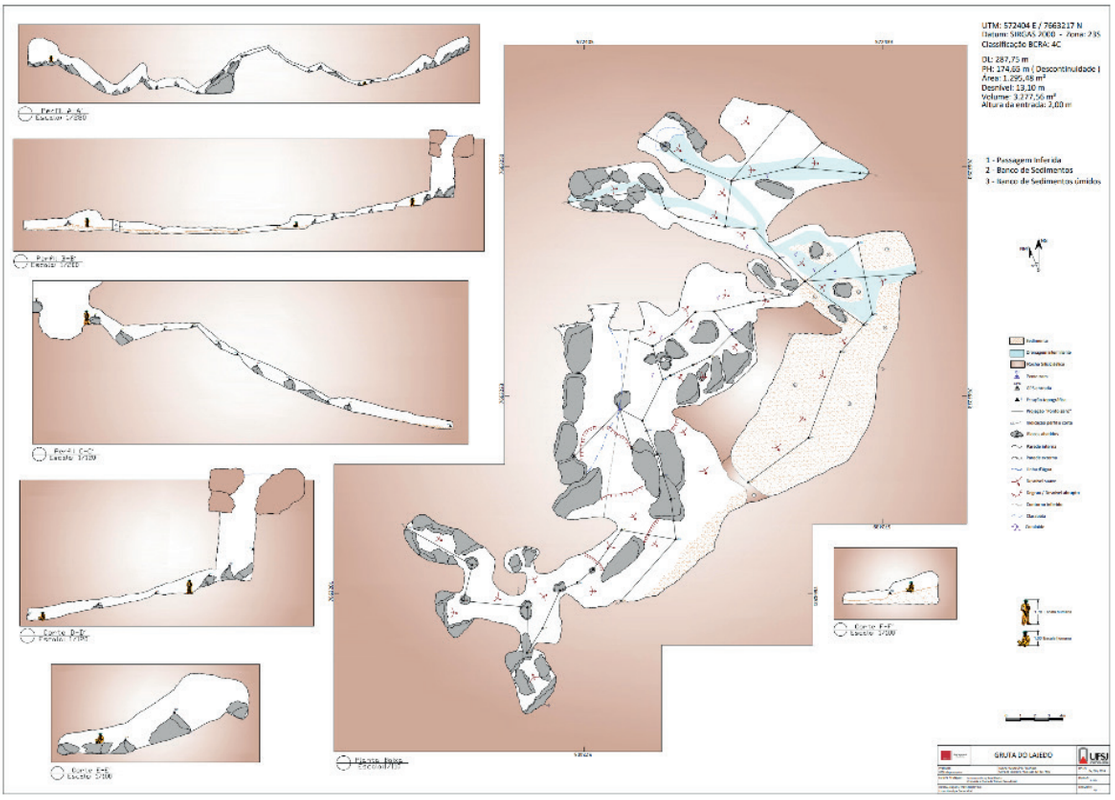


Figura 2: *Mapa topográfico da Gruta do Lajedo.*

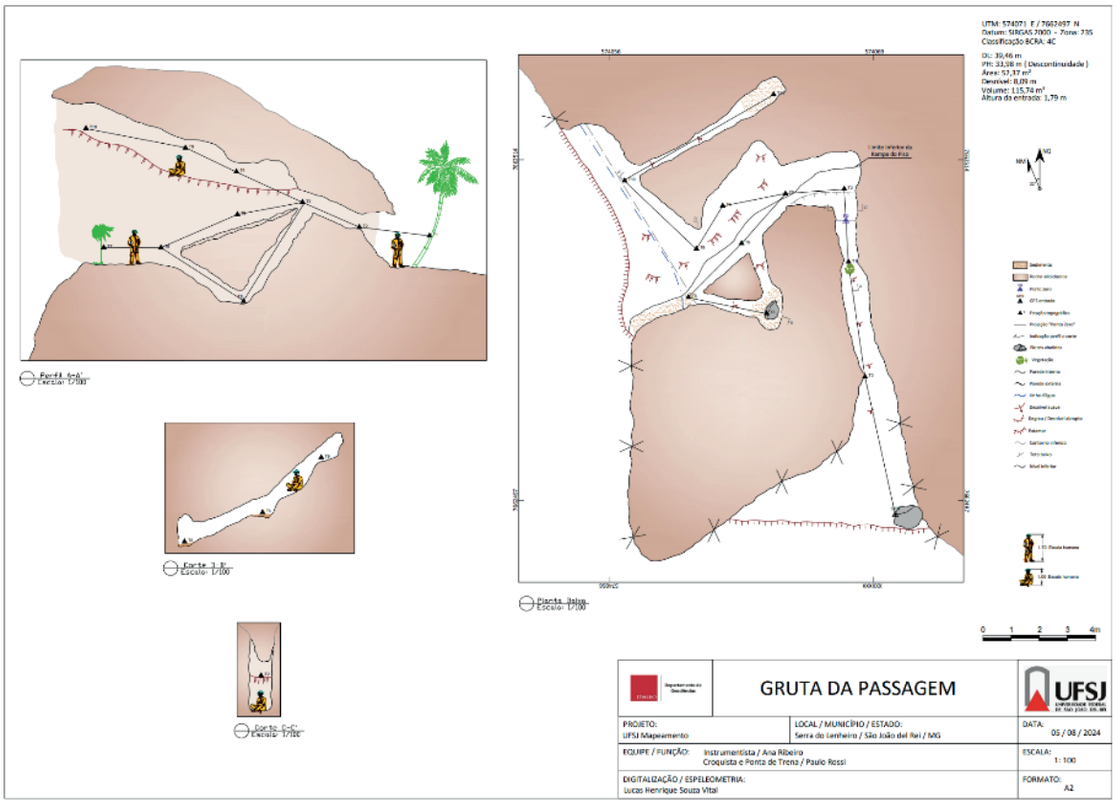


Figura 3: *Mapa topográfico da Gruta da Passagem.*

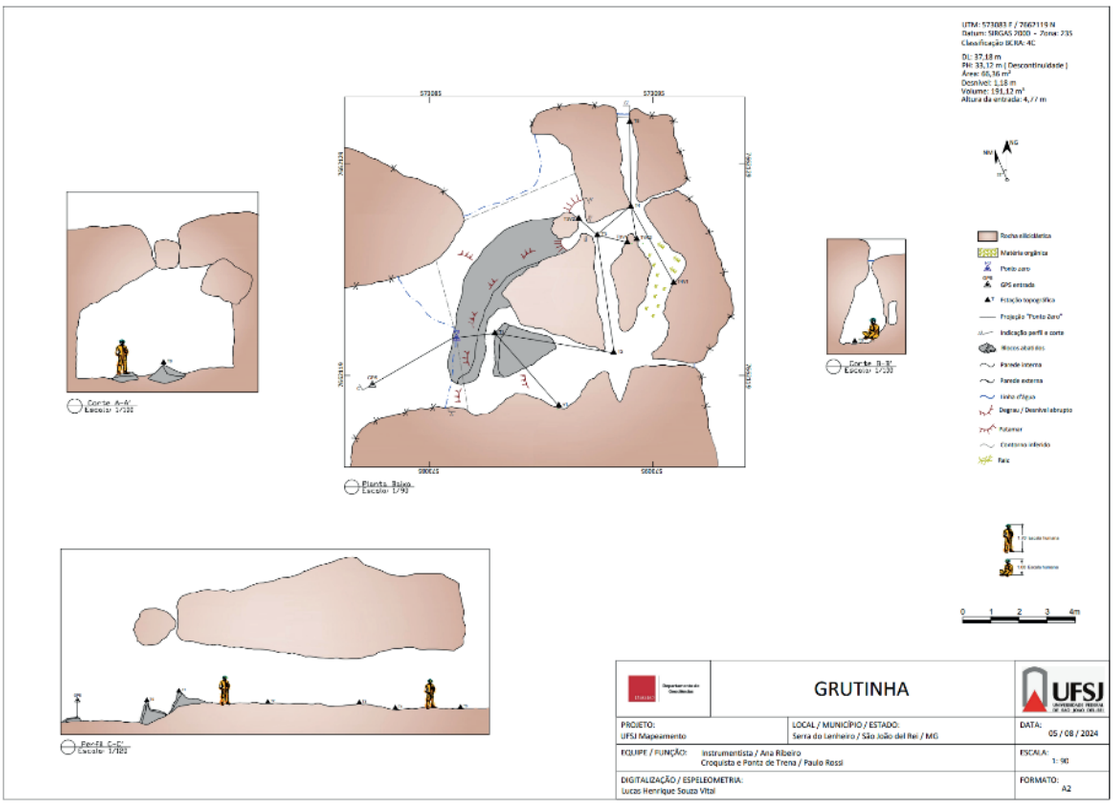


Figura 4: *Mapa topográfico da Grutinha.*

4. Discussão

As cavernas registradas na Serra do Lenheiro ocorrem em cotas altimétricas superiores a 1.000 m. Todas apresentam entradas voltadas para W, correlacionável com direção oposta ao mergulho do quartzito. Especificamente das três localizadas no compartimento Serra das Almas, duas apresentaram espeleometrias semelhantes no intervalo entre 1.070 e 1.090 m, pocionadas em vertente serrana e patamar intrasserano (Gruta da Passagem e Grutinha). Suas planimetrias assumem aproximação pelo padrão curvilíneo ramiforme, apesar das diferenças de controle lito-estrutural. Estes cenários indicam potencial a feições espeleológicas menores a intermediárias.

A Gruta do Lajedo apresentou destaques dimensionais e geoespeleológicos. Sua espeleometria, em comparação com cavernas publicadas no entorno (serras de São José e Lenheiro), apresenta valores máximos, conforme a Tabela 2.

Sua correlação com ampla estrutura antiforme em topo serrano indica condições de potencial maturidade em contextos similares. Ou seja, locais próximos aos topos, cuja energia direta de águas meteóricas, junto a estruturas geológicas maiores, potencialmente geram cavernas maiores.

Por fim, nota-se que nos frontes dos compartimentos serranos, voltados para oeste, há potencial para a formação de abrigos, em função do desmonte erosivo. Tal interpretação é corroborada pela existência de abrigos visíveis a distância, além de dois sítios com pinturas rupestres no sopé do Morro dos Três Pontões (PASSARELLI, 2023). Soma-se, a recorrência de falhas e fraturas, exposições rochosas escarpadas verticais, vertentes declivosas na faixa de 60° a 70°, com rupturas claras para patamares semi-planos e depósitos de matacos como fatores potenciais de ocorrência de feições espeleológicas superficiais.

Tabela 2: *Cavernas publicadas nas serras próximas das cavernas analisadas.*

NOME	LITOLOGIA	ALT. (m)	DESENVOLVIMENTO LINEAR (m)	DESNÍVEL (m)	ÁREA (m^2)	VOLUME (m^3)	DETALHE DE MAPEAMENTO	INSERÇÃO NO RELEVO	SERRA DE INSERÇÃO	FONTE
GRUTA DO CAITITU	Quartzito	1.027,00	159,75	11,20	AUSENTE	AUSENTE	BCRA-4C	Vertente serrana	LENHEIRO	BARBOSA et al. (2019)
CAVERNA DO GALO	Quartzito	1.315,00	142,00	23,10	538,00	1.452,00	BCRA-4C	Vertente serrana	SÃO JOSÉ	BRANDÃO et al. (2022)
LAPA DO JAIR	Quartzito	AUSENTE	97,00	AUSENTE	648,00	AUSENTE	BCRA-4C	Vertente serrana	SÃO JOSÉ	CARDOSO et al. (2015)

5. Conclusão

A elaboração dos mapas topográficos, espeleometrias e a interpretação da paisagem e de atributos geoespeleológicos permitiram identificar as condições atuantes na espeleogênese do setor noroeste da Serra do Lenheiro (compartimento Serra das almas). Cada uma das três cavernas apresentou uma particularidade específica. Estas condições embasarão prospecções futuras a novas feições.

Simultaneamente, permitiram registrar atributos relevantes para preservação do patrimônio espeleológico brasileiro, assim como da Zona de Tombamento da Serra do Lenheiro, e sua comparação com cavernas já publicadas no entorno. Pesquisas futuras detalharão seus atributos.

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Registro e caracterização da paleotoca "Caverna do Ribeiro" como potencial geossitio do Projeto Geoparque Prudentópolis - RN

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Resumo

Este trabalho tem como objetivo realizar o registro, bem como a caracterização morfológica de uma paleotoca, denominada: 'Caverna do Ribeiro', localizada na comunidade Terra Cortada no município de Prudentópolis, Paraná, Brasil. Situada em arenitos da Bacia do Paraná (Permianos), trata-se do primeiro registro de Paleotoca com essas características no Estado do Paraná, a cavidade apresenta sulcos variados, profundos e longos, provavelmente produzidos por mais de um tipo de animal. Essas marcas de garras são características de abrigos escavados por megafauna, e a cavidade constitui um importante icnofóssil. A pesquisa visa documentar as principais características da cavidade, ajudando a entender sua formação e importância paleontológica e espeleológica. Além disso, o estudo amplia o conhecimento sobre as cavidades subterrâneas, a megafauna e os ecossistemas pretéritos do município de Prudentópolis, o qual foi identificado como potencial área de chancela da UNESCO para criação de um futuro Geoparque. O cadastro de cavidades subterrâneas como essa é essencial para sua proteção legal, conservação e desenvolvimento de estudos científicos, garantindo a preservação desse importante patrimônio natural. Destaca-se, assim, o valor da paleotoca como patrimônio geológico, paleontológico e espeleológico, visando à sua preservação, bem como apresentado esse bem como um potencial geossítio do Projeto Geoparque Prudentópolis – PR.

Abstract

This study aims to record and characterize the morphology of a paleoburrow named "Caverna do Ribeiro," located in the Terra Cortada community in the municipality of Prudentópolis, Paraná, Brazil. Situated in sandstones of the Paraná Basin (Permian), this is the first recorded paleoburrow with these characteristics in the state of Paraná. The cavity exhibits varied, deep, and long grooves, likely produced by more than one type of animal. These claw marks are characteristic of shelters excavated by megafauna, making the cavity an important ichnofossil. The research seeks to document the main features of the cavity, contributing to the understanding of its formation and its paleontological and speleological significance. Furthermore, the study expands knowledge about underground cavities, megafauna, and past ecosystems in the municipality of Prudentópolis, which has been identified as a potential UNESCO-endorsed area for the establishment of a future Geopark. The registration of subterranean cavities like this one is essential for their legal protection, conservation, and the advancement of scientific studies, ensuring the preservation of this important natural heritage. Thus, the paleoburrow is highlighted as geological, paleontological, and speleological heritage, emphasizing its preservation and presenting it as a potential geosite within the Prudentópolis Geopark Project – PR.

Resumen

Cette étude vise à enregistrer et à caractériser la morphologie d'un paléoterrier nommé « Caverna do Ribeiro », situé dans la communauté de Terra Cortada, dans la municipalité de Prudentópolis, Paraná, Brésil. Située dans les grès du bassin du Paraná (Permien), il s'agit du premier enregistrement d'un paléoterrier avec ces caractéristiques dans l'État du Paraná. La cavité présente des sillons variés, profonds et longs, probablement produits par plus d'un type d'animal. Ces marques de griffes sont caractéristiques des abris creusés par la mégafaune, faisant de cette cavité un ichnofossile important. Cette recherche vise à documenter les principales caractéristiques de la cavité, contribuant ainsi à la compréhension de sa formation et de son importance paléontologique et spéléologique. De plus, l'étude permet d'élargir les connaissances sur les cavités souterraines, la mégafaune et les écosystèmes passés de la municipalité de Prudentópolis, identifiée comme une zone potentiellement reconnue par l'UNESCO pour la création d'un futur Géoparc. L'enregistrement des cavités souterraines comme celle-ci est essentiel pour leur protection juridique, leur conservation et le développement d'études scientifiques, garantissant ainsi la préservation de ce patrimoine naturel important. Ainsi, la valeur du paléoterrier en tant que patrimoine géologique, paléontologique et spéléologique est mise en avant, soulignant la nécessité de sa préservation et le présentant comme un géosite potentiel du projet Géoparc Prudentópolis – PR.

1. Introdução

Paleotocas são túneis escavados por vertebrados da megafauna do Pleistoceno na América do Sul. A inclusão de paleotocas no Cadastro Nacional de Cavernas está condicionada à sua acessibilidade e ao nível de preservação. Esses dois aspectos possibilitam a classificação das

paleotocas em quatro categorias:

A. Muito raras:

Essas paleotocas estão abertas e completamente preservadas, apresentando seção circular e várias marcas visíveis nas paredes.

B. Raras:

Algumas paleotocas evidenciam erosão no piso e colapso do teto, podendo atingir alturas que ultrapassam 3 metros.

C. Comuns:

Paleotocas que contêm sedimentos em diferentes estágios de preenchimento são bastante frequentes.

D. Muito comuns:

Estas são paleotocas totalmente preenchidas por sedimentos, também conhecidas como crotovinas.

Somente as paleotocas pertencentes aos dois primeiros grupos devem ser registradas como cavernas no Cadastro Nacional de Cavernas, desde que seu estado de preservação indique que não desaparecerão em um curto período devido a processos geológicos naturais.

O município de Prudentópolis, localizado na região centro-sul do estado do Paraná, a aproximadamente 200 km da capital Curitiba, destaca-se por seu rico patrimônio natural, com especial relevância para os aspectos geológicos, geomorfológicos e paleontológicos. A região abriga ambientes diversificados de grande valor paisagístico e científico, incluindo uma grande quantidade de cânions, imponentes cachoeiras e escarpas, com destaque para a Escarpa da Serra da Esperança, que separa, naturalmente, o 2° do 3° planalto paranaense.

Geologicamente, a região possui rochas sedimentares do Paleozoico e ígneas do Mesozoico, da Bacia Sedimentar do Paraná. As formações mais antigas, como a Serra Alta (Permiano médio, cerca de 270 milhões de anos), são seguidas pelas formações Teresina e Rio do Rasto (Permiano superior, cerca de 260 a 250 milhões de anos). Na borda da Serra Geral, limitando o 2° e 3° Planalto, encontram-se as formações Pirambóia (Triássico, cerca de 250 a 200 milhões de anos) e Botucatu (Jurássico/Cretáceo, cerca de 200 a 145 milhões de anos), além das rochas ígneas do Grupo Serra Geral (Cretáceo, cerca de 135 milhões de anos) (SILVA; LICCARDO, 2019).

Embora a região seja predominantemente composta por rochas não carbonáticas, como arenitos, argilitos, siltitos e basaltos, que são menos propensas à dissolução química e à formação de cavernas, é registrada a presença de cavidades subterrâneas situadas na Serra da Esperança, comumente designadas como cavernas. No entanto, essas cavidades são relativamente raras, pois as rochas da área, em sua maioria, não favorecem o processo de carstificação, que é a dissolução das rochas, especialmente as calcárias, pela ação das águas superficiais e subterrâneas.

Dentre as cavidades de interesse, destaca-se a Caverna do Ribeiro, localizada em arenitos da Formação Pirambóia. Inicialmente identificada por registros e relatos locais, uma investigação mais detalhada revelou que, na realidade, trata-se de uma paleotoca — um túnel escavado por animais da megafauna pleistocênica.

O objetivo deste estudo é registrar e descrever a caracterização morfológica da paleotoca "Caverna do Ribeiro", bem como, apresentar seu potencial em ser um dos geossítios do Projeto Geoparque Prudentópolis, a fim de auxiliar na compreensão da sua origem e a sua importância dentro do contexto geológico, espeleológico e paleontológico da região e da Serra da Esperança, enquanto um importante patrimônio, visando à sua preservação.

2. Materiais e Métodos

Dessa maneira, as atividades iniciais envolveram pesquisas bibliográficas para avaliar o conhecimento pré-existente sobre a área de estudo. Informações preliminares de pesquisadores e moradores locais, particularmente relacionadas ao patrimônio espeleológico, também foram consideradas. Imagens de satélite e mapas topográficos foram analisados para identificar feições espeleológicas, padrões geomorfológicos, contextos geológicos e a infraestrutura de acesso na região.

O levantamento de campo foi conduzido por uma equipe multidisciplinar, no mês de maio de 2022. As atividades basearam-se nos dados obtidos previamente e contaram com a colaboração de moradores locais, além do uso de mapas para identificar acidentes geográficos, elementos estruturais, litologias e outras características relevantes. A Caverna do Ribeiro foi georreferenciada com GPS Garmin, registrando coordenadas geográficas, altitude e sua posição relativa ao relevo local.

Equipamentos Utilizados:

- Bússola SUNNTO: para medição de ângulos horizontais;
- Clinômetro SUNNTO: para medição de ângulos verticais;
- Trena Laser Bosch DLR40: para determinação de distâncias;
- Bric4: ferramenta de alta precisão para mapeamento subterrâneo, que determina vetores 3D de azimute, inclinação e distância.

A caracterização topográfica seguiu a metodologia da British Cave Research Association (BCRA), utilizando simbologia homologada nas Normas e Convenções Espeleométricas da SBE (1991), com adaptações específicas. Os mapas finais priorizaram a elaboração de plantas em projeção horizontal, utilizando a escala topográfica BCRA na categoria 6D.

Durante a topografia subterrânea, foram aferidas variáveis geomorfológicas como altura, largura, profundidade e direção, com base na metodologia de Buchmann et al. (2009). Foi mensurado o desenvolvimento linear da paleotoca e elaborado um croqui em planta baixa. Em casos onde marcas de garras foram observadas nas paredes da cavidade, registraram-se sua descrição detalhada, localização relativa ao teto e base da caverna, e registros fotográficos

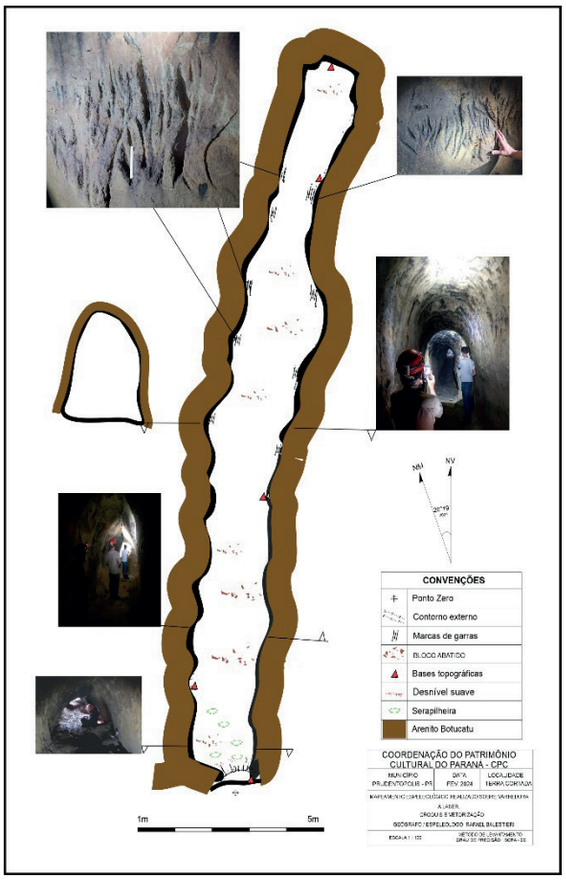


Figura 1: *Mapa topográfico da Paleotoca "Caverna do Ribeiro".*

3. Resultados

Este geossítio situa-se em arenitos da Formação Pirambóia que, junto à Formação Botucatu e Grupo Serra Geral, compõem a "Sequência Jurássica-Eocretácica" da Bacia do Paraná (Milani et al. (1997). Esta sequência compreende o intervalo do registro estratigráfico em que se posicionam os sedimentos eólicos da Formação Botucatu, flúvio-eólicos da Formação Pirambóia e as rochas magmáticas do Grupo Serra Geral, originadas no início da ruptura do continente Gondwana e do surgimento do Oceano Atlântico.

A Formação Botucatu é constituída principalmente por arenitos quartzosos de granulação fina a média, de coloração vermelha, rósea ou amarelo-clara, bem selecionados, maturo, podendo conter feldspato alterado e cimentado por sílica ou por óxido de ferro, que lhe confere a coloração rosa avermelhada. Como estrutura característica desses arenitos, ocorre estratificação cruzada planar ou acanalada, de médio a grande porte de grande porte (campos de dunas eólicas) com raras intercalações de arenitos com estratificação plano-paralela (interdunas secas). Esta formação corresponde a um grande sistema eólico seco, um deserto.

De acordo com Mühlmann, et al (1974) a Formação Pirambóia é formada principalmente por arenitos esbranquiçados, amarelados e avermelhados, médios a muito finos, síltico argilosos, grãos polidos, subangulares e subarredondados, com intercalações de finas camadas de argilitos e siltitos. Localmente ocorrem arenitos conglomeráticos com seixos de argilito. As características litológicas, sedimentares e o conteúdo fossilífero, à base de conchostrácios, ostracodos e vegetais continentais, indicam uma origem continental fluvial com depósitos de rios meandrantes e pequenas lagoas associadas em condições climáticas oxidantes.

Suas características litológicas e geomorfológicas não são comumente associadas a relevos cársticos, por isso, toda cavidade encontrada na região deve ser submetida a uma análise técnica para a constatação de sua gênese pelos especialistas capacitados. No caso da Caverna do Ribeiro, devido a combinação litológica, geomorfológica, suas dimensões e marcas, a cavidade foi finalmente reconhecida como uma Paleotoca.

Segundo BERGQVIST e MACIEL "... paleotoca é definida como uma estrutura biogênica similar a um túnel feita por vertebrados" e o termo crotovina "... é uma estrutura semelhante mas que foi posteriormente preenchida por sedimentos, destacando-se da rocha circundante por sua cor e textura diferentes". BECHTEL afirma que, "... entre as várias espécies que Darwin (2008) se refere, (...) o Megatherium, Scelidotherium, Mylodon darwinii além de outras espécies que compuseram a Megafauna e Grandefauna ...", representam os possíveis responsáveis pela construção das paleotocas. Tais espécies, cujos registros podem ser encontrados na Argentina e Sul do Brasil, são conhecidas como fossoriais e semi-fossoriais, sendo aquelas as que se alimentam e vivem embaixo da terra e, estas as que saem debaixo da terra para se alimentar.

Recursos encontrados exclusivamente no sul América, até onde sabemos, são túneis cavados Mamíferos extintos do Pleistoceno Megafauna, como assim registra FRANK et al. (2013): "The builders of the tunnels probably are giant armadillos (e.g. Pampatherium, Holmesina, Propraopus) and ground sloths (e.g. Megatherium, Eremotherium, Glossotherium, Lestodon, Mylodon, Catonyx). It seems that the narrowest tunnels (Ø ~0.8 m) are from the armadillos, the wider tunnels from different genera of ground sloths, whose body masses range between 0.8 and 5.0 tons".



Figura 2: *Imagens internas da Paleotoca "Caverna do Ribeiro".*

4. Discussão

Nos trabalhos de campo foi possível verificar que a referida Paleotoca está integralmente preservada, sem preenchimento e cuja seção é praticamente circular, sem apresentar feições de colapso de teto nem de erosão do piso (Fig. 2). Essas paleotocas, são raras e apresentam as paredes e o teto cobertos por centenas de marcas produzidas pelo organismo escavador. Entre essas marcas, há marcas de escavação, marcas de arraste de carapaça e marcas diversas de contato, sendo assim, podemos confirmar a grande relevância do objeto de estudo

e a grande importância em defini-lo como um geossitio integrante do Projeto Geoparque Prudentópolis – PR.

O termo Geossítio é utilizado para definir os locais com elementos geológicos específicos de valores significativos culturais e científicos, conforme a Geodiversidade e critérios atendidos no processo de classificação e inventário.

De acordo com Brilha (2005) os geossítios referem-se a um ou mais elementos da geodiversidade resultantes da ação de processos naturais ou de atividades antrópicas, delimitados geograficamente, apresentando valor científico, pedagógico, cultural e turístico.

Como observado, a Paleotoca "Caverna do Ribeiro" foi classificado de grande Relevância cientifica dados suas características e estado de preservação. Sendo assim, recomenda-se a utilização de medidas de geoconsevação. O desenvolvimento de estratégias para a geoconservação do local inventariado deve levar em consideração fatores como a relevância das informações geológicas observadas no geossítio, além do grau de vulnerabilidade aos impactos a que ele está submetida, de modo a criar mecanismos que facilitem a aproximação das pessoas e também protejam estas áreas de interesse geológico.

Nesse sentido, os principais aspectos considerados relevantes para a conservação da Paleotoca "Caverna do Ribeiro", localizada na cidade de Prudentópolis diz respeito ao seu valor científico, que inclui o registro da história geológica da área. Assim, a promoção do turismo sustentável do sugerido geossítio em benefício da população local é uma forma de valorizar este sítio de interesse geológico. Para o fazer de forma eficaz, deve ser implementadas estratégias para ajudar a planejar visitas tanto para turistas como para a comunidade acadêmica e científica através de uma gestão adequada e de iniciativas de avaliação destas áreas. Do ponto de vista científico, a pesquisa contribui para esse avanço do desenvolvimento sustentável ao agregar informações técnicas e científicas ao patrimônio geológico estudado para aumentar sua relevância relativa como geossítio. Além disso, uma população que conhece o significado construído pela geolocalização pode disseminar esse conhecimento e aumentar o nível de proteção e valorização dessas áreas. A atribuição de valor à geodiversidade confere qualidade ao património geológico.

5. Conclusão

Essas marcas de garras são características de abrigos escavados por megafauna, relevando as características de um importante icnofóssil. Por meio de uma análise criteriosa, a cavidade subterrânea foi identificada como uma paleotoca e suas marcas devidamente registradas nos materiais cartográficos produzidos.

A Caverna do Ribeiro é citada no livro "As linhas de Prudentópolis"[1], onde apresenta uma foto do interior da cavidade e três exploradores: Beto Lopes, Cesar Halicki e Marcos Rudek. Na legenda desta foto ressalta-se que foram encontrados "sinais de visitação de tempos imemoriais contrastam com recentes". Portanto, era conhecida, e faltava apenas uma análise mais criteriosa para a identificação como uma paleotoca. Atualmente não existe nenhuma ação de proteção, situando-se em meia encosta, já na Serra da Boa Esperança que separa o Segundo do Terceiro Planalto paranaense. Situa-se em arenitos da Formação Pirambóia da Bacia do Paraná e segue uma linha de fratura/falha, que tornou a rocha mais fácil para ser escavada pelo animal.

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Methodology proposal for predicting spatial patterns of talus pseudokarst

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Abstract

Research on pseudokarst is scarce and rarely extends beyond field descriptions of local processes. Whereas the connections between carbonate caves and topography have been extensively studied, there are no methodologies for predicting the potential occurrence of natural cavities formed by different processes. This represents a considerable gap, not only for speleology but also for decision makers working on territorial planning and related public policy. The study area was a granite outcrop region with talus pseudokarst in São Paulo State, Brazil, where cave prospection has been carried out for two decades. Using GIS platforms, I determined values for topographic variables on each opening of 43 caves (Altitude, Topographic Wetness Index and Slope) and conducted Kolmogorov-Smirnov tests to assess whether cave occurrence was explained by each variable. The result was a talus pseudokarst potential map for the study region, which was subsequently tested in the field and led to the discovery of 4 new caves. With further model improvements, this methodology could be useful for pseudokarst prospecting around the world and promote territorial planning that protects the areas with highest probability of containing natural cavities.

Resumo

PROPOSTA DE METODOLOGIA PARA A PREVISÃO DE PADRÕES ESPACIAIS EM PSEUDOCARSTE DE TÁLUS. Pesquisas sobre pseudocarste são escassas e raramente se estendem para além de uma descrição de campo de um processo local. Enquanto as relações entre cavernas carbonáticas e a topografia já foram extensamente mapeadas, não existem metodologias para previsão do potencial de ocorrência de cavidades formadas por outros processos. Essa falta é uma lacuna considerável, não só para a espeleologia, mas também no âmbito do planejamento territorial e políticas públicas relacionadas. A área de estudo foi uma região de afloramento granítico com pseudocarste de tálus no estado de São Paulo, Brasil, onde são prospectadas cavernas há 20 anos. Em ambiente GIS, determinei valores para variáveis topográficas em cada abertura de 43 cavidades (Altitude, *Topographic Wetness Index* e Declividade) e conduzimos testes de Kolmogorov-Smirnov para testar o quanto da presença de cavidades podia ser explicada por cada uma dessas variáveis. O resultado foi um mapa de potencial de ocorrência de pseudocarste para a região de estudo, que foi posteriormente testado em campo e permitiu a descoberta de 4 novas cavidades. Calibrado para novas variáveis, esta metodologia poderia ser útil para prospectar pseudocarste ao redor do mundo e promover planejamento territorial que proteja locais com alta probabilidade de cavidades naturais.

Resumen

PROPUESTA DE METODOLOGÍA PARA LA PREDICCÍON DE PADRONES ESPACIALES DE PSEUDOCARSTE DE TÁLUS. Investigaciones acerca de pseudocarste son escasas y en pocos casos se extienden para allá de descripciones de campo de procesos locales. Mientras las conexiones entre cavernas carbonáticas y la topografía fueron estudiadas de manera extensa, no existen metodologías para predecir el potencial de ocurrencia de cavidades naturales formadas por otros procesos. Eso representa una brecha de conocimiento no sólo para la espeleología, sino que también para planificación territorial y políticas publicas relacionadas. El área de estudio fue una región de afloramientos graníticos con pseudocarste de tálus en el Estado de São Paulo, Brasil, donde cavernas son prospectadas hace 20 años. Utilizando plataformas GIS, determinamos valores para variables topográficas de 43 cavernas (Altitud, *Topographic Wetness Index* y Pendiente) y conducimos testes de Kolmogorov-Smirnov para testar se la ocurrencia de cavernas podría ser explicada por cada variable. El resultado fue un mapa de potencial de pseudocarste de tálus para la región de estudio, que fue posteriormente testado en campo y llevó a la descubierta de 4 nuevas cavernas. Con mejoras futuras, la metodología podría ser útil para prospección de pseudocarste en todo el mondo y promover planificación territorial que proteja las áreas con las más grandes probabilidades de contener cavidades naturales.

1. Introduction

Not all natural cavities result from the chemical weathering of soluble rocks, and the diversity of processes that form the so-called pseudokarst generates an even greater variety of relationships between caves and the landscape. Carbonate terrains are well known in their relationship with the landscape, with categories such as sinkholes, resurgences, blind valleys, karren, and many other specific landforms of karst relief and the topographic positioning of natural cavities (KARMANN, 2000). Extensive studies have been conducted in recent decades to spatially predict locations of karst occurrence and the distribution of natural cavities in this type of terrain (e.g., JANSEN & LAMBLEM, 2012; PUTRA et al., 2022; HUNG et al., 2002; WEISHAMPEL et al. 2011). The results have been widely used in public policies for land-use planning and impact mitigation on these fragile types of relief and their unique relationships with the biota.

However, such studies have been scarcely conducted for pseudokarst,

a term used for a vast range of different processes. According to HALLIDAY (2007), there are at least eight different types of cavities classified as pseudokarst, formed by processes as distinct as the solidification of lava flows, physical weathering by sea waves, and the gravitational accumulation of blocks. In many of these cases, the processes involve unique connections with topography and larger-scale spatial patterns, making it difficult to map the potential for their occurrence. This gap impacts not only speleology and related sciences but also decision-making processes related to land-use planning. Brazilian legislation mandates the protection of an "influence area" for each natural cavity, which should be determined through specific studies (IBAMA, 1990). There are studies that establish this influence area in carbonate karst, which are only possible due to in-depth knowledge of the processes forming such cavities (ICMBIO, 2022). However, no bibliography explains how to conduct such studies for processes in insoluble rocks, which are so distinct from karst and from each other. Another issue, at a broader scale of land-use planning, is the lack of knowledge about areas most likely to contain pseudokarst natural cavities, which prevents public policy decisions from protecting the most fragile areas of these unique and often overlooked landscapes.

This study proposes a methodology to investigate the connections between cavities and relief variables, which, in theory, can be applied to other types of pseudokarst beyond talus pseudokarst.

2. Materials and Methods

The study area corresponds to the outcrop region of the Morungaba Granitoids, which, according to the map by PERROTA et al. (2006), occurs in the municipalities of Vinhedo, Louveira, Valinhos, Itatiba, Campinas, and Morungaba, in the State of São Paulo, Brazil. At its center lies the Serra dos Cocais, in Valinhos, which was declared an Environmental Protection Area (APA) in 2004 (VALINHOS, 2004). This area is of geomorphological interest due to its relief of rocky outcrops/fields of boulders—typical forms of semi-arid climates—found in a subtropical climate. On a morphostructural scale, the body is located at the edge of the Jundiaí Plateau and the peripheral denudation of the Paraná-Cape-Karoo Sedimentary Basin (ROSS & MOROZ, 1997). Thus, the Neoproterozoic granitoids (600±20 Ma; VLACH, 1985) were exposed during the Permian period, buried by the sediments of the Itararé Group, and later by the entire sedimentary sequence of the Paraná-Cape-Karoo Basin, only to be reexposed at the beginning of the Cenozoic (AB'SABER, 1949). The pluton's main lithologies include biotite monzogranites, biotite quartz monzonites, and syenogranites (VLACH, 1985), which are more resistant to erosion than the metasediments in which it is embedded.

Currently, the Morungaba granitoids serves as a substrate for an ecotone between forest vegetation (seasonal semideciduous forest and dense ombrophilous forest) and savanna-like vegetation (Cerrado and rupestrian fields). The climate is classified as Cfa according to the Köppen classification system, with annual maximum temperatures of 27°C, annual minimum temperatures of 12.2°C, and annual precipitation of 1,462 mm, concentrated in the summer but never dropping below 40 mm per month (Climate-Data.org). Over the Morungaba granitoids, a thick weathering mantle has developed, composed of red-yellow argisols, a type of soil characterized by a high clay content of mineral origin, low base content, and low natural fertility (DOS SANTOS et al., 2011). This weathering mantle, combined with mass movements common in this type of soil, shapes the region's geomorphology, which is dominated by elongated hills and flat-topped mounds (PONÇANO, 1981).

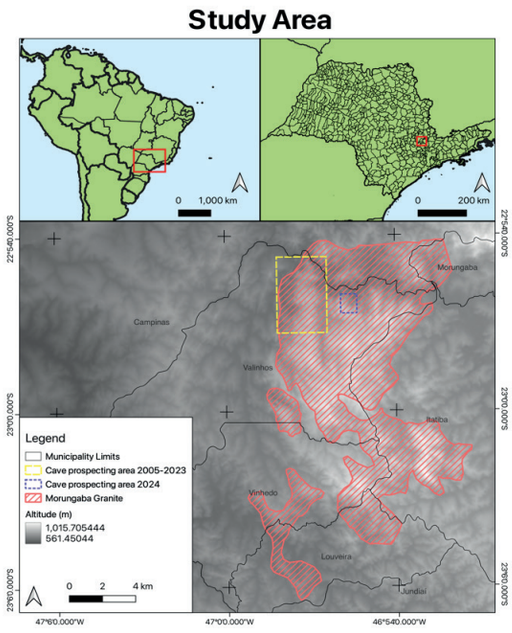


Figure 1: *Study area, corresponding to the outcrop area of the Morungaba Granitoids.*

To describe the topographic positioning of the natural cavities in the Morungaba granitoid body, I created a pseudokarst occurrence potential map for the region. For this, I used the 43 geographic coordinates of cave entrances provided by the Geo Speleology Group (GGEO), collected over 20 years of prospecting (2005–2024) in the northwestern part of the Serra dos Cocais (Fig. 4). In GIS environment, the following data were extracted for each of these coordinates: elevation, slope, and TWI (Topographic Wetness Index) from a raster file with 30m resolution obtained from OpenTopography.com (ESA, 2024). These variables were selected for their ability to demonstrate critical characteristics of slope dynamics, particularly regarding locations where large blocks would accumulate. The TWI is especially relevant and has already been used to explain accumulations of certain nutrients, pH variations, and even vascular plant diversity along slopes (GIESLER et al., 1998; ZINKO et al., 2005). The test for altitude follows the observation that "boulders cover the slopes and tops but not the bottoms of dry valleys" (Christofoletti, 1967, free translation). Slope was included in the analysis as it determines the gravitational force acting on each boulder.

Next, a two-sample Kolmogorov-Smirnov (KS) test was performed, comparing the distribution of the three numerical variables at cave entrances with the distribution of the same three variables across the Serra area where caves were prospected (Fig. 4). The null hypothesis (H0) was that the cave distribution had no relationship with any of

the metrics, and if true, both distributions would be similar ($p > 0.05$). However, if $p < 0.05$, it was considered that the likelihood of the cave data being a random subsample of the landscape data would be very low, and H0 would be rejected. The KS test was chosen over similar goodness-of-fit tests due to its compatibility with continuous variables with two unknown distributions (ZAR, 1999). Additionally, another series of KS tests was conducted to verify whether the variable distributions followed a normal curve.

To extract landscape data and the coordinates of cavity entrances, the OpenTopography DEM and the MMQGIS plugin (MINN, 2021) were used. The plugin allows generating a data table from each pixel of a raster layer in QGIS 3.24. The TWI was calculated using the SAGA plugin (CONRAD et al., 2015) and the BEVEN & KIRBY (1979) method with the following function.:

$$TWI = ln\,(a/tan\,(d))$$

a represents the upstream area draining to a given point and d the slope at that point.

The next step, therefore, was to create a pseudokarst potential map for talus caves in the region within a GIS environment. The TWI and Elevation values in which 90% of the cave records concentrated (between the 5th and 95th percentiles) were considered. I then mapped as high-potential pseudokarst occurrence zones all landscape points with TWI values between -7.319 and -2.399; Elevation values between 753.160 and 830.032; and the lithology as Morungaba granitoids.

After generating the pseudokarst potential map, a new field trip was conducted to a poorly sampled area north of the municipality of Valinhos. Three days of prospecting were carried out (December 17–19, 2024) in areas within the raster of highest potential for talus caves, noting and naming newly discovered natural cavities. The prospected area was the CEFOL Country Club, located on a north-facing slope covered by Seasonal Semideciduous Forest.

3. Results

The Kolmogorov-Smirnov test showed that for both elevation and TWI, the null hypothesis was rejected ($p = 1.974E\text{-}09$ and $p = 0.0015$, respectively). This indicates that caves tend to concentrate in locations with specific intervals of these variables, which differ from the intervals found in the overall landscape. However, for slope, the same was not observed ($p = 0.0308$), and this variable did not show explanatory power for the positioning of caves in the landscape. Additionally, the distribution of caves along the TWI and elevation gradients (separately) did not show significant differences from a normal curve. This may support the idea of a correlation between the phenomena, as normal curves are rare in spatial data (STRIMBU et al., 2009).

A pseudokarst potential map for talus caves was produced (Fig. 2), showing that the expected position of cavities surrounds the granitic massif, excluding its flattened top.

Over the three days of prospecting, nine new natural cavities were found, all within the area predicted to have the highest pseudokarst occurrence potential. These ranged from small shelters (openings taller and wider than their total horizontal development) to very deep cavities (horizontal development > 5m) that acted as sources for small streams.

The areas mapped as having high pseudokarst potential were observed in the field as dry or wet valleys covered by boulders ranging from metric to decametric sizes. In most of the area, the granite blocks were not significantly stacked or had their interstices filled with finer sediment, thus not forming significant cavities. However, the largest cavities observed were generally associated with large trees, such as a *Cariniana cf. legalis*. As observed in other cavities in the region, large trees appear to play an important role in the formation and/or maintenance of the pseudokarst geomorphology in the Morungaba Granitoids.

Overall, I conclude that the model created using a simple statistical operation (two-sample KS test) was able to predict, with good accuracy, locations where new cavities would be found.

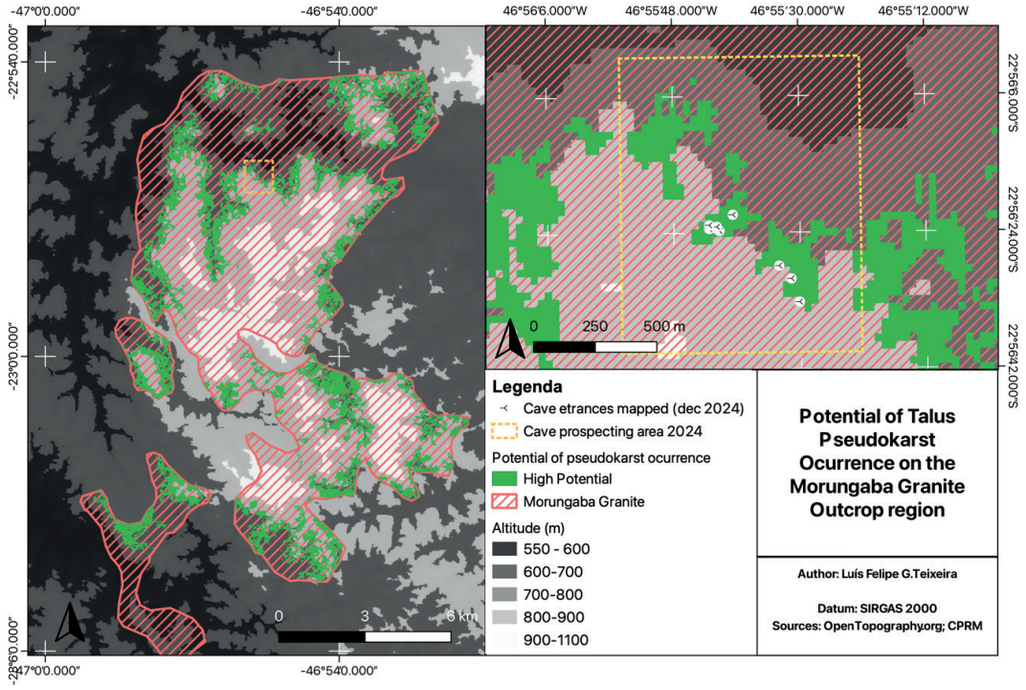


Figure 2: *Potential pseudokarst occurrence within the study area (left) and summary of the prospecting fieldwork conducted from December 17 to 19, 2024 (top right). The potential map helped to identify 9 previously unrecorded cavities in the region.*

4. Discussion

The relationship between topographic variables and the development of natural cavities is not a new finding. It is not surprising that most studies showing such connections focus on areas of carbonate karst. In most cases, however, the mainly used variables were visual analyses of structural lineaments (e.g., HUNG et al., 2002) and the Topographic Position Index (TPI; PUTRA et al., 2022; WEISHAMPEL et al., 2011). The TPI has also been used for pseudokarst of piping (BERNATEK-JANKIEL & JAKIEL, 2021) since it is more widely studied as a civil engineering/geotechnical problem.

TWI has also been used to detect natural cavities. Interestingly, it has been more often used for pseudokarst. For example, the study by JANCEWICZ et al. (2019) describes the position of a mixed pseudokarst cave, combining talus pseudokarst and piping pseudokarst (*sensu* HALLIDAY, 2007), in a sandstone cuesta as being related to TWI values 2 standard deviations above the local mean and to a closed depression. According to the authors, the depression acts as a sediment trap, accumulating both larger boulders and finer sediments. Other works, such as GENG et al. (2023), demonstrated a strong correlation between the degree of pseudokarst development in loess sedimentary rocks (a fine, erosion-prone but poorly soluble sediment) and TWI.

These results suggest that TWI may indeed be more effective in predicting the position of pseudokarstic entrances. This would be particularly useful for talus pseudokarst, as its formation process is essentially different from that of soluble karst, being based on sediment deposition rather than erosion. However, it would still be necessary to incorporate TPI analysis and structural lineament traces into the model, comparing the predictive power of each variable.

5. Conclusion

The proposed methodology demonstrates advancements in the study of talus pseudokarst geomorphology, enabling the prediction of locations with a higher probability of containing natural cavities. It is still necessary to refine the model by adding new variables with high predictive power and increasing the dataset. Another important step would be to replicate the study in other talus pseudokarst regions in granite, such as northwest Eswatini (OBEREDEN et al., 2014) or central Spain (CALVO et al., 2013). Furthermore, it would be valuable to test other statistical models beyond the KS test, such as Principal Component Analysis (PCA), which allows for the integration of multiple variables.

However, the model has the advantage of being easily replicable for other variables and contexts, making it applicable beyond the Morungaba granitoid body. An improved model could have applications in territorial planning, as it may predict the locations of unexplored caves and assist in water resource management (PUTRA et al., 2022). Overall, future studies on pseudokarst should involve more comparisons between different areas with similar processes, rather than focusing solely on the description of isolated local patterns.

Acknowledgments

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Karren-like features in the granites of Quixadá, Ceará, Brazil: an introduction

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Abstract

Granite landscapes exhibit unique features for geomorphological studies, including inselberg fields defined as steep rock masses formed by surface lowering. In Brazil, such fields are documented in regions like Itatim (BA) and Quixadá (CE), with significant geotourism and geomorphological potential. This study focuses on the Quixadá inselberg field, part of the proposed Sertão Monumental Geopark. It aims to identify dissolution forms and understand the geochemical processes shaping granite microfeatures. The research employed bibliographic reviews, field observations, photogrammetry, and global comparisons with features in Sri Lanka, Australia, and South Africa. Results reveal tafoni, gnammas, and karren in granites, features typically associated with carbonate lithologies. Microscopic evidence suggests selective dissolution in less resistant minerals, such as mafic enclaves and biotite. The dissolution processes in Quixadá highlight the complexity of silicate weathering and its role in relief formation. This study enhances understanding of granite terrains' geomorphological and heritage potential, emphasising their scientific and cultural importance.

Resumo

As paisagens graníticas apresentam formas únicas para o estudo da geomorfologia, incluindo campos de inselbergs, definidos como massas rochosas íngremes formadas pelo rebaixamento das superfícies circundantes. No Brasil, esses campos são registrados em regiões como Itatim (BA) e Quixadá (CE), locais com potencial geoturístico e geomorfológico. Este estudo foca no campo de inselbergs de Quixadá, localizado no proposto Geoparque Sertão Monumental. A pesquisa visa identificar formas de dissolução e compreender os processos geoquímicos envolvidos na evolução desses micro-relevos em granitos. Foram utilizadas revisões bibliográficas, observações de campo, fotogrametria e comparações globais com feições similares no Sri Lanka, Austrália e África do Sul. Os resultados apontam a presença de tafoni, gnammas e karren em granitos, características geralmente atribuídas a litologias carbonáticas. Microevidências indicam dissolução seletiva em minerais menos resistentes, como enclaves máficos e biotita. Os processos de dissolução em Quixadá destacam a complexidade do intemperismo em rochas silicáticas e seu papel na formação do relevo. Este trabalho amplia o entendimento sobre o potencial geomorfológico e patrimonial das paisagens graníticas, reforçando a relevância científica e cultural desses sistemas.

Resumen

Los paisajes graníticos presentan formas únicas para el estudio de la geomorfología, incluyendo campos de inselbergs, definidos como masas rocosas escarpadas formadas por el descenso de las superficies circundantes. En Brasil, estos campos se encuentran en regiones como Itatim (Bahía) y Quixadá (Ceará), áreas con gran potencial geoturístico y geomorfológico. Este estudio se centra en el campo de inselbergs de Quixadá, parte del propuesto Geoparque Sertão Monumental. El objetivo es identificar formas de disolución y comprender los procesos geoquímicos que moldean estas microformas en granitos. La investigación combinó revisiones bibliográficas, observaciones de campo, fotogrametría y comparaciones globales con características similares en Sri Lanka, Australia y Sudáfrica. Los resultados revelan tafonis, gnammas y karren en granitos, formas típicamente asociadas con litologías carbonáticas. Evidencias microscópicas indican disolución selectiva en minerales menos resistentes, como enclaves máficos y biotita. Los procesos de disolución en Quixadá destacan la complejidad del intemperismo en rocas silicatadas y su relevancia en la evolución del relieve. Este trabajo contribuye al entendimiento del potencial geomorfológico y patrimonial de los paisajes graníticos, subrayando su valor científico y cultural.

1. Introduction

Granite landscapes exhibit unique forms for the study of geomorphology (MIGON, 2006). Among these forms, TWIDALE (1982) identifies inselberg fields as one of the main components of this type of landscape. Inselbergs are steep rock masses with concave or convex tops formed by lowering the surrounding surface (MIGON & GOUDIE, 2003).

In Brazil, studies report inselberg fields in the northeastern region,

such as in Itatim, Bahia; Patos, Paraíba; Chaval, and Quixadá, Ceará (LIMA; CORRÊA-GOMES, 2015; MAIA et al., 2015; MAIA & NASCIMENTO, 2018; MAIA et al., 2022; CORDEIRO et al., 2023).

According to GRAY (2004), geodiversity can be distinguished by the following values: intrinsic, cultural, aesthetic, economic, functional, scientific, and educational. The scenic beauty resulting from relief forms on granite surfaces encompasses a value of geodiversity, turning Inselberg field areas into a geomorphological heritage (CLAUDINO-SALES, 2018; MONTEIRO et al., 2023).

The Quixadá inselberg field is in Ceará (Fig. 1), northeastern Brazil, and is part of the proposed Sertão Monumental Geopark (FREITAS et al., 2019). The proposal includes 20 geosites, most related to inselberg types adorned with various geomorphological features.

The study area has a hot, semi-arid tropical climate marked by irregular rainfall, with an average annual precipitation of 700 mm. It is geologically situated on the Quixadá pluton, part of the Itaporanga intrusive suite (PINÉO et al., 2021), consisting of monzonites, monzogranites, quartz monzonites, and syenites.

According to the geomorphological map proposed by COSTA et al. (2020), the area lies on the Sertaneja Surface 1 (Superfície Sertaneja 1), with altitudes between 50 and 250 meters and flat to slightly undulating slopes.

Based on the classification by MAIA et al. (2015), the Quixadá inselbergs are defined as follows: Type 1 – marked by dissolution features; Type 2 – marked by fracturing features; Type 3 – granite massifs with low microfeature incidence. Inselbergs of Group 1 are associated with weathering forms such as tafoni, gnammas, and karren (MAIA & NASCIMENTO, 2018).

Despite significant advances in studies, no classification for dissolution features has been determined, considering the varying sizes and evolutionary stages of forms recurrent in Type 1 inselbergs (Fig.2). Therefore, this study aims to identify and characterise dissolution forms on these granite inselberg surfaces.

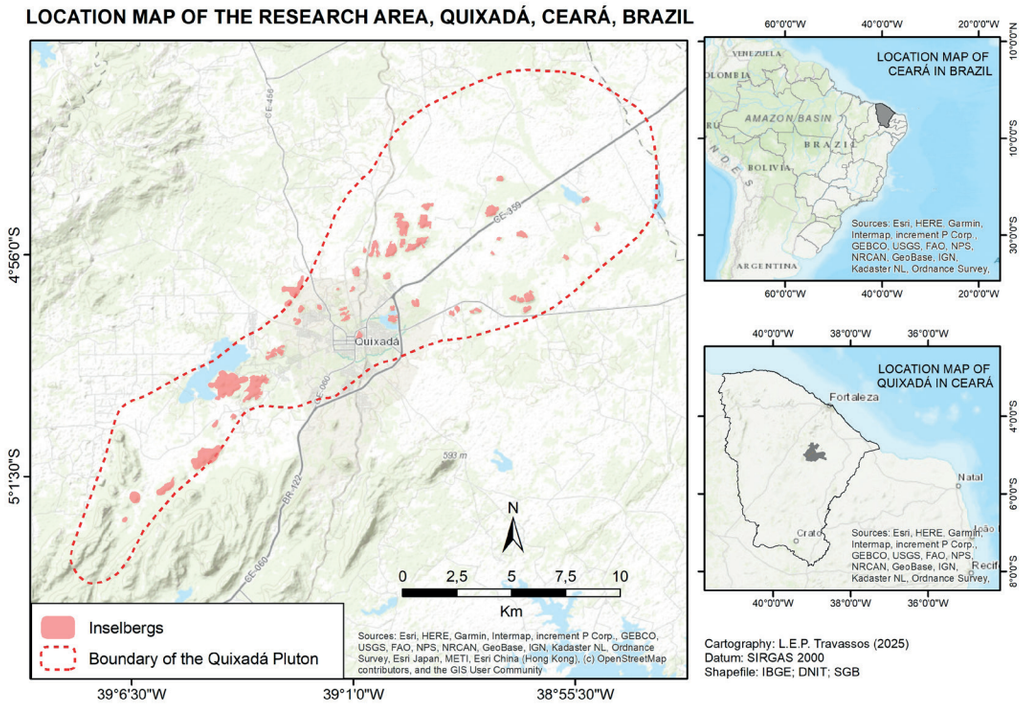


Figure 1: *Geographical Representation of the Study Area in Quixadá, Ceará, Brazil: Highlighting Inselbergs and the Quixadá Pluton Boundary.*

2. Materials and methods

A comprehensive literature review on geomorphology focused on karren in limestone, sandstone and quartzite outcrops. After this, the literature review focused on karst-like features in granite. Foundational and contemporary works by TWIDALE (1982), MIGOŃ & DACH (1995), MIGOŃ, & GOUDIE (2003), MIGOŃ (2006, 2010), OSBOURNE et al. (2013), MICHNIEWICZ, RÓŻYCKA & MIGOŃ (2015) and PÉREZ, (2023) provided the theoretical basis for understanding dissolution processes in crystalline rocks.

The fieldwork was also aided by direct observation of geomorphological features, photographic documentation, and GPS and photogrammetry via Remotely Piloted Aircraft (RPA). During field activities, the main geomorphological features on the inselbergs were identified and classified, including various Karren features such as runnels and kamenitzas. The collected data were analysed qualitatively for this first research to understand local processes' dynamics better.

The findings were compared to documented karst-like features in southern and central Sri Lanka, the Eyre Peninsula (South Australia), inselbergs at Vredenburg and Witteklip, Western Cape Province of South Africa, the Enchanted Rock (Texas, US), the tors of Waldviertel (Lower Austria) So, the methodology combined field observations and comparative studies to understand the geomorphological processes shaping the inselbergs of Quixadá comprehensively.

3. Results

Dissolution forms are commonly associated with karstic landforms, whose genesis is directly linked to the presence of water in carbonate lithologies (WHITE, 1988). For a long time, quartzose rocks were considered highly resistant to chemical weathering (TRICART & CAILLEUX, 1972). Cavities formed in silicate rocks are often classified as pseudokarst due to the low solubility of these rocks. In this context, mechanisms other than dissolution were believed to be the main drivers of their formation (AUBRECHT et al., 2008). However, this perspective has been reconsidered, given evidence of karst-like forms developed on other lithologies (WRAY, 1997). The term "non-traditional karst" has been adopted (ANDREYCHOUK et al., 2009; TRAVASSOS, 2019).

Microscopic evidence indicates dissolution processes in silicate rocks (WRAY, 1997). YOUNG (2010) reports the formation of ruiniform relief in Australia, with clear marks of dissolution processes. This site features formations like towers, ridges, and pinnacles like those developed in carbonate terrains.

Despite their high resistance to weathering, granite reliefs exhibit dissolution microfeatures. Cavities are formed via dissolution on the surface and underground (MIGON, 2006). Features such as tafoni, gnammas, flared slopes, and karren are associated with dissolution processes in granite terrains (TWIDALE & VIDAL ROMANI, 2005).

A case of karst-like features granite rocks is found in Sri Lanka. Osborne et al. (2013) report granite features such as inselbergs and tors and microfeatures like dissolution basins and rills (Runnels and Flutes). Similarly, MIGON (2010) highlights the Spitzkoppe inselberg in Namibia, where dissolution microfeatures such as pits, dissolution basins, and tafoni are also observed. The pits and tafoni on this inselberg are believed to be among the most developed in the world (MIGON & GOUDIE, 2003).

In Brazil, the inselberg field of Itatim, Bahia, displays dissolution features like those reported in other locations (LIMA & CORRÊA-GOMES, 2015). Tafoni exceeding 50 meters in height are developed along inclined joints conducive to water retention (MAIA et al., 2022).

One can observe that dissolution features such as gnammas help develop Karren-like features through selective weathering in minerals less resistant than granite, such as mafic enclaves or biotite.

4. Discussion

Weathering processes in silicate minerals, such as quartz and feldspar, present in granitic rocks are highly complex and influenced by chemical, physical, and environmental factors. These processes significantly alter rock structures, contributing to landscape evolution and geomorphic features.

Quartz, a primary constituent of silicate-rich rocks, is often considered resistant to chemical weathering due to its low solubility and slow reaction rates under surface conditions. However, research demonstrates that solutional weathering in quartz-rich rocks is critical for increasing porosity, weakening the rock structure, and enabling subsequent physical erosion. This process is described by the concept of arenization, wherein the dissolution of quartz at crystal boundaries transforms a cohesive rock into a less stable, sand-like material. Arenization primarily acts along grain boundaries, facilitating intergranular dissolution and increasing porosity, which amplifies susceptibility to mechanical erosion (MARTINI, 1979).

The dissolution of quartz occurs at the molecular level and is driven by interactions between silica and water. Quartz dissolves to form orthosilicic acid (H_4SiO_4), with the rate and extent of dissolution influenced by factors such as pH, temperature, and cations or organic acids. Under alkaline conditions (pH > 9), silica dissolution rates increase significantly due to ionisation processes. Conversely, acidic conditions, particularly in environments with high organic acid content, slow the dissolution due to buffering effects, as observed in tropical and temperate environments (RIMSTIDT & BARNES, 1980; DOERR, 1999; AUBRECHT et al., 2011).

Microscale dissolution features, such as pits and embayments, support the role of solution-controlled processes in weakening quartzite and sandstone. These features are intensified along high-energy surfaces, such as grain edges and overgrowth boundaries, where chemical reactivity is higher (HURST & BJORKUM, 1986; WRAY & SAURO, 2017).

Granites and gneiss are composed predominantly of quartz, feldspar, and mica, and their weathering is driven by chemical dissolution and physical disaggregation. Phantomisation, a two-stage process, is believed to be a key mechanism in granitic weathering. This involves the chemical weakening of the rock matrix through feldspar dissolution, followed by mechanical removal of residual material (OSBORNE et al., 2013).

Studies in Sri Lanka reveal significant features formed by weathering in gneiss and granite, including caves, inselbergs, and boulder fields. Processes such as spalling, phantomisation, and feldspar dissolution contribute to these features. Phantom rock formation, where the matrix or cement of the rock is chemically altered or removed, results in structurally weakened zones that guide cave formation. This process has been observed in caves like Sthreepura Cave, where quartz meshworks and feldspar solution zones are prevalent (OSBORNE et al., 2013).

Phyllosilicates such as kaolinite and illite are notable in weathering quartz-rich rocks. These minerals dissolve in acidic and alkaline conditions, contributing to porosity and structural disaggregation. Organic acids, often derived from vegetation, enhance this process, particularly in tropical environments (CORRÊA NETO & FILHO, 1997; DE MELO & GIANNINI, 2007). In some cases, phyllosilicates act as aquitards, retaining moisture and intensifying quartz dissolution through localised weathering zones (PICCINI, 1995; WRAY & SAURO, 2017).

Environmental factors such as temperature, precipitation, and rock structure significantly influence weathering. Fractures and joints provide pathways for water infiltration, facilitating chemical reactions. In gneiss and granite, weathering often follows structural features like foliation planes or joints, enhancing cave development. High rainfall accelerates silica and feldspar dissolution, often producing clay minerals like kaolinite. Numerical models suggest that arenization requires prolonged environmental stability, spanning hundreds of thousands of years, to significantly alter porosity and enable erosion (MARTINI, 1979; WRAY & SAURO, 2017).

Silica speleothems, including stalactites and flowstones, are evidence of ongoing silicate dissolution in vadose zones. These formations demonstrate active chemical weathering within the rock matrix, not just along fractures, and highlight the role of silica leachates in shaping karst-like landscapes (OSBORNE et al., 2013). Weathering in silicates and granites produces distinct geomorphological features, such as quartz caves, ruiniform relief, and tower karst (Fig.2). Arenization in quartz-rich rocks increases porosity and mechanical breakdown. In contrast, phantomisation in granites and gneiss produces karren, often resembling carbonate karst systems. These processes underscore the importance of chemical weathering in shaping silicate-dominated landscapes.

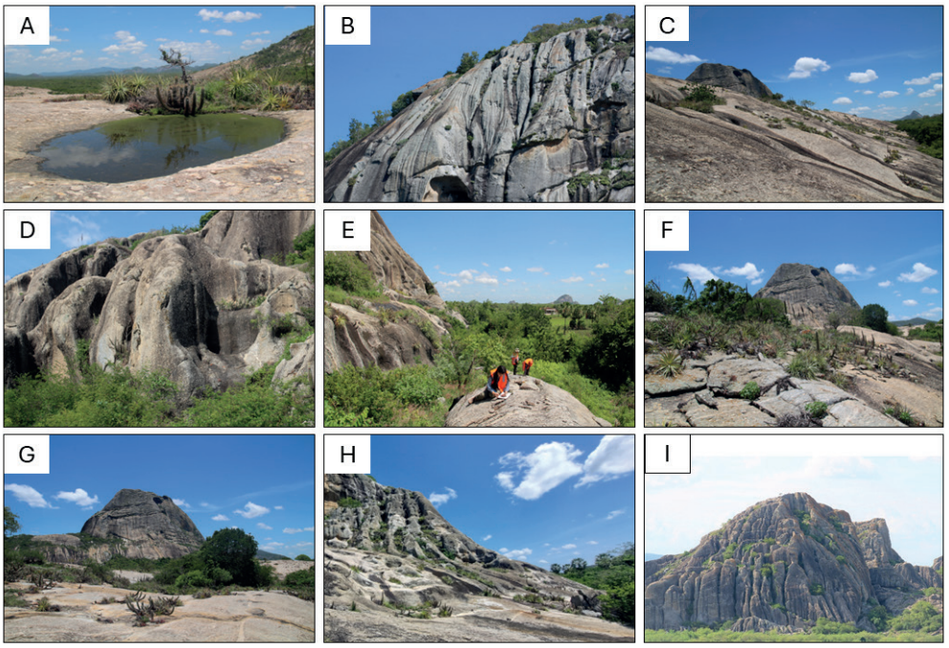


Figure 2: *A) A large gnamma that can also be perceived as a Kamenitza. B) View emphasises the complex and integrated dendritic network of rill channels flowing from the top to bottom, as rillenkarren and rinnenkarren do. C) Rills downslope connect to kamenitzas above. D) An example of rundkarren is a probable sub-aerial formation, such as limestone outcrops. E) View that shows most of the karren features as megakarren. F) Weathered vertical or near-vertical fractures known as kluftkarren. G) At the bottom of the picture, one can see a meanderkarren following the slope and the rock's weakness. H) Outcrop with various types of karren. I) Flutes developed along vertical joints.*

5. Conclusion

Granite landscapes represent a unique and essential component of geomorphological studies, showcasing diverse features shaped by weathering and dissolution processes. Among these, inselberg fields are significant geomorphological entities, often associated with impressive micro, meso and microfeatures that provide insights into the dynamic interplay of chemical and physical weathering. Inselbergs, characterised by steep rock masses with concave or convex tops, are formed by lowering surrounding surfaces and are commonly found in arid and semi-arid regions (MIGON, 2006; TWIDALE, 1982; GOUDIE, 2004).

In Brazil, these features, such as the Quixadá inselbergs, demonstrate the geomorphic potential of granite terrains, where dissolution processes, despite the high resistance of silicate rocks, contribute significantly to their evolution.

The study of granite dissolution microfeatures, such as tafoni, gnammas, and karren, reveals the influence of environmental factors like precipitation, temperature, and rock structure on weathering processes, which can emphasise the role of selective weathering in minerals such as biotite and mafic enclaves. These findings challenge traditional assumptions of silicate resistance and expand the understanding of geomorphologic diversity.

In Quixadá, Ceará, the Inselberg field contributes to the proposed Sertão Monumental Geopark, illustrating the intersection of geodiversity and geomorphological heritage. With its hot, semi-arid tropical climate and the geological context of the Quixadá pluton, the region provides a natural laboratory for studying weathering dynamics and their impact on landscape evolution. The dissolution features observed in Type 1 inselbergs, marked by tafoni and karren, underscore the importance of continued research into their geochemical genesis and evolutionary processes.

Ultimately, granite terrains, with their unique relief forms and microfeatures on a regional scale, not only enrich the scientific understanding of weathering but also hold cultural, aesthetic, and educational value as part of geodiversity.

By integrating field observations, comparative studies, and advanced methodologies such as photogrammetry, this research contributes to a deeper comprehension of the mechanisms shaping granite landscapes and their role within broader geomorphic systems.

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Valinhos' Granitic Pseudokarst: 20 years of research

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Abstract

The present work briefly summarizes and compiles all speleological research done on Serra dos Cocais, a hill range located in Valinhos county, São Paulo State (Brazil), where granitic talus pseudokarstic formations can be found. We explore GGEO's "Cavernas de Valinhos" project over its 20 years of development, presenting the results available so far, reflecting upon how the research effort has interacted with the county's community, as well as suggesting what next steps may be taken. We conclude that GGEO's Valinhos Project's impact has been more social than scientific, influencing local politics and environmental preservation efforts, rather than exclusively focusing on academic publications. This shift in perspective aims to highlight the potential pseudokarst has as a subject for the general public, as well as contribute to recent publications documenting granitic pseudokarst in speleological literature with a Brazilian case study.

Resumo

O presente trabalho brevemente sumariza e compila toda pesquisa espeleológica realizada na Serra dos Cocais, uma região serrana localizada no município de Valinhos, São Paulo, onde formações pseudocársticas graníticas são encontradas. Explora-se o projeto "Cavernas de Valinhos" do GGEO, ao longo de seus 20 anos de desenvolvimento, apresentando os resultados obtidos até o momento, contemplando como a pesquisa alcançou e interagiu com a comunidade local, e sugerindo alguns próximos passos a serem tomados. Conclui-se que o impacto do Projeto Valinhos possui uma natureza mais social que científica, influenciando a política local e movimentos de preservação ambiental, ao invés de se limitar exclusivamente a publicações acadêmicas. Tal mudança de perspectiva busca ressaltar o potencial que pseudocarste possui como um tema para o público geral, além de somar às publicações recentes sobre pseudocarste granítico na literatura espeleológica, os complementando com um estudo de caso brasileiro.

1. Introduction

This paper focuses on the granite caves found in the city of Valinhos (São Paulo, Brazil) and its region, studied by two caving groups, Grupo de Estudos da Serra do Mar (GESMAR) and Grupo da Geo de Espeleologia (GGEO), over the course of 20 years. We aim to compile and present the results and insights accumulated during GGEO's "Cavernas de Valinhos" project ("Caves of Valinhos", or simply Valinhos Project), the challenges faced, its social impact and the next steps in its development.

According to the latest speleological data survey, only 2,1% of Brazil's registered caves occur in granitoids (CECAV-ICMBIO 2023), a number that, as previously stated by SOUZA et al. (2023), reflects the low production of scientific knowledge around the topic in Brazilian speleology. It must be noted, however, that there has been a significant increase in international publications regarding granitic pseudokarst in recent years (e.g. VAQUEIRO-RODRÍGUEZ et al. 2020; SANJURJO--SANCHEZ et al. 2021; RUBAN 2022), a trend we aim to complement with a Brazilian case study.

The granitic caves studied are specifically located on Serra dos Cocais, a ridge that encompasses several counties, such as Valinhos, Vinhedo, Louveira and Itatiba, in the State of São Paulo. Geologically, the region is characterized by the Morungaba Batholith, a pluton mainly composed of biotite monzogranite and biotite quartz-monzonite, as described by VLACH (1985). In recent expeditions, GGEO has recognized some regional compositional variation of the Serra granitoids (mostly on a S-N axis), including a notable presence of hydrothermal quartz on the northern Serra, occurring often in decimetrical veins, and has collected samples in order to proceed with petrographic analysis, yet to be realized, as further local scale geological projects are being planned as part of the research effort.

The landscape's morphology is composed by "boulder fields" (figure 1-A), where boulders of various shapes and sizes are distributed along the flat hilltops (MIGON 2006). Climate in the region is subtropical and humid, with well defined seasons (ALVARES et al. 2007), but, as MIGON (2006) demonstrates, climatic influence on the formation of such landforms is minor.

2. History of research in the region and methods

In 2005, GESMAR and GGEO both began, independently, making caving expeditions to Serra dos Cocais. Existence of the caves was known about in the region, but as far as documentation goes, caving groups only started visiting in 2005. In 2007, ZAMPAULO et al. published GESMAR's findings, describing two caves (Gruta Santa Rita and Gruta Espírito Santo) and expressing concern for the preservation of natural cavities in the regions, reinforcing how important such cavities are for the local ecosystem and water availability. Unfortunately, their fears proved true, as of today Gruta Santa Rita's creeks have completely dried up and the cave has collapsed.

GGEO frequently visited the region, increasing the number of expeditions, initially limited to field records. The trips continued up to 2007, when the group put the project on hiatus. In 2015, however, the project was brought back as a structured and systematic endeavor, named "Projeto Cavernas de Valinhos" (Valinhos's Caves Project), and has been continuously developed since then. ÁVILA et al. (2019) published, for the first time, the group's results, listing 22 newly discovered caves, a number that has, since then, more than doubled (see "*Results*"). SANTOS-SOUZA et al. (2020) made another publication about the project, focusing on geospeleological aspects, formation processes and speleoclimate. In 2023, publications were made about the speleothems found within the granitic caves (FERNANDES et al. 2023), and a detailed study was conducted on one cavity's speleoclimate (SOUZA et al. 2023). In 2023, GGEO's findings gained significant media attention, leading to interviews and articles about the caves. The group was contacted by Valinhos' city hall for cooperation. Their report influenced the urban and environmental zoning plan. Later, GGEO presented the project in a city council session (TRUS, 2023) and received honors. Negotiations for educational activities in public schools were paused due to local elections.

Due to GGEO's nature as a student group, field research faces resource limitations. Initially, expeditions were informal, with landowner permission to camp and record cave findings. As the project gained recognition, legal concerns prompted a formal authorization process. Systematic methods were adopted after the hiatus, including survey forms and topographical mapping using manual instruments like pocket clinometers, azimuthal compasses, and laser distance meters. Afterward, the sketches were digitized and completed using digital illustration software, ensuring accuracy and accessibility while providing an excellent learning opportunity for new members.

With the main hill of the Serra dos Cocais range becoming territory disputed by various political and economic parties, authorization to enter the properties and proceed with research started to be denied, with some landowners threatening to take legal measures if group members were to be spotted. As of 2024, GGEO put research on the central Serra on hiatus, focusing instead on a smaller hill located east, known as Serra dos Lopes. In one year, 16 natural cavities were identified in the new research area, where work has been graciously aided by Clube de Campo Valinhos residential club and Centro de Formação e Lazer Valinhos (directed by Sindicato dos Químicos Unificados), the latter playing a pivotal role in both scientific and preservation efforts in the Serra dos Cocais range.

Despite the adversities faced, the Valinhos Project continues to develop and expand. Recently, TEIXEIRA (2024 unpublished) made the granitic caves of Valinhos the theme of his graduate final paper, a landmark achievement for the project. Our hope is that, as a student group, many members of GGEO shall continue this trend of incorporating pseudokarst as the theme of their research, increasing scientific production on a subject that seems underrepresented in Brazilian speleology.

3. Geospeleology: Formation processes, cave morphology and speleothems

The formation of granite caves diverges from processes associated with conventional karst systems, as granitic rocks are less soluble than carbonates. These caves typically form in minimally ornamented talus deposits on intermediate slopes (TEIXEIRA 2024 unpublished) or in rock accumulations at cliff bases (HALLIDAY 2007). Such formations are distinctive geomorphological features that remain underexplored.

Granite caves are often located on east-west slopes (SANTOS-SOUZA et al. 2023), with vertical and horizontal developments forming randomly. Chambers are connected by narrow passages (figure 1-B and C), frequently requiring climbing or crawling. These caves are commonly associated with both surface and subsurface watercourses.

The genetic evolution process begins with the exposure of intrusive bodies and infiltration of meteoric water through faults, fractures, and horizontal joints formed due to pressure release during exhumation (SANTOS-SOUZA et al. 2023) or thermal fatigue (ÁVILA et al. 2019).

Water percolation enhances chemical weathering, rounding blocks into tors or boulders (FINLAYSON & HAMILTON-SMITH, 2003). Weathered material becomes fine-grained regolith, transported downhill to fill valleys (MARTINS 2011; ÁVILA et al. 2019).

Boulders develop pronounced spheroidal exfoliation while shifting, accumulating together, and forming voids filled by regolith, as shown in Figure 2-C. Over time, rainfall removes regolith, leaving behind empty spaces known as granite cavities. Following their formation, vegetation and roots (e.g., fig tree) often develop, playing a critical role in stabilizing granite blocks (ÁVILA et al., 2019).

Speleothems in granite caves are rare due to the low solubility of granitic rocks. However, structures like coralloids (1-E and F), primarily composed of opal-A, and flow formations have been documented (e.g., VIDAL-ROMANIi et al., 2010; VAQUEIRO-RODRIGUES & VIDAL-ROMANI, 2020; FERNANDES et al., 2023).

Researchers such as VIDAL-ROMANI et al. (2010, 2015) observed microorganisms, including bacteria, fungal hyphae, and spores, suggesting their potential involvement in speleothem formation, raising discussions about labeling these structures as "biothems" or "biospeleothems".

A recent study by FERNANDES et al. (2023) analyzed coralloid samples from Gruta das Cordas (Valinhos-SP) and Gruta das Caneluras (Bragança Paulista-SP), identifying opal-A, detrital crystals from source rocks, and biogenic minerals like barite. Despite abundant bioessential elements in microcavities, direct microbial involvement in these formations remains inconclusive.

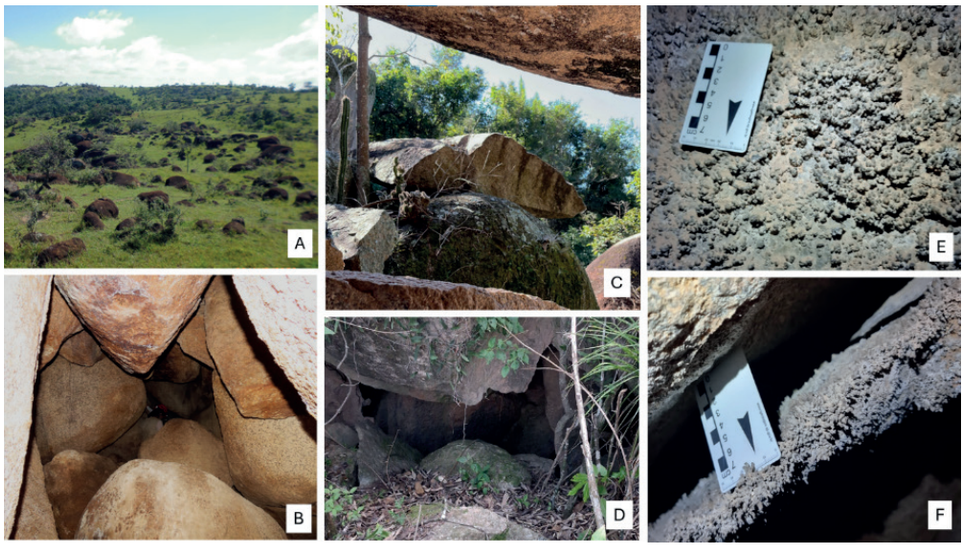


Figure 1: *A - boulder fields; B - view of typical cave passage in the Caverna Ponto Frio; C - dense vegetation growing amidst rockpiles and permeating cave formation; D - Internal view from outside of the Gruta da Encosta, illustrating typical cave entrance; E - Coralloids on cave floor in Gruta dos Corais; F - Coralloids formed on and under a sheet of partially disjointed granite in Gruta dos Corais.*

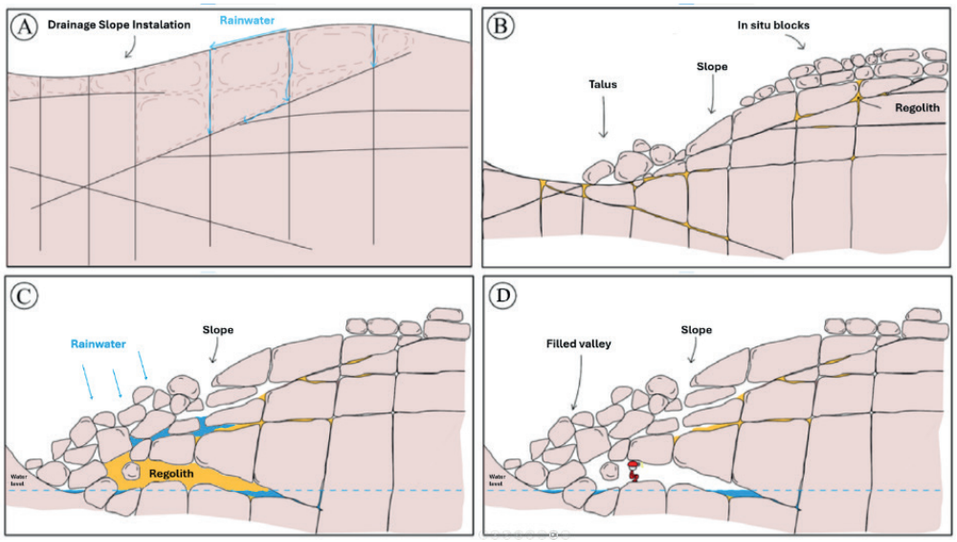


Figure 2: *Simplified evolutionary/genetic model for the formation of granite caves in Serra dos Cocais. A - Exposure of the massif, installation of drainage systems, and initiation of slope formation; B - Weathering action, differentiating the boulders through fractures, formation of the boulder field, water circulation through open fractures, formation of regolith, partial filling of valleys, and some voids between boulders; C - Accumulation of blocks with interiors filled by regolith; D - Generation of empty spaces after the transport of regolithic material. Adapted from SANTOS-SOUZA et al., 2023.*

4. Results

Presently, there are 58 documented granitic cavities in Serra dos Cocais, of which two were registered by GESMAR in 2005, while the rest was identified by GGEO's Valinhos Project. However, only four caves are currently registered in the national speleological database, and making the data officially available should be made a higher priority going forward. Regarding topography, 10 caves were fully explored and mapped, 2 by GESMAR and 8 by GGEO, respectively. We hope to see these maps compiled and published in the near future. See Figure 4 for cave distribution along the Serra

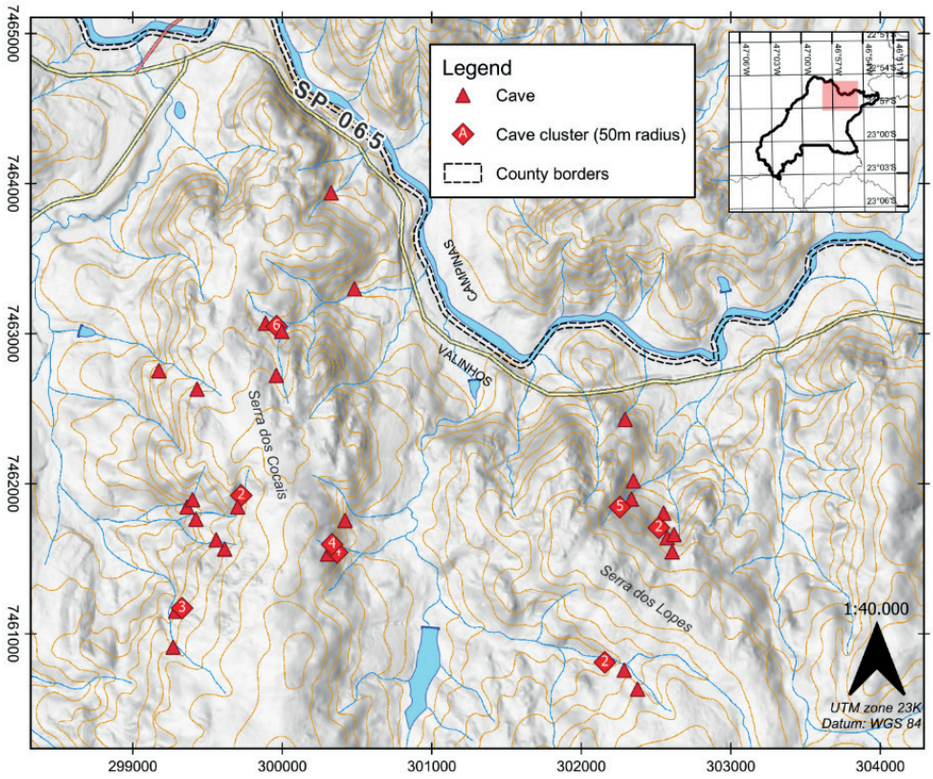


Figure 3: *Caves documented by GGEO's Valinhos Project. Top right shows the research area's location (in red) relative to Valinhos county (in black). Map updated as of jan/2025.*

5. Discussion: social, scientific and environmental implications

The Valinhos Project began as a student research initiative, seeking to understand more about granitic pseudokarst and its intricacies. However, one of its pillars today is the social impact it has on the local community, arguably, it has become the main focus of the project. As aforementioned, GGEO is a student group that relies on its own resources, seriously limiting what can be done in terms of research, but it does not limit the group's potential to reach the local citizens. While locally the existence of caves was always known, their volume and quantity were severely underestimated.

When the results reached local media outlets, some people initially questioned the novelty, as the existence of caves in Serra dos Cocais was somewhat known, albeit on a smaller scale. As the news spread, locals realized that the county contained numerous caves, sparking a growing interest in this part of their landscape. We suggest that GGEO and other groups in similar situations start formally documenting these testimonies to quantify and demonstrate the research's impact.

In terms of preservation, documenting cave occurrences helped directly shape politics surrounding Serra dos Cocais, influencing the county's urban planning, delaying potentially harmful real estate development and making the community care about something they now see as much more than boulders on hills.

TEIXEIRA's study (2024, unpublished) integrated geological and biological factors to propose guidelines for zoning an Environmental Protection Area through statistical tests and landscape analysis.

Still, the project's scientific aim was never forgotten, as attested by FERNANDES et al. (2023) and SANTOS-SOUZA et al. (2023) recent publications. While they do not present results about the whole pseudokarstic system in Serra dos Cocais, they take the first steps in a series of questions yet to be answered. Both of them are case studies, analyzing in great detail single occurrences of their respective subject, and by increasing sample size, that being contemplating other caves in speleoclimate and speleothem research, comparisons may be made and conclusions could be drawn.

6. Conclusion

The "Valinhos Project," initiated in 2005, is a student-led initiative demonstrating significant progress in cave prospecting and mapping, as well as studies on speleogenesis, speleoclimate, and interdisciplinary approaches combining geology and biology. The project shows potential to support proposals for environmental zoning aimed at protecting geological and geomorphological heritage while fostering detailed research on local flora and fauna, contributing to the conservation and sustainable management of the Serra dos Cocais.

Despite its progress, challenges remain, including integrating data into the national speleology database (CANIE), implementing educational initiatives, producing outreach materials, and formalizing public testimonials to measure social impact. Achieving these goals requires strengthening research efforts and fostering active collaboration with local landowners.

It is our belief that pseudokarst research, including on granitic rocks, shall continue to receive increasing interest in the following years. While first disregarded as a theme of low speleological potential because of low material solubility, granitic caves have shown to contain many unique features and intricacies hitherto deemed improbable.

Acknowledgments

The Valinhos Project was built by multiple generations of spelunkers, and we would like to thank everyone who participated in the last decades of research, as well as thank GGEO for the opportunity to participate in it and for all it has taught us. We are especially grateful to Fabio MOTTA for helping us expand this project further and making the most recent expeditions possible, as well as allowing us to play an important role in preserving Serra dos Cocais' biodiversity. Our gratitude is extended to Universidade de São Paulo's Institute of Geosciences, for always supporting the project and GGEO, as well as IAG/USP's Abrahão de Moraes Observatory, for housing our research team whenever possible. Finally, we thank Sindicato Unificado dos Químicos for recently funding and trusting in our work, graciously inviting us to work on Centro de Formação e Lazer Campinas' premises, allowing expansion of the research area.

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Origin of loess pipes and caves: Overlooked effect of confinement in tunnel erosion

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Abstract

Approximately 10% of the Earth's land surface is covered by loess. Mainly short caves are relatively common in loess. The ability of loess to maintain vertical cliffs indicates its considerable strength, but at the same time loess is susceptible to rapid erosion. The erosion mechanisms of undisturbed loess in pipes and caves are poorly understood due to the rapid development of these features during heavy rains or snowmelt. We developed and tested a confinement technique to simulate erosion in the deeper loess profile to explain tunnel erosion and stabilization mechanisms in loess pipes, caves, and deep gullies. Our loess blocks encased in concrete exhibit erosion rates and progressions similar to those in natural loess under field conditions. The experiments revealed a dual behavior of loess controlled by confinement: unconfined loess blocks disintegrate rapidly by air slaking when exposed to even a small trickle of water, while loess confined by the surrounding soil mass retains its original structure and resists erosion by flowing water. Pre-existing pipes <8 cm in diameter tend to resist expansion, while larger pipes or fractures induce roof instability, leading to collapse and rapid enlargement into caves. This mechanism explains the frequent development of loess caves from animal burrows and along fractures.

1. Introduction

In numerous locations across the globe, deep gorges have been carved into the loess, with vertical cliffs reaching heights of up to several tens of meters. The capacity to sustain vertical cliffs indicates the considerable strength of the loess, yet simultaneously, the loess is susceptible to rapid erosion. Loess thus exhibits a somewhat unexpected combination of properties: it is surprisingly firm as friable sediment, yet simultaneously highly erodible. Gully erosion plays a pivotal role in the formation of loess landforms, significantly alters the original land surface and is responsible for a considerable proportion of eroded sediment from loess catchments (Zhu 2012).

Large soil pipes and caves (often referred to as tunnels) are common in loess (e.g. Lukić et al. 2009; Pavuza and Plan 2013; Peng 2018). Zhu (2012) studied about 970 loess caves on the Loess Plateau, China. The depth of the caves is limited to 30 meters below ground level, with the majority occurring at a single level. They are located above the groundwater table in the unsaturated zone and below the area that gets extensively wetted after rains. Loess caves are steep. The caves exhibit dendritic pattern, whereby numerous inlets converge to form a single outlet. Inlets do not occur in flat plateau, instead they are dominant at slopes with gradients exceeding 30o (Zhu 2012; Peng 2018). Inlets possess a considerably larger volume (diameter up to 20 m) than the draining caves (cross-section below 3 m^2). Also, field surveys showed frequent temporary blockages of caves due to roof collapses. Inlets occur abruptly after catastrophic storm events, e.g. 67 inlets occurred after single storm in 2000 with a recurrence interval of 50 years (Zhu 2012) and the mean velocity of intermittent cave flow was 0.26 m/s (Zhu, 2012). All discharge from the caves was derived from overland flow entering via the cave inlets. Peng (2018) studied factors controlling the occurrence of loess caves and found that shallow caves develop from animal and plant holes, whereas deeper ones develop along tectonic fractures.

While considerable attention was paid to erosion experiments of topsoil in loess, much less is known about the erosion mechanisms of undisturbed loess occurring in pipes, or caves (Quiao et al. 2018). Wang et al. (2019) presented clear evidence for gravitational collapse (failure) as the most important erosion mechanism in loess caves.

It was shown that friable sandstones and locked sands at the boundary between engineering soils and soft rocks can be stabilized by tight radial confinement, for example, in a concrete casing (Bruthans and Řihošek 2017; Filippi et al. 2021). Such casing acts as if small sample of material is part of a larger outcrop. Stress and confinement applied to a sample avoids material expansion (dilation), which is often a prerequisite for material structure failure. Recently, it was demonstrated that confinement and overburden stress are important stabilizing mechanisms in loess that avoid its erosion by air slaking (Vojtíšek and Bruthans 2024).

The objective of this work is to simulate erosion in the deeper loess profile (loess pipes and caves), and to help explain erosion and stabilization mechanisms.

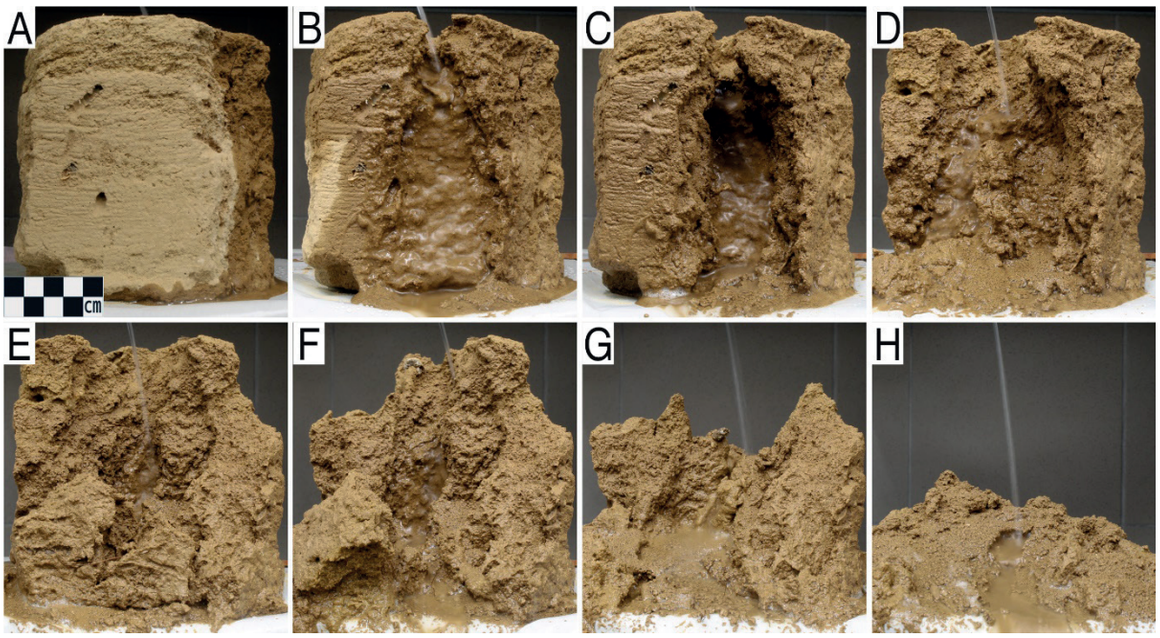


Figure 1: *Time-lapse photographs showing the course of the erosion experiment of an unconfined UN.x.2 loess block. Total volume of water used: A 2,1 L, B 6,9 L, C 10,5 L, D 11,4 L, E 12,6 L, F 13,5 L, G 18,6 L, H 19,5 L. The unconfined block was rapidly eroded away by small trickle of water.*

2. Materials and methods

Loess blocks (decametric in size) were sampled from an overhanging loess outcrop at the abandoned Hubenov loess pit. The field experiment was conducted at the Střeleč quarry instead of Hubenov, as Střeleč offered better accessibility and sufficient water supply. Loess at both sites has similar properties, with the Fe-Al oxides and hydroxides serving as the primary of cohesion agents, while carbonates and organic matter contribute as minor cohesion agents.

The weathered soil layer was removed to ensure that the blocks consisted only of loess with preserved structure. Two types of experiments were conducted: unconfined blocks, where all sides were exposed, and confined blocks, where the loess was encased in concrete. The unconfined blocks were placed on a concrete slab covered with plastic sheeting. For the confined experiments, the blocks were wrapped in 2-4 layers of wrapping foil before being embedded in a 3-8 cm thick quick--setting concrete casing reinforced with fiberglass mesh. The purpose of encasing the blocks in concrete was to prevent dilatation, the increase in volume that leads to fracturing and structural damage. By preventing dilatation, the behavior of the loess block simulated the conditions of a continuous loess mass, where the surrounding soil constrains expansion. Importantly, the wrapping foil was not tightened and did not compress the blocks, it served solely as a protective layer to prevent concrete or its leachates from penetrating into the loess and possibly altering its strength or erosion resistance.

The confined blocks were not completelly encased in concrete, some faces were left exposed to simulate the conditions of loess surfaces in natural pipes or caves. Some blocks were further modified by drilling holes or creating fractures to introduce pre-existing secondary porosity, allowing water to flow more rapidly than through the natural intergranular pores in loess

In the experiments, a stream of water was applied directly to the blocks as an erosion agent. As erosion progressed and most of the loess was removed from the affected area (the thickness of the loess at a given place was diminishing), the water flow was redirected to ensure that the erosion process continued and to avoid situations where erosion would be limited by the absence of loess. Three different flow rates were used: low (4-5 mL/s), medium (16 mL/s), and high (~330 mL/s).

Eroded loess was collected in a small container situated directly under the experimental blocks. At exponentially increasing durations of erosion steps (1 min, 2 min, 4 min, 8 min, 16 min, 30 min, 60 min, 2 h, 4 h, etc.), the water flow was stopped and the sediment container was replaced. The collected sediment was dried under laboratory conditions (25°C, 45% RH) to a constant weight, and the dry mass for each erosion step was recorded. The flow rate was multiplied by the duration of each erosion step to calculate the total volume of water causing erosion. Subsequently, The erosion rate was then normalized and expressed as the dry mass of loess eroded per a unit volume of water (g/L).

To compare the behavior of loess blocks in the laboratory with in situ loess, a field experiment was conducted at the Střeleč quarry. The surface zone was carefully removed to expose loess with intact original structure, and the water flowed through a predrilled hole in the loess outcrop.

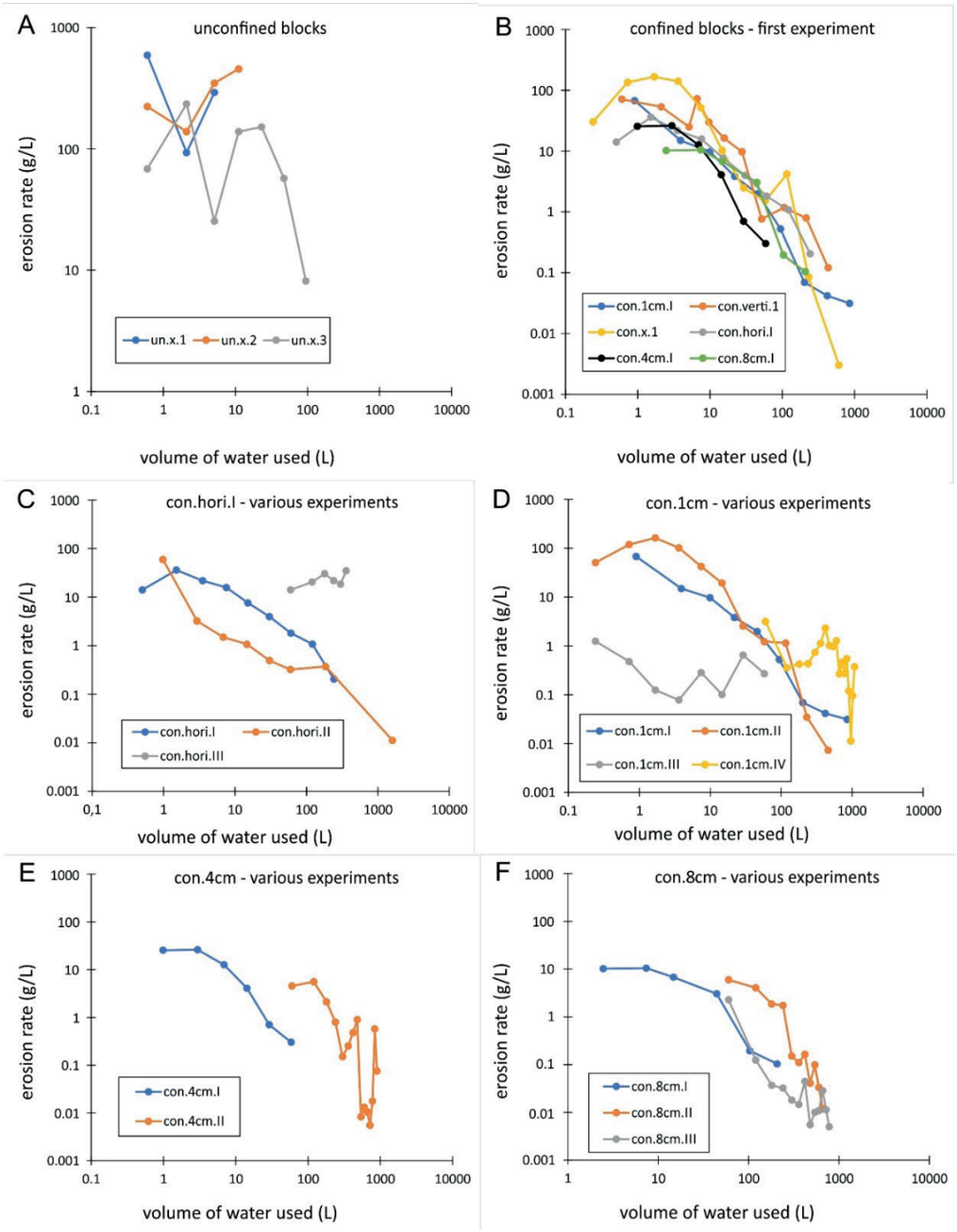


Figure 2: *Change in erosion rate with erosional progress: A – Unconfined blocks; B – Confined blocks, first experiment C – Confined blocks CON.hori -various experiments; D – Confined blocks CON.1cm -various experiments; E – Confined blocks CON.4cm -various experiments; F – Confined blocks CON.8cm -various experiments. As the individual experiments differed in the flow rate used, the evolution of the erosion rate is plotted against the accumulated volume of water used.*

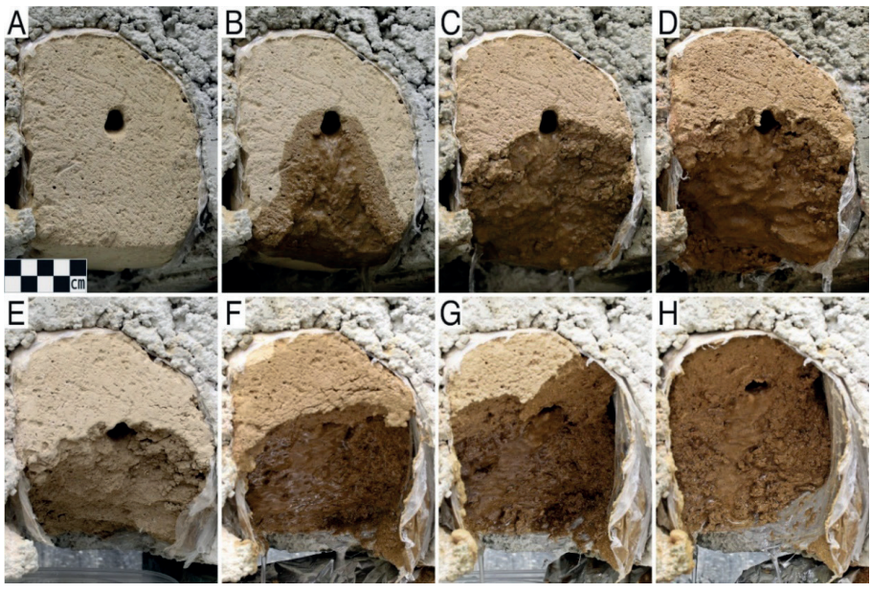


Figure 3: *A to D – CON.1cm erosion experiment; E to H – erosion experiment CON.1cm.II. Total volume of water used: A 0 L, B 0,3 L, C 1,5 L, D 35 L, E 850 L, F 853 L, G 855 L, H 864 L.*

3. Results and discussion

The experiments carried out on loess erosion have revealed a significant distinction between the erosion behavior of confined and unconfined loess blocks. Unconfined blocks consistently exhibited a high erosion rate that did not decrease with time (Fig. 1), whereas confined blocks eroded only in parts that were not well confined (Figs. 3, 4). Once these less confined parts eroded, the erosion rate decreased rapidly, typically following a power-law relationship (Fig. 2). This clearly shows that when loess is restrained from dilation (expansion), its resistance to erosion increases significantly. This stabilization effect can be achieved simply by preventing lateral dilation to the sides, even when the front of a loess block remains exposed to erosive agents. The simulated confinement simulates natural loess conditions such as erosion within a pipe, deep gully or cave wall where the surrounding loess mass prevents dilation. The results provide an unexpected dual nature of loess as a material with seemingly incompatible behaviors: unconfined loess, such as a block fallen to a cave floor or gully bottom, acts as a highly erodible material where even a low-intensity water flow results in high erosion rates (hundreds of g/L). Whereas, loess confined by the surrounding soil mass is much more resistant to erosion (erosion rate less than 1 g/L), unless structural failure occurs due to excessive tension, shear due to its own weight or seepage forces (such as loess in a cave).

The experiments with predrilled holes in confined loess blocks (CON.1cm, CON.4cm CON.8cm), show a remarkable resistance of loess to erosion by flowing water. Contrary to expectations, these holes with a diameter less than 8 cm did not expand significantly under the shear forces exerted by flowing water, even at high velocities. This finding suggests that pre-existing openings <8 cm in diameter are insufficient to cause effective erosion by water alone. On the contrary when the hole diameter exceeds about 8-15 cm, roof failures become frequent because the loess cannot support itself, leading to rapid enlargement of the opening. The exact threshold is propably to be material specific to some extent and requires further research.

The existence of this threshold has far-reaching implications for understanding cave formation in loess. Smaller pre-existing openings remain relatively stable with minimal erosion by flowing water, whereas larger openings expand rapidly due to the ceiling failures and subsequent rapid removal of the collapsed debris by water flow. This finding is consistent with field observations that pipes and caves in loess often follow larger pre-existing openings – such as badger burrows, easily eroded sandy layers or open fractures (Peng et al. 2018; Quiao et al. 2018).

The field experiment conducted at the Střeleč quarry demonstrated that the behavior of confined blocks under laboratory conditions is comparable to that of in situ loess (Fig. 5). This shows that the use of concrete frames effectively simulates the conditions acting on natural in situ loess. Observations from both laboratory and field experiments indicate that, prior to being entrained by flowing water, loess first disintegrates from a cohesive mass into fragments, which are only then transported by flowing water. In dry loess, air slaking can break down wetted loess into very fine particles that cause turbidity in water, making disintegration a key prerequisite for erosion.

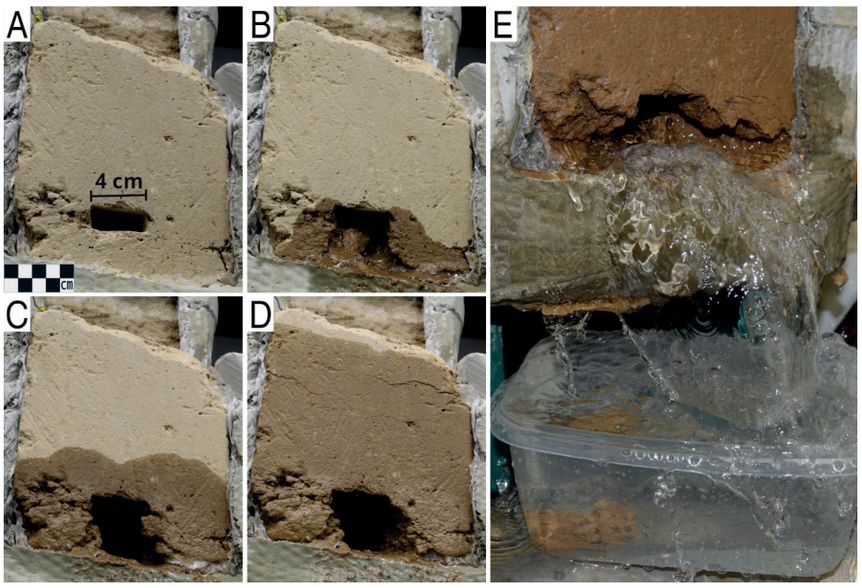


Figure 4: *A – Erosion experiment CON.4cm; B – Clear water coming out of the hole during the CON.4cm.II experiment. Total volume of water used: A 0 L, B 1,5 L, C 4,9 L, D 28,3 L. See transluscent water not eroding confined loess.*

4. Conclusion

Study of the origin and evolution of caves in loess is complicated as they are created nearly instantly under heavy rains, when field observations are hazardous for both people and equipment. Laboratory study of erosion in deeper loess profile is complicated by the need to properly simulate field conditions. This study demonstrates that loess blocks confined in concrete show erosion rate and progression similar to loess eroding in situ in the field. This approach enables the simulation of piping erosion on decametric blocks in laboratory under conditions similar to those found in the field, allowing to test conditions under which pipes evolve into caves and the processes that contribute to their enlargement.

Experiments demonstrated that loess has a dual behavior. Decametric or smaller unconfined loess blocks disintegrate rapidly by air slaking when exposed to even a small trickle of water, and can be washed away within tens of minutes with erosion rates typically in the hundreds of g/L. On the contrary, when loess is confined by surrounding soil mass and has its unweathered original structure, such as in the sides of a pipe or cave, it may resist erosion by flowing water, resulting in erosion rates often well below 1g/L of applied water. Under these circumstances, seepage forces and gravity failures drive pipe expansion into cave. Confinement thus serves as an important stabilizing mechanism, significantly increasing the erosional resistance of loess in situ. The difference in loess behavior is due to confinement's effect on loess dilatation (expansion), which preconditions its disintegration into fragments that can be transported by water. If the loess cannot freely dilate, its resistance to erosion is considerably increased. For effective stabilization of loess, it is sufficient to prevent lateral dilatation, even if the front side of the loess remains free. This condition mimics erosion in a pipe or cave, where dilation is restricted by the surrounding loess mass.

Concerning pipe diameter, there is a threshold between about 8 and 15 cm. Pre-existing holes smaller than this threshold tend to resist enlargement, while larger holes or fractures trigger ceiling instability, leading to collapse and rapid expansion into cave. For loess pipes and caves to form, a pre-existing space or inhomogeneity, such as fractures, is critical. This explains why loess caves often develop from animal burrows, along fractures, or other inhomogeneities.

Acknowledgments

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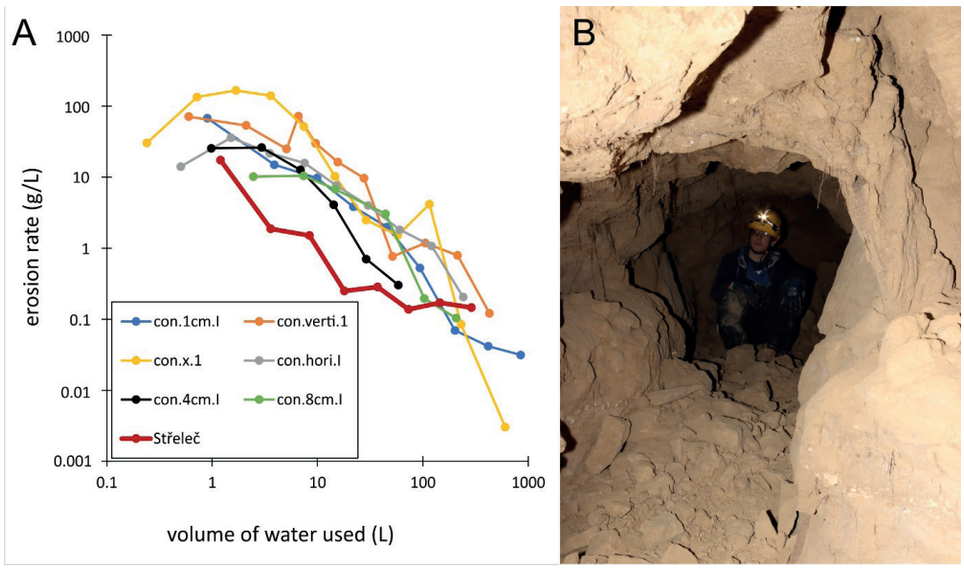


Figure 5: *A – Comparison of erosion rate on loess in situ in quarry face in Střeleč with laboratory experiments. B – Loess cave in Věstonice, Czech Republic developed along badger hole. Note debris on the floor from cave enlargement caused by the collapses of the cave roof.*

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Session 13

VOLCANIC CAVES

Geoheritage values and conservation of the Billemot Cave in Jeju Island, South Korea

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Abstract

Billemot Cave is a labyrinth-type, multi-leveled lava tube cave which is approximately 10,050 m in length. This cave was considered as a strong candidate for extensional World Heritage Site. It exhibits a braided maze form, predominantly developing in one direction, with pathways intricately divided by numerous lava pillars of varying sizes. Inside the cave, various lava speleothems and micro-topographic features enhance its geoheritage values. Especially notable are the lava speleothems such as tubular lava helictites, cylindrical lava stalactites (up to about 20 cm long), and lava stalagmites (approximately 75 cm high). Additionally, diverse micro-topographic features further elevate its geoheritage significance. The cave also contains numerous secondary speleothems composed of opaline silica, enhancing its scenic value. Sediment deposits up to about 2 meters thick, have been transported through small cracks in the cave ceiling. They span approximately 1.4 km and may serve as a potential indicator for tracing paleoclimate. Numerous vertebrate skeletons, presumed to be from cats or badgers, have been found above the sediment deposits. Also known are the other animal bone fossils, including those of brown bears, red deer, and roe deer, which are estimated to be Paleolithic in age. To conserve the geoheritage value of the cave, the Jeju Special Self-Governing Province conducted environmental restoration as well as extensive surveys. This involved removing all graffiti and various waste materials to restore its integrity.

1. Introduction

Billemot Cave is located on the western part of Jeju Island, approximately 100 km south of the Korean Peninsula (Fig. 1). Jeju Island is a volcanic island formed by multiple volcanic activities that occurred from around 1.5 million years ago to the historical period. The overall topography of Jeju Island is characterized by the central Hallasan shield volcano, about 360 monogenetic volcanoes (scoria cones, tuff cones, and tuff rings), and expansive lava plateaus in the coastal lowlands (Woo et al., 2013). It is estimated that approximately 150 lava tube caves are distributed on Jeju Island. Among these, some have been recognized for their natural heritage value and are legally protected as national or provincial monuments. In 2007, the 'Jeju Volcanic Landforms and Lava Tubes', including the serial sites of the Geomunoreum Lava Tube System, Seongsan Ilchulbong Tuff Cone, and Mt. Hallasan, was inscribed as the World Natural Heritage property in Korea for criteria (vii) and (viii). At that time, UNESCO recommended to extend other additional significant caves and volcanic landforms. Consequently, Billemot Cave was selected as a strong candidate (JSSGP, Jeju Special Self-Governing Province, 2016). The cave possesses high natural and cultural heritage values. However, it was excluded from the final candidate list due to insufficient geological data such as its precise dimension and formation processes as well as its integrity issues (i.e., intactness).

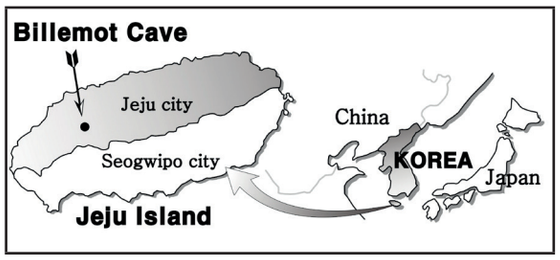


Figure 1: *Location of the Billemot Cave.*

Recognizing the significance of Billemot Cave's geoheritage values, the JSSGP and the National Heritage Service in Korea have undertaken various projects. Detailed cave exploration, mapping, and scientific investigation were conducted to determine its exact dimension and the geographic distribution on the surface. Additionally, to conserve the cave biodiversity and to enhance the geoheritage value through restoration, various projects were carried out to remove various discarded wastes and graffiti within the cave. Also, systematic and effective management plan was established for sustainable natural conservation. This paper aims to introduce some results obtained by the Cave Research Institute of Korea through these projects.

2. Methods

To obtain accurate data on the dimension of the cave, its distribution on the surface, and the thickness between ceiling of the cave and overlying surface, a high-resolution 3D scan survey was conducted. Ground-based laser scanning technology was utilized to produce an accurate pointed, cloud-based 3D model of the cave, measuring its location, passage direction, and scale. The thickness from ceiling of the cave to the surface was measured by comparing the vertical position of the cave with the surface elevation. To verify the accuracy of the 3D scan survey and its relationship to the exact location of the cave, core drilling survey was conducted.

Various special lava speleothems and micro-topographic features formed by subsequent lava flows after the cave formation as well as secondary minerals were documented and marked on the cave map. Some speleothems were sampled, cut in the laboratory, prepared into thin sections, and observed under a polarizing microscope. For sedimentological analysis of cave sediments, three sites were selected for logging, and undisturbed sediment samples were continuously collected with depth using transparent acrylic slabs (5 cm × 20 cm × 1 cm and 7 cm × 30 cm × 1 cm). From the slab samples, subsamples of 2 cm thickness were obtained. Various analyses such as grain size, water content, and organic matter content as well as soft X-ray photography, were conducted on the sediment samples. Following a review of existing archaeological data, field investigations were conducted to confirm the excavation sites associated with the archaeological data. A distribution survey of animal bones within the cave was also conducted. For environmental restoration, the current level of pollution was first assessed to determine the types and distribution of waste for collection. The removal of graffiti, such as paint, employed dry and wet cleaning methods similar to those used in cleaning stone cultural heritages. These efforts were designed to minimize impacts on cave fauna by assessing their habitat status in advance and taking measures to reduce any potential effects on them.

3. Results

The total length of the cave is approximately 10,050 meters (main passage = about 2,830 m, branch passages = about 7,220 m). The average thickness between cave ceiling and the surface is approximately 13.9 meters (minimum = about 5.0 m, maximum = 26.6 m). The relief between the cave entrance and the end point of the main passage is about 132 m (Fig. 2).

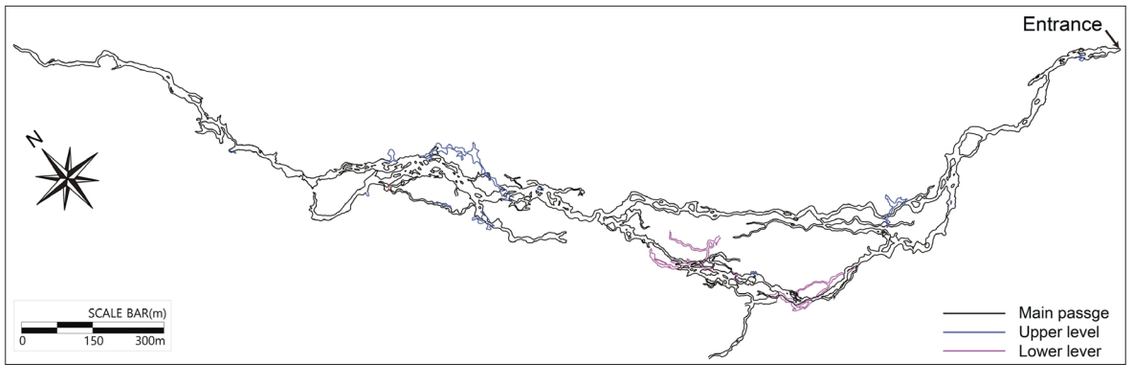


Figure 2: *Plan map of the Billemot Cave.*

Overall, the cave was formed in a southeast to northwest direction and it features a maze-like network structure with multiple branches and levels. This kind of high-resolution data allows for the accurate identification of the cave's location, providing essential data to protect the cave as well as the safety of residents living nearby. Also, any human activities near the cave can be regulated. Utilizing the results from ground-based laser scanning, two-dimensional and three-dimensional spatial analyses can be conducted through overlapping analyses with digital terrain maps, continuous cadastral maps, and orthophotos. This information has provided fundamental data for future management plan related to cave conservation and future potential threats by human activities.

Inside Billemot Cave, primary lava speleothems such as lava stalactites and straws, lava stalagmites, lava columns, and lava helictites are heavily distributed, and those speleothems have formed during the same period as the cave formation. Especially notable are the numerous cylindrical large-sized lava stalactites and stalagmites with a about 75 cm-high lava stalagmite. They are distributed throughout the entire section of the cave (Fig. 3). Examinations of the cylindrical lava stalactites under a microscope revealed that they display typical basalt texture with fine to medium-sized (1–5 mm) olivine and thin, rod-shaped plagioclase, with well-developed vesicles (Fig. 4).

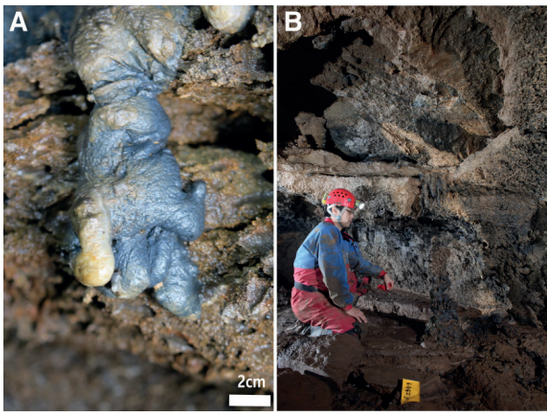


Figure 3: *Erratic-sized lava stalactites. Note that the stalactite in (B) is about 75 cm long.*

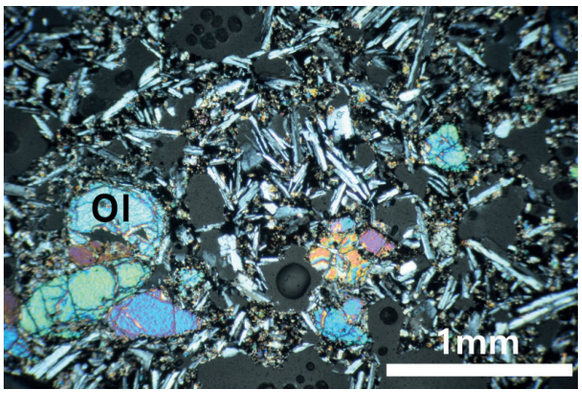


Figure 4: *Cross-polarized thin section photomicrograph of lava stalactite. Ol= olivine.*

Billemot Cave displays a variety of micro-topographic features such as gutters, lava levees, lava drapes, lava pillars, lava shelves and benches, rock falls, welded collapsed lithified lavas, lava balls and drafts, lava tongues, lava flowlines, and oval-shaped ceilings. Especially notable are the presence of numerous large and small lava pillars, which created a complex network of intricate mazes (Fig. 5). Secondary speleothems, which have been formed by groundwater into the cave after the cave was finally cooled down, are found. Most of them have a shape of cave corals (Fig. 6A), which are entirely composed of opaline silica. Examinations of such siliceous cave corals under a microscope show irregular, but continuous growth laminae, which effectively demonstrate the complex growth history of these secondary speleothems (Fig. 6B).

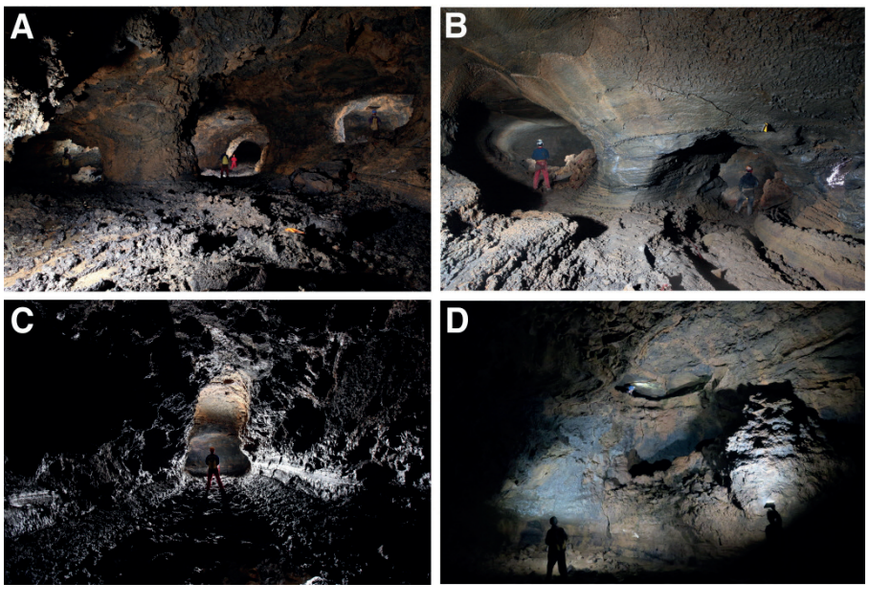


Figure 5: *Various shapes of the passages in Billemot Cave and internal features. (A) Typical anastomosing passages in the cave, (B) Divided passages by lava pillar, (C) Single main passage with lava benched on both sides, (D) Multi-levelled passages.*

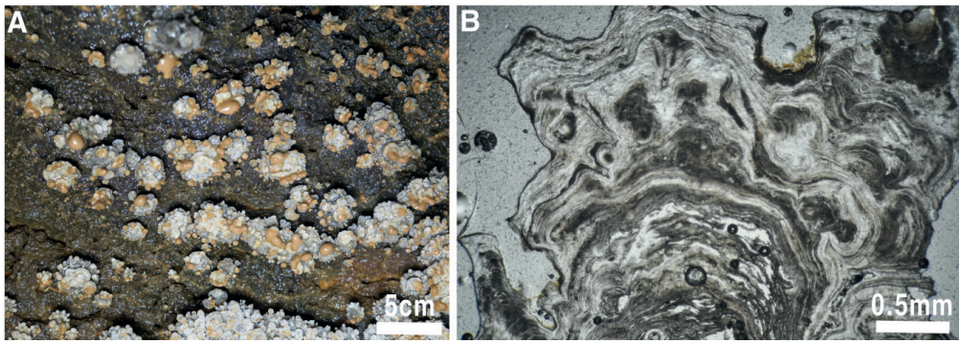


Figure 6: *(A) Cave corals formed by secondary mineralization on cave wall and floor. (B) Plan-polarized thin section photomicrograph of (A), composed of opaline silica. Note numerous growth laminae within the cave coral.*

Currently, most of the animal bones found inside the cave are rodent skeletons which were recently brought into the cave by accident. Previously discovered skeletal remains include bones from the brown bear (*Ursus arctos*), red deer (*Cervus elaphus*), and roe deer (*Cervus capreolus*). The presence of brown bear bones probably supports the theory of land connections between Jeju Island and the Korean Peninsula during previous glacial periods. The discovered deer bones have been reported to be abundant in Europe during the Late Pleistocene and it is interesting that the similar kind of animals also has been frequently found in South Korea during the Middle Pleistocene. Additionally, the analysis of the deer bones identified two teeth and one joint bone classified as continental sika deer (*Cervus nippon*), and some of the bones exhibited the butchering marks as a trace of human activities (Park et al., 1985).

Muddy sediments with various thickness are distributed along the main and branch passages of Billemot Cave (Fig. 7). It appears that the sediments are entirely derived from the surface through the cracks in

ceiling. They are primarily consisting of silt-sized quartz grains and clay minerals. Compared to the branch passages, relatively thicker sediments tend to be deposited along the main passageway. Additionally, relatively thicker sediment layers are also found in areas where there are branching passages or where rock collapses are dense, particularly toward the downstream sections of the cave. Overall, the sediment texture and composition are similar throughout the entire section. This kind of cave sediments with varying thickness of several meters has not been reported in any volcanic caves on Jeju Island. It is expected that the sediment deposits may provide significant information on past climate changes on the surface of Jeju Island. The sediments also can draw the minimum age of the cave formation.

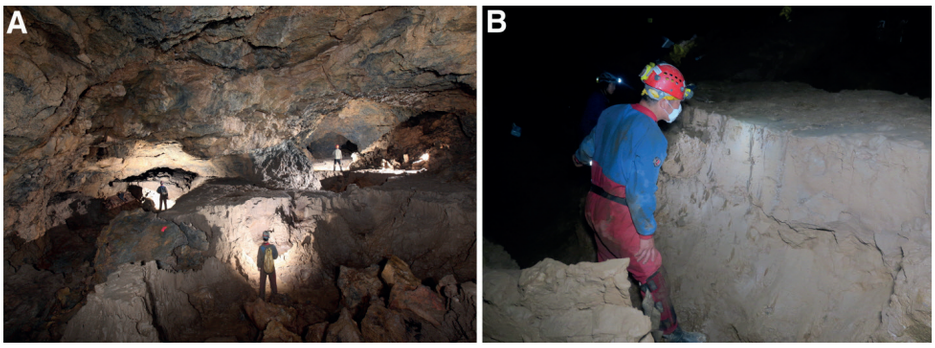


Figure 7: *Cave sediments in Billemot Cave.*

4. Cave restoration: Removal of graffiti and trash

For the graffiti removal, both dry and wet cleaning methods are employed. For dry cleaning methods, bamboo sticks, brushes, scalpels, tweezers, and dental tools are used to remove any contaminants with enough force to prevent damage to the rock surfaces. The sites where the dry cleaning was not effective were treated with wet cleaning methods. For this, distilled water was used with brushes and sponges to remove most of the graffiti. In locations where removal was still not possible, solvents (ethyl alcohol) were utilized to eliminate the graffiti. For most sites, these methods were very effective (Fig. 8). The methods for dry and wet cleaning are as follows, respectively. Dry cleaning procedure is as follows: (1) Conduct experiments to determine the intensity and frequency of cleaning for each location in advance. (2) Remove dust from the cleaning areas using a brush. (3) Use various types of small tools as mentioned above to remove contaminants without any damage to rock substrates. (4) Use a soft brush to remove any residual dust and imported materials during cleaning. Wet cleaning procedure is as follows: (1) Conduct experiments to select a solvent (ethyl alcohol, methyl alcohol, acetone, or thinner) for the different types of paint in the cave, ensuring minimal impact on cave fauna and the cave environment, and ensuring worker safety. (2) Perform experiments to determine the intensity and frequency of wet cleaning for each location. (3) Try to lower the intensity and frequency of overall surface cleaning with distilled water and ethyl alcohol to minimize impact on cave fauna and the cave environment. (4) Ensure that no contaminated cleaning solution remains on the rock surfaces by using distilled water and scientific cleaning tissues and towels for removal.

In order to collect various types of litter abandoned inside the cave, all the crevices and narrow spaces were checked. Depending on the size and type of the trash, tweezers, a portable rechargeable vacuum cleaner, and magnets were used for collection. After transporting the collected trash outside the cave, some items were kept for future educational purposes, but others were processed through recycling.



Figure 8: *One examples of the graffiti site showing the removal effect in Billemot Cave.*

5. Conclusions

Billemot Cave is the longest cave among both limestone and volcanic caves in South Korea, with a size of approximately 10,050 m. It features a labyrinthine structure with a variety of lava and secondary speleothems as well as very special micro-topographic features in the cave. Inside the cave, there are also sedimentary deposits and animal skeletons, and some of them are Paleolithic in age, which may well hold potential values for paleoclimate implications. Significant efforts were made for the restoration and conservation of the Billemot Cave for effective management. In the future, further research on the origin of lava flows for the cave formation and formation processes of this labyrinth-type passages would further enhance its geoheritage values.

Acknowledgment

The authors are grateful to the Jeju Special Self-Governing Province World Heritage Headquarters and Korea Heritage Service who supported several projects to the Cave Research Institute of Korea.

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Morphometric analysis of lava tubes.

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Abstract

Lava tubes are objects of great interest not only for their role in the formation of lava flow fields on Earth but also for their implications on the emplacement of lava terrains across the Solar System. These features have been detected on the surface of Mars and the Moon through satellite imagery as sinuous collapse chains interpreted as surface evidence of subsurface conduits. To date, subsurface conduits have not been observed yet. Indeed, through the study of terrestrial analogues, it is possible to infer the potential lava tube morphologies beneath the surface of Mars and the Moon. Different authors have proposed possible morphometrics indices to describe the genetic features of some particular karst caves. Here, we have applied the same approach to terrestrial lava tubes. Digitizing lava tube surveys in several sites all over the world allowed us to extract dimensional parameters and gather them in a global database. Lava tubes on Earth have different morphologies and sizes, potentially associated with specific eruptive (effusion rates, trend and duration of the eruption) and slope parameters. In this work through the correlation of all the variables, we had obtained useful information to understand lava tube genetic processes and their evolution on Earth and possibly on other planetary bodies.

1. Introduction

Interest in planetary geology has increased in recent years, with a growing focus on planetary analogues. Among the planetary features considered as analogues, lava tubes are suitable structures for future human bases being natural shields against space weathering and micrometeorite impact and being charachterized by a comfortable surface environment with low thermal excursion. Lava tubes are primary volcanic rock caves (KEMPE,2019) defined as a "roofed conduit of flowing lava, either active, drained, or plugged" (HALLIDAY, 2004; SAURO et al., 2020). These features work as thermally efficient conduits, where the minimization of heat loss allows the transport of lava flows over long distances up to several tens of kilometres, playing a key role in forming many lava flow fields (CALVARI & PINKERTON 1999; TOMASI et al., 2022). The genetic processes proposed for these peculiar cavities are: "overcrusting", which occurs due to the quick cooling of the surface and lateral levees of a lava channel (HALLIDAY, 2004; KEMPE 2019; SAURO et al., 2020);"shallow inflation", which initially acts within thin sheets of pahoehoe and thus is usually characterized by an elongated superficial bulge d and an original horizontal elliptical cross-section (SAURO et al., 2020), and "deep-inflation", which formed through inflation along deep inception horizons following previous lava flow boundaries where, after inflation, the conduit has been enlarged by downward thermo-mechanical erosion and breakdown phenomena (KEMPE 2019; SAURO et al., 2020; TOMASI et al., 2022).

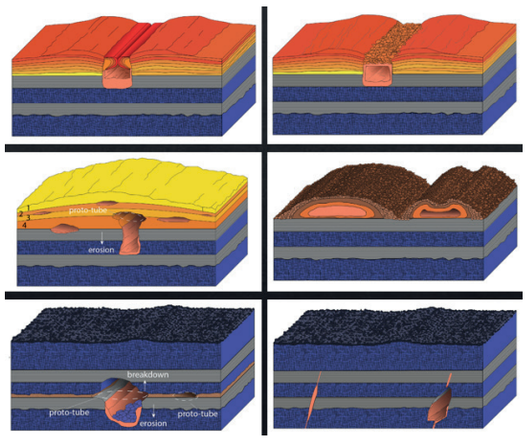


Figure 1: *The three main genetic processes proposed for lava tube formation, from top to bottom: overcrusting, shallow inflation, and deep inflation (modified from Sauro et al., 2020).*

As for the karst caves, even the lava tubes show a wide variety of morphologies and patterns in the function of several parameters. There are several types of lava tubes: (a) single-trunked systems; (b) double (or multiple) trunked systems; and (c) superimposed-trunked systems (KEMPE, 2019). The main patterns observed for lava tubes are the single tube which can be sinuous or rectilinear and braided tube with splitting and reconnections (SAURO et al., 2020), loop morphology, or branches that developed in different directions. The multi-level features are related to superimposed levels connected by lava falls, shafts (SAURO et al., 2020), or often by internal skylights. Thanks to digitalization many dimensional parameters and morphometric indices can be derived from 2D surveys (PICCINI, 2011). Morphometric indices have been proposed to describe the genetic features of some particular

types of karst caves (KLIMCHOUK, 2003; PICCINI, 2011). Therefore, a similar approach was used in this work to extract parameters and indices to characterize and better understand the lava tubes and their evolution from a quantitative perspective.

2. Materials and methods

For this work, 36 lava tube surveys were taken into account from five different areas: Mount Etna Lanzarote Iceland Galapagos, and Hawaii. These places are similar considering the deep source of the magma, and the basaltic emplacement. The selected surveys had a length higher than 100 meters, complete with the plan map and the longitudinal sections. All of them were digitalized using AutoCAD software to reconstruct the plan map longitudinal sections and cross-sections. The dimensional parameters extracted from the surveys were useful for deriving important morphometric indices. Some of the most interesting are: *PL* the total length of the cave not considering the inclination, and the Es the long side of the minimum oriented rectangle including the plan map. The ratio between *PL* and *Es* results in the *Hci*, horizontal complexity index (PICCINI, 2011). Other important parameters are the average slope of the cave and the AP which is the area of the plan map. The *Ap-Es* is an index described in this work for lava tubes (the ratio of *Ap/Es*). The last two important parameters are the aspect ratio of the average cross-section Ar and the total vertical range *Vr* which is the sum of the negative and positive drop of the cave. Field observation of some of the biggest lava tubes in Lanzarote and Mount Etna had a role in understanding some of the results of the morphometric analysis and allowed us to observe some morphologies not visible in the surveys.

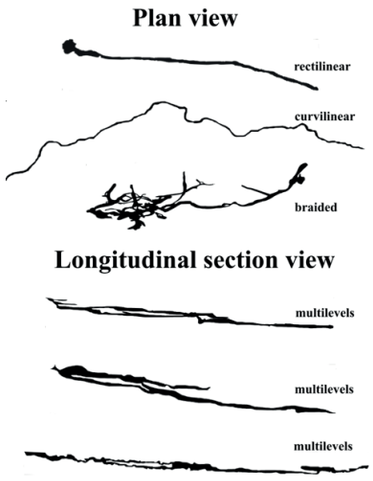


Figure 2: *The plan view of lava tube sketches highlights the varieties of lava tube patterns. The Longitudinal section sketches show the multilevel structures of lava tubes.*

3. Results

Thanks to digitalization, 27 dimensional parameters, and morphometric indices were extracted and gathered in a database. Thanks to the 3D model of La Corona lava tube, was possible to compare and prove the reliability of the methods adopted for this work. Indeed some parameters and indices extracted from the 3D model of La Corona (SAURO et al., 2020), show a good match with the data obtained through the 2D digitalization. Once compared parameters and indices some interesting results were observed. In particular, the plot of *PL* and *Es* highlighted the boundary between single-type and braided-type tubes, the *Hci* was correlated with the slope showing two different ranges in which single tubes and braided tubes can form. The *Ap-Es* vs *Ar* plot shows a possible evolution of the caves, Indeed, the *Ap-Es* index is correlated to the lateral coalescence that can occur in a lava tube, while *Ar* shows the possibility of whether a vertical incision occurs or not. The last plot of *Ar* vs *Vr* highlighted a possible way to distinguish the genetic processes related to the cross-section of the lava tubes and the role of thermal and mechanical erosion. For high values of *Vr*, low values of *Ar* were observed, while low values of *Vr* may be related to both high and low values of *Ar*. These results highlighted the relationship between the controlling factors (Effusion Rate, slope) and the resulting lava tube morphologies. The results are confirmed by the internal morphologies and presence or absence of lava layers of the three caves observed in the field, La Corona and Los Naturalistas in Lanzarote, and Tre Livelli on Mount Etna.

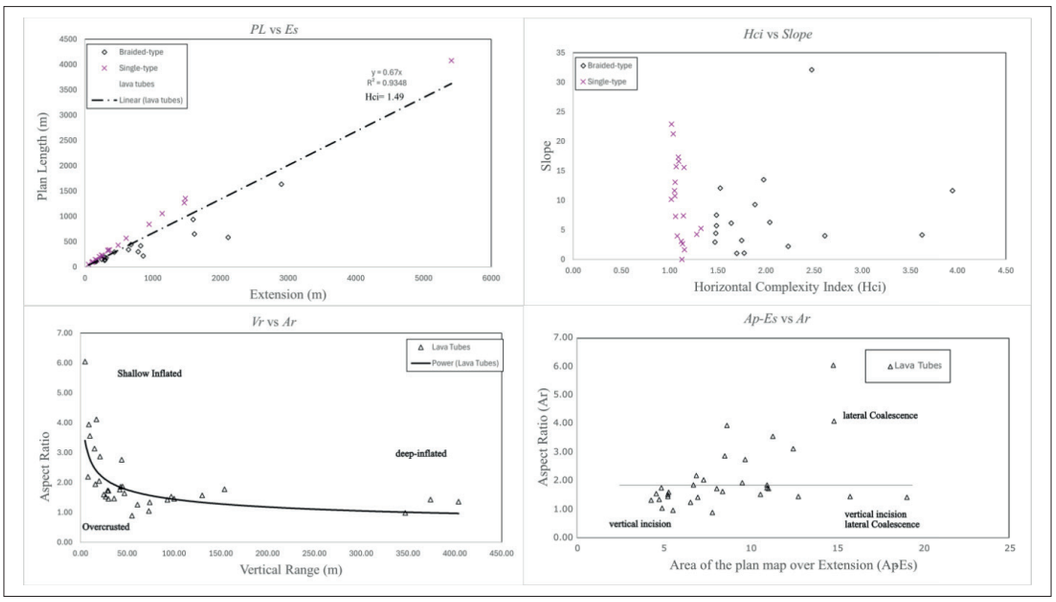


Figure 3: *The results of correlation of the parameters and morphometric indices 1) Plan Length vs Extension results in the Horizontal complexity index which allow us to classify lava tubes: 2) The Hci vs the slope plot highlight the role of slope in forming lava tubes, for slope higher than 15 braided tubes does not form except for one tubes, 3) The Vertical range vs Aspect ratio show the variation of Ar in function of the Vertical range which gives information about the possible genetic processes; 4) The morphometric index Ap-Es vs the Aspect ration highlight the role of coalescence processes in the lava tubes evolution during their formation.*

4. Discussion

During the last decade, thanks to the improvement of digital surveying, the morphometrics approach has been increasing for the studies and investigation of natural cavities (KLIMCHOUK, 2003; PICCINI, 2011). This method, used for the first time for lava tubes, has made it possible to find statistical ways to classify these caves, thanks to the already-known *Horizontal complexity index* (PICCINI, 2011). Moreover, other parameters and indices, including one described specifically for lava tubes, led us to go deeper into understanding the formation and evolution of these caves. In this work the *Ap-Es* Index was designed specifically for lava tubes, it shows the lateral coalescence events in lava tubes. Indeed, it was called the “lateral coalescence index”. This index, correlated to the Aspect ratio, can highlight the cave’s evolution in terms of lateral coalescence and vertical erosion. These events can explain the genetic and evolutionary processes that lava tubes .underwent Instead, compared to the Aspect ratio, the total vertical range highlights the genetic process of the lava tubes, distinguishing from shallow to deep-inflated and overcrusting processes.

5. Conclusion

The digitalization of 2D surveys allows us to perform more detailed and quantitative descriptions of these subsurface features. This work opens several new possibilities in studying lava tubes, having a statistical approach to classifying these cavities and better understanding the role of controlling factors in lava tube formation and evolution. Thanks to the huge inventories, the produced dataset can be implemented with many more data that can be used to get deeper into this study. In addition, laser scanner surveys, with a higher resolution, can be used to deepen morphometric analyses for those morphologies not present in 2D surveys. In the future, a possible correlation between internal and external morphologies on Earth will be made, in order to gain insight into the interior of these caves on other planetary bodies as well.

Acknowledgments

We gratefully thank all the lava tube explorers around the world, this work would not be possible without their work, surveys, and documentation of these awesome caves.

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The Hraunrásir project: exploring the mineralogy, microbiology and evolution of newly formed lava tubes in Iceland

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Abstract

The 2021 Fagradalsfjall eruption (March 19–September 18) provided a rare opportunity to study shield volcano emplacement in real time. Lava tubes played a crucial role in lava transport and field buildup, as documented through webcam videos, photos, and aerial photogrammetry. One year post-eruption, cooling lava tubes became accessible, allowing the Hruanrásir Project to investigate their formation, evolution, mineralization, and microbial colonization. Expeditions (October 2021–May 2024) revealed key findings: (1) magnetometry and 3D morphometry helped reconstruct lava tube emplacement; (2) at least nine metastable secondary minerals, some previously undescribed in lava tubes or Iceland, were identified at varying temperatures; (3) extremophile microbial life was detected in cooling tubes (70°–40°C), indicating rapid colonization within 20 months post-eruption. These results enhance our understanding of lava tube genesis, cooling processes, and early microbial colonization, with implications for planetary l.

1. Introduction

Iceland is an island of volcanic origin and geologically very young (about 20 million years old), known for its intense geothermal activity due to the presence of numerous volcanoes. About half of the country is characterized by rocks of volcanic origin, while 11% of the surface is characterised by the presence of several glaciers, including Vatnajökull, the largest glacier in Europe (about 8,100 km^2).

Among the volcanoes present, both active and inactive, fissure volcanism is the dominant eruptive process, characteristic of volcanic complexes on the oceanic ridge. This type of volcanism leads to lava outflows through fissures that open on the Earth's surface and can reach lengths of several kilometres. These fissures, at the end of the eruptive activity, can be filled by the solidification of the lava itself and covered by subsequent events.

The eruption of the Fagradalsfjall Volcano began in March 2021 and it was characterised by this specific type of volcanism with deep-sourced basaltic lavas characterized by low viscosities. Located on the Reykjanes Peninsula (Suðurland region), this small volcano had been dormant for over 800 years and its awakening was preceded by intense seismic activity lasting about one year, with a particular concentration in the two months before the eruption began.

In addition to fissure volcanism, the eruptions that occurred in the following months were characterised by powerful explosions that produced lava fountains several hundred metres high, attracting tourists from all over the world. For these reasons, the activities have been documented in detail not only by the Icelandic Meteorological Institute (Veðurstofa) but also by numerous researchers and enthusiasts who have consistently documented these phenomena with webcams and repeated aerial surveys (PEDERSEN et al., 2022).

After following and remotely observing the activities of this volcano for more than six months, the first speleological scouting in Iceland was organised in October 2021 to begin a project to monitor and study the formation of new volcanic cavities. Organised by the association La Venta, the 'Hraunrásir' ('lava' in Icelandic) project had several objectives including the identification of the main collapses and volcanic tubes formed following the eruption and their study from a microbiological, mineralogical and geomorphological point of view.

The Hruanrásir Project had the following objectives: 1) assess their morphology and the different mechanisms of lava tube genesis, 2) study their evolution during the cooling, 3) analyse which metastable secondary minerals form when the tube is still hot, and finally, 4) appraise how pioneer microbial life colonizes these originally pristine environments. All these topics have implications in the understanding of planetary lava tubes on Mars and other planetary bodies and their potential for astrobiology.

2. Materials and methods

2.1. Lava tube exploration and morphogenetic research

During the first exploration, activities were focused on the identification of volcanic collapses and conduits, clearly visible by observing the surface of the flows from aerial images.

To carry out these research activities, a Remotely Piloted Aircraft (APR) equipped with a thermal camera was used to easily identify the areas of interest with the presence of collapses and to measure the surface and inner temperatures, producing photogrammetric 3D models of several area of interest from both RGB and thermal images. These images and 3D models were used as a basis for the research carried out in the subsequent expeditions that have been realized between the years 2022 and 2024.

In the following expeditions, several volcanic caves were explored also using special thermal shield suits and fresh air breathing systems to explore some conduits with temperatures around 300°C and the presence of sulphurous gases.

Three-dimensional surveys were carried out with collision-tolerant drones (SANTAGATA et al., 2022) and mobile mapping laser scanning both outside and inside the caves. On the southern flank of the volcano, this made it possible to obtain a 3D survey of a section of approximately 500 metres of conduits, interrupted in some places by inaccessible collapses (Figs. 1-2). The Elios 3 collision-tolerant drone produced by the Swiss company Flyability was used to document and 3D scan inside the caves, especially in the most inaccessible parts where access was not possible in person due to high temperatures or the presence of collapses, while mobile mapping scanning was realized using a hand-held scanner, the BLK2GO, in the accessible areas and outside of the caves.

2.2. Environmental monitoring and secondary minerals

In addition to the three-dimensional survey, environmental monitoring and mineralogical sampling were carried out, starting 12 months after the end of the eruption. Hobo U23-A loggers in seven different lava tube sites, with initial temperature ranging 90-40°C. The monitoring has lasted two years allowing to document the variations in T and relative humidity across the cooling phase. Several samples of secondary minerals were collected from the same areas of the tubes, during the different subsequent expeditions. Samples were sealed in vacuum containers in order to minimise mineralogical transformations before analysis. During the main expedition of May 2023 a Secondary Electron Microscope and EDX from Thermo Fisher was installed at the base of the volcanic field, at about 20 minutes walking distance from the closest lava tubes. The SEM was installed inside a special tent with warming system provided by the Civil Protection of Iceland. Mineral samples were collected in the tubes, stored under vacuum conditions in T controlled containers, transported quickly to the lab tent and analysed immediately. This approach allowed to observe the metastable minerals in their original crystalline form and while they were changing in the vacuum of the SEM columns.

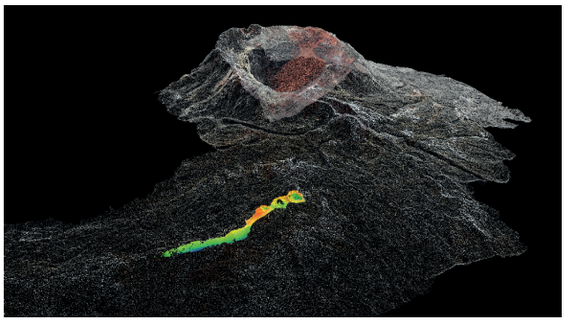


Figure 1: *The southern flank of Fagradaslsfjall main volcanic edifice with in colour the 3D model of a lava tube.*

The analysed sample where afterwards transported to the XRD laboratory in the Department of Geosciences of the University of Padova, to perform additional analysis with a STOE STADI IV 4-circle diffractometer equipped with Mo source and area detector CCD detector (Oxford Diffraction) suitable for rapid identification and structure determination. In addition, Raman analysis has been performed by the MicroRamanSpectra team (Padova) using a Raman XploraPlus© analysis apparatus with a 532 nm laser by Horiba Ltd.

2.3. Microbiology monitoring and analysis

In May 2023 the SEM imaging and Bioluminometer measurements allowed to identify which samples were featuring microbial colonies, helping the sample selection. To monitor the early colonization of the tubes, experimental jars with sterilized crushed basalt rock were prepared in the lab and then opened in the newly formed caves. Additionally, to compare with older lava tubes in the same area, coloured biofilms were collected from the walls of Búri Lava Tube, a ~1,000-year-old cave near the Fagradalsfjall Volcano, for analysis.

Basalt rock chunks were transported to the Molecular Environmental Microbiology lab (University of Bologna, Italy), where they were crushed, autoclave-sterilised and transferred in different sterile jars (5 g in each jar). These, without lid, were then located inside the newly formed lava tube to study the microbial colonization of the basalt over time. To this purpose, two jars were collected and processed for the analysis after 6 and 12 months of exposure to the cave environment. Sampling in Bùri lava tube was carried out wearing surgical mask and gloves and by using sterile spatula to avoid contaminations. All the samples were collected inside sterile tubes and brought to the MEMlab at UNIBO, where they were stored at -80°C until processing.

Microbial communities' composition within the collected samples was investigated by extracting DNA, amplifying the 16S rRNA gene and Illumina sequencing. Total DNA extraction from basalt and Bùri samples was carried out by using DNeasy PowerMax Soil and DNeasy PowerLyzer PowerSoil Kits (QIAGEN), respectively. The extracted DNA was then used as template to amplify the 16S rDNA hypervariable regions V3-V4 by using universal primers 341F and 805R and high-fidelity Ex Taq polymerase (TaKaRa). PCR amplicons were then sent to BMR genomics (Padova) for library construction and Illumina sequencing (Miseq platform). Raw sequences were processed with Qiime2 and DADA2 to get the amplicon sequence variants (ASVs), which were taxonomically characterized by running them in SILVA ACT database.

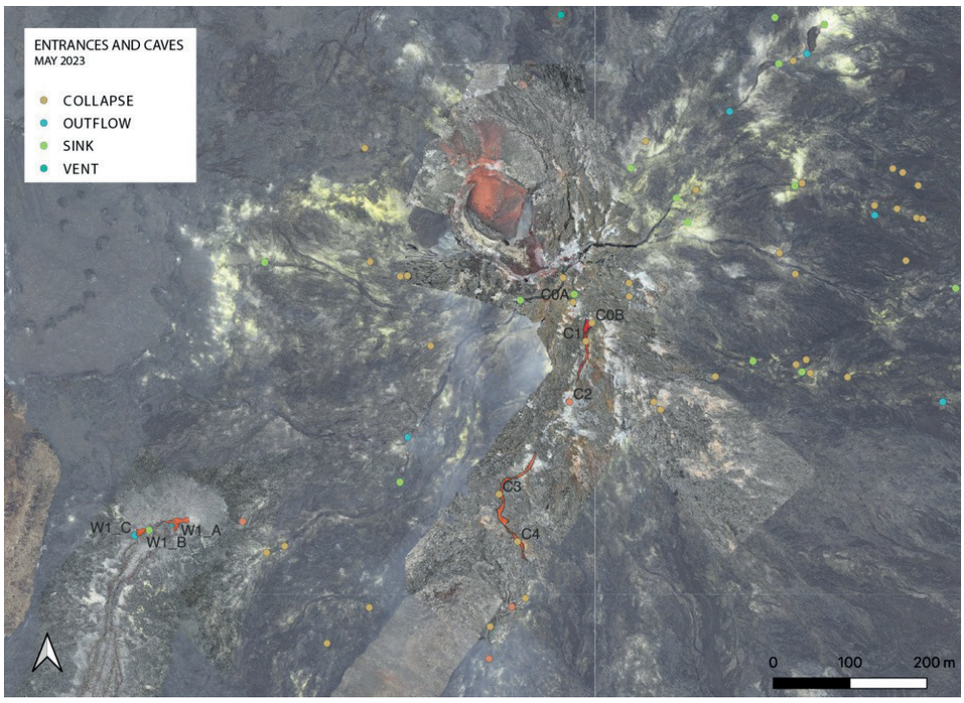


Figure 2: *Map showing all volcanic cave entrances (divided into tube roof collapses, channel sinks, outflows and vents) identified with the aerial surveys. In red the explored lava tubes, with C0A, C0B, C1, C2, C3, and C4 part of the same system.*

3. Results

3.1. Exploration and mapping

After the first in which activities were carried out exclusively with the use of a drone without accessing the lava field due to the high temperatures, in October 2022 some lava tubes have become partially accessible, being in a transient cooling phase. In order to explore these caves with still high temperatures, special equipment was used to cope with the extreme environmental conditions.

First it was necessary to establish safety procedures in which three people equipped with special aluminium protective suits with special gloves and helmets, thermal imaging cameras, gas detectors and with appropriate breathing systems were able to progress for about 20 minutes inside the caves. This allowed to explore and document the most inaccessible parts of the caves with extreme conditions. Thanks to these technologies, we explored five different cavities, with two of them presenting important development. The most important lava tube system is found on the southern flank of the volcano where a 550 meters long conduit divided in different sections was mapped. During the first exploration this tube was still very hot (air temperature between 70° to 250° C) but with several entrances allowing a quick access to the different segments to perform the topographical 3D survey.

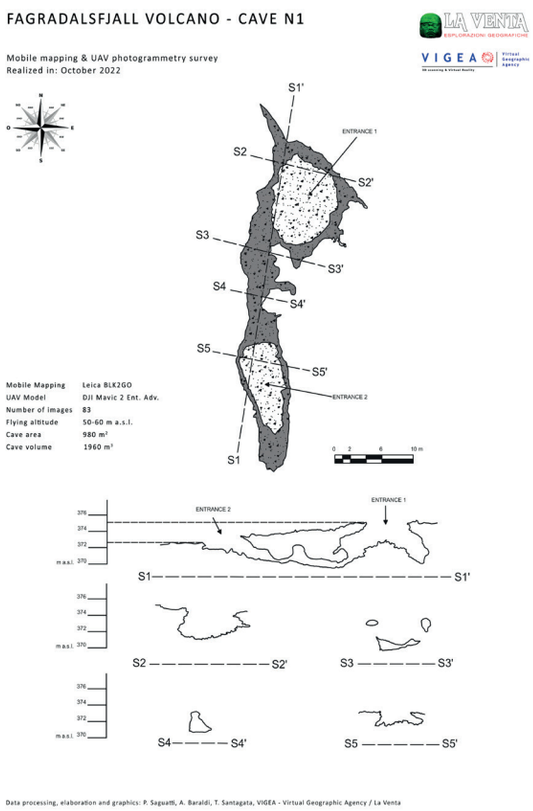


Figure 3: *Plan and section drawings of one of the conduits.*

3.2. Laser scan survey

Through the photogrammetric surveys conducted outside and the 3D mapping carried out inside the caves with collision-tollerant drones and mobile mapping techniques, it was possible to obtain a complete three-dimensional model of the volcanic area in which the caves were located (Fig. 1) and classic speleological plans and sections drawings of the different conduits surveyed (Fig. 3).

In addition, the study of the tubes with different methods (magnetometry, 3D morphometry, etc.) has allowed to propose hypothesis on the emplacement mechanism of Fagradalsfjall lava tubes.

3.3. Mineralogy and environmental monitoring

Very peculiar metastable minerals have been identified, mainly sulphates with different hydration levels depending on temperature and relative humidity of the tube environments (Fig. 4). In general, the loggers showed that while T is diminishing, relative humidity is rising, bringing to the mineral transformations that have been documented along the different expeditions (Fig. 5). The samples are still under analysis, but some of the species identified were never reported before for either cave environments or lava tubes (FORTI, 2005; ONAC & FORTI, 2011). The list includes:

- Mirabilite $Na_2(SO_4)\cdot 10H_2O$
- Thénardite $Na_2(SO_4)$
- Aphthitalite $K_3Na(SO_4)|$
- Cyanochroite $K_2Cu(SO_4)_2\cdot 6H_2O$
- Omongwaite $Na_2Ca_5(SO_4)_6\cdot 3H_2O$
- Hexahydrite $Mg(SO_4)\cdot 6H_2O$
- Wulffite $K_3NaCu_4O_2(SO_4)_4$
- Parawulffite $K_5Na_3Cu_8O_4(SO_4)_8$
- Blödite $Na2Mg(SO_4)_2\cdot 4H_2O$

Transformation between different phases has been observed during SEM analysis, with crystal clusters and pseudomorphs.

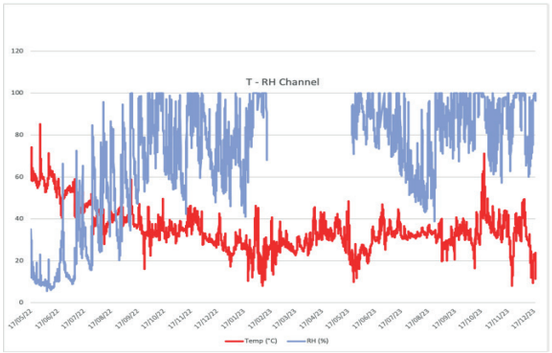


Figure 4: *Temperature and relative humidity evolution in the lava tube W1_A from May 2022 to December 2023.*

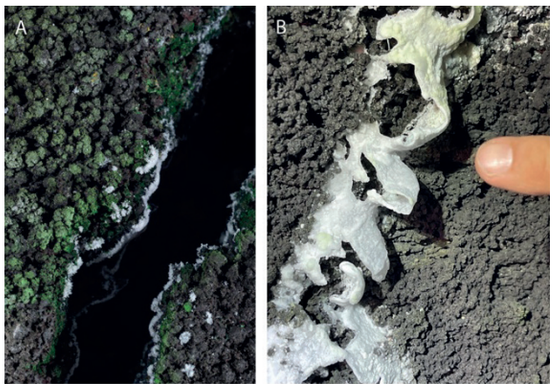


Figure 5: *Secondary minerals of Cyanochroite (A) and Wullfite (B) growing on fractures of the cooling lava tube walls.*

3.4. Analysis of the first microbial colonizers of newly formed lava tube

Extremophile microbial life has been detected in at least two different cooling lava tubes, at temperatures ranging between 70° and 40° C. These bacteria represent the first colonizers of the extreme environment, showing that life quickly colonizes and/or proliferates only 20 months after the eruption end and lava tubes form, with implication for astrobiology.

Microbial community analyses were carried out by processing different samples that were collected from newly formed lava tubes (F1P1 and F1P2 in Fig. 6) during the cooling down process and corresponded to basalt rock pieces that were previously collected from proximal soil site, smashed and sterilized inside small jars in the lab (and then opened and exposed inside the newly formed lava tubes to monitor the possible microbial colonization over time. Other samples (B1A, B1B, and B4 in Fig. 6) were collected from the ancient lava tube Bùri cave that formed around 1000 years ago and represented a lava tube environment where the cooling down process has finished leading to a stable and cold environment.

Microbial community composition analysis indicated that initial colonizers of the basalt sediments inside the newly formed lava tube during the cooling process were mainly represented by Alphaproteobacteria and Gammaproteobacteria belonging to the phylum Pseudomonadota. After six months, a shift in the microbial community composition was observed (F1P2 sample), with a progressive increase of the relative abundance of bacteria belonging to other phyla like Acidobacteriota, Actinobacteriota, Bacteroidota, Firmicutes. The comparison of the microbiology of the F1 newly formed lava tube and the Bùri cave showed that Bùri samples generally showed higher bacterial diversity suggesting a higher functional heterogeneity probably in association to a more stable and less selective environment. Different bacteria with chemolithotrophic activities were found in both the types of caves. In the newly formed lava tubes these bacteria are typically associated with soil and plant rhizosphere (e.g. *Burkholderiaceae*), while in Bùri these bacteria are typically associated with oligotrophic subterranean conditions (e.g. *Nitrosomonadaceae* and *Nitrosococcaceae*)

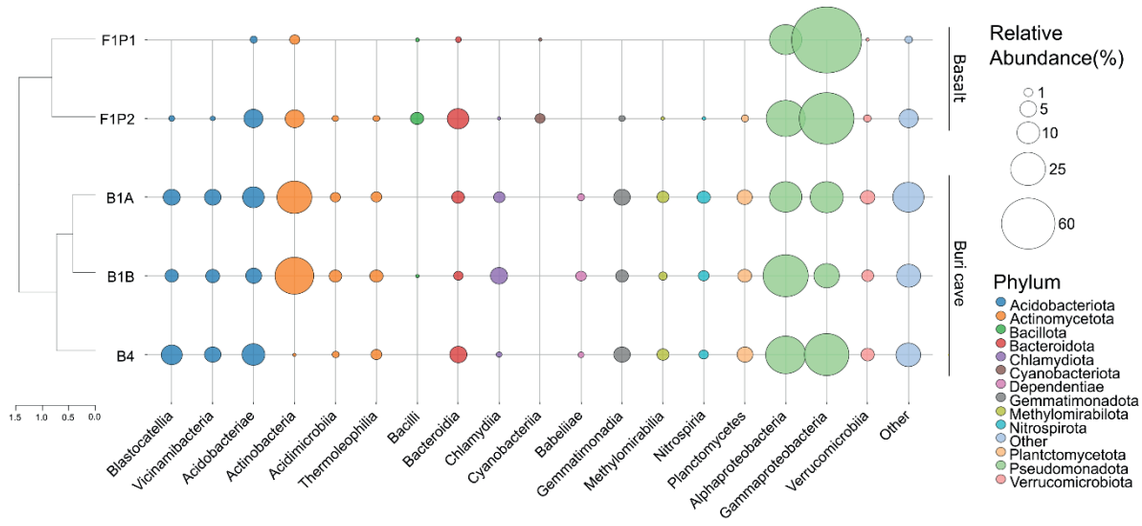


Figure 6: *Bubble plot showing the microbial community composition at class level inside the newly formed lava tube F1 (samples F1P1 and F1P2) and the ancient lava tube Bùri cave (B samples).*

4. Conclusion

This project brought together a diverse team of researchers, both from Iceland and other countries, performing a total of five expeditions (October 2021, May 2022, October 2022, May 2023 and May 2024) on Fagradalsfjall allowing unprecedented observations of these newly formed subsurface environments. The project explored and mapped some important lava tubes on the southern flank of the volcanic cone, with cooling tunnels still presenting T between 450° to 40°C. The study of the tubes with different methods (magnetometry, 3D morphometry, etc.) has allowed to reconstruct their emplacement mechanism.

3 Spectacular metastable minerals have been sampled from different tubes at different T: up to know we have identified at least nine different species, some of them never described before in lava tubes; several mineral structures are under analysis with potential new minerals to be described in the next months.

Microbiological analyses indicated that there is an evolution in the microbial colonization of newly formed lava tubes and the colonization initiates as soon as the cooling process starts. The DNA-based analyses indicated a big difference between the newly formed lava tube under analysis and the ancient lava tube Bùri in terms of bacterial diversity and microbial community composition. The difference is probably due to the stability, oligotrophic conditions and cold temperatures that characterize the ancient lava tube, although different bacteria could be detected in both types of caves that are characterized by chemolithotroph activities and could be potentially involved in biogeochemical cycles (mostly N_2 cycle).

Acknowledgements

This project has been realised with the financial contribution of a National Geographic Grant with the participation of scientists from the Department of Pharmacy and Biotechnology of the University of Bologna, the University of Padova, the CNR IBE of Sassari, the IRNAS-CSIC Institute of Seville, the Icelandic Meteorological and Volcanological Center, the Icelandic Institute of Natural History, the University of Iceland, the University of South Florida and with the support of companies leaders in UAV and topographical surveys Flyability and Vigea, the Italian company Icon snc, which provided the necessary equipment to carry out the explorations using breathing systems.

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Morphology and microclimate of a notable glaciovolcanic cave, Mount Meager, Canada

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Abstract

Within the Garibaldi Volcanic Belt, British Columbia, lies Mount Meager Volcanic Complex (Q̓welq̓welústen), a glaciated volcanic massif which last erupted approximately 2360 a. B.P. A novel glaciovolcanic cave system was first observed in the Job Glacier at Q̓welq̓welústen in 2016. Exploration was enabled by hybrid Self-Contained Breathing Apparatus (SCBA), while combined LiDAR and survey data revealed cave morphology. Investigations revealed the geothermal emissions and microclimate which shaped glaciovolcanic cave geomorphology.

The cave was formed from thermal flux originating from subglacial fumaroles and heated ground surfaces in the underlying edifice, combined with glacial ablation, which melted channels through the ice to the glacier surface. Subglacial rock surface temperatures of 94°C along with multiple distant fumarole vents resulted in speleogenesis of a multi-level cave system. Two primary chambers concentrated around fumaroles were joined by a conduit passage along the rock-ice margin. Minerals associated with fumarolic activity and hydrothermal alteration confirm historical and ongoing subglacial volcanic activity. Thermal flux and chimney effects to airflow influence distribution patterns of diverse volcanic gases, with H_2S, SO_2, CO_2, and CO present. Cave morphology and minerology data support the assertion that subglacial cavities were exposed by glacial retreat rather than caused by novel volcanic activity.

Résumé

Dans la ceinture volcanique Garibaldi, en Colombie-Britannique, se trouve le complexe volcanique du mont Meager (Q̓welq̓welústen), un massif volcanique glaciaire dont la dernière éruption remonte à environ 2360 av. B.P. Un nouveau système de grottes glaciovolcaniques a été observé pour la première fois dans le glacier Job à Q̓welq̓welústen en 2016. L'exploration a été rendue possible par un appareil respiratoire autonome hybride (SCBA), tandis que la combinaison des données LiDAR et d'enquête a révélé la morphologie de la grotte. Les enquêtes ont révélé les émissions géothermiques et le microclimat qui ont façonné la géomorphologie des grottes glaciovolcaniques.

La grotte a été formée à partir du flux thermique provenant des fumerolles sous-glaciaires et des surfaces chauffées du sol dans l'édifice sous-jacent, combiné à l'ablation glaciaire, qui a fait fondre les canaux à travers la glace jusqu'à la surface du glacier. Des températures de surface des roches sous-glaciaires de 94°C ainsi que de multiples évents de fumerolles ont entraîné la spéléogenèse d'un système de grottes à plusieurs niveaux. Deux chambres primaires concentrées autour des fumerolles ont été reliées par un passage de conduit le long de la marge de glace rocheuse. Les minéraux associés à l'activité fumerolienne et à l'altération hydrothermale confirment l'activité volcanique sous-glaciaire historique et actuelle. Le flux thermique et les effets de cheminée sur le flux d'air influencent les modèles de distribution de divers gaz volcaniques, avec la présence de H_2S, SO_2, CO_2 et CO. Les données morphologiques et minéralogiques des grottes soutiennent la conclusion selon laquelle les cavités sous-glaciaires ont été exposées par le retrait des glaciers plutôt que par une nouvelle activité volcanique.

1. Introduction

The processes whereby volcanic heat such as that from volcanic-magmatic systems interacts with glacial ice is termed glaciovolcanism, SMELLIE & EDWARDS, (2016). Where speleogenesis resulting from glaciovolcanism creates void spaces under ice, glaciovolcanic caves are formed, SOBOLEWSKI et al. (2022).

The global distribution of glaciovolcanic caves is limited, despite 245 locations which potential for glaciovolcanic cave formation, SOBOLEWSKI et al. (2022). These cave systems reveal diverse morphologies with both transient passages influenced by variations in volcanic heat flux, climate, and seasonality, and other passages in a state of dynamic equilibrium, STENNER et al. (2023); FLOREA et al. (2021).

The Mount Meager Volcanic Complex (MMVC) (Q̓welq̓welústen) is a large stratovolcano complex in the Garibaldi Volcanic Belt in southwestern British Columbia, Canada, comprised of six glaciated peaks, READ (1990). At approximately 2360 a. B.P. a major explosive eruption occurred at the MMVC, HICKSON et al. (1999). Glaciovolcanic cave openings were first observed remotely in 2015 and physically in 2016, ROBERTI et al. (2018); UNNSTEINSSON et al. (2024), (Fig. 1).

Volcanic gas emanating from the entrances prevented detailed study of the cave interior. Toxic gases such as H_2S, SO_2, CO_2, CO, CH_4, and others that create hazards are common in volcanic environments, WILLIAMS-JONES & RYMER (2015), while gas emissions evolve from CO_2-rich to SO_2-rich as a volcanic system reactivates; STIX & DE MOOR (2018). Examination of the microclimate within glaciovolcanic caves at the summit of Mount Rainier, USA revealed subglacial gas accumulations dependent on ambient air pressure, climate and cave morphology,

STENNER et al. (2022). Due to this fumarolic activity, eruptive history, and proximity to populations, MMVC was classified as a "Very High" threat volcano in Canada, KELMAN & WILSON (2024), and hence, are worthy of further monitoring and study. Modelling by UNNSTEINSSON et al. (2024) suggests that cave exposure is due to climate related glacial ablation rather than renewed volcanic unrest.

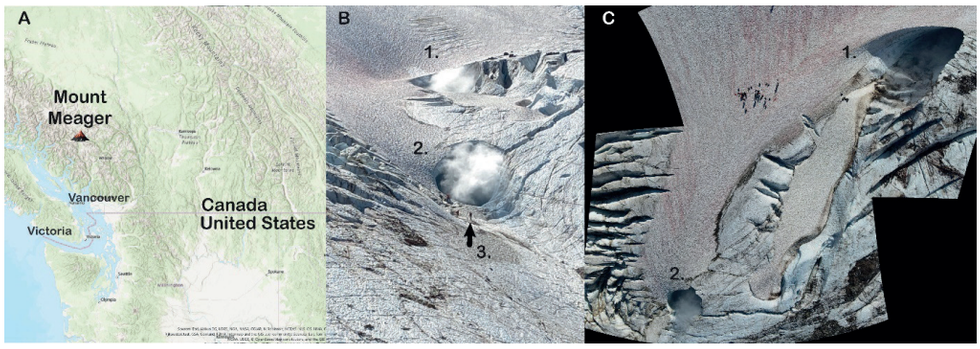


Figure 1: *A: Location of Mount Meager Volcanic Complex, British Columbia, Canada. B. Lateral view of the cave entrances on Job Glacier with visible gas plumes. 1: Upper entrance 1843 m a.s.l, 2: Lower entrance, 1775 m a.s.l. 3: Human for scale. C. Orthophoto plan view of cave entrances (1 and 2).*

2. Materials and methods

Cave survey and in-situ measurements of geochemical and environmental conditions were completed in September 2022. Survey was conducted using a Leica BLK360 Light Detection and Ranging (LiDAR) instrument, the EELS (Exobiology Extant Life Surveyor) sensor head which contains a Simultaneous Localization and Mapping (SLAM) instrument, and a Garmin Fenix 7 for azimuth measurements in the lower cave. Georeferencing of cave entrances used global navigation satellite systems (GNSS) references in the BLK360 and EELS scan data.

Post processing of LiDAR survey data and EELS sensor head data was using Cloud Compare, while Compass cave survey management software was used to generate a scaled line plot of Garmin data. An orthophoto of the cave entrances generated from uncrewed aerial system (UAS) photography. The orthophoto facilitated aligning the three survey datasets at appropriate scales against the entrances in Adobe Illustrator for final cartography. LiDAR Survey of the upper passages are graded UISv2 X- DEF while the lower passages are graded UISv2 2.

Temperatures were measured using a Seek Thermal Pro camera (-40 to 330 °C, ± 0.3°C) and an Omega HH11B digital thermometer (-20 to 1372 °C, ± 0.1°C). Novel procedural methods and Self-Contained Hybrid Integrated Evolution Life-support Device (SHIELD) Self Contained Breathing Apparatus (SCBA) were employed for exploration. Temperature and gas concentrations within ambient air were measured at 10 second intervals using body worn, calibrated RKI GX-6000 and GX-3R personal gas monitors with an upper detection limit of 200 ppm (H2S), 10 vol% (CO2), 2000 ppm (CO), 99.9 ppm (SO2), 40% (O2), and 5% CH4 (CH4 expressed as LEL, lower explosive limit).

Rock sample composition was analyzed using an ASD TerraSpec Halo Mineral Identifier (Malvern Panalytical). Visible to short wave infrared reflectance (VNIR/SWIR) capability is 350-2500 nm, spectral resolution 3 nm at 700 nm, 9.8 nm at 1400 nm, and 8.1 nm at 2100 nm. Calibration was performed with Spectralon®, and spectra were captured in triplicate. Spectra were splice corrected (splice correction gap = 5, no experimental slope correction) and converted from relative to absolute reflectance in ViewSpec Pro (v6.2) using a laboratory reference spectrum obtained with the same spectrometer.

3. Results

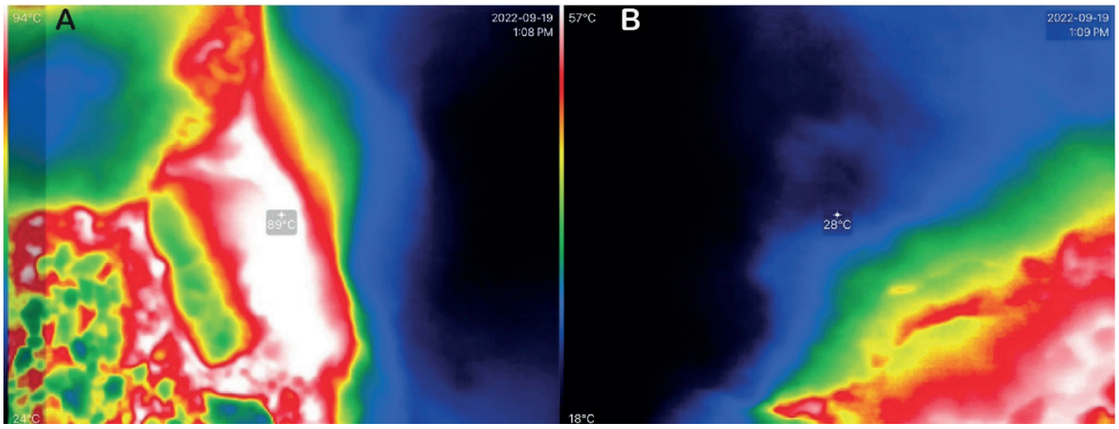


Figure 3: *Thermography of the cave interior. Left hand side color scale indicates temperature minima and maxima in each image, white=hottest, black=coldest. A: Heated sediments with 94°C maximum in image frame. B. Gas vapor clouds seeping from the cave floor at 28°C in image centre.*

Physical exploration and survey utilizing LiDAR, EELS SLAM and azimuth data along with photo monitoring of key areas revealed the cave morphology. The two entrances were connected and comprise a single system of subglacial passages, an elevated upper level, and a lower level following the rock edifice/ice margin (Fig. 2).

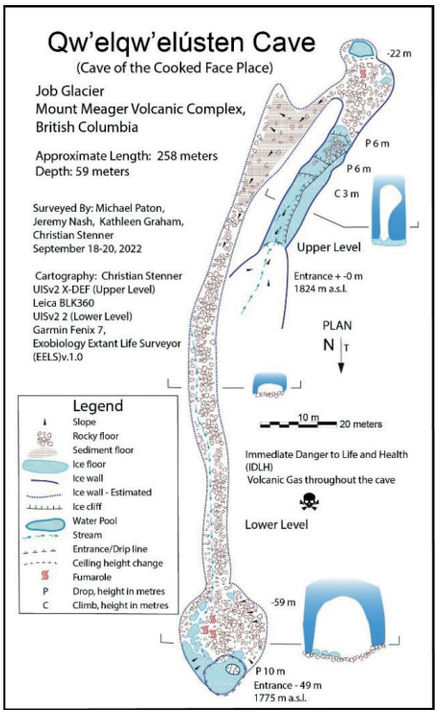


Figure 2: *Survey of the cave in plan view.*

The elevated upper level was characterized by a keyhole cross section passage with offset upper keyhole channel, entirely within ice, originating at a vadose-like entrance 18 m in height. The upper passage trended downward at -22° to a 3 m up climb, followed by two 6 m vertical drops. At the base of these drops was the bedrock surface of the volcanic edifice, at 22 m depth from the entrance and approximately 45 m below the glacier surface directly above.

This room was the location of the first of two large chambers, this one of 20 m height. The room was characterized by substantial intermittent serac fall, and visibility of 3 m due to steam vapor. Ground and fumarole temperatures within this room ranged from 24 °C to 94 °C with the maximum temperature of 94 °C measured with the Seek Thermal camera (Figure 3A). A distinct vent was located which measured 90.4°C, with visible degassing and visible mineral deposition around the vent.

This room was adjoined with two low ceiling areas, the first an alcove containing a pool of standing water, and the other accessing a sandy sediment slope with a -40° inclination. The sediment there measured 60°C. The passage continued with a phreatic-like cross section for approximately 165 m. Meltwater input from one side at 0°C created a streamway part way through this conduit; the stream encountered additional heated surfaces measured at 36°C. Ridges of rocky debris were on the left and right sides of the conduit floor. This conduit was connected to the second large chamber and the second entrance, a round dome shaped room with 10m pitch at the Northern end. Within this chamber visible fumarole degassing was present with vapors mostly carried towards the entrance. Serac fall was substantial with evidence of frequent breakdown ice on the floor so no fumarole measurements were taken. The total depth range was 59 meters from the top entrance to the lowest measured point (Fig. 2).

Ambient air temperatures measured with the portable gas detectors were 10-17.3°C in the vicinity of the fumarole. Gas concentrations close to the fumaroles reached maxima of 5200 ppm CO_2, >200 ppm H_2S, >100 ppm SO_2, 230 ppm CO, and 0% CH_4. Minima for gas levels was in the lower-level conduit, 600 ppm CO_2, 2.7 ppm H2S, 9.5 ppm SO_2, 0 ppm CO, and 0% CH_4, however, wide variability was observed in the readings over time even at stationary locations. The O_2 minimum was 20.4% at the fumarole.

Minerals associated with volcanic fumaroles and hydrothermal alteration were indicated by VNIR/SWIR analyses of rock samples from the cave. The presence of a steep absorption edge at on cave rock surfaces at 450 nm is indicative of elemental (native) sulfur, while features at ~670 nm and 900 nm indicative of ferric oxyhydroxides are observed on rock exteriors throughout the cave. Where the stream runs over heated sediment and rock, features consistent with goethite appear indicating hydrothermal alteration.

4. Discussion

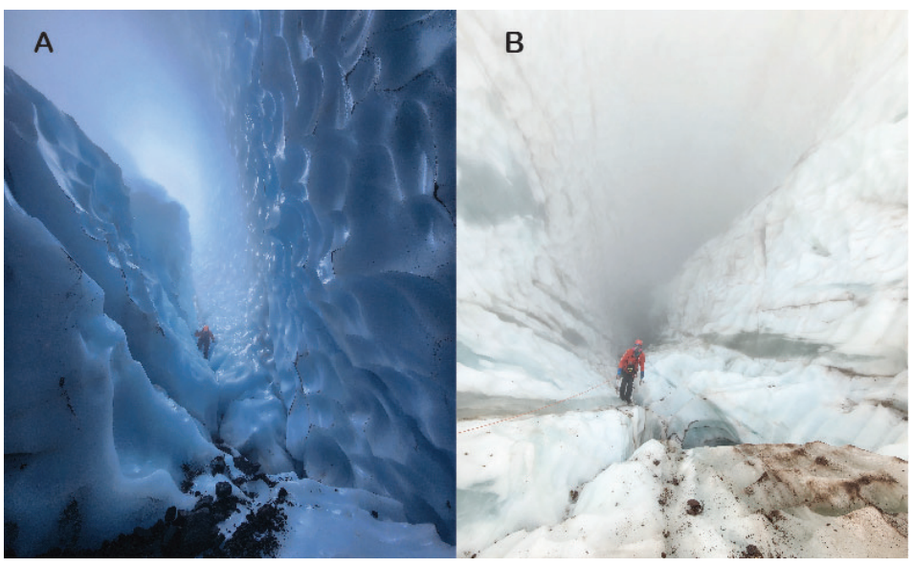


Figure 4: *Morphology of the upper cave showing offset keyhole cross section. A: View from inside looking towards the entrance. B: Opposite view from the entrance looking inward.*

The survey data and climate measurements reveal mechanisms influencing cave morphology and microclimate. The primary influence is the two subglacial fumaroles which provide point sources of thermal flux, causing the steam dome cavity morphology as observed in Mount Rainier, e.g. STENNER et al. (2023). Point sources of heat are not the only factor as wider areas of heated bedrock and sediment were also found near the domed rooms. These areas of sediment were in the lower cave conduit, and in conjunction with meltwater input results in conduit morphology similar to an active englacial conduit at a glacier bed formed without volcanic influences (Fig. 5). Debris ridges comprised of rock and sediment lie approximately 0.5m from ice walls of the conduit as in Mount Rainier, STENNER et al. (2023); FLOREA et al. (2021) are indicative of a seasonal dynamic equilibrium causing passage diameter expansion and reduction.

The ambient air temperatures are unusually high for a glacier cave and reflect the influence of heated sediment and warm fumarole degassing. The lower-level conduit connecting the two domed rooms is maintained by thermal flux and airflow, due to chimney effects present similar to Mount Hood, PFLITSCH et al. (2017). Here they result from two connected entrances with ~49 m elevation difference and temperature disparity with the outside.



Figure 5: *The morphology of the lower cave, analogous to an englacial conduit. An active streamway is in the lower right side of the conduit, while debris ridges on the right and left side are visible.*

Subglacial heat flux from both fumarolic areas is not causing a chimney or rising conduit to form breaching the surface directly above the source as was previously presumed. The upper cave entrance exhibits a keyhole cross section whilst the lower dome room has breached the glacier surface at its' far end. This entrance, though vertical, is not a rising chimney (Fig 7). Modeling conducted by UNNSTEINSSON et al. (2024) reflected an expected chimney morphology and hints at additional parameters involved in genesis of glaciovolcanic conduit morphologies.

Other glaciovolcanic cave systems have typically revealed low concentrations of volcanic gas in ambient air. Emissions in other Cascade Volcanic Arc glaciovolcanic systems such as Mount Rainier are dominated by CO_2, STENNER et al. (2022), or steam vapor at Mount St. Helens SOBOLEWSKI et al. (2022b), with H_2S present historically at Mount Baker and Mount Hood, STENNER et al. (2022). CURTIS (2016) proposed that gasses in glaciovolcanic caves will be well mixed due to advection and concentrations is likely higher near the cave roof than the cave floor, where venting gas warmth overcomes negative buoyancy. This situation in the context of Mount Erebus is similar to that at Mount Meager and in opposition to Mount Rainier, STENNER et al. (2022). At Mount Meager the sulfidic gases and CO_2 were not as prevalent in the lower conduit, rising instead into the upper level, out the upper and lower entrances, and then cascading down the glacier surface while dissipating.

Overall, the data places Q̓welq̓welústen cave as a significant example within the known glaciovolcanic caves in literature reported in STENNER et al. (2023), at 59m the fourth deepest known.

Additionally, the morphology and subglacial minerology support the attributing the appearance of the cave openings in 2015 primarily to climate change rather than renewed volcanic unrest. Minerology, as reported in CLANCE et al. (2024), revealed sulfide crystals and hydrothermal alteration which support the view that the fumarolic activity has been ongoing prior to the voids breaching the surface in 2015 and their subsequent observation in 2016. UNNSTEINSSON et al. (2024) estimated total heat flux for the fumaroles of 5 +-3 MW and attributed glacial ablation as the major factor contributing to the appearance of the voids. This is especially seen at the lower entrance, where entrance formation results from the end, rather than the peak of the dome chamber exposed by being unroofed by glacial ablation.

Characterization of glaciovolcanic interactions at Q̓welq̓welústen will have significance as warming climate and resulting glacier retreat worldwide may reveal new subglacial fumarolic areas in volcanic areas. This weaker, glaciovolcanic equilibrium resulting in increased meltwater input into volcanic hydrothermal systems, reduction in pressure from ice loss, and changes to surface expression in those systems, have implications for any glaciated volcanic edifice, and any nearby populations.

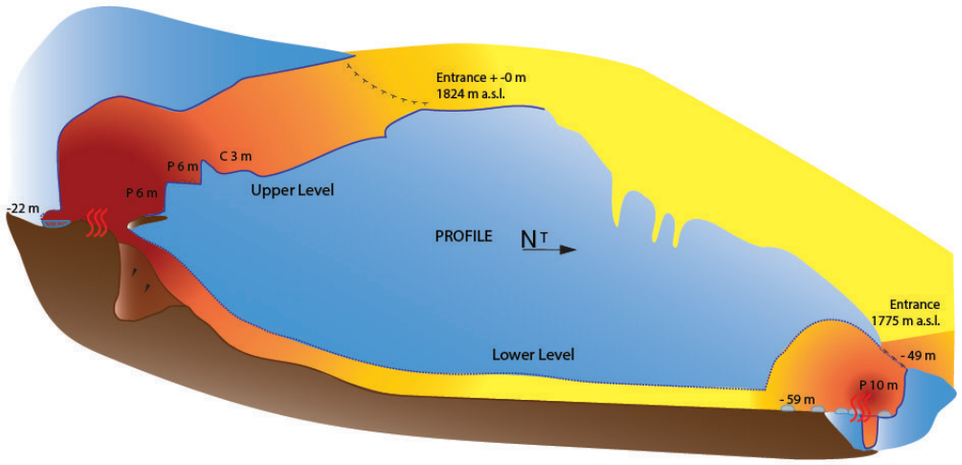


Figure 7: *Profile view of the cave with color gradient showing H2S concentrations. Scale: Deepest red = >200 ppm, lightest yellow = approximately 10-40 ppm.*

5. Conclusion

The Q̓welq̓welústen cave at MMVC is a significant example of a glaciovolcanic cave formed via interaction of subglacial thermal flux, a vapor plume containing sulfidic volcanic gases, internal micro climactic effects, and climate change. The cave was formed primarily via thermal flux from two distinct fumarolic areas and additional heat advected from warm rock surfaces. High ambient air temperatures from the subglacial heat flux and advection of air currents due to chimney effects influence the distribution of high levels of volcanic gases in the cave, causing their rising flow.

The morphology and minerology support the hypothesis that voids existed entirely sub glacially prior to their observation and entrances were created by glacial ablation exposing the underlying chambers, which are then maintained by continuing heat flux from degassing fumaroles and advection of warm air through the two entrances. Continued monitoring is necessary to assist in verifying if changes are occurring in the volcanic system, if further glacial ablation is influencing cave genesis or regression, or reducing the pressure overlying the volcanic system causing increased eruption risk.

Acknowledgments

We thank the Líl̓wat First Nation, as the lands at Q̓welq̓welústen are their traditional unceded territories. Special thanks to E. Cartaya, B. Swerdlow, T. Gall, S. Linn, and A. Walker who provided safety, surface support, and photo documentation. Additional support from A. Messinger, Special Projects Operations, Meager Creek Development Corporation, Innergex Renewable Energy, and No Limits Helicopter Adventures. Funding from the Trebek Initiative, a partnership between the Royal Canadian Geographical Society and National Geographic, and a Natural Sciences and Engineering Research Council of Canada Discovery grant (RGPIN-2016-03953). Some fieldwork was supported by an internal grant (Exobiology Extant Life Surveyor Project) supported by the NEXT Program, Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004). Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology. Field research was conducted under BC Parks permit 109950 and BC Ministry of Forests permit S26564

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Session 14

CLIMATOLOGY AND MONITORING

Relationship between environmental dynamics and geochemistry of well-ventilated caves in central Brazil

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Abstract

In central Brazil, high temperatures and a strongly seasonal hydrological regime increase potential evapotranspiration, raising drought risks and threatening local ecosystems. Understanding how climate variations driven by rising global temperatures impact regional climate and water availability is crucial. Monitoring studies performed in well-ventilated caves of central Brazil revealed that changes in relative humidity and potential evaporation significantly influence the hydrological cycle, as detected through oxygen and carbon isotope ratios. This study focusing on the Lapa da Onça cave, located in the Peruaçu Kasrt canion the in northern Minas Gerais state. The study aimed to determine how temperature, relative humidity, and precipitation impact carbon and oxygen isotopy in speleothems of open cave systems.

Our findings showed that calcite deposition rates depend not only on water availability in aquifers but also on environmental conditions, closely linked to temperature. Additionally, temperature and relative humidity directly influence the isotopic behavior of carbon and oxygen. Temperature had a stronger impact on seasonal variability of $\delta^{18}O$ and $\delta^{13}C$, while relative humidity has significantly affected on iterannual variability of $=\delta^{18}O$. These parameters revealed a clear seasonal cycle, aligned with patterns of high temperature and humidity, highlighting their critical role in understanding regional hidroclimate dynamics.

1. Introduction

Speleothems are considered by the scientific community as highly precise paleoclimatic records, capable of providing high-resolution chronological information, including annual and sub-annual scales. Their chemical and isotopic variations reflect changes in climatic and environmental parameters such as temperature and precipitation depending on the local environmental conditions (FAIRCHILD et al., 2006). However, advancing research in this field requires a broader geographical distribution of records and monitoring of environmental dynamics in karst systems to more accurately relate climatic factors to geochemical and isotopic variations.

Despite global advancements, there are still few studies that connect current environmental dynamics with geochemical proxyes such as stable isotopes, trace elements, and calcite deposition rate on tropical cave site . This gap limits the reliable interpretation of paleoclimatic and paleoenvironmental records, as the hydrogeochemical responses of karst aquifers are higly dependent on local conditions. In this context new monitoring efforts are essential to prevent ambiguous or erroneous interpretations.

This study focus on Lapa da Onça, a well-ventilated cave located in the in the North of Minas Gerais State in a region occupied by the Brazilian Cerrado biome, a savannah-type vegetation characteristic of an tropical seasonal climate with dry winters and rainy summers (Stríkis et al., 2024). The primary objective of this study is to enhance our understanding of how environmental conditions, associated with cave atmosphere temperature and relativy humidity, affect the carbon and oxygen isotope signals recorded in speleothems.

2. Materials and methods

2.1. Hydrogeochemical and Isotopic Monitoring of Onça Cave

The monitoring of Onça Cave began in February 2018 and was conducted monthly until November 2019. From earlier March to December 2020, no sampling activities were conducted due to the COVID-19 pandemic. From the beginning of 2021, sampling campaigns were resumed on a monthly basis until September 2023.

The monitoring occurs at five specific points in the cave, identified as P1 to P5, with installations ranging from areas near the entrance to internal regions with active dripping, as shown in Figure 1.

Data of local rainfall, temperature, and humidity (external and cave environmet) were collected using automate data loggers manufactured by Hobbo, model U23-00, while drip rate was manually measured with stopwatches during field visits.

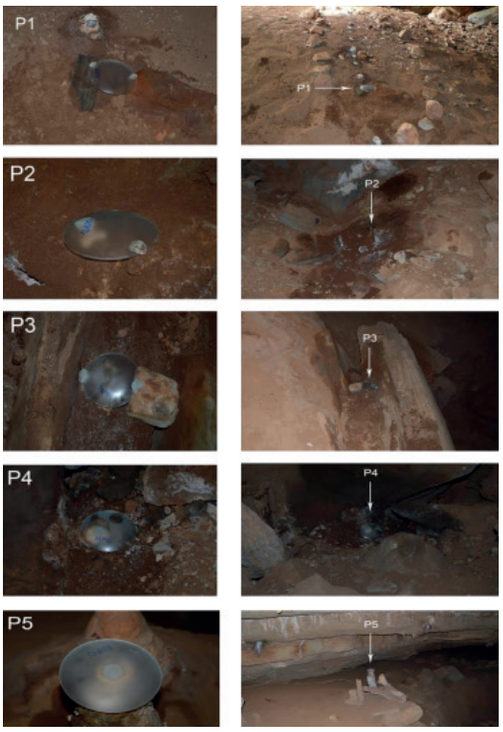


Figure 1: *Hydrogeochemical monitoring points installed in Onça cave.*

2.2. Calcite Sampling for Isotopic Analysis

To monitor the calcite precipitation rate and the oxygen and carbon isotopic composition of speleothems, calcite deposition experiments were carried out on artificial substrates. For this purpose, we used concave glass substrates replaced at monthly basis at the monitoring sites P1 to P5 (Figure 1). The glass substrate installed in the cave are sandblasted beforehand to create a rough surface that facilitates calcite deposition. These substrates are fixed at monitoring points using epoxy resin. Deposition rates are determined by weighing the substrates abefore and after the sampling.

Calcite samples for isotope analysis collected by scraping the glass substrate at 3 to 4 points, following the procedures outlined in STRÍKIS et al (2024).

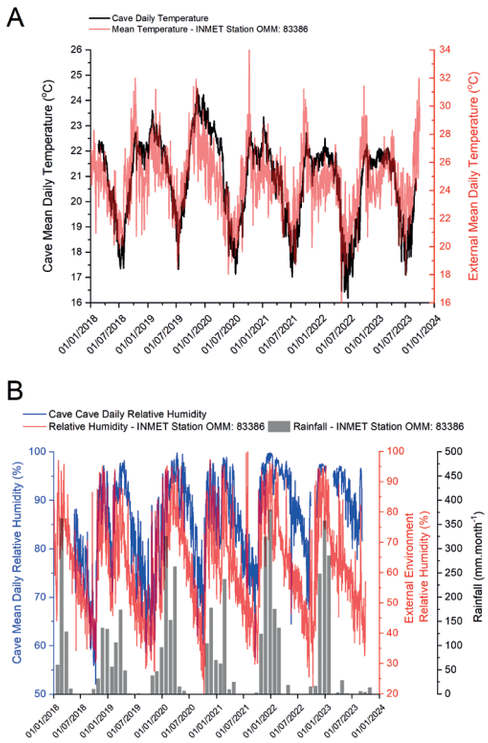


Figure 2: *A) Comparison between Onça Cave daily mean temperature (black) and the external environment (red). B) Comparison between daily mean cave atmosphere relative humidity (blue) and the external relative humidity (red) and monthly precipitation (grey). Measurements from external environment were obtained from the local meteorological station from the Instituto Nacional de Meteorologia (INMET – OMM: 88336) at Januária City, located 40 km southwest of the cave.*

2.3. Isotopic Analysis of $\delta^{18}O$ and $\delta^{13}C$ in Recent Carbonate

Isotopic analyses of carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) were performed at LIESP-CPGEO of IGc/USP using a DeltaPlus Advantage mass spectrometer. During the process, calcium carbonate reacts with H_3PO_4, releasing CO_2. This gas is separated via gas chromatography and analyzed automatically. Isotopic ratios are measured with a precision of ±0.08 ‰ ($^{13}C/^{12}C$) and ±0.1 ‰ ($^{18}O/^{16}O$) and expressed in parts per thousand (‰) relative to the international VPDB standard. The values are corrected using international standards (NBS-18, NBS-19) and internal standards (REI, VICKS).

3. Results

3.1. Environmental Parameters of Gruta da Onça

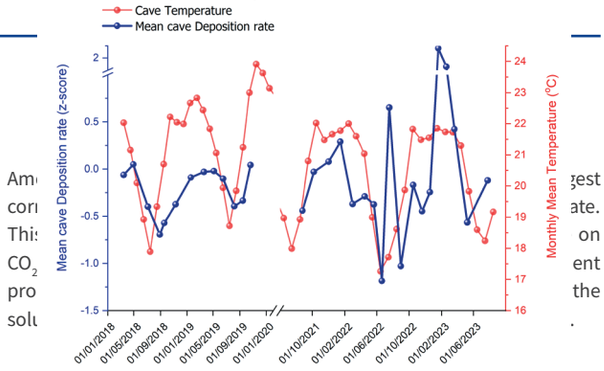
The environmental monitoring of Onça Cave began on 02/20/2018, with temperature measurements taken at three distinct locations: near the cave entrance, in the center of the cave, and within the innermost part of the monitored cave chamber. Temperatures range from 16°C to 26°C, with lower amplitudes in the interior (16.8°C to 22.9°C). Peaks occur from October to April (21°C to 24°C), while minimum values are recorded between June and August (17°C to 19°C) (Figure 2). Seasonal control is influenced by external temperature, closely following external minimums (r = 0.75, p-valeu < 0.05) Relative humidity, ranging from 51% to 100%, gradually increased from 2018 to 2023, correlating with seasonality and precipitation (Figure 2). The wettest months (November to March) coincide with higher rainfall, while the driest months (June to September) show a gradual decrease in humidity (Figure 2). The relationship between internal and external temperature and humidity demonstrates environmental impacts on the cave.

3.2. Drip Rate

Drip rates measured at five points in Lapa da Onça from 19 seconds to 12 minutes and 29 seconds. To compare these points, data were normalized using the z-score, allowing for analysis of seasonal variations on a relative scale. The comparison suggest seasonal consistency, with peaks in September 2018, January, June, August, and September 2019, December 2021, and September 2022 and 2023. Drip rates respond to monthly rainfall peaks after 6 to 9 months, indicating the influence of autogenic recharge and water percolation time through the karst.

3.3. Calcium Carbonate Deposition Rate

The monitored calcite deposition rate was normalized using the z-score (). A seasonal pattern was observed, with peaks between January and May. Individual comparisons revealed a strong consistency between drip rate and calcite precipitation, although some discrepancies remains.



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Figure 3: *Comparison between cave mean deposition rate (blue) and monthly mean cave temperature (red) at Onça Cave.*

3.4. Stable Carbon and Oxygen Isotopes in Recent Carbonate

Stable carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotopes were analyzed in 520 samples of recent carbonates collected from 130 glass slides across five monitoring points. The data, presented graphically, show consistent seasonal and interannual variations, with a trend of reduction over time. Normalized curves highlight relative variations in $\delta^{18}O$ and $\delta^{13}C$, with amplitudes ranging from -2 to 2. Both normalized averages (data on z-score) reveal similar patterns, suggesting a progressive decrease in $\delta^{18}O$ and $\delta^{13}C$ values across the five points during the monitoring period.

3.5. Relationship Between Environmental and Isotopic Parameters

The relationship between temperature, relative humidity, and isotopic values of $\delta^{18}O$ and $\delta^{13}C$ was analyzed. Rainfall was excluded as it only controls the drip rate. The comparison between temperature and cave mean $\delta^{13}C$ and $\delta^{18}O$ calculated for the five monitored point (here presented in z-score values) shows a good consistence in respec to seasonal (intrannual) variability (Figure 4A). Variations in calcite $\delta^{13}C$ and $\delta^{18}O$ exhibit a coherent relationship with cave relative humidity. Notably, lower humidity levels coincide with lower $\delta^{18}O$ values and higher temperatures during October and November, while higher humidity and elevated $\delta^{18}O$ values are observed in the cooler months from May to August (Figure 3B).

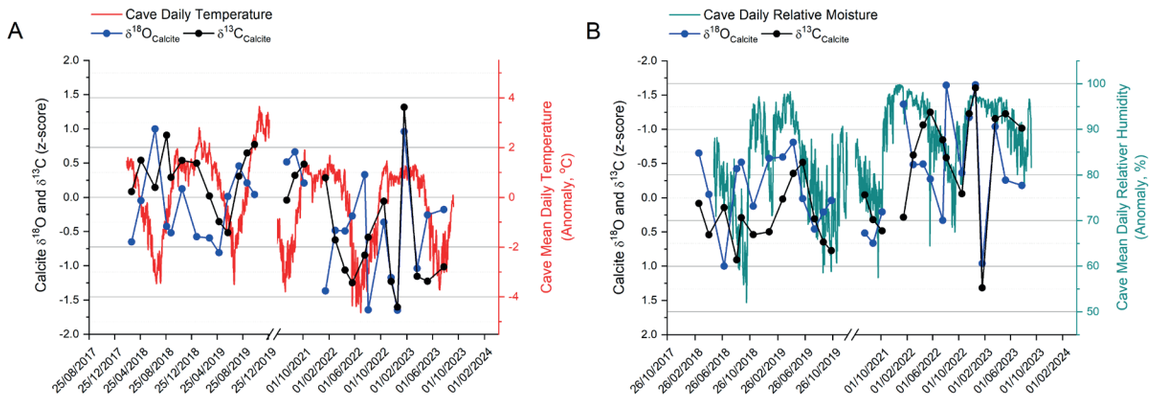


Figure 4: *A) Comparison of δ18O and δ13C from calcite precipitated in artificial substrates (data on z-score) with the cave atmospheretemperature anomaly during the monitored period. B) As in «A» but with the relative humidity. Note the reversal of the Y-axis scale in the graph in B.*

4. Discussion

The environmental factors influencing isotopic composition at Onça Cave cave were analyzed on a seasonal scale. The cave's average temperature fluctuates by 8.3°C, ranging from 16.2°C to 24.5°C, with maximum values occurring between October and March/April and minimum values between June and August (15.8°C to 16.2°C). This seasonal amplitude of 8.5°C is significantly higher than in confined caves, such as Lapa dos Anjos (STRIKIS, 2015), located close the Onça Cave and where variations reach only 0.5°C. Internally, the cave's temperature is more closely aligned with external minimum temperatures.

Relative humidity at Onça Cave averages around 85%, with seasonal fluctuations mirroring external conditions. This contrasts with caves of restricted air circulation, where humidity is consistently near 100% (STRIKIS, 2015; CRUZ et al., 2007). The cave's drip rate shows a delay of 6 to 9 months relative to rainfall peaks, reflecting the time required for meteoric water to percolate through the karst system.

Drip rate is crucial for $CaCO_3$ deposition but not the sole controlling factor. Temperature plays a significant role by affecting CO_2 solubility; higher temperatures decrease CO_2 solubility, promoting calcite precipitation through degassing (DREYBDROADT, 2005 ; FAIRCHILD & BAKER, 2012). This highlights the interplay between temperature and deposition rates in the cave environment.

Seasonal isotopic data ($\delta^{18}O$ and $\delta^{13}C$) show consistent cycles linked to variations in temperature and humidity, both of which influence speleothem isotopic composition. Low humidity induces kinetic fractionation, enriching isotopic values due to the preferential loss of lighter isotopes through evaporation. In the same way calcite $\delta^{18}O$ tends to present an inverse relationship with relative humidity due evaporative effects. Temperature also directly impacts isotopic fractionation, influencing calcite deposition (FAIRCHILD & BAKER, 2012). Theoretical $\delta^{18}O$ calculations align closely with observed data, confirming that temperature is the primary seasonal driver of $\delta^{18}O$ variability, although interannual variations require additional explanation.

Over the monitoring period, a gradual decrease in temperature was observed, corresponding to wetter years (Figure 4A). While lower temperatures typically increase calcite $\delta^{18}O$, the decline in $\delta^{18}O$ values between 2018 and 2023 cannot be fully explained by temperature alone (Figure 4A). In contrast the kinetic fractionation process, dirven by a decreasing in cave relative humidty results in a calcite isotope enrichemt of $\delta^{18}O$ and $\delta^{13}C$ as lighter isotopes are preferentially lost to the vapor phase. Conversely, an increse in relative humidity reduces this effect, leading to more negative $\delta^{18}O$ and $\delta^{13}C$ values.

The relationship between rising humidity and isotopic trends suggests that relative humidity plays a critical role in isotopic variability, particularly on interannual scales (Figure 4B). Temperature dominates seasonal variations, while humidity significantly influences longer-term patterns. These findings highlight the complex interactions between environmental factors shaping isotopic composition in well ventilated caves from tropical areas, like Onça Cave.

5. Conclusion

The five-year geochemical and hydrological monitoring of the Onça cave, in Central Brazil, revealed how temperature and humidity influence the geochemistry of speleothem carbonates, enabling the identification of climatic effects driven by temperature and relative humidity. The cave temperature ranges from 16.2°C to 24.5°C, adjusting with external minimums, and with maximum values occurring from October to March/April. Relative humidity shows greater variation near the entrance and smaller fluctuations in the interior, remaining consistent across monitoring points.

Drip rates, higher between June and September, respond to accumulated rainfall with a delay of several months, influencing $CaCO_3$ deposition. However, temperature also plays a critical role; as it increases, CO_2 solubility decreases, favoring solution supersaturation and calcite precipitation. Experiments with artificial substrates revealed that carbonate isotopic composition depends on drip water, temperature, and cave atmosphere relative humidity, which affect evaporation and enrich $\delta^{18}O$ and $\delta^{13}C$ values during warmer periods.

Environmental parameters display marked seasonal cycles, directly influencing the depositional and isotopic behavior of speleothems. This study contributes to understanding climatic variations and interpreting paleoclimate reconstructions based on analyses from well-ventilated caves.

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Preliminary data on the rhythmic tidal flow inside the Bue Marino Cave (Sardinia, Italy)

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Abstract

The multidisciplinary research promoted by Italian Speleological Society in the flooded sections of the Bue Marino, a vast coastal karst system in the center of the western basin of the Mediterranean Sea, aims to investigate how tidal fluctuations influence the water main chemical and physical parameters (temperature, electrical conductivity) and to assess their effects on hypogean ecosystems. For the first time, a temperature and salt anomaly was recorded at 2,600 meters from the sea inlet, at a depth of approximately -4.5 meters (a dive lasting over 240 minutes with depths between 6 and 35 meters). This anomaly appears to be the direct consequence of tidal fluctuations acting by piston effect on different and only loosely interconnected water basins. The tides have proven to be the main driving force regulating the dynamics in the anchialine end sections of this branch of the cave. When not influenced by significant precipitation, the water flowing in the Middle Branch exhibits regular variations (occurring within hours) in its parameters, behaving as in a 'rhythmic spring'. Tidal fluctuations cause this phenomenon: cooler, fresher, less dense water moves cyclically, wedging over warmer, denser seawater. Obviously further experimental analyses will implement in the near future these preliminary results.

1. Introduction

With a currently explored length of about 28 km, Bue Marino cave is the final part of the Eastern Supramonte coastal karst complex, the largest explored so far in the Mediterranean Sea, whose total mapped length now exceeds 72 km. The cave is subdivided divided into three distinct branches: South, Middle, and North, converging near the sea inlet with two spectacular caverns [FANCELLO et al. (2017), HUTŇAN (2013)] (Fig. 1).

South Branch: The South Branch now serves as an overflow for water circulating in the entire Eastern Supramonte karst complex and it is only active during heavy rainfall. Upstream of the show-cave tourist route and up to the "Sifone Terminale" lake, the conduit consists of galleries above sea level with their floor covered by sedimentary deposits, speleothems, and ancient rock morphologies. Under normal conditions, water originates from diffuse drips that feed limited water circulation, which does not interact with marine saltwater.

Middle Branch: This 4.5 km branch consists of often giant, mostly submerged conduits interwoven with 40 sumps stretching toward Codula Ilune. This branch is in hydrological connected with the Mediterranean Sea. Due to the length and depth of the sumps, ongoing exploration is technically complex. One of yet achieved research project results put in evidence the presence of significant, yet unexplored, drainage routes.

North Branch (Fig. 1): This branch consists of wide fossil galleries, with clear signs of an ancient sea level about eight meters higher than the present one, evidenced by Lithophaga boreholes. The flooded conduits lead to three lakes: the Emerald Lake (Lago Smeraldo), the Abyssal Lake (Lago Abissale), and the Black Lake. Beyond the sumps, the Czech Branch extends, representing the active part of the system. This section includes a complex network of largely flooded tunnels over seven km long, consisting of 42 siphons and numerous lakes fed by an underground river, which shows significant flow rates during heavy seasonal rainfall.

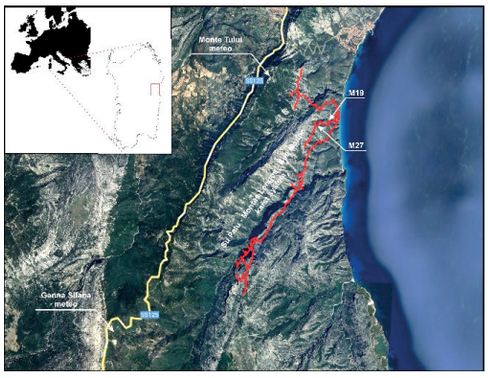


Figure 1: *Karst system map, the weather stations and the monitoring points in the Bue Marino North Branch.*

The ongoing multidisciplinary research project leaded by Società Speleologica Italiana (SSI) aims to investigate how tidal fluctuations affects the chemical and physical parameters in the flooded karst system (i.e. changes in water level, temperature, and electrical conductivity).

The goal is to assess tidal effects on the biodiversity of hypogean ecosystems. Cave divers, who, over the years, noticed thermal and halocline anomalies in the flooded passages of the Middle Branch inspired this research. The study aims to determine whether, aside from the intense and brief phases associated with rare flood events, the level variations linked to tidal fluctuations can exert constant energy on the flooded coastal karst systems over time.

In the long term, this energy may prove to be more significant than that generated by typical karstic water flow.

The research utilizes continuously collected monitoring data obtained

with the help of experienced cave divers operating several kilometers from the sea entrances.

In the first phase of this project, it was possible to measure for the first time a significant thermal anomaly 2.6 km from the sea inlet and at a depth of 4.5 meters below sea level. The anomaly reached 3°C with intermittent variability in sync with tidal fluctuations.

2. Materials and methods

During the project, high-resolution aligned and calibrated sensors recorded data at 5 minutes interval (during 2023) and 1-minute interval (during 2024):

− Eijkelkamp CTD-Diver (temperature, conductivity and level) + Baro-Diver (temperature and barometric pressure);

− Gemini Tinytag Aquatic 2 - TG-4100 (temperature).

Monitoring stations were located, with reference to the existing survey, in M19 (1,050 m from the sea inlet) and M27 (2,600 m from the sea inlet) of Middle Branch.

Data from these stations were compared to the level changes measured in Lago Abissale in 2023, and Lago Smeraldo and Lago Abissale in 2024 (Fig. 2).

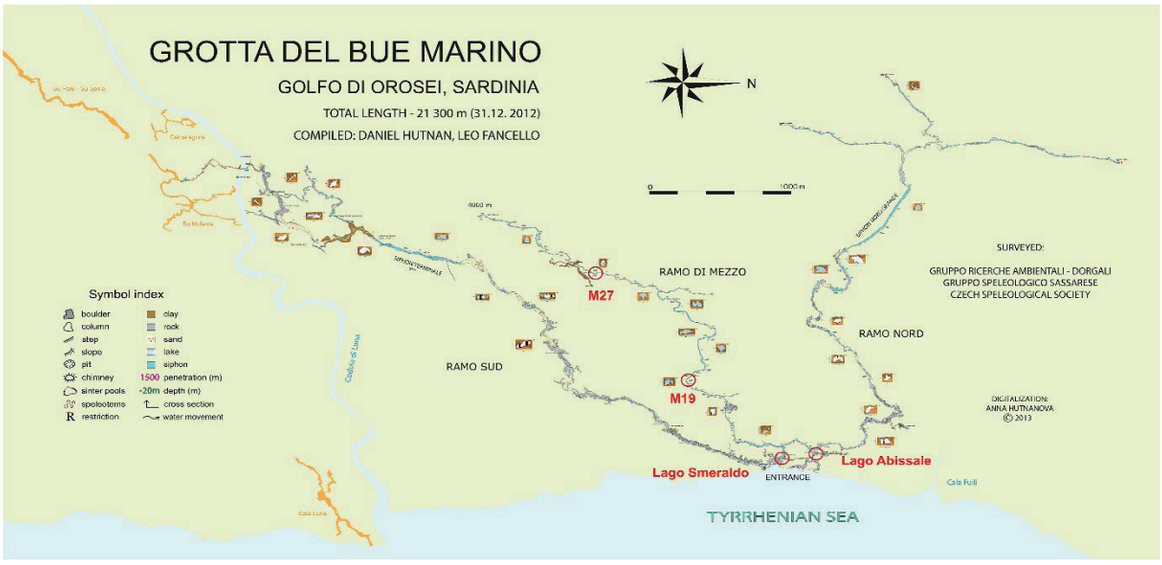


Figure 2: *Survey of Bue Marino Cave with the location of monitoring sensors (from Hutňan 2013, modified).*

3. Results

The data collected in July 2023 at station M19 did not reveal a correlation between temperature and tidal phases, although slight temperature stratification occurred, with a 0.08°C increase in the sensor placed at the deepest point. On the other hand, the monitoring had shown a direct correlation between tides and electrical conductivity: tidal peaks corresponded to a rise in conductivity of +0.20 mS/cm at the shallowest sensor (-0.88 m) and +0.24 mS/cm at the deepest sensor (-1.32 m).

Both sensors showed a general increase in values over the monitoring period. These observations align with tidal level variations of about +34 cm [Chiesi & MURGIA (2023)].

In October 2023, the monitoring at station M27 revealed a clear correlation between temperature fluctuations and tidal phases: significant temperature variations (±2.1°C) occurred rapidly and were out of sync with tidal peaks. Temperature drops occurred about 2.5 hours before the tidal peak, while increases lagged by about 3 hours, rising by +1.6°C in just 15 minutes. Three Gemini TG-4100 temperature sensors were also placed at station M27, approximately 120 meters apart, at a depth of about -4.5 m. The temperature variations recorded by the sensors 80 meters downstream ranged from 17.1 to 17.3°C, while those recorded 40 meters upstream ranged from 20.0 to 20.2°C, highlighting a significant temperature differential of about 3°C over a distance of just over 100 meters.

Conductivity also showed a direct correlation with tidal fluctuations, with values increasing with depth. Electrical conductivity at the sensor placed at -4.5 m dropped from 46.5 to 29.7 mS/cm in about 30 minutes, eventually reaching a minimum of 22.65 mS/cm shortly after the tidal peak. As with temperature, conductivity values returned to initial levels in about 15 minutes. Analysis of data collected between August 17 and 30, 2024, confirmed substantial synchronicity between tidal levels at all four measuring stations. At station M19, a clear correlation between temperature variations and tidal phases occurred starting on August 18 (Fig.3). The deepest sensor (-4.95 m) recorded the most significant fluctuations between August 21 and 23 (+/- 0.15°C), with values gradually stabilizing in the following days. The shallowest sensor (-1.55 m) recorded slightly more minor temperature variations (+/-0.1°C), with a tendency toward slight cooling. A more pronounced stratification of temperature was also confirmed during this period, with a differential of about +/- 0.9°C.

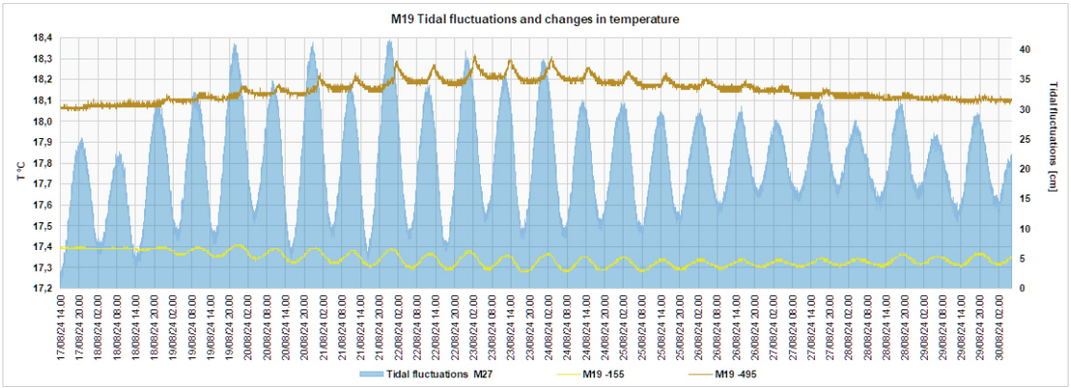


Figure 3: *M19 tidal fluctuations and changes in temperature.*

The analysis of electrical conductivity at M19 (Fig. 4) confirmed a clear stratification of the water, with the deep sensor recording more saline values and a differential of +/- 6.8 mS/cm. The overall trend in both sensors indicated a slight decrease in values. Between August 18 and 24, the deepest sensor recorded the best correlation between conductivity and tidal fluctuations, with values gradually decreasing over the following days. The shallowest sensor showed a similar, though more subdued, trend.

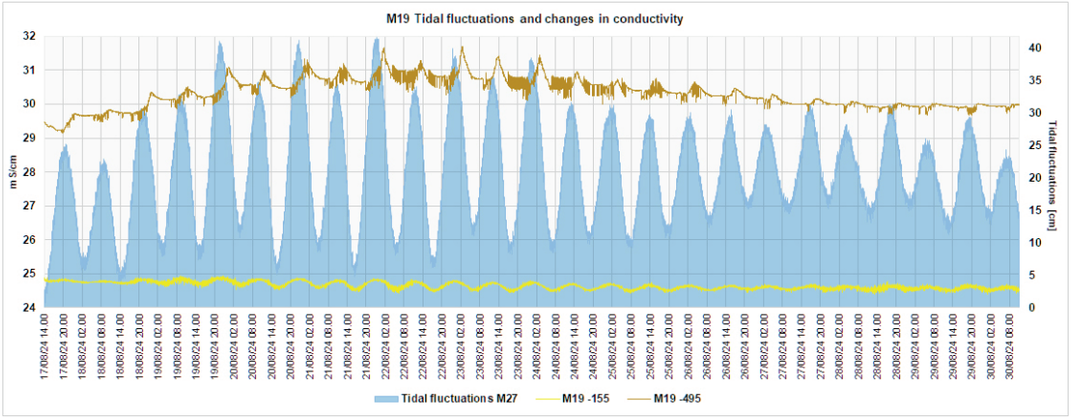


Figure 4: *M19 tidal fluctuations and changes in conductivity.*

At station M27, both sensors recorded direct correlations between temperature changes and tidal fluctuations (Fig. 5), along with clear thermal stratification. The deep sensor (-4.5 m) recorded temperatures 3°C higher than the surface sensor, with fluctuations of +/- 2.5°C contained within +/- 0.25°C at the surface sensor (-1.1 m). Conductivity fluctuations (Fig. 6) followed the same pattern as temperature, with stratification increasing with depth. The deepest sensor recorded a peak of +47 mS/cm compared to the surface sensor, with fluctuations of +/- 30 mS/cm at the deep sensor and +/- 0.25 mS/cm at the surface.

A comparison of the temperatures recorded by the deep sensors at M19 and M27 (Fig. 7) reveals two main trends. The first, more evident, concerns the rapid temperature decreases at M27, and the equally rapid temperature increases at M19 recorded between August 18 and 26.

After this period, from August 26 until the end of the monitoring period, the cooling and warming effects at the two stations gradually decreased, with the temperatures at both sites trending back toward the conditions observed at the beginning of the monitoring period.

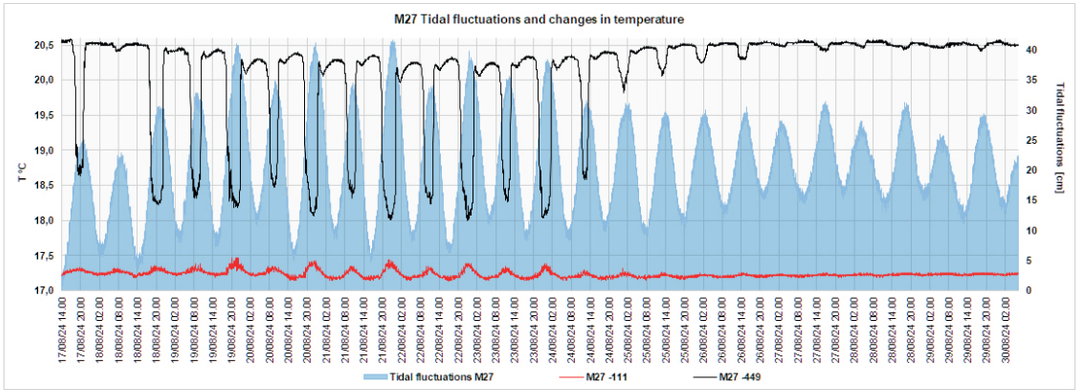


Figure 5: *M27 tidal fluctuations and changes in temperature.*

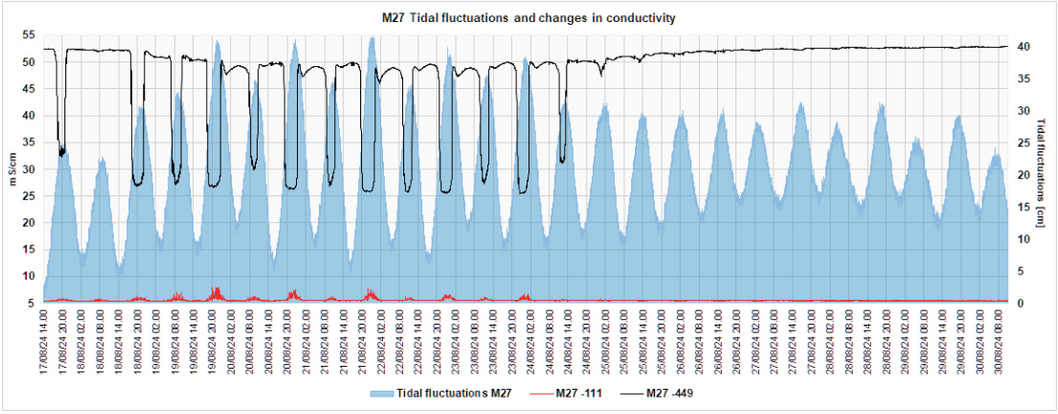


Figure 6: *M27 tidal fluctuations and changes in conductivity.*

The blue and orange lines in Fig. 7 correspond to the interpolated curves obtained by smoothing the peaks and troughs from the temperature values at M19 and M27. They graphically made evident the second trend which caused between August 22 and 24, a gradual temperature decrease of about 0.3°C at station M27, while in the same period, at M19 the temperature gradually increased of about 0.15°C. After August 24, the interpolated curves suggest that the temperatures at both stations tended to return to the initial monitoring conditions.

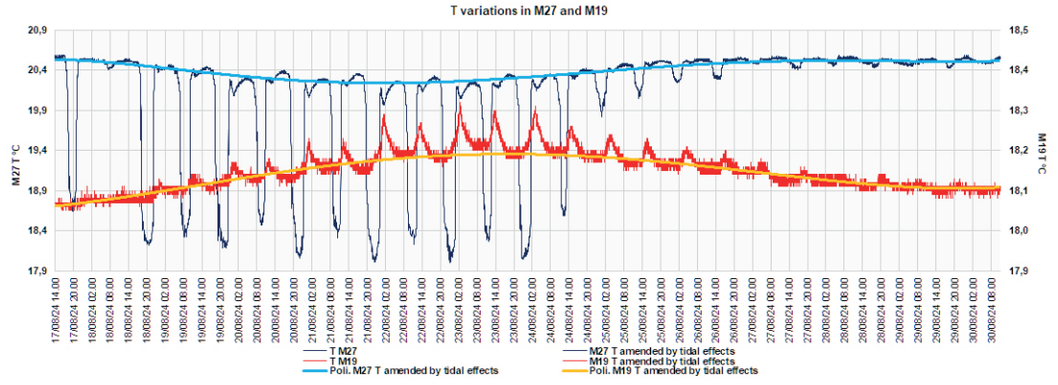


Figure 7: *M27 and M19 temperature variations.*

The above analysis, especially the damping of temperature and electrical conductivity values in the last few days of the monitoring period, can be correlated with two intense rainfall events that affected the monitoring area on August 14 and 15. The first event was recorded at the Genna Silana rainfall station between 1:00 and 2:00 p.m. on August 14 (56 mm), while the second was recorded on August 15 at two stations: the Genna Silana station between 10:00 p.m. and midnight (23 mm) and the Monte Tului station between 8:00 p.m. and midnight (21 mm). These meteorological inputs likely introduced new water, chemically and physically different from the one already in the flooded passages of the system. It is possible to consider this influx of water as a kind of "tracer" interacting with the existing hydrodynamics of the karst system. Given the arid period during which the monitoring occurred, it is plausible that this new water only recharged some parts of the aquifer without triggering significant outflows in the karst conduits. Given these assumptions, it is possible that around station M27, the cooler and less conductive new water interacted with the warmer, more conductive resident water, but influenced by tidal fluctuations. Because of this dynamics, the Middle Branch may have been subject to pulses of "new" water drawn from the supply areas, later gradually diluted by the tidal oscillations within the already resident water. This mechanism could also explain the temperature variations observed at M19, where the resident water was slightly colder than the one injected into the conduits by tidal fluctuations.

Based on these assumptions, a detailed analysis of the temperature variations at M19 and M27 was possible (Fig. 8), in order to define the time lapses occurring between the minimum temperatures recorded at M27 and the temperature peaks observed at M19 between August 20 and 24.

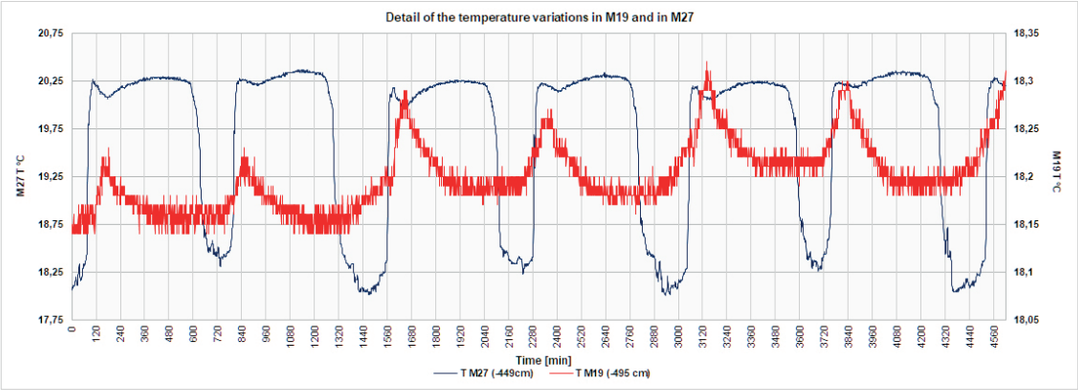


Figure 8: *Detail of the temperature variations in M19 and M27.*

In this context, the time lag between the peaks at M19 and the minimum temperatures at M27, following each tidal oscillation, were measured and a table of event timings were developed, estimating the corresponding delays and calculating the maximum water transmission velocity within the Middle Branch for each tidal oscillation based on the 1,600-meter distance between the two stations.

The calculated maximum tidal pulse propagation velocity within the conduit range from 8.6 to 13.8 meters per minute, grouped into consistent velocity categories.

4. Discussion

The monitoring data collected allowed us to understand how water flows within the Middle Branch of the Bue Marino Cave, which is directly in connection with the Mediterranean Sea and extends at least as far as station M27. For the first time, a thermal and saline anomaly has been recorded at a depth of approximately -4.5 meters. Tidal oscillations seems to induce this anomaly affecting very different water reservoirs linked together. Therefore, excluding flood events that occasionally affect the entire karst system, tides are the main driving force regulating the dynamics in the anchialine final sections of the karst system. When not influenced by significant rainfall, water flowing in the Middle Branch exhibits regular rhythmic variations (occurring over hours) in its chemical and physical parameters, behaving as "rhythmic springs" whose hydraulic mechanisms are still unsolved [BADINO (2017)]. In this case, tidal fluctuations are the responsible of the rhythmic behavior, which do not cause significant changes in flow rate but only small variations in temperature and conductivity. Cooler and fresher -therefore less dense- water cyclically moves in, wedging itself above warmer, denser seawater.

The most famous example of a "rhythmic spring" is the Pliniana Spring in Torno (Como, Italy), mentioned by Pliny the Elder in his Naturalis Historia (77-78 AD): "*In comensi iuxta Larium lacum fons largus oris singulis semper intumescit et residit*" (In the district near Lake of Como, a copious spring always swells and subsides every hour). Fascinating is the detailed description and discussion that Pliny the Younger provides in a letter to his friend Licinius Sura, dated between 23 and 79 AD: I have brought you from my homeland the little gift of a phenomenon, which is entirely worthy of the depth of your mind.

A spring that comes out from a mountain, flows between rocks and gathers in a little spot ideal for a picnic; from which, then, it flows into Lake Como.

Its behavior is astonishing: three times a day it rises and falls with constant variations in level. This is clearly seen and it gives considerable pleasure to the eye. When you sit near and eat, and drink from that same source, which is very fresh, it rises or falls at regular intervals.

If you put a ring or anything else out in the dry, the water gradually wets it and, finally, it is submerged and then uncovered again, and for a certain time remains dry. If you stop to observe this phenomenon, you will see it renew itself two and three times.

Could this be the result of some hidden wind, which first opens and then closes the mouth of the spring, according as [the current of air] is entering, thus pushing back the water, or is being pushed out by it?

We see the same phenomenon occurring in flasks - and in all vessels of this kind - which have no immediate and free connection with the outside. For these too, although inverted and tilted, held back by an unknown contrary wind, retard the liquid, which does not come out except with frequent hiccups.

Are the laws of the ocean the same as those of this spring? Is it then the same reason why the sea now rises, now falls, that causes this small spring to first gush forth and then to stop?

Or does this spring behave like rivers, which, when they flow into the sea, are hindered or even driven back by contrary winds or the force of the waves? Is there something that delays its course for a few moments?

Or do the internal channels have a very different size from each other, so that, in the period in which they fill up again to replace the waters discharged outside, the river becomes scarcer and slower, and, once the pipes have filled up again, it runs faster and more copious?

In short, is there some internal and hidden container, which when it empties increases the flow of the source, while when it is full it decreases it?

Now, if I have sufficiently described to you how this phenomenon develops, you, who are capable of it, try to find the causes that produce this phenomenon that for me is too complex.

Greetings.

5. Conclusion

Today, the observed phenomena deserve further investigation in similar contexts within the Mediterranean Sea basin to obtain reliable answers to some of Pliny the Younger's hypotheses some two thousand years later.

In our case, while the gathered clues strongly point to tidal forces, the hydraulic model governing this "submarine rhythmic spring", located 2.6 kilometers back stream the sea inlet and at a depth of 4.5 meters, remains an enigma.

Giovanni Badino, whose witty friendship and whose work inspired many of the considerations expressed here, would have jumped for joy at being able to observe, study and interpret this phenomenon. Now he's laughing somewhere, seeing the mess he left us in.

Acknowledgement's

Without the professionalism and tenacity of the cave divers of the Phreatic APS team, these observations would not have been possible: our gratitude and esteem go to them. As always, we are very grateful for the availability and irreplaceable support of Maria Grazia Fronteddu, a true problem-solving machine for all the studies we have been carrying out for several years in this wonderful, incredible and infinite karst system.

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Proyecto «Perlas de caverna en el Avenc Montserrat Ubach» (Pirineos catalanes): monitorización de la formación de pisólitos y de las condiciones hidroclimáticas

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Abstract

This project has among its specific objectives the monitoring of the Montserrat Ubach cave's hydroclimatic conditions to deepen the understanding of its internal dynamics, as well as the processes involved in the formation of its pearl nests, a topic that has been scarcely studied to date. Additionally, it is essential to assess the cave's vulnerability to the effects of global change, planetary warming, and the recent drought that affected the region—factors whose impact has not yet been determined. The data obtained through monitoring will provide insights into the processes influencing pearl formation. The sampling procedures carried out include CO_2 level measurements, in situ temperature monitoring, water and carbonate sampling for stable isotope and trace element analysis, drip count assessments, and the weighing of a selection of pearls from the Pou de la Xineta nest. Preliminary data suggest that the cave responds relatively quickly to external atmospheric variability, and it is expected that the pearls will experience their most significant growth during the autumn and winter seasons.

Résumé

Le projet a pour objectifs spécifiques le suivi des conditions hydroclimatiques de la caverne Montserrat Ubach afin d'approfondir la compréhension de sa dynamique interne ainsi que des processus impliqués dans la formation de ses nids de perles, un sujet encore peu étudié à ce jour. Par ailleurs, il est essentiel d'évaluer la vulnérabilité de la caverne face aux effets des changements globaux, du réchauffement planétaire et de la récente sécheresse qui a affecté la région, des facteurs dont l'impact reste encore indéterminé. Les données issues du suivi permettront d'obtenir des informations sur les processus influençant la formation des perles. Les procédures d'échantillonnage mises en œuvre comprennent la mesure des niveaux de CO_2, le suivi in situ de la température, l'échantillonnage des eaux et des carbonates pour l'analyse des isotopes stables et des éléments traces, le comptage des gouttes et la pesée d'une sélection de perles du nid du Pou de la Xineta. Les données préliminaires indiquent que la caverne réagit relativement rapidement à la variabilité atmosphérique externe, et il est attendu que les perles connaissent leur croissance la plus significative pendant les saisons d'automne et d'hiver.

Resumen

Este proyecto tiene entre sus objetivos específicos la monitorización de las condiciones hidroclimáticas de la caverna Montserrat Ubach con el fin de profundizar en el conocimiento de su dinámica interna, así como en los procesos de formación de sus nidos de perlas, cuya investigación hasta el momento ha sido limitada. Asimismo, resulta fundamental evaluar el grado de vulnerabilidad de la caverna frente a los efectos del cambio global, el calentamiento planetario y la reciente sequía que afectó a la región, factores cuyo impacto aún no ha sido determinado. Los datos derivados del monitoreo nos proporcionarán información sobre los procesos que influyen en la formación de las perlas. Los muestreos llevados a cabo son: niveles de CO2; medición in situ de temperatura; muestreo de aguas y carbonatos para análisis de isótopos estables y elementos traza; conteo de los goteos; y pesada de una selección de perlas del nido del Pou de la Xineta. Los datos preliminares indican una respuesta de la cueva a la variabilidad atmosférica exterior relativamente rápida y se espera que las perlas tengan su mayor crecimiento durante las estaciones de otoño e invierno.

1. Introducción

El proyecto «Perlas de Caverna del *Avenc Montserrat Ubach*: monitoreo de su formación y de las condiciones hidroclimáticas» cuenta con el soporte de l'Ajut Dona Naturalista 2024 de la Institució Catalana d'Història Natural (ICHN) y se llevará a cabo inicialmente de mayo de 2024 a abril de 2026. El objetivo general del proyecto es ampliar el conocimiento sobre el Avenc (sima) Montserrat Ubach (Odèn, el Solsonès ; Fig. 1), uno de los principales puntos de interés geológico del recientemente constituido Parque Geológico y Minero de los Contrafuertes del Pirineo. En reconocimiento a sus características, importancia geológica y valor histórico y patrimonial (Martínez, 2019), la caverna fue declarada en 2019 por la Generalitat de Cataluña como Espacio de Interés Geológico de Cataluña, la máxima distinción que el gobierno autonómico otorga al patrimonio natural.

El Avenc Montserrat Ubach, descubierta y explorada en 1963, posee una serie de características que la convierten en un enclave geológico de excepcional relevancia:

-Su principal interés geológico radica en que constituye un fragmento accesible de una zona de infiltración de un karst en conglomerados. Se trata del mejor ejemplo conocido en Cataluña de una cavidad desarrollada en este contexto geológico y uno de los más significativos a nivel mundial.

-Con una profundidad de 202 metros, fue reconocida como la cavidad subterránea más profunda de Cataluña durante 15 años y, durante 20 años, como la más profunda del mundo en formaciones de conglomerados. En la actualidad, continúa siendo un referente internacional en el estudio de este tipo de materiales.

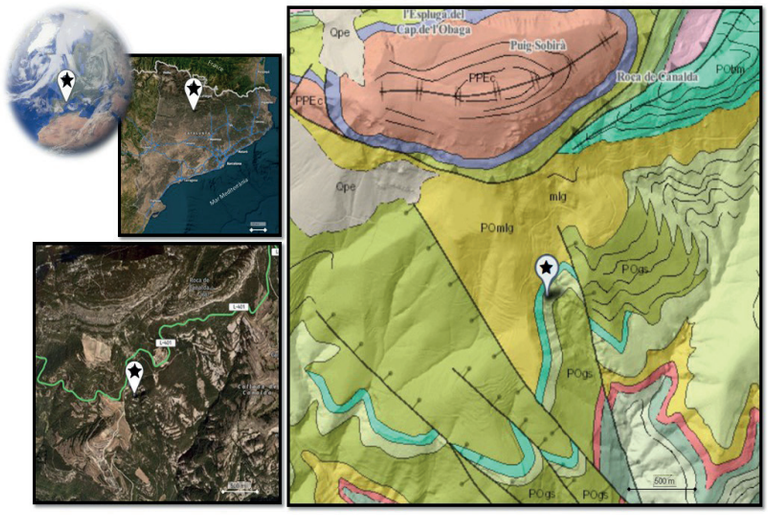


Figura 1: *Localización del Avenc Montserrat Ubach en el municipio de Odèn, comarca de Solsonés (Catalunya, Península Ibérica). La sima está formada en conglomerados del Oligoceno (Era Cenozoica, Periodo Paleogeno) los cuales están incluidos en el sistema aluvial superior de Berga. Al Norte de la cavidad, se observa una brecha monomíctica (azul celeste) del Oligoceno inferior incluida también el sistema aluvial superior de Berga. Más al Norte, encontramos margas, limolitas i areniscas con intercalaciones de conglomerados del Oligoceno (Formación Molassa de Solsona; POmlg). Respecto a los materiales más al sur, POgs corresponde a areniscas arcósicas, lutitas rojas y conglomerados del Oligoceno, también del Sistema Aluvial superior de Berga. Fuente: elaboración propia a partir de Instamaps, Googlemaps y ICGC.*

-Asimismo, destaca la presencia de diversos yacimientos de «perlas de caverna» o pisólitos, los cuales se consideran los más abundantes de Cataluña y son especialmente susceptibles al expolio. Entre estos, resulta especialmente notable el hallazgo de un ejemplar de dimensiones extraordinarias, con un peso de 730 gramos, considerado uno de los más grandes documentados a nivel mundial (Fig. 2).

Este proyecto tiene entre sus objetivos específicos la monitorización de las condiciones hidroclimáticas de la

caverna con el fin de profundizar en el conocimiento de su dinámica interna, así como en los procesos de formación de sus nidos de perlas, cuya investigación hasta el momento ha sido limitada. También, resulta fundamental evaluar el grado de vulnerabilidad de la caverna frente a los efectos del cambio global, el calentamiento planetario y la reciente sequía que ha afectado a la región, factores cuyo impacto aún no ha sido determinado.



Figura 2: *Ejemplar de La Perla hallado en el Avenc Montserrat Ubach. De dimensiones extraordinarias (91,95 x 80,00 x 80,10 mm) y con un peso de 730 gramos es considerado uno de los más grandes documentados a nivel mundial (Auroux, 2013).*

Los datos derivados del monitoreo nos proporcionarán información sobre los procesos que influyen en la formación de las perlas. Cabe destacar que las perlas de caverna o pisólitos constituyen depósitos

relativamente raros y de difícil hallazgo, además de ser aún poco estudiados. Se trata de concreciones de calcita que se encuentran en el suelo de algunas cavidades subterráneas y también en repisas, nichos de paredes, sobre estalagmitas, en el fondo de gours y microgours, así como en coladas. A diferencia de otras formaciones pétreas, no están adheridas a la roca debido a la vibración del agua de la pequeña charca en la que se localizan, provocada por el goteo que la alimenta. Se trata, por tanto, de procesos complejos y altamente sensibles a las variaciones. En resumen, se espera que la comparación de la evolución a lo largo del tiempo de parámetros ambientales de la caverna, como el CO_2, los datos geoquímicos del agua y los carbonatos ($\delta^{18}O$, $\delta^{13}C$ y elementos traza) contribuya a comprender la variabilidad estacional e interanual de la cueva.

Estudios previos han investigado la morfogénesis de pisólitos y oólitos (Ullastre y Masriera, 1973; Forti y Perna, 1983; Forti y Pensabene, 1989) o han analizado características como el peso, el tamaño o la densidad (Auroux, 2013 y las referencias allí citadas). En cuevas del Líbano, se ha desarrollado un estudio petrográfico y geoquímico (Nader, 2007). Destaca el relevante estudio de Forti et al. (1978), en el que se llevó a cabo la primera simulación del crecimiento de perlas dentro de una cavidad.

No obstante, es importante señalar que aún queda mucho por descubrir, y se desconoce gran parte de la información sobre los procesos y las tasas de crecimiento de las perlas.

Los resultados que se presentan en este estudio son preliminares y en última instancia se tiene el objetivo de poder caracterizar y cuantificar el crecimiento anual de algunas de las perlas en un nido de perlas concreto (Fig. 3).

2. Materiales y métodos

El presente proyecto está realizando el monitoreo de los parámetros ambientales y hidroclimáticos de la sima des de mayo de 2024 y pretende llevarlo a cabo como mínimo hasta abril del 2026. Interesa visitar la sima tras cada cambio estacional, de manera que se realizarán como mínimo cuatro campañas de muestreo por año.

El acceso a la sima requiere conocimientos técnicos de espeleología muy específicos, y el proyecto cuenta con un equipo de personas espeleólogas con un profundo conocimiento de la cueva. Sus nombres pueden ser consultados en Agradecimientos.

La primera campaña espeleológica, de carácter exploratorio, sirvió para decidir los puntos exactos de la caverna dónde tomar medidas y se llevó a cabo al iniciar el proyecto (mayo 2024). Posteriormente, se han realizado tres campañas más, correspondientes a los cambios de estación: junio y octubre de 2024 y enero de 2025. También se realizó otra en julio de 2024 con el objetivo de colocar una baliza de protección para el nido de perlas, efecto de estudio (Fig. 3).

Las medidas de CO_2 se toman en cada campaña en los 8 puntos de muestreo indicados en la Fig. 4, con un Carbon Dioxide Meter PCE-7755. Las mediciones de temperatura se realizan con Tinytags en cuatro puntos de la cueva, de manera que se quedan midiendo in situ entre una campaña y la siguiente. Cabe destacar que el medidor de CO_2 también provee datos de temperatura y humedad puntuales.

En tres puntos de la cueva se han colocado soportes de vidrio para recoger carbonato precipitado (Fig. 4). Asimismo, en estos mismos puntos se mide el pH de las aguas y se realiza recuento de las gotas por unidad de tiempo. También se recoge agua para analizar isótopos estables ($\delta^{18}O$ y $\delta^{13}C$) y elementos traza. También se pretende realizar estos mismos análisis en los carbonatos precipitados (Cisneros et al., 2021). Las aguas para analizar son filtradas y almacenadas en tubos cerrados sin contener aire y refrigerados.

Respecto a las perlas, actualmente se toma el peso de varias de ellas con una balanza de precisión (± 0,01 g). Para evitar sesgo en los pesos de las perlas por diferencias en la humedad de la atmosfera de la cueva entre un muestreo y otro y también debidos a evaporación de agua en la perla al sustraerla de su gour, se utiliza un vaso de precipitados con agua como contenedor de la perla en la balanza.



Figura 3: *a) Baliza de protección para el nido de perlas efecto de estudio. b) Nido de perlas en el Pou de la Xineta (Fig. 4). Fotos: cortesía de Marc Garriga.*

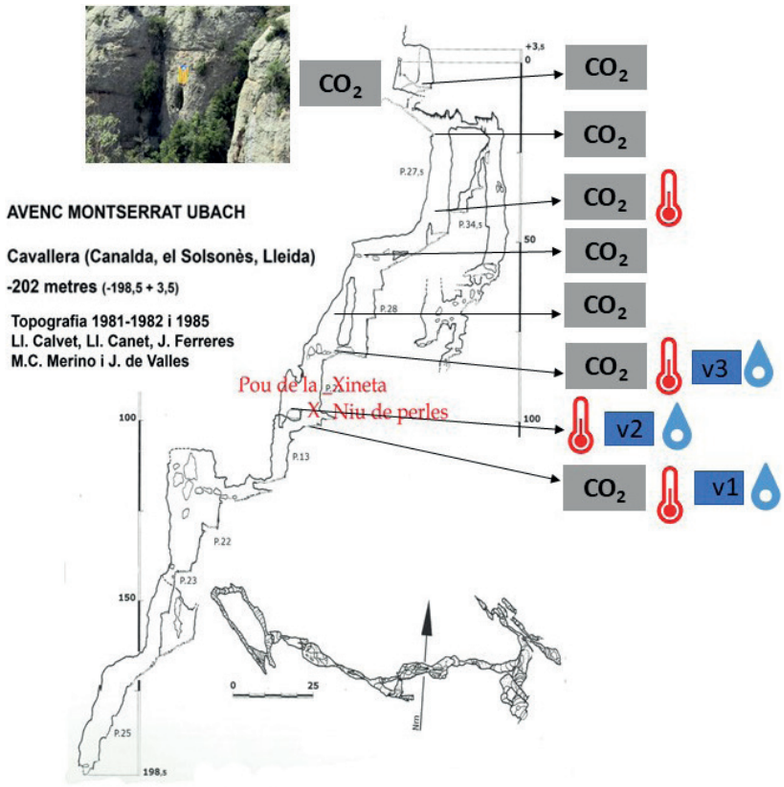


Figura 4: *Topografía del Avenc Montserrat Ubach con los actuales puntos de muestreo; CO_2; temperatura, recogida de carbonatos con vidrios (rectángulos azules); y muestreo de aguas (gotas).*

3. Resultados

Como ya se ha mencionado, los resultados mostrados aquí son preliminares dado que el monitoreo sigue en curso. En invierno y otoño se han obtenido niveles inferiores de CO_2 que en las estaciones más cálidas (Fig. 5). En julio se han obtenido los niveles más altos. A la profundidad de unos 50 metros, se obtuvo un cambio abrupto en la campaña de octubre principalmente en los niveles de CO_2 pero también de temperatura y humedad. Destaca la campaña de julio, en la que llovió abundantemente. Esto nos permitió observar que la humedad era del 100 % en todas las profundidades de la cueva muestreadas.

Respecto a los datos de temperatura obtenidos in situ en la cueva, hasta dónde sabemos, muestran valores relativamente estables a lo largo de cada estación. La profundidad menor (50 m aproximadamente) muestra una respuesta más rápida a los cambios atmosféricos del exterior que las profundidades mayores (descenso de ~ 0.2 °C durante el primer mes de invierno).

En relación al muestreo de carbonatos, la primera muestra se ha obtenido en enero de 2025. En las estaciones cálidas previas no se ha observado precipitado de carbonatos en los 3 vidrios colocados.

El muestreo de las aguas está todavía en curso. Los pH de las aguas de los gours varían entre 6 y 7. Todavía no es posible describir patrones claros a lo largo del tiempo. Respecto a la cuantificación de la tasa de goteo, las observadas en mayo y enero son similares. Sin embargo, en octubre, mes que fue bastante lluvioso en 2024 en la región, se observó que los goteos que alimentan el nido de perlas efecto de estudio eran más numerosos y también más rápidos.

En referencia a la cuantificación del crecimiento de las perlas, hay que decir que la metodología ha ido evolucionando a lo largo de las campañas de muestreo. Inicialmente se probó a medirlas, pero la irregularidad de sus formas hizo que esto fuera impreciso, realizándolo con instrumentación manual como pueda ser un pie de rey de alta precisión. Con un presupuesto adecuado, se podría invertir en instrumentos digitales diseñados para la ocasión, similares a escáneres 3D. De momento, el proyecto ha optado por cuantificar los pesos de las perlas con la balanza, así como también hacer macrofotografías con papel milimetrado. Durante las primeras campañas, se observó que los pesos obtenidos no tenían consistencia. Ello se debía en parte a que las perlas, al ser sustraídas de su gour, están expuestas a evaporación y por lo tanto, su peso se modifica. Es por ello que se ha rediseñado el método de pesada incluyendo un vaso de precipitados con agua sobre la balanza, para así minimizar el sesgo derivado de la pérdida de agua por evaporación. Además, hemos observado recientemente que los goteos son capaces de hacer saltar las perlas de su nido. Por todo esto, aún no se dispone de datos de la evolución del peso de las perlas seleccionadas.

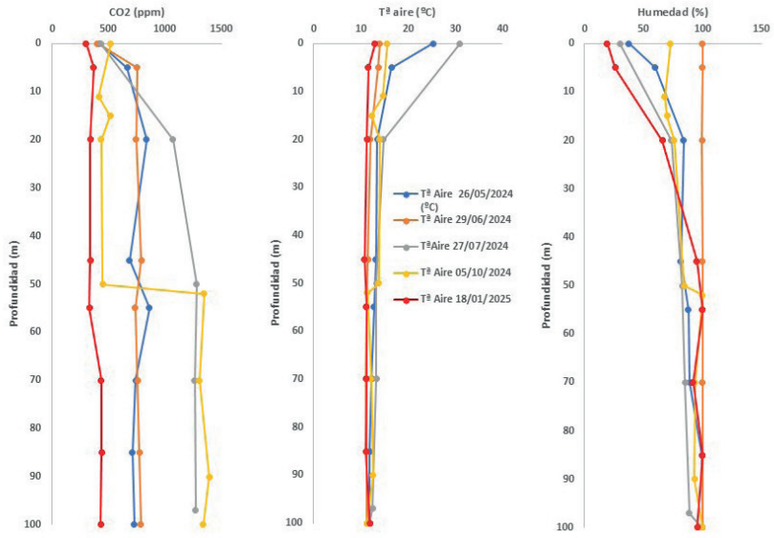


Figura 5: *Perfiles de CO_2 (ppm), temperatura (°C) y humedad realizados durante cada campaña a l'avenc Montserrat Ubach.*

4. Discusión y conclusiones preliminares

Los datos brutos de los perfiles de CO_2 obtenidos indican que la sima se ventila más en las estaciones más frías (otoño e invierno; Fig. 5). Es posible que el aire frío, al pesar más que el caliente, penetre con mayor facilidad en el acceso de la cueva, ventilándola. Esto es coherente con el hecho de que es en pleno julio cuando se han obtenido los niveles más altos de CO_2 la cueva.

El hecho de que el carbonato no precipitará en las estaciones cálidas en los vidrios de muestreo y que la primera vez que se observó precipitación fuera en invierno, parece apuntar que será está la estación más plausible dónde esperar un mayor crecimiento de las perlas.

La hipótesis de esperar más crecimiento en las perlas en las estaciones frías (otoño e invierno) parece coherente con el hecho de haber observado más goteos y más rápidos en octubre en el nido de perlas efecto de estudio. Cabe destacar que, como ya se ha mencionado, ese mes fue lluvioso en la región. Esto parece indicar que la respuesta de la sima en términos de régimen de goteo a las variaciones ambientales del exterior es relativamente rápida. Esta afirmación está en consonancia con los datos de humedad obtenidos en todas las profundidades de la cueva el día de la campaña de julio; aquel día, de lluvia abundante durante varias horas, la humedad obtenida fue del 100 % (Fig. 5).

De esta manera, aunque los datos de los que se dispone son todavía preliminares y ni tan solo se ha completado un ciclo anual entero de monitoreo, parece plausible indicar que el crecimiento de las perlas se ve afectado por la variabilidad climática del exterior de la cueva y por ende, por el calentamiento global y las sequías cada vez más severas.

Cabe destacar que las zonas de montaña de los Pirineos catalanes están registrando incrementos de temperatura más pronunciados que el resto del territorio, lo que intensifica los impactos del cambio climático en esta área (OCCC, 2024). Durante la primera mitad del siglo XXI, se prevé un aumento significativo de la temperatura anual, tanto media como máxima y mínima, que podría superar los +4 °C en la región pirenaica, independientemente del escenario de emisiones considerado. En cuanto a la pluviometría y, al igual que en el resto de Cataluña, todas las proyecciones apuntan a una reducción significativa en el número anual de días con precipitaciones débiles (20 días menos) y a un aumento en la duración máxima de las rachas secas (20 días más). Este escenario sugiere que las sequías serán más intensas en todo el territorio durante los próximos 30 años (OCCC, 2024).

En este contexto, parece resiliente la intención de cuantificar el crecimiento de estas raras formaciones que suponen los pisólitos. Confiamos en que los datos de monitoreo conjuntamente con dataciones de U-Th, las cuales ya sea ha demostrado funcionan para este tipo de formaciones (Liao et al. 2020), puedan ayudar a discernir de alguna manera cómo esta "nueva variabilidad hidroclimática inducida" está modificando las condiciones ambientales de las cavidades kársticas.

Agradecimientos

Agradecemos sinceramente a la Institución Catalana de Historia Natural (ICHN) por la confianza depositada y el apoyo económico proporcionado; sin l'Ajut a la Dona Naturalista 2023 este proyecto no hubiera sido posible. El Equipo espeleológico de las perlas está formado por: Muntsa Pérez, Eduard Badiella, Jenar Indurain y Òscar Silvestre (SIS-Secció d'Investigacions Subterrànies, Centre Excursionista Terrassa); Lluís Roqueta i Marc Garriga (SECEM- Secció d'Espeleologia-Centre Excursionista Montserrat Manresa); Eva Fernández i Núria Gual (Flash Black Corb Barcelona); Yolanda Soto, Marc Navarro, Miquel Romà y Toni Rocias (Equip de Recerques Espeleològiques de l'Agrupació Excursionista Catalunya -ERE-AEC); Jordi Gutiérrez i Mario Temprano (Espeleo Grup Anoia -EGAN); Txema Torné EDES- Centre Excursionista de la Comarca de Bages-Manresa); Raquel Daza (Espeleo Club Dinàmic. UEC de Tortosa). Sin todos ellas y ellos, este proyecto tampoco sería posible.

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Understanding the variability in gas concentrations of Carlsbad Cavern

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Abstract

Cave air circulation, which is driven by weather changes on the surface, provides an important control of the cave environment by influencing gas transport. Here, we study gas dynamics in Carlsbad Cavern, which exhibits two different airflow mechanisms: 1) barometric airflow and 2) circulating convective airflow. To obtain information about ventilation processes and their influence on gas dynamics, we measure CO_2 and radon concentrations at high time resolution along with airflow velocity, barometric pressure, temperature, and relative humidity at six sites within Carlsbad Cavern. A simple gas transfer model was fit to measured CO_2 decreases in Carlsbad Cavern to test whether the model provides a useful approximation of gas transfer between the surface and a large underground volume when the two are linked by a convection cell. The exponential model provides a reasonable fit to observed curves during the onset of convection periods. Model parameters suggest that exchange times between the surface and the main passage are on the order of days and that tourists may be the primary source of CO_2. A more isolated site in the cave exhibits an exchange timescale of approximately a month.

1. Introduction

Cave air circulation provides an important control of the cave environment through its influence on gas, dust, and aerosol transport. Gas concentrations heavily depend on cave airflow as ventilation transports gases out of caves (CIGNA, 2005; GOMELL & PFLITSCH, 2022 (a)). Without cave air circulation, gases such as carbon dioxide (CO_2), can build up inside these underground enclosed spaces. Cave airflow is heavily influenced by surface temperatures and pressure, as the cave atmosphere constantly tries to equalize with the surface atmosphere. Differences between surface air and cave air temperatures produce density differences that cause air to circulate from the surface into the cave (CIGNA, 1968).

Carlsbad Caverns National Park is a UNESCO World Heritage Site located in the Guadalupe Mountain range of Southeast New Mexico that attracts over 300,000 annual visitors worldwide. Carlsbad Cavern is over 30 miles long and has the largest cave chamber by volume in North America, the Big Room (HILL, 1990), which has a volume of approximately 3.7x106 m3 (estimate provided by the Cave Research Foundation survey) and is located about one mile from the Natural Entrance.

Carlsbad Cavern has two main airflow mechanisms, barometric airflow and circulating convective airflow (KILLING-HEINZE et al., 2017). Barometric airflow, air currents that reverse in response to atmospheric pressure changes (CONN, 1966; GOMELL et al., 2021; GOMELL & PFLITSCH, 2022 (a); GOMELL & PFLITSCH, 2022 (b)), occurs in the cave year-round. When surface air pressure is higher than cave air pressure, surface air will flow into the cave. When surface air pressure is lower than cave air pressure, cave air will flow out of the cave (PFLITSCH et al., 2010).

Circulating convective airflow starts at the Natural Entrance and penetrates about a mile into the cave (Fig. 1) (KILLING-HEINZE et al., 2017). Circulating convection occurs in Carlsbad Cavern during late October to March, when cold air sinks into the cave along the floor, warms up inside the cave, rises to the ceiling, and flows out the same entrance near the ceiling (AHLSTAND, 1980; COVINGTON & PERNE, 2015). In April to early October, the surface temperatures are much higher than the cave temperatures, stagnating the cave air by shutting down the circulating convective airflow cell and allowing CO_2 and radon concentrations to stay high (CHENG et al., 1997).

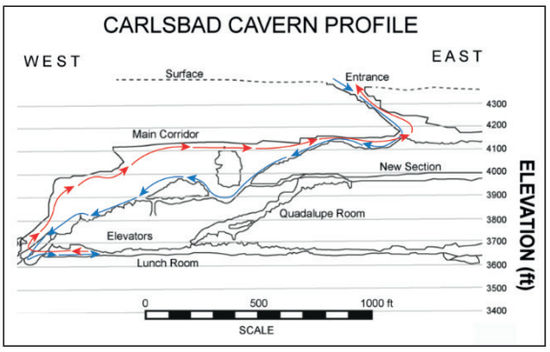


Figure 1: *The Carlsbad Cavern circulating convective cell is active when cold air during winter months sinks into the Natural Entrance, flows downwards to the Big Room warming up along the way, and rises back out of the cave near the ceiling. Adapted from a Carlsbad Cavern profile provided by the Cave Research Foundation.*

Many studies have demonstrated that ventilation by surface air is the primary control on concentrations of radon and CO_2 (SPÖTL et al., 2005; CIGNA, 2005; KOWALCZK & FROELICH, 2010). However, there have been very few studies modeling gas dynamics in caves with circulating convective airflow. Here, we apply a simple gas transfer model previously used to quantify gas transfer by a convection cell (MILANO & GABROVŠEK, 2009) to see whether it provides a useful approximation of gas transfer in Carlsbad Cavern. We also use model coefficients to quantify timescales of gas exchange. Determining how ventilation and gas sources interact to control cave gas concentrations will allow a better understanding of how gases vary within cave systems, with implications for the interpretation of paleoclimate records (SPÖTL et al., 2005, patterns of speleogenesis (COVINGTON et al., 2021), and human health (CHENG et al., 1997; AL--ZOUGHOOL & KREWSKI, 2009)

2. Materials and methods

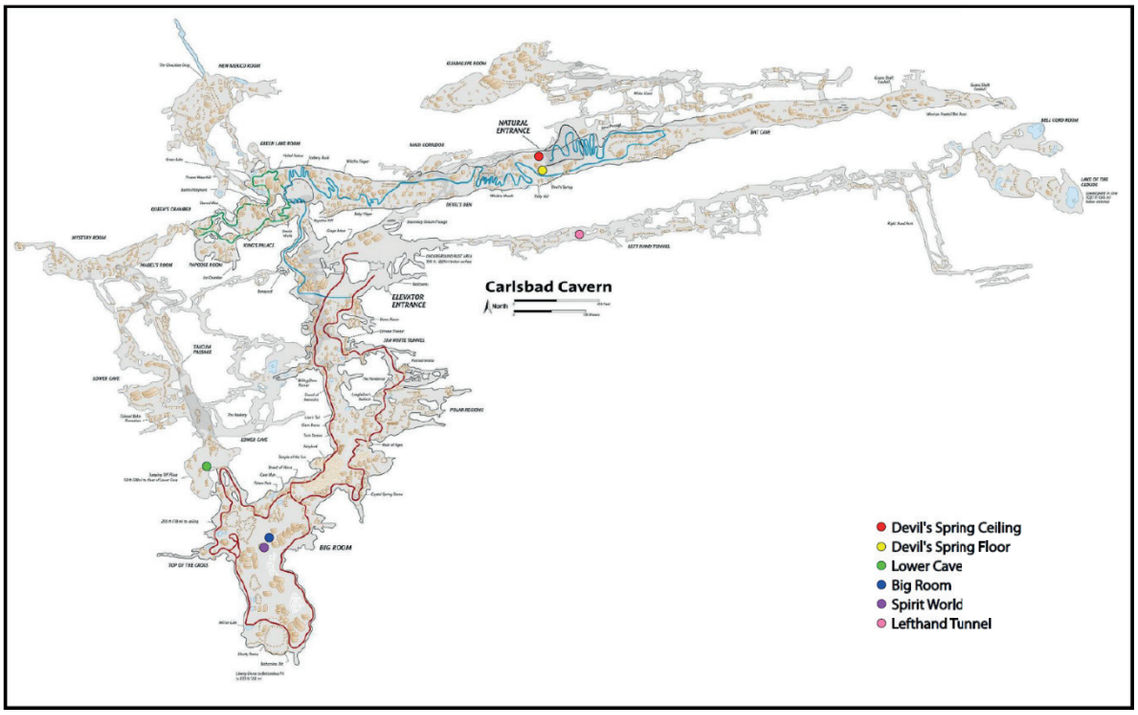


Figure 2: *Six speleometeorological stations were deployed in Carlsbad Cavern at Devil's Spring, Lower Cave, the Big Room, Spirit World, and Lefthand Tunnel. Two stations were deployed at Devil's Spring. One is placed closer to the ceiling (Devil's Spring Ceiling) and the other is placed closer to the floor (Devil's Spring Floor).*

Six speleometeorological stations were constructed and deployed at five locations in Carlsbad Cavern to study how different airflow mechanisms influence gas concentration dynamics. Monitoring sites (Fig. 2) were selected with sensitivity to historic, cultural, and natural resources and based on the results of prior airflow and hazardous gas studies in Carlsbad Cavern (WILKENING & WATKINS, 1976; KILLING-HEINZE et al., 2017). Two stations were placed at Devil's Spring, which is the closest monitoring site to the Natural Entrance and is in the circulating convective airflow cell. The first station, Devil's Spring Floor, is placed close to the floor to capture the dynamics of the cold air entering the cave. The second station, Devil's Spring Ceiling, is placed close to the ceiling to capture the dynamics of the warm air exiting the cave. The Lower Cave station has the lowest elevation and is in the crossover zone between the circulating convective airflow and barometric airflow. The Big Room is also a potential crossover zone between circulating convective airflow and barometric airflow. Temperatures in the Big Room are heavily influenced by body heat from the thousands of visitors this room receives a year. Spirit World is located in the entryway of a passage that enters the Big Room in a high alcove at the ceiling 80 m above the floor. The final station, Lefthand Tunnel, is most likely influenced by barometric airflow or a cold air trap (KILLING-HEINZE et al., 2017).

Deployment of stations began on September 15, 2024, and data collection will continue until December, 2025. Each station comprises a radon monitor, a CO_2 detector, and an atmospheric sensor to measure barometric pressure, relative humidity, and temperature. Devil's Spring Floor and Lefthand Tunnel stations contain anemometers to measure wind speed and direction. Surface conditions are monitored by the Carlsbad Cavern National Park weather station located at the top of the ridge containing Carlsbad Cavern. Due to delays in acquiring equipment, measurement of radon and some meterological parameters did not begin until later in the study. CO_2 concentrations are the only data that have been continously collected since the original deployment. While a central goal of the full study is to analyze the covariation of radon and CO_2, here we will focus on the CO_2 data that are already available.

Gas transfer between a cave chamber and the surface atmosphere via a convection cell can be approximated with a simple differential equation based on mass conservation (MILANOLO & GABROVŠEK, 2009). The model assumes a constant rate of air exchange between the chamber and outside atmosphere, in which case the rate of change of gas concentration in the chamber is a linear function of the difference between inside and outside concentrations and the production rate of the gas within the chamber. This leads to the following relation,

$$\frac{dC_C}{dt} = -\frac{Q}{V}(C_C - C_A) + \frac{P}{V}, \qquad (1)$$

where C_c is cave air CO_2 concentration, C_A is surface atmosphere CO_2 concentration, P is CO_2 production rate, t is time, Q is air discharge, and V is cave volume. We do not attempt to separate natural CO_2 production from production by tourists, though both sources are potentially important. Prior work by the park has demonstrated that tourists are a substantial contributor to CO_2 in the cave. Under the assumption that C_C is the only variable that changes in time, Equation 1 is separable and can be integrated to produce a solution that is an exponential function:

$$C_C = \left(\frac{P}{Q} + C_A + C_0\right)\left(1 - e^{-\frac{Q}{V}t}\right) + C_0, \qquad (2)$$

where C_0 is the initial CO_2 concentration measured at the start of the period. The exponential function was fit to periods where the convection cell turns on and CO_2 concentrations drop. There are two unknowns in this model, P and Q. For V, we use a prior estimate of the volume of the Big Room. We also let C_0 vary as a fitting parameter, so that noise in the data does not strongly influence the initial condition. This model was fit to CO_2 concentrations to see how well it performs at Carlsbad and whether the best-fit model parameters are stable or vary with event or location.

3. Results

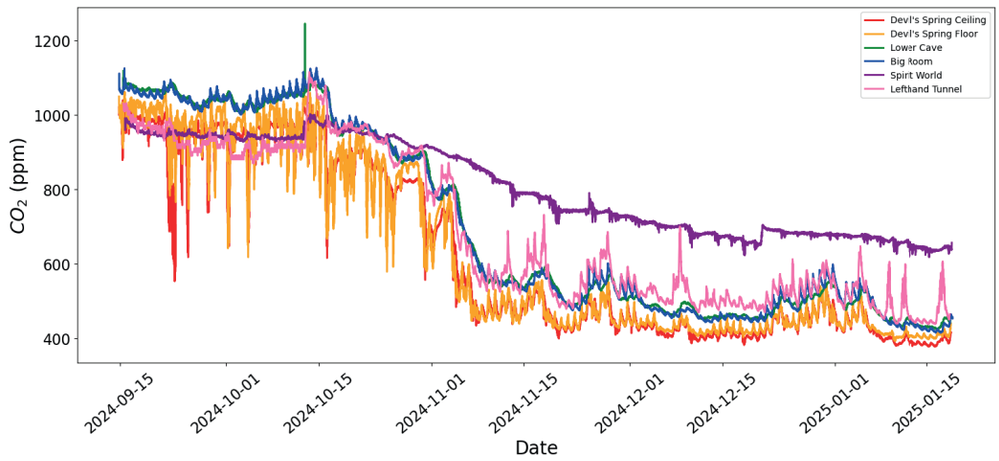


Figure 3: *CO_2 concentrations at all stations from September 15, 2024 to. January 18, 2025. All six stations show a drop in CO_2 concentrations when the surface air starts to cool down below cave temperature.*

The speleometeorological stations deployed in Carlsbad Cavern have measured CO_2 concentrations since September 15, 2024 (Fig. 3). CO_2 concentrations at the start of the monitoring period were around 1000 ppm. CO_2 concentrations then decreased starting in mid-October, coinciding with the onset of surface temperatures that drop below cave temperature.

By the end of October, all stations recorded two notable drops in CO_2 concentrations, with the second drop being the most pronounced. Both events lasted approximately 3.5-4 days. The first occured from around midnight on October 31, 2024, until midnight on November 3, 2024. The second began two days later, around noon on November 4, 2024, and continued until midnight on November 8, 2024.

Following these drops, CO_2 concentrations remained relatively low across all six stations. For Lower Cave, Big Room, and Spirit World, the concentration decreases exhibit an exponential pattern. Consequently, the exponential function (Eq. 2) was fit to the measurement curves for both events at these locations (Fig. 4). The exponential function provides a good fit to observed concentration changes at Lower Cave and the Big Room. However, the Spirit World curve is approximately linear over this time scale. Consequently, the time constant that determines curvature can not be precisely determined for this site over such a short period.

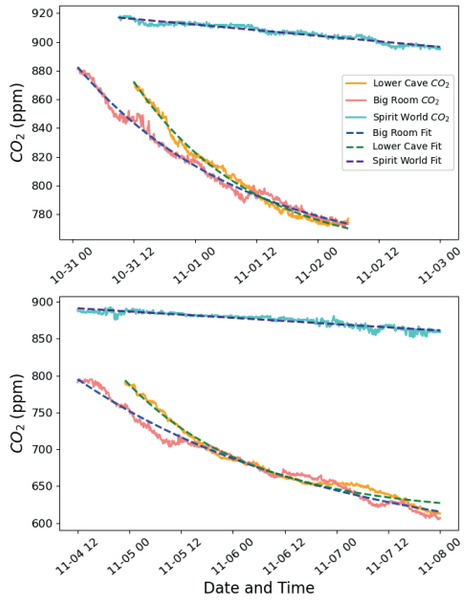


Figure 4: *The fit of the exponential function (Eq. 2) to the two rapid decreases in CO_2 concentrations at the Lower Cave, Big Room, and Spirit World stations. While both Lower Cave and Big Room display clear concave upward curvature, the Spirit World curve is nearly linear over this period.*

From October 15, 2024 – January 15, 2025, the decrease in CO_2 at Spirit World resembles an exponential curve. Therefore, we also fit Eq. 2 over this longer period for Spirit World, and it matches the measurement curve relatively well despite the higher starting value for the fit.

P, Q, and C_0 were calculated for the Lower Cave and Big Room sites based on the estimated volume of the Big Room (3.7×10^6 m^3). For Spirit World, where it is less clear what the representative volume would be, we simply provide the raw fit values in terms of the timescale, $\tau = V/Q$, and the production per volume, P/V. Values of the fitting parameters are provided in Fig. 6. Big Room and Lower Cave have similar parameters. τ for Big Room and Lower Cave ranges from almost a day to about 2.5 days, while τ for Spirit World is tens of thousands of days for both smaller periods. However, this value cannot be trusted due to the linearity of the curve over this shorter period. CO_2 production rates for Lower Cave and Big Room differ by a very small margin from October 31, 2024 - November

3, 2025, and they are the exact same for November 4, 2024 – November 8, 2024. Spirit World CO_2 production rates for both of those time periods are slightly larger.



Figure 5: *The fit of the exponential function (Eq. 2) to the long-term decrease in CO_2 concentrations at Spirit World from October 15 – January 15, where concave upward curvature is clearly visible.*

		P (m^3/s)	Q (m^3/s)	C_0 (ppm)	τ (days)	$\frac{P}{V}(\frac{1}{day})$
October 15, 2024 – January 15, 2025	**Spirit World**	--	--	983	38.8	$1.31x10^{-5}$
October 31, 2024 – November 3, 2024	**Lower Cave**	$4.52x10^{-4}$	44.2	872	0.968	$1.05x10^{-5}$
	Big Room	$4.61x10^{-4}$	35.6	881	1.36	$1.08x10^{-5}$
	Spirit World	--	--	917	37500	$1.16x10^{-5}$
November 4, 2024 – November 8, 2024	**Lower Cave**	$3.71x10^{-4}$	35.0	791	1.22	$8.64x10^{-6}$
	Big Room	$3.71x10^{-4}$	17.2	791	2.49	$8.64x10^{-6}$
	Spirit World	--	--	889	78400	$1.10x10^{-5}$

Figure 6: *The parameters used to fit Eq. 2 to the CO_2 data for each location during periods of decreasing CO_2. P is the production rate of CO_2 in m^3/s, Q is the air discharge in m^3/s, C_0 is the initial CO_2 concentration in ppm, τ is the time constant for gas exchange, V/Q , and P/V is the production rate of CO_2 per cubic meter of air.*

4. Discussion

The measured CO_2 dynamics within Carlsbad Cavern provide important insights into the cave's ventilation patterns. The initial period of elevated CO_2 concentrations from mid-September to mid-October suggests limited cave ventilation, likely due to warm surface temperatures that make surface air less dense than cave air. This period of stagnation aligns with expected seasonal transitions where surface cooling has not yet activated the circulating convective airflow cell.

The two significant CO_2 reduction events at the end of October and early November are particularly notable. Both drops in concentration lasted approximately 3.5 days, indicating a shift in cave air ventilation in Lower Cave, Big Room, and Spirit World. The second event has a more pronounced decline, which may have resulted from stronger surface cooling that enhanced cave-air exchange with the surface. The successful fitting of Eq. 2 to the observed CO_2 decreases in Lower Cave and Big Room, and the plausible range of physical parameters, suggests that the model provides a useful approximation of gas transfer between the surface atmosphere and the cave atmosphere when the circulating convective cell is active in these two locations.

To examine the plausibility of the parameter values in the model, and to constrain the importance of different CO_2 sources, we first compare CO2 production rates to those expected from the respiration of tourists. A single human produces about $6.4x10^{-6}$ m^3/s of CO_2 while exercising lightly (JACOBSON, 2019). Carlsbad Caverns normally receives between 300-1300 tourists per day during late October and early November. If we use 1000 tourists as a representative number, and each tourist spends 1/10 of a day (~2.4 hours) in the cave, then the daily average production rate is about $6.4x10^{-4}$ m^3/s. This number is on the same order of magnitude as our estimated P values (Fig. 6), suggesting that tourists may be the primary source of CO_2 during this period. The calculated Q values (Fig.6) can be compared against observed air velocities at Devil's Spring, which peak around 0.5 m/s during periods of active circulation. If we assume that approximately half of the passage cross-section is occupied by descending airflow, then the cross-section for air discharge at that site is around 100 m^2. This would produce a Q value of ~50 m^3/s, which is similar to values estimated from the model. τ parameters for the Big Room and Lower Cave sites are within the same range as those calculated in a similar study (WILKENING & WATKINS, 1976).

The lack of curvature in the CO2 curve at Spirit World over short periods produces spurious τ values (Fig. 6) when fitting the exponential model. However, the successful fitting of Eq. 2 to the long-term exponential curve pattern at Spirit World from October 15, 2024 – January 15, 2025 indicates that this model may work for longer periods in this location. The gas exchange rate for Spirit World must be much slower than for the main cave, with an exchange timescale of greater than one month. Spirit World, which is located in an alcove in the ceiling of the Big Room, may act as a warm air trap during periods of active convection, slowing the exchange of gases into that volume.

5. Conclusion

Continuous CO_2 monitoring from six speleometeorological stations in Carlsbad Cavern since September 15, 2024 shows that a circulating convective airflow cell is flowing in two areas of the cave, Lower Cave and the Big Room during cooler months. Elevated CO_2 levels during hotter surface temperatures drop notably following a decrease in surface temperatures, leading to rapid CO_2 reductions that resemble exponential curves. A simple exponential gas transfer model produces a good fit to measured CO_2 concentrations.

Two of the sites display rapid gas transfer, on a timescale of days, and one site displays much slower gas transfer, on the timescale of a month. Parameter values determined from fitting the exponential function are physically plausible given estimated cave volume, observed airflow, and approximate CO_2 production rates of tourists. The fact that CO_2 production rates estimated in the model are similar to those estimated from tourists suggests that tourists may be the primary source of CO_2 during the study period. Spirit World appears to be isolated from the main convection cell and exhibits much slower gas exchange.This study is still ongoing until mid-December 2025. By the end of the study, radon concentration, CO_2 concentration, relative humidity, barometric pressure, temperature, and wind velocity datasets should be complete

for all six stations. This will aid further analysis and expand current knowledge of cave air ventilation to more areas of the Carlsbad Cavern. Understanding ventilation processes is critical for interpreting past and present cave environments, understanding patterns of speleogenesis, and monitoring human health.

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Relação entre chuva e temperatura na cavidade N3_0020 associada a litologias em ferro

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Resumo

Ao longo de um ano e meio monitorou-se a cavidade N3_0020 associada a litologias ferríferas localizada em Carajás, estado do Pará. O monitoramento englobou dados externos e internos à cavidade; dados externos – pluviometria, temperatura e umidade; dados internos – infiltração, temperatura e umidade. As temperaturas no período chuvoso geralmente decaem em relação à estiagem. Observou-se que a temperatura no interior da cavidade sofre influência da infiltração das águas – as águas escoam sobre a canga quente infiltrando/percolando rapidamente elevando a temperatura na cavidade. Na estiagem, praticamente sem infiltração de água, a temperatura no interior desta cavidade decai. A temperatura também decai quando há grandes períodos de chuva, onde o período de insolação não é suficiente para aquecer a canga e consequentemente as águas superficiais.

Abstract

Over a period of one and a half years, the N3_0020 cave, associated with iron lithologies in Carajás, Pará, was monitored. The monitoring encompassed both external and internal data: external parameters included rainfall, temperature, and humidity, while internal parameters comprised infiltration, temperature, and humidity. Temperature trends indicated a general decrease during the rainy season compared to the dry season. It was observed that temperature within the cave is influenced by water infiltration—rainwater flows over the heated canga, rapidly infiltrating and percolating, which results in an increase in cave temperature. During the dry season, when water infiltration is minimal, the cave temperature decreases. Additionally, prolonged periods of rainfall lead to a temperature decrease, as insufficient sunlight prevents the heating of the canga and, consequently, the surface water.

Resumen

Durante un año y medio fue monitoreada la cavidad N3_0020 asociada a litologías de hierro ubicada en Carajás, estado de Pará. El monitoreo incluyó datos externos e internos a la cavidad; datos externos: precipitaciones, temperatura y humedad; Datos internos: infiltración, temperatura y humedad. Las temperaturas durante la temporada de lluvias generalmente disminuyen en comparación con la temporada seca. Se observó que la temperatura dentro de la cavidad está influenciada por la infiltración de agua: el agua fluye sobre la canga caliente, infiltrándose/percolándose rápidamente, elevando la temperatura en la cavidad. Durante la sequía, al no haber prácticamente infiltración de agua, la temperatura en el interior de esta cavidad desciende. La temperatura también baja cuando hay periodos prolongados de lluvia, donde el período de insolación no es suficiente para calentar la canga y consecuentemente las aguas superficiales.

1. Introdução

Desde os primórdios os seres humanos estão acostumados a utilizar os recursos disponíveis de modo a facilitar suas condições. Com a revolução industrial o uso dos recursos tornou-se frenético como forma de acumulação de riqueza. O monitoramento é uma ferramenta que auxilia no diagnóstico e permite investigar a cavidade ao longo do tempo, através da caracterização das condições anteriores a determinado evento (natural ou não) e a permanente vigilância.

No caso de cavidades, ao buscar informações que demonstrem a real interferência do meio externo em sua dinâmica ecossistêmica, é possível propor áreas de proteção eficientes.

Timo et al. (2019) ressaltam a importância do monitoramento espeleológico para gerar dados que evidenciem a interferência do meio externo nas condições ambientais e físicas das cavidades. Esse conhecimento é fundamental para a preservação do patrimônio espeleológico e a utilização sustentável dos recursos naturais.

O acompanhamento temporal das variações de temperatura e umidade nas regiões internas e externas das cavidades fornece dados para análise estatística. A partir desses dados, é possível entender como o meio externo interfere no microclima subterrâneo, semelhante ao trabalho desenvolvido por Lobo et al. (2009).

Para compreender as relações das condições externas no ambiente cavernícola foram monitorados ao longo do tempo a temperatura, umidade e pluviometria/infiltração.

O microclima em cavidades é influenciado por características inerentes, como topografia, geometria, distribuição e quantidade de entradas, incidência de luz solar, confinamento espacial, entre outros. Esses fatores são significativos nas trocas de fluxos de energia e massa entre o ambiente interno e externo (Lobo, 2012 e 2013; Travassos, 2016).

A circulação do ar no interior da cavidade pode ser afetada pela morfologia e consequentemente o microclima cavernícola. A entrada de ar varia em cavernas com piso ascendente, descendente ou outras geometrias, assim como o posicionamento dos pontos de entrada. Além disso, há diferenças na circulação em função das estações do ano e/ou do ciclo diurno.

2. Materiais e Métodos

A cavidade foi instrumentada com sistema de monitoramento remoto de temperatura (T em ºC) e umidade (UR em %). A periodicidade da coleta foi horária. O posicionamento dos equipamentos foram: um externo à cavidade, um na entrada, um no meio (a depender do tamanho da cavidade) e outro na parte distal. Na Figura 1, a seguir, temos o exemplo deste posicionamento.

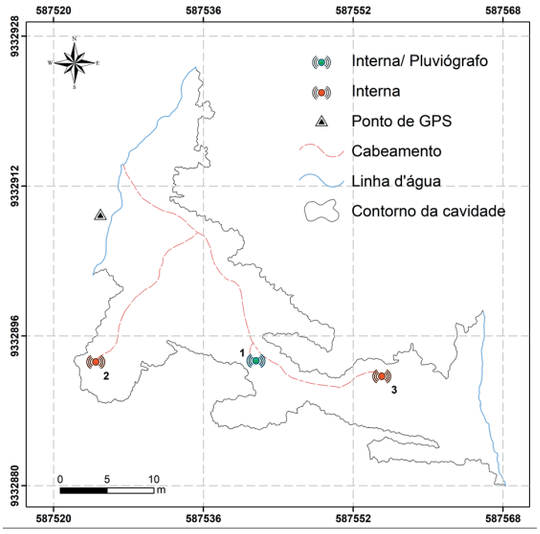


Figura 1: *Localização dos equipamentos no interior da cavidade.*

Para o monitoramento hídrico, foram instalados dataloggers para aferição da pluviosidade, em local externo à cavidade, na área de contribuição hídrica, de forma a monitorar os aportes hídricos. O mesmo logger também coletou dados climáticos.

No interior da cavidade, também foram instalado dataloggers para estimar a quantidade e variação das águas infiltradas.

Em relação aos equipamentos, unidade externa é um datalogger alimentado por bateria não recarregável de longa duração que registra periodicamente dados de temperatura e umidade em uma memória interna não-volátil. Além dos sensores de temperatura e umidade incorporados, há também uma porta de expansão em que podem ser conectados sensores de vários tipos, como sensor pluviométrico por exemplo. Possui comunicação com rede celular (2G/3G/4G) e a possibilidade de instalação de módulo de comunicação via satélite Iridium, como é o caso das unidades do Pará (Figura 2a e 3a). A unidade interna é semelhante possuindo a porta de comunicação, que pode ser utilizada para comunicação com uma unidade externa para envio remoto dos dados (Figura 2b e 3b).

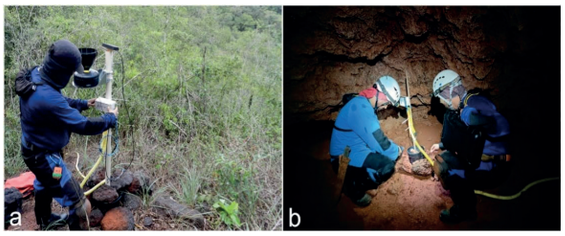


Figura 2: *a. Unidade Externa. b. Unidade Interna.*

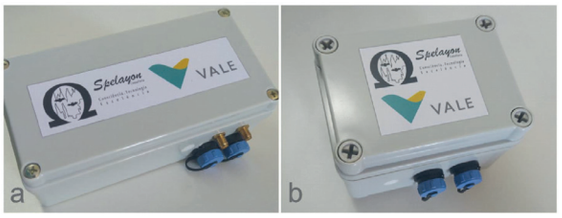


Figura 3: *Detalhes das unidades: a. Externa. b. Interna.*

A cada campo, identificou-se os pontos de infiltração no interior da cavidade no dia da visita, além da realização da manutenção dos equipamentos e eventualmente a coleta de dados dos loggers. Os dados são enviados de forma remota.

O resultado de tais monitoramentos forneceu um diagnóstico do clima da cavidade e seu entorno.

Os dados foram analisados por meio de procedimentos analítico-descritivos e estatísticos. Na primeira etapa, foi feita a estatística descritiva dos dados, com a identificação das médias, amplitudes e desvio padrão, através de gráficos de barras e linhas.

3. Resultados

A cavidade monitorada situa-se no município de Parauapebas, distrito de Carajás (N3_0020), Pará. A cavidade está inserida na alta vertente, na base da quebra do relevo de escarpa em encosta de aproximadamente 12 m de altura. Possui 2 entradas, sendo a entrada principal ampla com teto alto e a segunda entrada estreita. Seu desenvolvimento é essencialmente linear com condutos laterais que possuem dimensões reduzidas e conduto principal alongado seguindo direção NW-SE (Figura 4).



Figura 4: *a.Entorno da cavidade; b.Entrada principal.*

A partir da construção do MDE gerou-se o mapa de declividade (Figura 5) seguindo a base da Embrapa (1999), sendo elas: 0 a 3% (plano), 3,1% a 8% (suave ondulado), 8,1% a 20% (ondulado), 21% a 45% (forte ondulado), 46% a 75% (montanhoso) e 76% a 100%(escarpado).

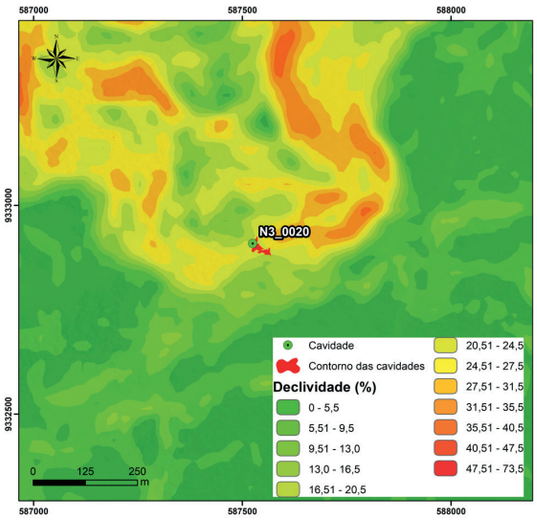


Figura 5: *Mapa de declividade do terreno.*

As cavidades associadas a litologias ferríferas situam-se em condições onde a infiltração de águas de chuva é essencial à sua dinâmica. Na canga a porosidade primária caracteriza-se pela presença de interstícios predominantemente não conectados. A infiltração/percolação ocorre através da porosidade secundária, definida por descontinuidades abertas, fratura verticais e acamamento horizontal ou seguindo o relevo. Na formação ferrífera predomina a porosidade primária, com percolação predominante vertical. Na época de chuvas essas cavidades podem mostrar grandes infiltrações/percolações de água na forma de gotejamentos e jorros de água no teto e paredes. A paisagem se transforma na época de estiagem como pode ser observado na figura 6.

O monitoramento de pluviosidade e infiltração ocorreu através dos equipamentos -pluviógrafos e dataloggers - instalados em setembro de 2022 na região externa e interna da cavidade N3_0020. Neles foram aferidos dados de temperatura, umidade e pluviosidade/infiltração a depender da localização. Na Figura 7 pode ser verificado o gráfico gerado a partir dos registros do pluviógrafo externo relativo aos meses de setembro de 2022 a julho de 2024, além do pluviógrafo dos registros de infiltração no interior da cavidade. Os meses que não foram apresentados no gráfico são justificados pela ausência de eventos.

Na Figura 8 são apresentados os dados de Temperatura máxima, mínima, média e desvio padrão referentes aos meses de outubro de 2022 a abril de 2024. Em janeiro duas unidades foram substituídas (interno 2 e 3) para manutenção e por isso não há dados desses equipamentos neste mês. Em março os equipamentos denominados externo e interno 2 também apresentaram falhas assim como o interno 1 de junho a agosto.

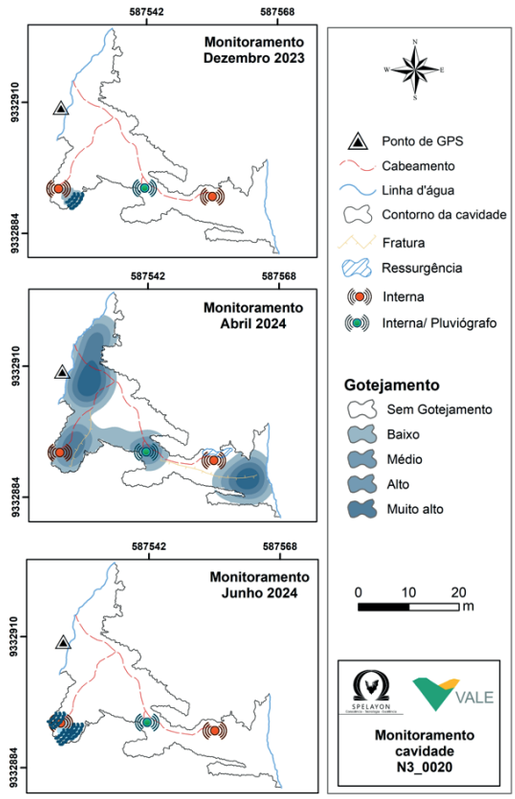


Figura 6: *Indicação dos pontos observados na cavidade nos meses de novembro de 2020 a janeiro e março de 2021.*

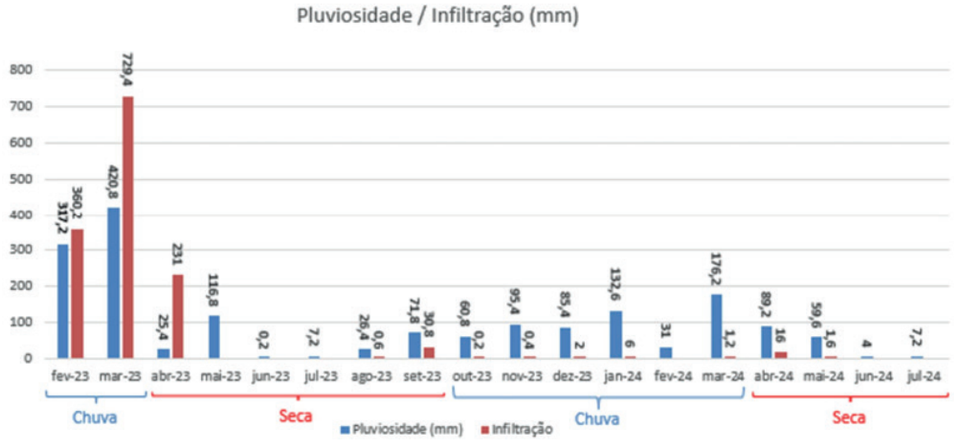


Figura 7: *Gráfico de pluviometria e infiltração – cavidade N3_0020.*

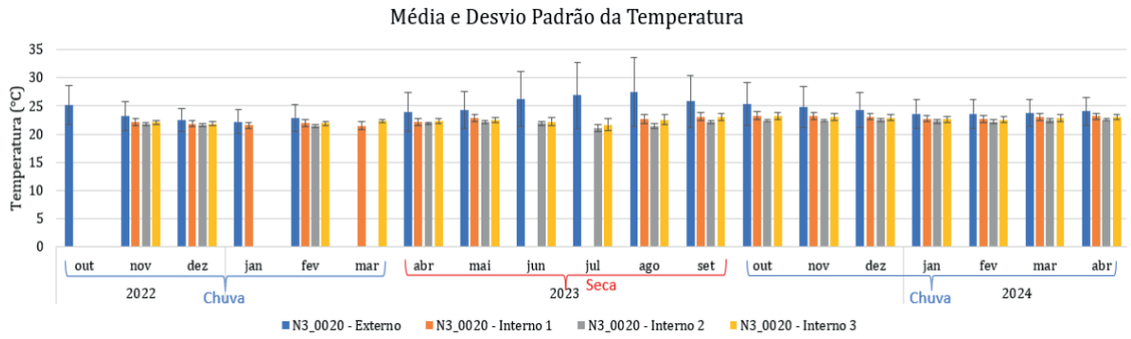


Figura 8: *Gráfico em barras com as médias da temperatura registradas pelos equipamentos e barras de desvio padrão.*

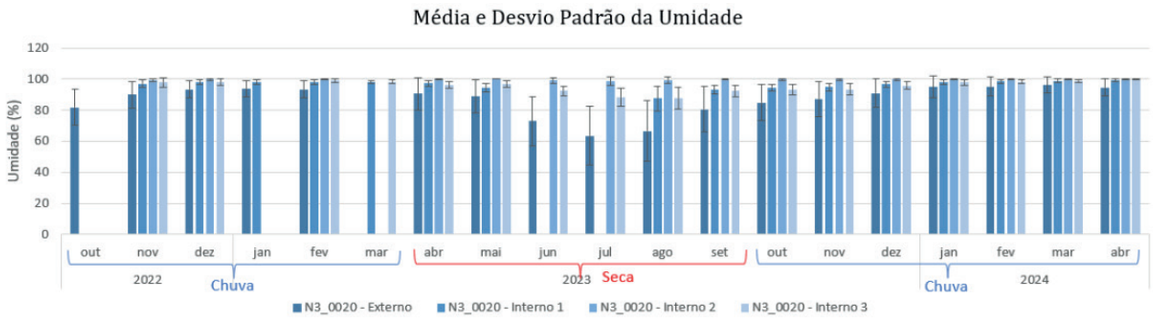


Figura 9: *Gráfico em barras com as médias da umidade registradas pelos equipamentos e barras de desvio padrão.*

4. Discussão

O microclima em cavidades é influenciado por características inerentes a esses ambientes, como topografia, geometria, distribuição e quantidade de entradas, além de elementos externos como incidência de luz solar e confinamento espacial. Esses fatores são significativos nas trocas de fluxos de energia e massa entre o ambiente interno e externo (Lobo, 2012 e 2013; Travassos, 2016).

Esses fatores conferem uma atmosfera distinta às cavidades, diferenciando-as de outros sistemas atmosféricos. A caracterização da atmosfera cavernícola é feita através de medições de temperatura e umidade relativa do ar, pressão atmosférica e fluxos de água, conforme estabelecido por Lobo (2012).

De acordo com Lobo (2013, apud Bailey, 2005; Badino, 2009), os elementos que configuram a atmosfera cavernícola podem variar devido a interferências com o meio externo, como confinamento espacial, estabilidade dos parâmetros físico-químicos, estratificação vertical, movimentação relativamente pequena de massa e energia, menor disponibilidade ou ausência total de luz e o número e posição dos acessos ao ambiente externo.

O desenvolvimento da cavidade interfere na circulação do ar em seu interior, e, como consequência, a morfologia afeta o microclima cavernícola. A entrada de ar varia em cavernas com piso ascendente, descendente ou outras geometrias, e o posicionamento dos pontos de entrada também interfere. Além disso, há diferenças na circulação em função das estações do ano e/ou do ciclo diurno.

O monitoramento dos atributos microclimáticos (temperatura ambiente – T – e umidade relativa do ar – UR) é realizado mensalmente, com registros horários e contínuos. No interior das cavidades, os aparelhos são distribuídos nos locais onde foi verificada dinâmica hidrológica, zonas de fragilidade, além das regiões de entrada (zona exterior e interna), fundo e salão principal. Como pode ser observado, o desvio padrão é menor em equipamentos instalados em partes mais profundas da cavidade, o que é coerente com a ideia da variação de temperatura ser menor em ambientes cavernícolas. As médias de temperatura possuem valores constantes e parecidos entre si durante todo o período e a umidade é mais alta no interior das cavidades.

Com o início das chuvas as águas iniciam sua caminhada para a cavidade. Nem toda a chuva atinge a cavidade, depende da saturação do solo. À medida que a chuva se intensifica e satura o solo as águas começam a atingir a cavidade. Inicialmente as temperaturas destas águas influenciam no clima da cavidade, aumentando-a. Com o aumento da pluviometria e menor quantidade de sol, há um reflexo na temperatura interna e externa à cavidade, deixando as temperaturas mais semelhantes. Na estiagem, onde as águas praticamente cessam na cavidade, a temperatura externa e interna sofre maior diferença, com aumento da temperatura externa e decréscimo da interna (Figura 10).

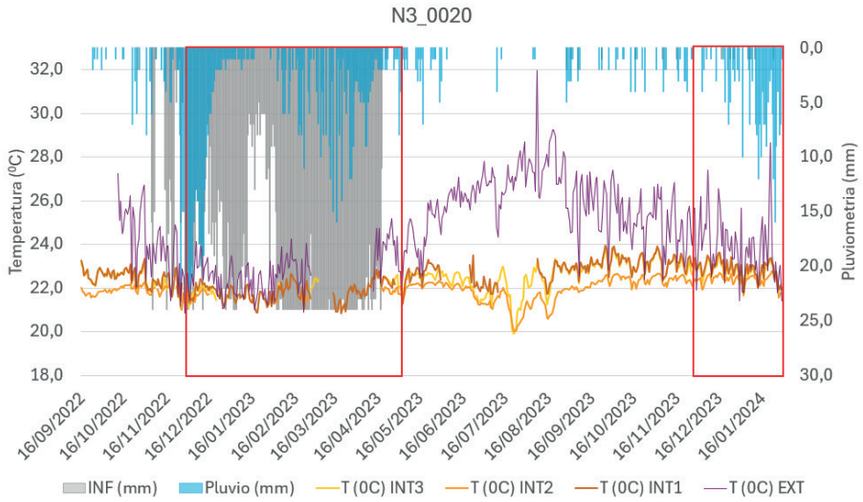


Figura 10: *Gráfico em barras com pluviometria (Pluvio) e infiltração (INF) e linhas mostrando as temperaturas externas e interna na cavidade.*

5. Conclusão

Como observado, a temperatura no interior da cavidade sofre influência da infiltração das águas de chuva. A pequena espessura do teto (variando de 2m a 20m) e a presença de descontinuidades garante que as águas rapidamente atinjam a cavidade, não dando tempo de modificarem sua temperatura. Assim, águas que escorrem sobre a canga quente chegam à cavidade aumentando sua temperatura; com a continuidade das chuvas e a falta de insolação, as águas esfriam reduzindo a temperatura tanto externa quanto interna. Na estiagem, com o terreno seco, as águas de chuva geralmente não atingem a cavidade. A explicação passa pela evaporação das águas, interceptação pela vegetação (evapotranspiração) além da retenção da água no solo até a saturação. Nesta época ocorrem as maiores divergências entre as temperaturas externas e internas à cavidade, com a temperatura do meio hipógeo atingindo seus menores valores (Figura 10).

Como adendo, temos conclusões sobre o monitoramento remoto. Este sistema permite reduzir as constantes visitas a campo, minimizando impactos sobre a cavidade e reduzindo a exposição do indivíduo ao risco. O monitoramento remoto é uma tendência. Conjuntamente com inteligência artificial para tratamento dos dados, fornecerá agilidade de resposta e auxiliará na conservação de cavidades.

Agradecimentos

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Underground monitoring and mapping in conglomerate karst, a case study from “Castel Sotterra” Cave (Veneto, Italy)

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Abstract

The “Castel Sotterra” cave, with a length of ~7 km and a depth of ~125 m, is the largest cave on the Montello Hill and the fourth largest conglomerate cave in the world. The cave provides a unique environment for studying underground microclimatic patterns and their role in the ecology of a non-traditional multi-level cave system.

Speleological surveys and explorations coupled with temperature monitoring reveal the thermal dynamics and properties of a conglomerate cave, specifically how temperature variations correlate with cave levels, conduit intersections, and external climatic variations during precise temperature tracking. The goal is to reveal nuanced patterns of air movement that may be the same or different from traditional cave systems. Along with the monitoring, a three-dimensional cave map is being developed to provide spatial context for the temperature data and to identify potential connections between cave passages and the surface.

Temperature data are key to assessing the suitability of the cave for underground animal populations, such as Chiroptera, which are commonly found in Castel Sotterra Cave. These environmental parameters have wider implications for understanding the resilience of the cave ecosystem in the face of pressures from ongoing environmental issues such as habitat destruction, pollution and climate change.

1. Introduction

Caves represent a unique and fragile subterranean environment, where climatic characteristics reflect the complex interplay between external factors such as temperature and precipitation, cave morphology resulting from speleogenesis, and the physical properties of the substrate. The thermal properties of a cave depend primarily on heat conduction from the atmosphere and advection from water and air inflow (Badino, 1995). Monitoring temperature variations inside caves serves multiple purposes in modern speleological activities. Historically, tracking water flow along conduits and detecting slight variations in air movement have been the most common indicators of potential unexplored passages and entrances during exploration. However, a scientific approach using data loggers placed at key locations can reveal interactions within the underground environment, including the physical thermal state of a cave and its ecosystem (e.g., Luetscher et al., 2008; Dominguez-Villar et al., 2023). In this study, we explore how temperature variability is closely related to cave morphology in the unique environment of Montello Hill (Figure 1A), which is considered the “Classical Karst” of conglomerate (Ferrarese and Sauro, 2005). The Montello Karst has evolved rapidly over the last ~350 kyr, forming a well-developed multi-aquifer karst system influenced by substrate lithotypes and active tectonics.

In the Castel Sotterra Cave, temperature monitoring has been integrated with a new mapping project to provide modern visualizations of the cave, which are useful for scientific research. We observed how temperature variations influence the habitability of different cave sectors for bats, representing the archetype of cave-dwelling animals. The Castel Sotterra Cave is one of the most important hibernacula for bats in the Veneto Region, and sight counting can provide valuable information on the status of *Rhinolophus* species.

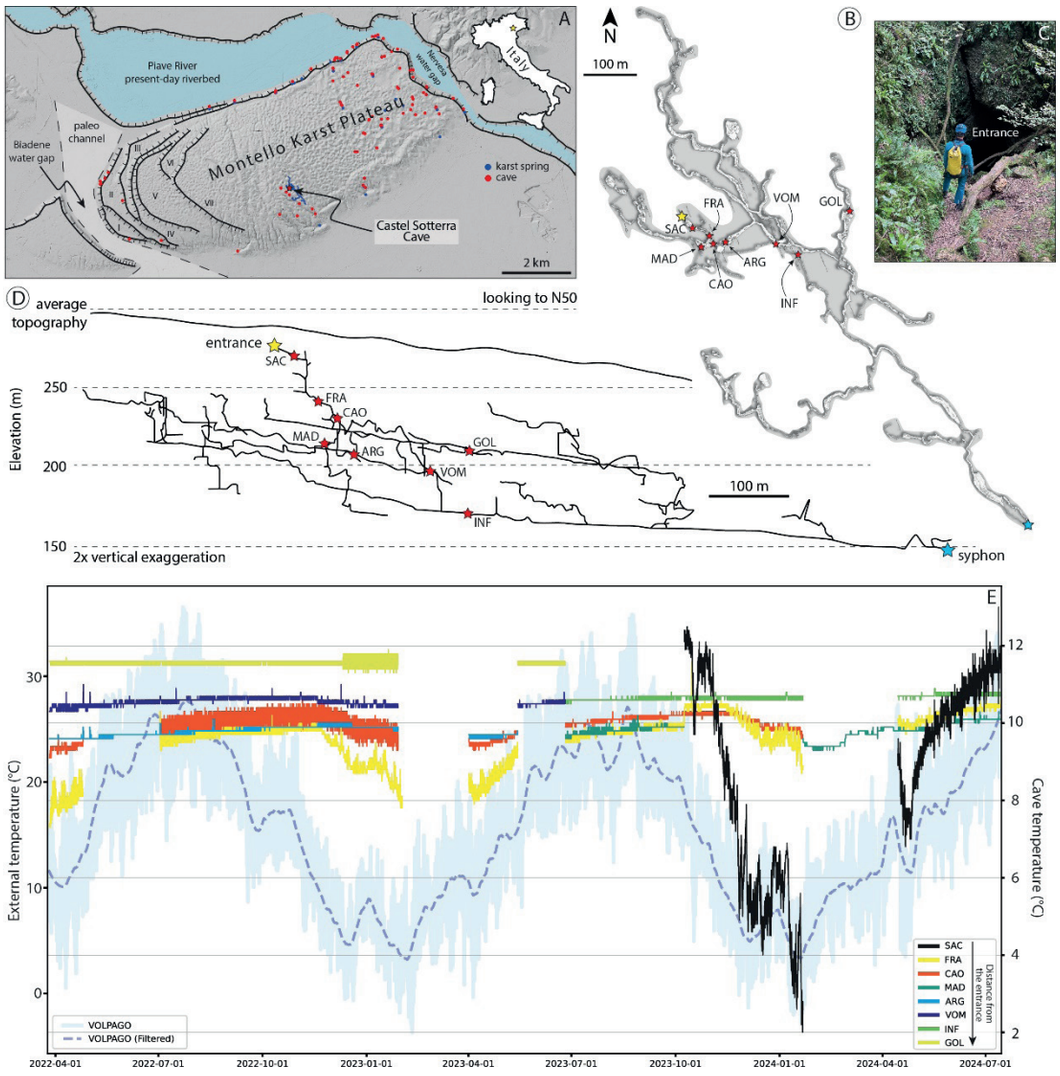


Figure 1: *(A) Map of Montello Hill showing caves entrances and Castel Sotterra Cave. (B) Planimetric map of Castel Sotterra Cave showing temperature datalogger positioning. (C) Picture of the entrance of Castel Sotterra Cave. (D) Vertical cross-section of the cave with datalogger positions. (E) Temperature monitoring of the last three years. The y-axis on the left shows temperature measured at the nearest ARPAV station (Volpago del Montello), the y-axis on the right shows temperature measured by dataloggers. Abbreviations: SAC, Saccardo Room; FRA, Frana Room; CAO, Caos Room; MAD, Madonna Room; ARG, Argilloni; VOM, Vomito Pit; INF, Inferiori Canyon; GOL, Golem Room.*

Following the precursor study by Badino (2004), we aim to initiate a long-term project in the Montello Hill conglomerate karst to better understand the effects of Climate Change, which are already evident in this ephemeral underground environment (e.g., Obleitner et al., 2024). Extended climate data series will be invaluable in predicting the adaptations that ecosystem actors will need to make in response to rising temperatures and extreme weather events.

2. Materials and methods

The temperature monitoring program inside the Castel Sotterra cave was carried out using Elitech RC-5+ loggers, stationed in different sectors of the cave and suspended from the ceiling at human eye level. The loggers have an internal NTC thermal resistor with a precision of 0.5°C. Temperature was recorded every 5 minutes between 2022 and February 2023, every 10 minutes in Spring 2023, and every 30 minutes from Summer 2023 onwards. The external temperature is monitored by open-access data from the ARPA Veneto agency, which provides the temperature every 1 hour at Volpago del Montello, the nearest meteorological station (~ 2.5 km from the cave entrance).

An initial analysis of the dataset was performed using a private online repository designed by the authors to manage temperatures from multiple caves, divided into cave sectors based on available surveys. Each temperature series is visualized on a timeline graph to control the spatial and temporal distribution of the records. Simple tools such as outlier removal and calibration factor are available, and the data can be exported in .xlsx or .csv format, showing metadata about the loggers. The online platform is currently under development but will be released for public use in the near future to contribute to open data science, possibly according to the FAIR data criteria.

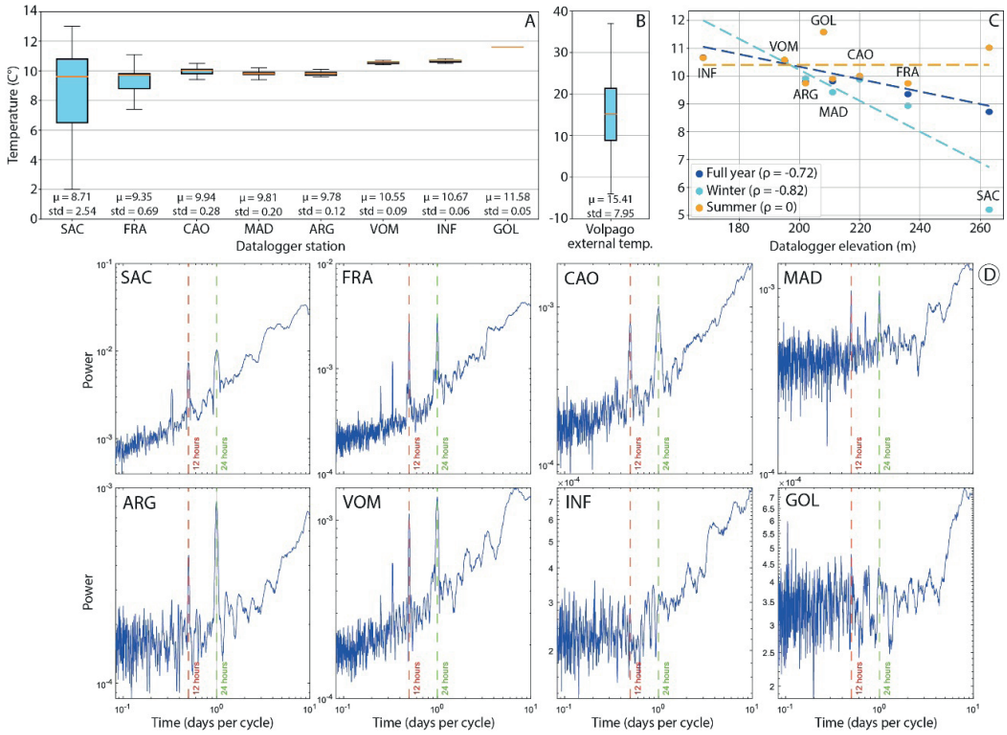


Figure 2: *(A) Boxplot showing temperature ranges measured by dataloggers. Light-blue boxes indicate temperature values between the second and the third quartiles, red lines represent the median value. At the bottom of boxes arithmetic means and standard deviations are shown. (B) Boxplot for temperature recorded at Volpago del Montello ARPAV station. (C) Mean values plotted against datalogger elevations (relative to the sea level). Means are calculated over three different time intervals. The inverse linear relationship between temperature and elevation is shown by dashed lines and Pearson's coefficients. (D) To highlight the high-frequency daily temperature oscillation a spectral analysis in the time domain shows peaks at 12 and 24 hours.*

Secondly, the time-temperature series were analyzed in the Python environment for statistical analysis using the scipy.stats and scipy.signal packages, and in MATLAB for spectral analysis using the Fast Fourier Transform function and filtering curves using a function from the Signal Processing Toolbox.

Topographic mapping of the cave was performed using a modified Leica Disto-X laser telemeter and the mobile application Topodroid. Data were measured relative to the first survey station at the entrance of the cave and to fixed points at the beginning of each cave branch. In addition, the previous map of the cave, made in the 90's by polygonal lines measured with an analog compass and clinometer, was computerized on C-Survey software and reprojected in a three-dimensional visualization in the Loch package. In the GIS environment, each station of the old survey was associated with X, Y, Z coordinates and plotted against the 2m resolution LiDAR-based digital elevation model (provided by the Veneto Region online repository).

Monitoring of bats was done by visual counting, differentiating between the two species found in the cave, and by bat acoustic detectors placed in locations similar to the temperature dataloggers.

3. Results

The Castel Sotterra cave is a hydrologically active multi-level cave carved in clastic sequences composed mainly of carbonatic conglomerate beds alternating with sandstone-siltstone intervals. The characteristic speleogenesis in Quaternary fluvial deposits is characterized by the interconnection of the cave levels, closely related to the landscape evolution of the Montello hill, large collapses and vadose pits or canyons. The cave is located on the southeastern side of the Montello Hill (Figure 1A), the mapped groundwater flow pattern is southeastward (see syphon location in Figure 1B), following the declining topography and conglomerate bedding. The entrance is at the bottom of a steephead valley (Figure 1C). Three major cave levels are found (Figure 1D), which are nearly parallel to each other along their entire length. It is noted that low angle cave conduits occur along fine-grained horizons in the substrate and are often vertically connected by steep and narrow vadose canyons.

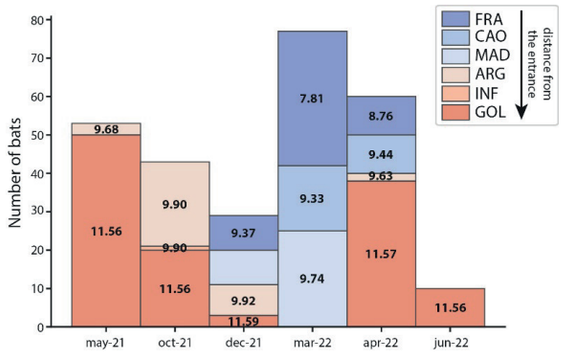


Figure 3 : *Bat counting histogram between Spring 2021 and Summer 2022. Values inside boxes refer to monthly-averaged temperature calculated on out dataset between Spring 2022 and Summer 2024.*

Eight stations were selected for temperature measurements with dataloggers (Figure 1B, D) along the entire cave between the entrance and the bottom of the active vadose canyon. The current dataset presented here reports time series between April 2022 and July 2024 (Figure 1E). Periods of missing data were due to systematic errors in data collection (e.g. February-March 2023) or intentional to account for logistical issues related to datalogger placement and data download. In general, the lowest and highest temperatures recorded in the cave are ~ 2 °C and ~ 12 °C, respectively, near the entrance in the first station in the Saccardo Room (SAC), but at ~ 40 m depth in the Frana Room (FRA) the amplitude of the annual temperature oscillation is reduced between ~ 7.5 °C and ~ 10.5 °C. The temperature generally increases on average towards the deeper (Inferiori Canyon, INF) and more distant (Golem Room, GOL) stations from the entrance, reaching a stable temperature of ~ 11.6 °C.

A positive correlation between cave temperature and external temperature measured at Volpago del Montello is highlighted by our data. The first three stations from the entrance (SAC, FRA, CAO) recorded low amplitude temperature variations forced by external thermal events, contrary to seasonal trends, such as in January 2023 and April 2024. It is also noted that the maximum temperature reached by the stations due to seasonal variations is not centered in August, as for the external record, but it has reached in November (Figure 1E).

Median values and arithmetic means of temperatures are gradually increasing going far from the entrance (Figure 2A), while the distribution of collected data show a decreasing trend (Figure 2A). The amplitude of the variability ranges is also different in different periods of the year. Considering the elevation of each station with respect to sea level as a reference, in summer the temperature has small variations in relation to station elevation (Figure 2C). Conversely, in winter, the inverse linear relationship between elevation and temperature is stronger (Figure 2C).

The spectral analysis in the time domain performed on the recorded data highlights the presence of two peaks at 12 and 24 h, reflecting the daily temperature variability (Figure 2D). This variability is present at all stations except at INF and GOL, and the relative power of the peaks decreases as one moves away from the entrance. The spectral analysis does not reveal other notable peaks that recur in more than one station on longer cycles, such as the seasonal cycle, due to the lack of a time series longer than one year without interruption.

Considering the monitoring of bats in the most visited areas of the cave, the number of specimens ranges between 10 and 80 (Figure 3). During the hibernation period, it cannot be excluded that more than 100 individuals may also be present, as bats have been reported to inhabit other cave conduits that are difficult to access during routine monitoring visits. Only two species commonly found in caves in the Veneto region have been documented: almost all individuals belong to *Rhinolophus hipposideros* (Bechstein, 1800), while no more than three individuals of *Rhinolophus ferrumequinum* (Schreber, 1774) have been reported at the same time, although more might inhabit unchecked branches. Other species frequenting the cave have been found only as subfossils. Bones of adult and juvenile *Myotis myotis/blythii* have been found in the mid level of the cave, while *Miniopterus schreibersii* remains have been identified in the upper levels.

During the hibernation period, from late October to late March, bats are mainly found in cooler areas (~ 8-10 °C), whereas during the summer months, they prefer warmer zones (~ 10-12 °C) (Figure 3). Bat guano is commonly present as accumulated deposits, varying in thickness from a few centimeters to several meters, observed in wide conduits in the upper, middle, and lower levels of the cave. Some guano mounds can be considered subfossils due to the absence of active colonies. Additionally, some bell-shaped cavities feature a darker alteration layer on the ceiling of large conduits, formed due to bat-induced corrosion of carbonatic conglomerate.

The current presence of other species in the cave, aside from the two mentioned above, is sporadic and has only been documented through prolonged recordings with automatic bat detectors placed inside the cave.

4. Discussion

The Castel Sotterra cave acts as a cave dominated by processes of thermal conduction and advection between the airflow coming from the only entrance, the water coming from the precipitation occurring on the top of the karst plateau, and the substrate. The thermal gradients calculated by linear regression (Figure 2C) are: (1) ~ 2.2 °C/100 m for annual averaged data sets, (2) ~ 5.6 °C/100 m for winter, (3) a stable gradient for summer. Between the entrance and 200 m elevation, the cave volume can be considered as belonging to the heterothermic zone (see Luetscher and Jeannin, 2004). Below, the homothermic vadose zone shows thermal stability throughout the year, so that only small variations are detected at the two deeper stations. The role of air advection is well recognized in the first ~ 80-100 m of depth of the cave, corresponding to the stations where spectral analysis highlights small temperature variations on a daily basis. The Castel Sotterra cave can be considered as a shallow network of karst conduits where the underground microclimate is strongly conditioned by external seasonal variability and the occurrence of extreme meteorological events. In addition, the huge influx of water caused by extreme precipitation is able to locally modify the temperature exchange heat by advection. Water is uniformly distributed along the pervasive fracture network and then concentrated along active canyons in the lower levels of the cave. The presence of long horizontal conduits favors thermal stratification in sectors of the cave in the uppermost levels, but far from the entrance. For example, at the station in Golem Room (GOL), which is at the same level as Madonna Room (see Figure 1D), the temperatures recorded are interestingly higher and almost stable and identical within the measured time series. The Golem Room can only be reached by descending to the Vomito Pit station (middle cave level) and then ascending to the upper level. The thermal stability of the upper level suggests that the cave has only one entrance. Nevertheless, the remains of *Myotis myotis* and *Miniopterus schreibersii* have contributed to new hypotheses on the morphological evolution of the cave, such as the presence of other openings in the past. The decreasing trend in the amplitude of seasonal variability along the cave profile is justified by the distance of the entrance, which provides air circulation (Figure 2A). The time shift observed between the peak of temperature outside the cave and the peak recorded at shallower stations from August to the first half of November is a period when the cave accumulates heat until the day when the outside and inside temperatures are equal. For three months, the temperature is constantly increasing due to the inflow of air that exchanges heat by advection.

5. Conclusion

Castel Sotterra Cave, the largest cave in the Montello Hill conglomerate karst plateau, provides a unique opportunity to reveal climatic patterns in a multi-level structured cave. Temperature monitoring and topographic mapping help to correlate the response of cave thermal dynamics, controlled by cave morphology, to external climatic variations. Initial results show that temperature variations are related to cave levels and intersections between horizontal and vertical vadose morphologies. Most of the cave belongs to the heterothermic zone,

where the thermal gradient varies within the year following seasonal fluctuations. The observed thermal pattern suggests that the air circulation is mainly controlled by external temperature variations, whose influence decreases with depth and distance from the entrance until thermal stability is reached.

The temperature has a critical impact on the ecology of the cave, especially for bat populations such as *Rhinolophus hipposideros* and *Rhinolophus ferrumequinum*, which require specific conditions for hibernation. In Castel Sotterra, the sectors that are more sensitive to external environmental pressures are also among the most important for the cave ecology.

This study highlights the importance of temperature monitoring in understanding the resilience of subterranean ecosystems and the data collected will provide a baseline to have information on future changes and guide conservation efforts in the fragile karst environment.

Acknowledgments

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The project takes part to the Speleo Meteo project by Società Speleologica Italiana (www.speleometeo.it).

The digital elevation model is taken from the Veneto repository (https://idt2.regione.veneto.it/idt/downloader/download). Meteorological dataset are available at ARPAV website (https://www.arpa.veneto.it). The software used in this work are: C-Survey (https://csurvey.it/site), TopoDroid (https://sites.google.com/site/speleoapps/home/topodroid), QGIS Desktop 3.34.3, Adobe Illustrator 2023, Python 3.11.4, MATLAB R2022b.

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Microclimatic Dynamics and Conservation of Furna Feia Cave: Challenges for Sustainable Public Use

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Abstract

The Furna Feia National Park in the Brazilian semi-arid region is on the verge of being officially opened to public visitation. Situated within the lush landscape of the Caatinga biome, Furna Feia is the largest and most voluminous cave in the region and serves as the park's main tourist attraction. The cave's interior is richly adorned and hosts a highly specialised and endemic fauna. In planning to use this extremely sensitive environment, various studies must be conducted to establish control measures to monitor the cave environment to minimise its impact. In this context, the present research was conducted to provide a preliminary diagnosis of Furna Feia's microclimatic behaviour based on temperature and relative humidity monitoring between 2022 and 2024.

Résumé

Le Parc National de Furna Feia, situé dans la région semi-aride du Brésil, est sur le point d'être officiellement ouvert au public. Enclavée dans le paysage luxuriant de la caatinga, Furna Feia est la plus grande et la plus volumineuse grotte de la région, constituant l'attraction touristique principale du parc. L'intérieur de la cavité est richement orné et abrite une faune hautement spécialisée et endémique. La planification de l'utilisation de cet environnement extrêmement sensible doit prendre en compte diverses études visant à établir les éléments de contrôle à surveiller pour garantir un impact minimal sur l'environnement cavernicole. Dans ce contexte, la présente recherche a été développée pour offrir un diagnostic préliminaire du comportement microclimatique de Furna Feia, basé sur les résultats d'un suivi de la température intérieure et de l'humidité relative de l'air, réalisé entre 2022 et 2024.

Resumen

El Parque Nacional de Furna Feia, ubicado en la región semiárida de Brasil, está a punto de ser oficialmente abierto a la visita pública. Inserto en el exuberante paisaje de la caatinga, Furna Feia es la cueva más grande y voluminosa de la región, y constituye el principal atractivo turístico del parque. El interior de la cavidad está ricamente ornamentado y alberga una fauna altamente especializada y endémica. La planificación para el uso de este ambiente extremadamente sensible debe considerar diversos estudios que busquen establecer los elementos de control a ser monitoreados para garantizar un impacto mínimo en el entorno cavernícola. En este sentido, se desarrolló la presente investigación, que presenta un diagnóstico preliminar del comportamiento microclimático de Furna Feia, basado en los resultados de un monitoreo de la temperatura interna y la humedad relativa del aire, realizado entre los años 2022 y 2024.

1. Introduction

Conservation Units are among the main tools for protecting natural resources in Brazil. These natural territories, legally established by public authorities, encompass the physical space, the environmental resources, and their most relevant natural features. The management of these areas is carried out under a special administrative regime, and they are granted appropriate protection guarantees (BRASIL, 2000).

In Brazil, Conservation Units are divided into sustainable use and strict protection. Sustainable use units allow the exploitation of natural resources, provided that sustainability and social equity are ensured. Strict protection units aim to preserve ecosystems from human interference but allow the indirect use of their attributes. National Parks, which fall under strict protection, primarily aim to preserve natural ecosystems, conduct scientific research, and promote public use through environmental education, recreation, and ecotourism activities (BRASIL, 2000).

In northeastern Brazil, the Furna Feia National Park, established in 2012 in the semi-arid region of Rio Grande do Norte state, aims to preserve the biodiversity and speleological heritage of the Caatinga biome (ICMBIO, 2020). The landscape is characterised by extensive limestone outcrops and the vastness of the Apodi Plateau, hosting archaeological sites and significant underground water reservoirs. In addition to its rich surface diversity, the park is notable for its cave systems and subterranean biodiversity (ICMBIO, 2020). The PNFF also seeks to promote recreational, educational, and leisure activities, balancing environmental preservation with sustainable public use.

Recreational and educational tourism in the park is already occurring regularly and has grown recently. During discussions for developing the

Furna Feia National Park management plan (ICMBIO, 2020), the need to plan public use was identified to prevent disorganised visitation and damage to speleological heritage. Brazilian legislation requires that tourist activities in caves follow specific regulations and special zoning to minimise impacts and ensure a positive visitor experience. Among various guidelines for managing caves open to visitation, monitoring microclimatic conditions is particularly emphasised (ICMBIO, 2022).

In this context, the cave microclimate stands out for its influence on the existence and preservation of speleological heritage components, such as rock art, speleothems, and rocks, as well as cave biota and the interaction between these elements (LOBO, 2012). Understanding its behaviour and the effects of anthropogenic impacts are important tools for managing tourism in caves. Recent studies have demonstrated that not only climate change but also human activities can influence cave microclimate behaviour, either due to structural interventions in the cave (ŠEBELA, TURK, PIPAN, 2015) or the presence of humans inside it (ŠEBELA, BAKER, LUKE, 2019).

Given the relevance of this type of study and its relative ease of implementation, monitoring the microclimatic conditions of a cave provides essential data for managing such attractions and is employed in various caves open to the public worldwide (ŠEBELA; TURK, 2022; GOMES, SANTOS, RUCHKYS, TRAVASSOS, 2021; SILVA et al., 2017; ROCHA; GALVANI, 2011; LARIO; SOLER, 2010; LONGHITANO; ROCHA; FURLAN, 2007; VERÍSSIMO et al., 2003; KRANJC; OPARA, 2002; ZELINKA, 2002). This study was developed in this context and aims to support the national park's management team in planning the public use of Furna Feia. Considering the park's imminent official opening to tourism, temperature and relative air humidity inside the cave were monitored from 2022 to 2024 to establish a diagnostic assessment of microclimatic conditions before the official implementation of visitation activities.

2. Materials and Methods

The PNFF (Furna Feia National Park) covers an area of approximately 8,494 hectares located between the municipalities of Baraúna and Mossoró in the western region of the state of Rio Grande do Norte (Fig. 1). This region, part of the Low Plateaus of the Potiguar Basin, is dominated by tabular landforms associated with the Apodi Plateau. The landscape, heavily eroded and karstified, is predominantly composed of carbonate rocks from the Jandaíra Formation (Cretaceous), which forms part of the Apodi Group in the Potiguar Basin, and sandstones from the Açu Formation (PESSOA-NETO et al., 2007).

The park, situated in the semi-arid northeast of Brazil, preserves a significant remnant of Hyperxerophilic Caatinga, harbouring a wide variety of species, including some endangered ones. According to climate, the region falls under the hot semi-arid climate classification (Bsh), according to Köppen-Geiger, characterised by scarce and irregular rainfall distribution, high average temperatures, and low relative air humidity (ICMBIO, 2020). The Carbonates of the Apodi Group

The carbonates of the Apodi Group are highly significant from a speleological heritage perspective, as they host over 90% of the caves recorded in Rio Grande do Norte. The Furna Feia National Park features various karst landforms, such as extensive lapiaz fields, dolines, and other exokarst features resulting from limestone dissolution (ALVES, 2020). The endokarst, which includes 208 registered caves (CECAV, 2024), was one of the primary reasons for the park's creation.

The park's caves stand out for their chemical, clastic, and organic deposits and rich biodiversity, including 16 troglobitic invertebrates, 14 of which are endemic (ICMBIO, 2020).

Furna Feia is set amidst the lush Caatinga in a karstic landscape characterised by solution pans (kamenitzas), rillenkarren, rain pits (craterkarren), and dissolution dolines. It is the largest and most voluminous cave in the complex, reaching 739 meters long and a vertical relief of 30 meters (ICMBIO, 2020). Its interior showcases various geoforms, including geodes and domes. The cave is richly decorated, featuring stalactites, stalagmites, curtains, flowstones, columns, and travertines.

In addition to its physical attributes, the cave's biotic aspects also deserve attention. It hosts a diverse array of bat species (VARGAS-MENA et al., 2018) and is a habitat for rare troglobitic species (BENTO et al., 2013).

From April 2022 to October 2024, the cave's microclimatic parameters were continuously monitored. Thermo-hygrometers (Testo 175H1) were configured to record data every 10 minutes. Four devices (FF1, FF2, FF3, and FF4) were installed in Furna Feia, with their spatial arrangement shown in Figure 1. It is important to note that the placement of the sensors inside the cave aimed to cover the likely route to be used by visitors and the different internal environments.

Data collection and processing were performed using the manufacturer's specific software for the dataloggers and electronic spreadsheets. The analysis model adopted for the diagnostic assessment was adapted from the methodology developed by Couto (2021) at Lapa de Antônio Pereira in Ouro Preto, Minas Gerais.

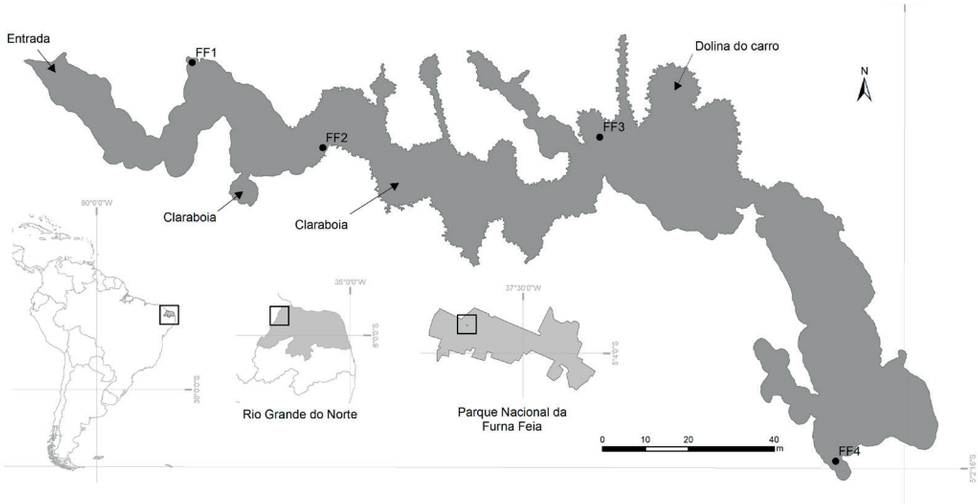


Figure 1: *Location of Furna Feia and the Stations for Temperature and Relative Humidity Monitoring.*

3. Results

The entrance of Furna Feia, where station FF1 is located, recorded the highest average temperature (28.6°C) and the largest variations, with a range of 5.8°C and a standard deviation of 0.8. The last chamber of the cave exhibits characteristics that promote greater stability, with a significantly lower temperature range compared to the entrance (1.8°C).

Regarding relative air humidity, the lowest average value, 75.2%, was recorded at the cave entrance (FF1), which also exhibited the highest range (54.2%). As the distance from the entrance increases, variations become subtler, and the average value approaches saturation, nearing 100%. Table 1 presents the descriptive statistics of the temperature and relative humidity values recorded inside Furna Feia, and Figure 2 shows the recorded temperature and relative humidity values over the monitoring period. Both graphs highlight the variation between day and night periods and the annual seasonality in each cave sector.

Table 1: *Descriptive Statistics of Temperature and Relative Humidity Values Recorded Inside Furna Feia (April 2022–October 2024).*

		Average	Standard deviation	Min.	Max.	Range
Temp. (°C)	FF1	28,6	0,8	25,2	31,0	5,8
	FF2	28,4	0,7	25,5	30,2	4,7
	FF3	24,9	0,7	21,7	26,5	4,8
	FF4	27,7	0,4	27,0	28,8	1,8
Relative humidity (%)	FF1	75,2	10,6	41,3	95,5	54,2
	FF2	79,8	9,7	47,7	96,7	49,0
	FF3	99,0	1,9	82,3	99,9	17,6
	FF4	99,9	0,0	98,6	99,9	1,3

Source: Research data.

4. Discussion

External climatic variations strongly influence the temperature recorded in different sectors of Furna Feia. As observed in caves in Europe (ŠEBELA; TURK; PIPAN, 2015; LECOQ et al., 2017), Oceania (BAKER, 2014), Asia (XIONG et al., 2023), Africa (NY RIAVO, G. V., ANTSA, L. J. R., AVOTRINIAINA, Z.M.R., STEVEN, B., 2021), and the Americas (GOMES, M.; SANTOS, D.J.; RUCHKYS, U.A.; TRAVASSOS, L.E.P., 2021; LOBO; BICHUETTE; SALLUM-FILHO, 2024), the behaviour of this parameter reflects, to a lesser extent, the diurnal/nocturnal and seasonal variations observed on the surface.

The significant dimensions of the main entrance to Furna Feia (approximately 8 m x 6 m) facilitate a greater energy exchange with the external environment in this sector. Consequently, the FF1 monitoring station, located near the entrance, recorded the highest variations and the highest average temperature. Slightly further from the entrance, still in the main passage, the FF2 station showed a behaviour very similar to FF1 (Fig. 2), but with a slightly lower average temperature (28.4°C), smaller standard deviation (0.7), and range (4.7°C). It is important to note that, although not as close to the main entrance, there are two external access points in the form of skylights between FF1 and FF2. This condition is one of the main factors causing the temperature behaviour at these two stations to be so similar.

The FF3 station was installed at a lower elevation compared to the others (approximately 20 meters below) and recorded the lowest average temperature (24.9°C), minimum (21.7°C), and maximum (26.5°C) values. Despite being a cooler environment than the others, this cave section is also strongly influenced by external variations observed at FF1 and FF2, likely due to its proximity to another external access point known as the “dolina do carro” (“car doline”).

The final section of the cave, where the FF4 station is located, is the area with the least external influence. The temperature exhibited much smaller variations than the other stations, with a standard deviation of 0.4 and a range of only 1.8°C. The greater distance from external access points, lower ceiling, and a slight narrowing of the main passage just past the “car doline” condition this environment and increase spatial confinement. The results of this research corroborate and complement those observed by SOBRINHO et al. (2016) during a short-term monitoring study conducted at the PNFF. These authors found that the temperature curve observed at the entrance of Furna Feia is very similar to that recorded by a monitoring station installed in the external environment at the time but with a smaller range. The 2016 records show a range of 5.19°C at the cave entrance, with a minimum of 26.72°C and a maximum of 31.91°C. Regarding the final section of the cave, where FF4 is located, SOBRINHO et al. (2016) recorded a minimum temperature of 27.53°C and a maximum of 27.64°C, with a range of only 0.11°C. The longer monitoring period in the current study refined the results observed by those authors, consolidating the last chamber of Furna Feia as the area where temperature tends to be most stable.

An analysis of Figure 2 supports these observations. The FF1, FF2, and FF3 temperature curves exhibit very similar behaviours concerning diurnal/nocturnal and seasonal variations. The significantly lower temperature recorded at FF3 stands out among the three curves.

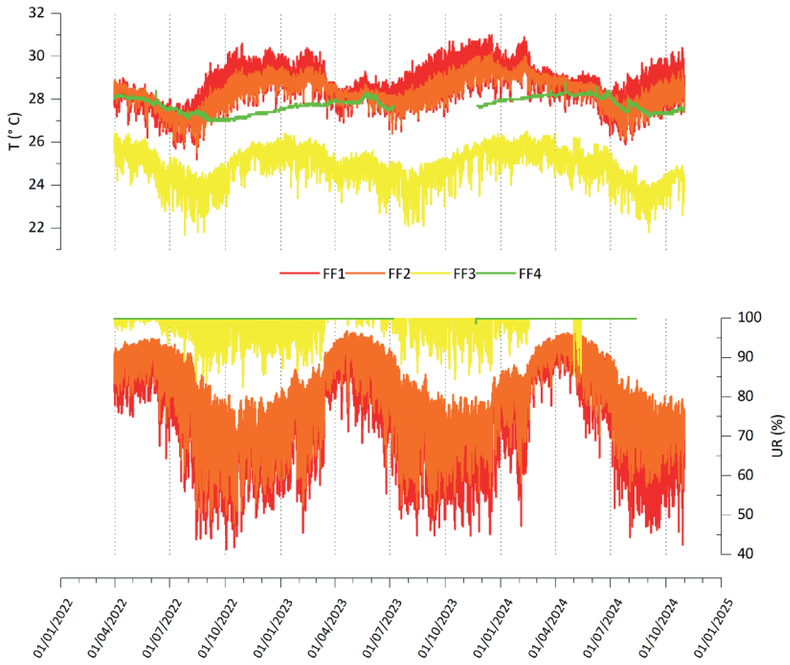


Figure 2: *Graphs Showing Continuous Monitoring of Temperature (T) and Relative Humidity (RH) in Furna Feia from 2022 to 2024.*

Regarding the final chamber of the cave (FF4), Figure 2 demonstrates that external variations can still be detected in this area, albeit with much lower intensity compared to other sectors. Notably, there is a lag in the perception of these oscillations. In the stations closer to the cave entrance, for instance, the temperature declines until the beginning of the second half of 2022, reaching its lowest values around mid-August, then rises. In FF4, however, the temperature continues to decrease until mid-September, only then beginning to warm up gradually.

As with temperature, external climatic conditions also influence relative air humidity. The region near the entrance (FF1) exhibited the greatest humidity fluctuations, with an amplitude of 54.2% and a standard deviation of 10.6. This area also recorded the lowest average humidity (75.2%), dropping to a minimum of 41.3% during the dry season. As one moves toward the final portion of the cave, the variations become progressively smaller. At FF2, despite its proximity to external access points, the amplitude of 49.0% was lower than that observed at FF1, and the average humidity (79.8%) was slightly higher.

The cave's morphology and proximity to the water table contribute to higher average humidity values at FF3 (99.0%). Even under these conditions, external variations were still detected, with an amplitude of 17.6% and a standard deviation of 1.9, albeit at a much lower intensity compared to areas closer to the entrance, as illustrated in Figure 2. However, the analysis of relative humidity at FF3 was compromised in 2024 due to a sensor malfunction.

This study is considered inconclusive for the final sector of the cave, where FF4 is located, as the equipment experienced operational issues and was out of service for an extended period. Nevertheless, based on the data that could be collected and the results from monitoring conducted by SOBRINHO et al. (2016), this region can be classified as an area where energy flow is significantly lower than in other sectors and humidity remains close to saturation for most of the year.

5. Conclusions

Even considering a relatively short monitoring period (30 months), this study identified that Furna Feia's microclimate behaviour follows the same pattern as other caves worldwide. External conditions affect both temperature and humidity, and this influence gradually decreases as the distance from exokarst access points increases.

The regions farthest from surface openings are characterised by low energy circulation and, therefore, are more susceptible to microclimatic changes caused by human presence. It is worth noting that the large bat colonies found in Furna Feia use the FF3 and FF4 regions as shelters. In this regard, it is important to observe that the factors influencing the choice of these areas are not yet fully understood, and it remains unclear how much this relative climatic stability contributes to their selection.

Given that human presence and alterations to the cave's physical structure can potentially impact the microclimate, it is essential to consider developing a continuous environmental monitoring program, including microclimatic monitoring, as part of the cave's visitation plan.

We believe it will be highly relevant for Furna Feia National Park management to pursue further developments from this research. It could include, for example, long-term monitoring, the installation of additional thermo-hygrometers CO_2 sensors, and the integration of microclimatic studies with research on cave fauna. Such measures would enable a more precise diagnosis and the exploration of other sectors of Furna Feia that were not considered in this study.

Considering the park's imminent official opening, implementing a monitoring system is crucial for better understanding the cave's microclimate and identifying potential anthropogenic impacts.

Acknowledgments

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Speleoclimate and Conservation: An Approach to Monitoring Tourist Caves in the Cavernas do Peruaçu National Park

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Abstract

The Cavernas do Peruaçu National Park, a candidate for UNESCO Natural World Heritage status in 2024, was the subject of the study titled "Microclimatic Monitoring of Tourist Caves in Minas Gerais." Seven of the park's main caves, featured in various visitor routes, were simultaneously monitored between 2018 and 2024. During this period, temperature and relative humidity behaviour were recorded at 10-minute intervals. The results allow for an analysis of the influence exerted by various external factors and cave morphology on the cave microclimate.

Résumé

Le Parc National des Cavernas do Peruaçu, candidat au Patrimoine Mondial Naturel de l'UNESCO en 2024, a fait l'objet d'une étude dans le cadre du projet de "Surveillance Microclimatique des Grottes Touristiques de Minas Gerais". Sept des principales grottes du parc, intégrées dans différents circuits de visite, ont été surveillées simultanément entre 2018 et 2024. Durant cette période, le comportement de la température et de l'humidité relative de l'air a été observé, avec des enregistrements effectués sans interruption toutes les 10 minutes. Les résultats obtenus permettent de mettre en évidence l'influence exercée par divers facteurs externes et par la morphologie des grottes sur le microclimat cavernicole.

Resumen

El Parque Nacional Cavernas do Peruaçu, candidato a Patrimonio Mundial Natural por la UNESCO en 2024, fue objeto de estudio del proyecto Monitoramento Microclimático de Cavernas Turísticas de Minas Gerais. Siete de las principales cavernas del parque, incluidas en los diversos recorridos de visita, fueron monitoreadas simultáneamente entre los años 2018 y 2024. Durante este período, se observaron el comportamiento de la temperatura y la humedad relativa del aire, con registros realizados ininterrumpidamente cada intervalo de 10 minutos. Los resultados obtenidos permiten observar la influencia que diversos factores externos y la morfología de las cavernas ejercen sobre el microclima cavernícola.

1. Introduction

According to official data, the Brazilian Speleological Heritage (BSH) currently comprises more than 25,000 registered caves (CECAV, 2024). However, studies suggest that the potential for cave occurrence in the country is immense, potentially reaching hundreds of thousands (PILÓ; AULER, 2019). Caves, or natural underground cavities as referred to in Brazilian legislation, are considered federal property (BRASIL, 1998) and are protected by a robust legal framework. The National Conservation Program for Speleological Heritage (MMA, 2009) stands out among the various provisions in this legislation. This program aims to promote the valorisation of this heritage and the integration of sectoral actions within an ecosystemic approach to its management. The program includes several guiding axes; one specifically addresses monitoring, assessing, preventing, and mitigating impacts on speleological heritage. It also proposes the creation of mechanisms and regulations to support the sustainable use of the BSH.

Regarding impact monitoring actions, the National Centre for Research and Conservation of Caves (CECAV) has been advancing initiatives in recent years to expand knowledge on this topic, particularly regarding speleoclimate or cave microclimate monitoring.

Intrinsic cave characteristics, such as spatial confinement, absence of light, and low incidence of direct solar energy, give rise to a unique atmospheric system distinct from that observed on the surface (LOBO, 2012). Despite the notion of isolation and relative stability, a cave's microclimate is influenced both by external climatic conditions (CIGNA, 2003) and by various internal processes, including human presence (ŠEBELA; PRELOVŠEK; TURK, 2013). Potential disturbances to cave climate parameters can affect the morphology and crystallisation of speleothems or even lead to their dissolution. Changes in temperature or relative humidity may also impact the spatial distribution of cave biota. Additionally, alterations in the cave microclimate can compromise paleontological, archaeological, and cultural records (TOOMEY III, 2009). Thus, the study of speleoclimate becomes a key element in developing

best practices for managing caves open to tourism (FREITAS, 2010), enabling a better understanding of the internal environment and its relationship with public use.

The Cavernas do Peruaçu National Park (CPNP) is a fully protected conservation unit that has seen a significant increase in visitor numbers in recent years. It includes tourist routes to eleven caves. Although the park has a well-developed set of visitation guidelines (IBAMA, 2005), these guidelines did not account for the caves' microclimatic characteristics when they were created.

The project Microclimatic Monitoring of Tourist Caves in the State of Minas Gerais was developed to address this knowledge gap. Between 2018 and 2024, it collected temperature and relative humidity data from seven caves in the CPNP. This study aims to present the project's main results, which will be detailed in future publications.

2. Materials and Methods

The Cavernas do Peruaçu National Park (CPNP) covers an area of approximately 56,500 hectares in the northern region of Minas Gerais, southeastern Brazil (Fig. 1), encompassing parts of the municipalities of Januária, Itacarambi, and São João das Missões. The park is situated in a transition zone between two major Brazilian biomes, the Cerrado and the Caatinga, which promotes diverse environments inhabited by various animal and plant species, many of which are endemic and endangered (IBAMA, 2005). According to the management plan, the conservation unit experiences temperatures ranging from 25°C to 29.5°C, with an average relative humidity between 55% and 83% (IBAMA, 2005).

A candidate for UNESCO World Natural Heritage status, the park stands out for preserving a significant portion of the region's magnificent karst landscape. Key features include dolines, karst valleys, fractured massifs, ruiniform towers, resurgences, steeped cliffs, karren of various shapes and sizes, and an impressive collection of caves.

The region's karst landscape develops on the Bambuí Group carbonate rocks, deposited at the end of the Precambrian over older granodioritic and granite-gneiss rocks of the crystalline basement. Overlying the carbonate and pelitic rocks of the Bambuí Group are Upper Mesozoic siliciclastic rocks of the Urucuia Formation (IBAMA, 2005).

The landscape is divided into four geomorphological units (Fig. 1):

3. The **Gerais Plateau**, located on the rocks of the Urucuia Formation above 760 m altitude.
4. The **Transition Zone**, located between 760 m and 720 m, is characterised by a flattened relief with occasional residual tabular hills and subsidence sinkholes.
5. The **Karstified Compartment**, where the limestones and dolomites of the Bambuí Group outcrop between 720 and 500 m altitude. This unit is predominantly marked by rugged relief, the absence of a perennial drainage network, and a wide variety of karst features.
6. The **São Francisco Depression** is characterised by a flattened relief with gentle undulations and carbonate hills of the Bambuí Group at altitudes ranging from 500 to 440 m (IBAMA, 2005).

The CPNP is situated in one of Brazil's most significant speleological regions, noted for its high concentration of impressive caves in terms of both forms and dimensions and the scientific importance of its numerous archaeological sites. Official government records indicate 161 caves within the park (CECAV, 2024), but ongoing studies suggest this number could be at least ten times higher. Of the known caves, eleven have been designated for public use and constitute the main attractions of the park's tourist routes. Caves such as **Lapas do Boquete, Bonita, Índio, Desenhos, Troncos, Cascudos, Carlúcio, Caboclo, Rezar**, as well as the **Arco do André**, and **Gruta do Janelão**, have seen increasing visitor numbers in recent years. The completion of infrastructure projects facilitating access to these attractions indicates likely further growth in visitation.

Seven of the caves open to visitors that have been most popular in recent years were selected for this study (Tab. 1).

Temperature and relative humidity data were collected and monitored continuously between 2018 and 2024. Thermo hygrometers (Testo 175H1) were used for this purpose and were configured to record data every 10 minutes. It is important to note that all cave visits are conducted with the accompaniment of guides, and only a few caves allow internal visitation.

Table 1: *Monitored caves and number of installed equipment.*

Cave	Length (m)	Equipment
Lapa Bonita – BON	420	10
Gruta do Janelão – JAN	4.740	6
Lapa do Rezar - REZ	380	5
Lapa do Índio - IND	150	4
Lapa do Carlúcio - CAR	160	4
Lapa dos Desenhos - DES	140	3
Lapa do Caboclo - CAB	100	3

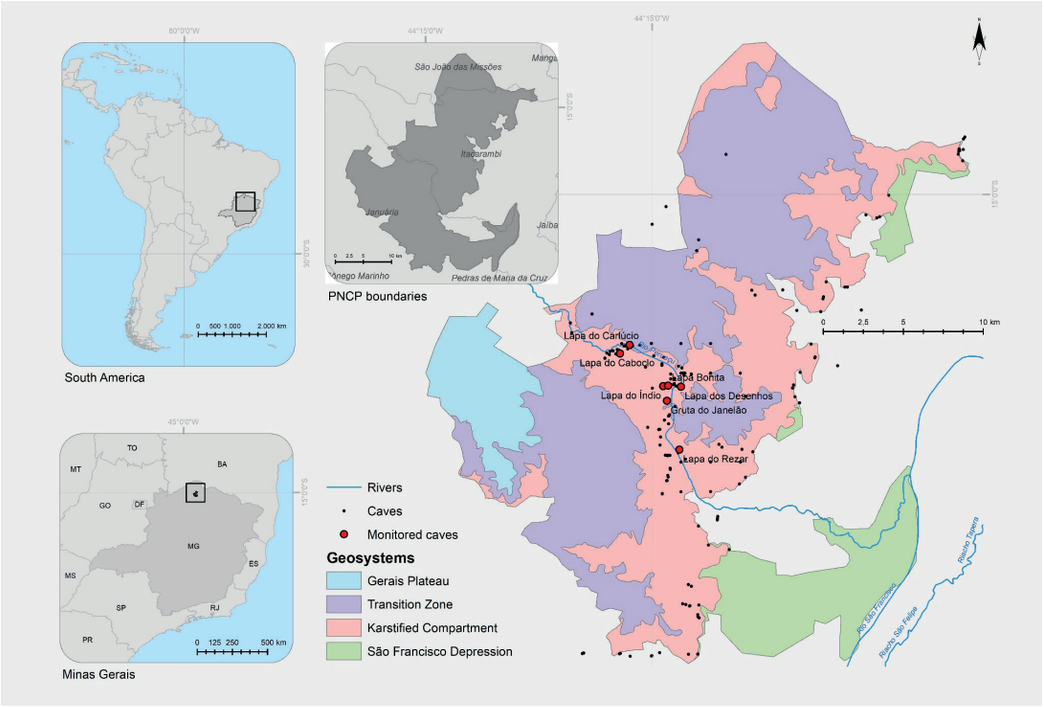


Figure 1: *Location map of the park, its geomorphological compartments and monitored caves.*

The spatial distribution of the equipment within the caves is measured in different cave environments. Specifically, for those caves that receive internal visitation, the monitoring also accounted for the routes visitors use.

Data collection and processing were conducted using the manufacturer's specific software for the dataloggers and electronic spreadsheets. The diagnostic analysis model was adapted from the methodology developed by Couto (2021), which involved creating two major datasets:

1. **Annual dataset:** This represents the general conditions of the monitored locations and serves as a reference for understanding the speleoclimate in these sites.
2. **Monthly dataset:** Enables the recognition of seasonal variations in the cave environment.

3. Results

The research generated a significant volume of data during the seven years of collection, exceeding 360,000 records per device. After statistical processing and analysis, the information was compiled and is presented in Tab. 2.

Due to Gruta do Janelão's intrinsic conditions (its length, large number of external accesses, and river presence), it was observed that, with the available number of devices, the results obtained at that time would not be satisfactory. Consequently, it was decided to reschedule the microclimate study of this cave for a future opportunity when a larger number of devices can be allocated to the project.

Table 2: *Basic descriptive statistics of data collected between 2018 and 2024. (Md: Mean, Mn: Minimum, Mx: Maximum, A: Amplitude).*

	Temperature (° C)				Humidity (%)			
	Md	Mn	Mx	A	Md	Mn	Mx	A
BON	20,8	10,6	31,8	21,2	87,3	22,5	99,9	77,4
REZ	23,7	10,5	36,4	25,9	67,1	15,4	99,9	84,5
IND	22,4	10,8	38,7	27,9	80,7	13,1	99,9	86,8
CAR	20,6	8,5	34,7	26,2	78,9	19,4	99,9	80,5
DES	23,5	10,3	42,0	31,7	67,9	16,4	99,9	83,5
CAB	23,3	11,4	33,9	22,5	69,1	20,3	99,9	79,6

The annual average values for each cave were grouped into two graphs: one representing temperature and the other relative humidity (Fig. 2a). These graphs illustrate the variations observed during the study period.

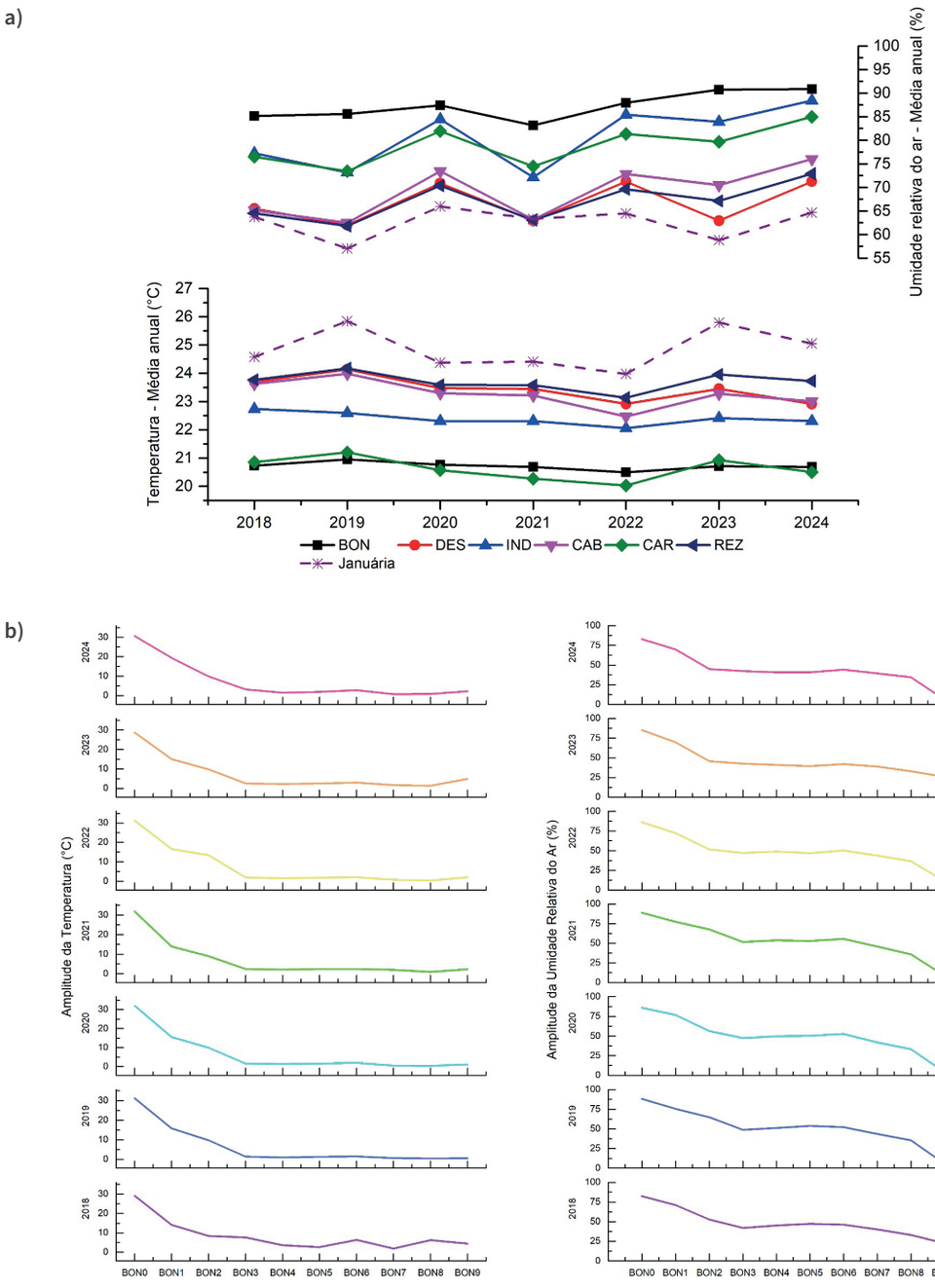


Figure 2: *Behavior of temperature and relative humidity during the study period. a) Variations in the averages for each cave. b) Seasonal variations in the variables across different sectors of Lapa Bonita.*

This research also evaluated climatic variables in a localised manner, considering the monitoring stations installed in different sections of the caves. Fig. 2b presents the temperature and humidity behaviour observed in Lapa Bonita, reflecting the conditions in the other monitored caves.

4. Discussion

As observed in various parts of the world (LOBO; BICHUETTE; SALLUM-FILHO, 2024; XIONG et al., 2023; NY RIAVO et al., 2021; GOMES et al., 2021; LECOQ et al., 2017; ŠEBELA; TURK; PIPAN, 2015; BAKER, 2014), the microclimate of the CPNP caves is influenced by external conditions. The results presented in Table 2 show a relationship between the cave's position in the relief and its microclimatic behaviour. The Peruaçu River crosses the park diagonally after leaving the geomorphological compartment of the Planalto das Gerais (Fig. 1). According to IBAMA (2005), this region of the CPNP has milder temperatures compared to other areas of the park. For example, Lapa do Carlúcio, located near the Planalto das Gerais, recorded the lowest average temperature (20.6°C) and the lowest minimum temperature (8.5°C). Conversely, Lapa do Rezar, located closer to the São Francisco Depression, where temperatures are higher, had the highest average temperature (23.7°C).

Regarding external conditions, both temperature and humidity behaviours were strongly influenced by external climatic variations. Data from the meteorological station of the National Institute of Meteorology (INMET, 2024) in Januária, approximately 40 km from the park, were included in Fig. 2a. The graphs show that the rise and fall of averages recorded by the station were mirrored in the caves. However, the spatial isolation characteristic of caves significantly attenuates variations in both temperature and humidity.

In addition to the relief position and external climatic conditions, the physical characteristics of the cavities also greatly influence the microclimate. For instance, Lapa Bonita and Lapa do Índio have significant conduit narrowings between their first chamber and subsequent sections, which limit energy exchange with the external environment. This results in very smooth temperature variations, tending toward stability, as evidenced by the curves in Fig. 2a. Energy exchange between the subterranean environment and the surface is also influenced by the cave's dimensions and entrance size. Smaller caves like Lapa dos Desenhos and Lapa do Caboclo showed higher average temperatures and lower humidity, with values closer to those recorded by the INMET station.

Another notable microclimatic feature this research highlights is the tendency for stability as the distance from the cave entrance increases. This behaviour was observed in all monitored caves, with results from Lapa Bonita selected to illustrate the discussion. In this cave, nine Thermo hygrometers were installed internally (BON1, near the entrance, to BON9, in the last chamber) and externally, a few meters from the entrance (BON 0).

Fig. 2b shows the amplitude values (temperature and humidity) recorded by each station for each year of the study period. The graphs reveal significant variations in the external station (BON 0), which gradually decrease as one moves toward the last sector of the cave. Temperature variations become almost imperceptible after passing the main conduit narrowing (between BON 2 and BON 3). For humidity, significant variations are observed in the intermediate sector of the cave but are lower than those in the first chamber (BON 1 and BON 2). The amplitude approaches zero in the last chamber, preceded by a major conduit narrowing.

5. Conclusion

The project developed in the Cavernas do Peruaçu National Park addresses a need explicitly stated in its management plan, which was created 20 years ago. Despite the importance attributed to this activity by the park's management, the monitoring of cave microclimate has never been implemented for various reasons beyond the scope of this manuscript. However, the results achieved by this research, as well as the methodology adopted during its execution, will serve as a solid foundation for the development of a robust monitoring program to be implemented by the CPNP management.

The presented results corroborate the patterns of variability in paleoclimatic parameters observed in various caves worldwide. Nevertheless, the major contribution of this work may lie in its sampling approach, which involved monitoring a significant number of caves simultaneously over an extended temporal span. The CPNP can use the resulting database from the analyses to revise the management plans for each cave open to visitation. In this regard, improving the control of tourist access is crucial to enable analyses that associate human presence in the cave environment with possible alterations in paleoclimatic parameters.

Considering the potential follow-ups to this project, it is important to note the identified need for a more detailed monitoring program with specific actions for Gruta do Janelão. Data collected from this primary attraction of the CPNP between 2018 and 2019 indicated that more devices would be required to produce a reliable diagnostic reflective of the cave's characteristics.

Finally, the publication of the project results is hoped to inspire further research on the conservation and sustainable use of speleological heritage.

Acknowledgements

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Karst Monitoring in Madre de Dios for Understanding Patagonia's Past Regional Climate

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Abstract

The karstic island of Madre de Dios located at 50°S on Chile's Pacific coast presents a unique opportunity for studying past climates due to their extreme isolation. Reconstructing past climate variations in Patagonia is crucial for understanding the Southern Westerlies, which influence global climate through precipitation variability and atmospheric-oceanic CO_2 exchange. Speleothems from caves provide high-resolution, erosion-sheltered records capable of capturing long-term climate evolution. During the UP2019 and UP2023 expeditions, temperature monitoring and isotopic analyses validated $\delta^{18}O$ as a reliable climate proxy. Notably, a stalagmite from Jackpot Cave, dated to 185-115 kyr, revealed growth during glacial conditions, which could only be explained by the presence of temperate glacier above the cave and pyrite-driven bedrock dissolution. In 2023, core drilling targeted older speleothems preserved in inactive galleries, with ongoing geochemical and dating analyses expected to establish refine paleoclimate records beyond going back several glacial-interglacial cycles in this region of the world.

1. Introduction

The karstic island of Madre de Dios (MDD) is located on the Chilean Pacific coast at 50°S and is difficult to reach due to its remoteness and adverse weather conditions. The French-Chilean association ("Centre Terre", www.centre-terre.fr) has been exploring these caves for almost thirty years and over the course of nine expeditions the latest of which was Ultima Patagonia 2023 (see companion paper HONIAT et al., 2025).

The orographic setting of Patagonia is responsible for a strongly asymmetrical rainfall distribution (Figure 1A): the western side of the Andes receives record-high amounts of precipitation (up to 7000-8000 mm/yr), while the eastern side of the mountain chain receives little moisture (~500 mm/yr) (Schneider et al., 2003). Therefore, the westerlies exert a first-order control on the precipitation at MDD. Paleoclimate records from this area, which are sensitive to changes in rainfall amount, can help to reconstruct the past latitudinal position and strength of the westerlies (LAMY et al. 2010).

To reconstruct past climate variations, several archives are at our disposal, such as lake, marine, or ice cores. During the last glaciation, the Patagonian ice sheet eroded much of the surface continental sedimentary archives (KILIAN and LAMY, 2012). At 50°S, most of the available records such as from lake sediments do not go back further than 16,000 years (MORENO et al., 2010, 2009). Speleothems found in caves are the terrestrial archives with the highest known resolution for recording climate evolution over ten of thousands of year (with the exception of varved lake sediments) and are protected from external erosion. Therefore, it is possible to reconstruct long-term climate variations in Patagonia through their study and extend the other proxy records available from this region.

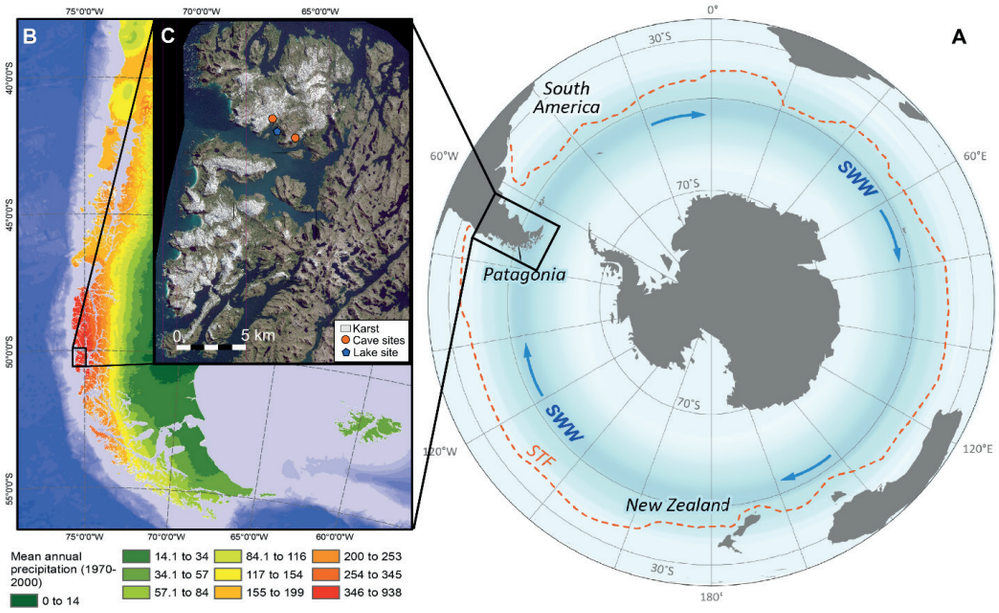


Figure 1: *A: Map of the Southern Hemisphere showing the Southern Westerly Wind (SWW) belt and the Subtropical Front (STF) today (© Jacob Bendle). B: Map of mean annual precipitation (in cm) in Patagonia (1970-2000). The westerlies bring large amounts of rain to the site site located on the west coast (figure modified after DAVIES et al. 2020). C: Satellite view of the Madre de Dios archipelago and location of the studied caves; the light grey areas are outcrops of karstified limestone/marble.*

The position and intensity of the Southern Westerlies, which sweep over Madre de Dios, are highly significant climatic elements in the Southern Hemisphere (THOMPSON, 2002; TOGGWEILER et al., 2006). Their variation influences the global climate through their role in regulating CO_2 exchange between the atmosphere and the ocean (TOGGWEILER, 2009). The long-term climatic evolution of the Westerlies remains partly unknown due to the lack of high-resolution paleoclimatic data directly related to the variability of precipitation, temperature, and/or wind. Reconstructing past changes in the westerlies during the Holocene and the Late Glacial Period will enhance our understanding of the mechanisms controlling the global climate before anthropogenic modifications, placing current climate changes into a long-term perspective.

2. Methods and Results

Temperature Records

During the UP2019 expedition, several stalagmites were collected, and preliminary geochemical analyses revealed their potential as paleoclimate archives (HONIAT et al., 2019). To aid in the interpretation of these paleoclimatic data, environmental monitoring in the caves was carried out. Temperature sensors were placed outside the 4 entrances + 1 cave, in the nearby entrance of the 3 entrances + 1 cave, and in the chamber where stalagmites were collected. Glass plates were placed at the sampling locations to collect modern calcite.

All the temperature sensors were retrieved in 2023, providing an uninterrupted 4-year record between UP2019 and UP2023 (Figure 1) with a measuring step every 2 hour. The external sensor (green in Figure 2), placed in a sheltered alcove of the 4 Entrances + 1 cave at an altitude of about 50 meters above sea level recorded the average temperature throughout the year on Madre de Dios. The temperature varied between approximately 4°C (minimum between July and September) and 12°C (maximum between February and March). The annual average temperature observed at the bottom of the 3 Entrances + 1 cave (orange in Figure 2) is around 5°C, which is 1.5°C lower than the external annual average temperature over the same period. Finally, the sensor placed in the entrance zone (blue in Figure 2) indicates stable temperatures similar to the cave's average temperature, except during the austral winter periods, when temperature drops occurred due to cold air incursions. Notably, the austral winter of 2021 in Madre de Dios was milder than those of 2019, 2020, and 2022, reflecting the significant temperature anomalies recorded on this continent. September 2021 was the hottest month ever recorded in South America, with a temperature anomaly of +1.9°C compared to the 1981-2010 average (NOAA Data, 2021).

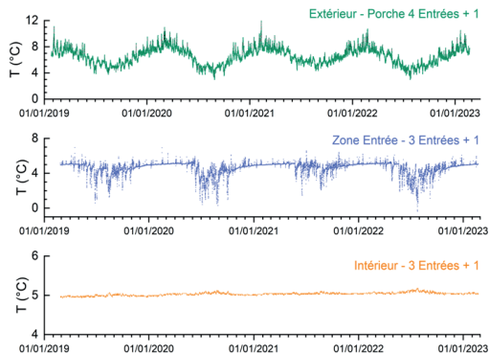


Figure 2: *Temperature recorded over four years outside the cave (green), in the entrance zone (blue), and inside the 3 entrances + 1 cave (orange).*

Modern Calcite

Two glass plates were placed in 2019 at the locations where stalagmites were collected: one in an alcove of the 4 Entrances + 1 cave and the other in the 3 Entrances + 1 cave. Unfortunately, the first plate slided from its base during the observation period. The second plate collected modern calcite (Figure 3A). Upon returning to the laboratory, microscopic observation confirmed that the material is indeed calcite, identified by the characteristic rhombohedral or half-rhombohedral shapes of the crystals. Calcite samples were collected by scraping the surface of the glass plate with a scalpel from the center of the droplet impact point outwards.

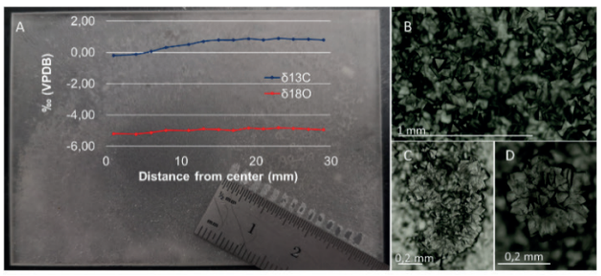


Figure 3: *A: Plate covered with calcite from the 3 Entrances + 1 cave, left at the location of the DENI stalagmite, showing the results of stable isotope analyses of the calcite ($\delta^{18}O$ of oxygen in red and $\delta^{13}C$ of carbon in blue). B, C, and D: Optical microscope observations of modern crystallization (2021-2023) covering the glass plate left in the 3 Entrances + 1 cave at different magnifications.*

The results of the 14 isotopic analyses of oxygen ($\delta^{18}O$ in red) and carbon ($\delta^{13}C$ in blue) are shown in Figure 3A. The isotopic analyses were performed using a Delta V Plus mass spectrometer connected to a Gasbench II (ThermoFisher) at the University of Innsbruck in Austria. For the carbon isotopes, we observe a slight enrichment (from -0.2‰ to 0.9‰), whereas the oxygen isotopes show almost no variation with distance from the center (from -4.9‰ to -5.1‰). This measurement, also known as the "Hendy test", can be used to evaluate whether calcite deposition occurred in isotopic equilibrium (Hendy, 1971). Kinetic fractionation varies depending on the drip rate, partial pressure of CO_2, and humidity during calcite deposition, potentially causing slight variations in the isotopic composition of the calcite. A long residence time of the water film due to a slow drip increases the chance of kinetic fractionation because of significant degassing and/or evaporation, primarily affecting $\delta^{13}C$ and $\delta^{18}O$, respectively. In the case of the glass plate data, only the $\delta^{13}C$ composition varies; thus, paleoclimatic data should be interpreted with caution for this indicator. The $\delta^{18}O$ data, on the other hand, are stable, validating its use as a climatic proxy.

Reference	Water-Calcite Temperature Relationship	$T(°C)_{calculated}$
Kim and O'neil (1997)	$1000\ln(\alpha) = 18.03(10^3T^{-1}) - 32.42$	4.7
Tremaine (2011)	$1000\ln(\alpha) = 16.1(10^3T^{-1}) - 24.6$	9.0
Coplen (2007)	$1000\ln(\alpha) = 17.4(10^3T^{-1}) - 28.6$	11.8

Table 1: *Results of paleotemperature calculations using four different water–calcite isotope fractionation equations.*

To further test the validity of the $\delta^{18}O$ calcite as a climate proxy, we

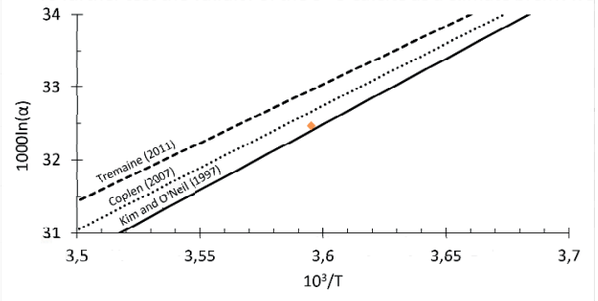


Figure 4: *Plot of calculated water-calcite oxygen isotope fractionation factors, based on the isotope values of modern calcite (from the glass plate in figure 3) and dripwater and cave air temperature (~5°C).*

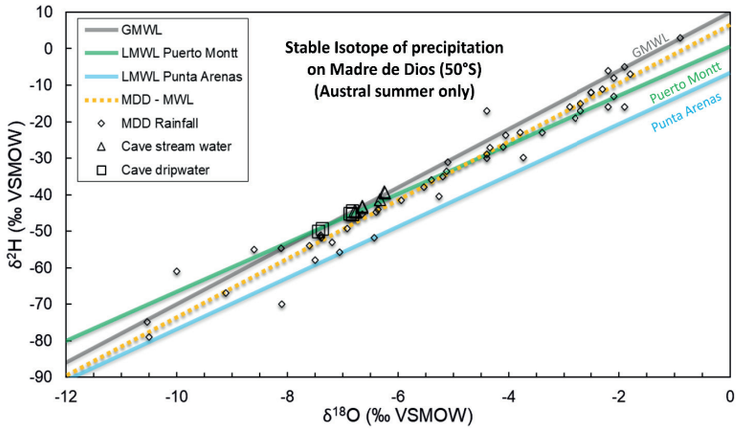


Figure 4: *Relationship between $\delta^{18}O$ and δ^2H values for water samples from MDD in different caves (Jackpot, 3 Entrées + 1, Cueva Pirates), along with the isotopic composition of rainfall from the global meteoric water line (GMWL), and local MWL from Puerto Montt and Punta Arenas. Rainfall data were collected during the UP2017 and UP2023 expedition and additional data from (MEYER et al, 2018).*

Water Sampling

An initial study aimed at investigating the dynamics and interaction of meteoric and groundwater in the karst systems of Barros Luco was conducted in 2017 by Gonzalo Navarro, Francisco Fernandoy, and Sebastián Crespo (NAVARRO et al., 2018). These authors established a local meteoric water line (LMWL) for the Madre de Dios archipelago: $\delta^2H = 7.58 * \delta^{18}O + 3.37$ ($R^2 = 0.95$; N=16). However, this curve is likely biased towards the summer period (January, February and March sampling dates), which also applies to the current study. Samples of water collected from January to March 2023 consisted primarily of groundwater (20 samples) and only of 2 surface samples.

In our study water was collected using a small syringe and directly injected into 3.5 ml vials without head space. The samples were analyzed using laser spectrometry (Picarro L2140-i CRDS at the University of Innsbruck) to determine the isotopic compositions ($\delta^{18}O$ and δ^2H, vs. VSMOW). In Figure 4, we compare the average isotopic composition of oxygen and hydrogen in rainfall from Madre de Dios (with an updated LMWL of $\delta^2H = 8.01 * \delta^{18}O + 6.54$ ($R^2 = 0.96$; N=51) with the Global Mean Water Line (GMWL) — the average isotopic signal of rainfall worldwide. Additionally, we compared these with the LMWL in Punta Arenas (~53° S) and Puerto Montt (~41° S). These data were obtained from CChEN (Chilean Nuclear Energy Commission) and represent a 24-year record from 1991 to 2015 (Sanchez-Murillo et al., 2018).

The isotopic compositions of the surface samples fall above the LMWL for Punta Arenas and samples closest to the GMWL are Karst groundwater samples show a much narrower range and cluster on the

Puerto Montt LMWL, but slightly above the MDD line (Fig. 5). The isotopic composition of groundwater approaching the GMWL could be explained by mixing and/or older groundwater that may be enriched in deuterium. Differences in isotopic values within the same cave can be attributed to whether streams or drip water from stalactites, assumed to have longer residence times in the epikarst, were sampled.

Speleothem Sampling

The stalagmites collected during UP2019 from the Jackpot cave contain elevated concentrations of uranium, allowing for high-precision dating (HONIAT et al., 2019). Stalagmite JCK1 grew between 185 and 115 ka. This is the first time that a speleothem from Madre de Dios has been dated to the period prior to the last interglacial. This stalagmite is rather unique for the region as it also grew during cold conditions of the penultimate glacial period, when the area was likely covered by a glacier (assuming a similar glacier cover as for the last glacial period ; see DAVIES et al. 2020). This speleothem therefore likely formed similar to subglacial speleothems elsewhere (SPÖTL et al. 2024). Because of its location close to the sea level, Madre de Dios was likely covered by temperate glaciers (whose base is at the melting point where liquid water coexists with ice) even during glacial periods. The growth of this speleothem during the penultimate glacial period confirms the presence of liquid water in the karst during cold phases. Because vegetation was lacking when the island was covered by ice, another acidifying agent is necessary. When sulfide minerals such as pyrite (observed in several places on Madre de Dios) are oxidized, sulfuric acid is produced and can dissolve the carbonate host rock. When the sulfuric acid dissolution is greater than the classical carbonate acid dissolution, the relative contribution of dissolved inorganic carbon from the host rock increases (instead of soil CO_2) and thus speleothem $\delta^{13}C$ values are getting close to the $\delta^{13}C$ signature of the host rock. That is what the preliminary stable isotope data of stalagmite JCK1 show.

Consequently, one focus of the 2023 expedition was the Jackpot cave where this subglacial speleothem was found. Jackpot cave is also one of the few caves on the island with hydrologically inactive conduits where pre-Holocene speleothems could have been preserved from the large deglacial flooding. We cored a large stalagmite/flowstone at the base of shaft P28 in the Jackpot cave at -185m (Figure 3) using a 4 cm diameter drill (called Clémentine or JCK2). One other stalagmite (JCK3) was collected in addition to the core. A temperature logger was installed at the location of the JCK1 stalagmite. The average temperature measured near the JCK1 stalagmite was 5.4°C between 02/18/23 and 02/26/23. The analysis and dating of these two new speleothems is currently in progress.



Figure 5: *Coring of the inactive stalagmite at the base of P28 in the Jackpot cave and scan of the Clémentine core (length 50 cm).*

3. Conclusion

Our environmental monitoring work provides a solid foundation for interpreting paleoclimatic and hydrological data derived from speleothems in Madre de Dios. Future research will focus on reconstructing past changes of the Westerlies in Patagonia using speleothems, as well as using a lake core collected in 2019.

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Response of the cave air CO_2 concentration in Modrič Cave (Croatia) to meteorological events

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Abstract

Various (palaeo)climatic and (palaeo)environmental studies conducted in the Modrič Cave (Croatia) over the past decade required a long-term monitoring of the carbon-dioxide (CO_2) concentrations in the cave air since the variations of CO_2 govern (non)deposition of speleothems which are extensively used in paleoclimatic studies. Initial results (based on values measured once a month) confirmed that the cave ventilation and responding CO_2 concentrations were driven by the chimney-effect, caused by the differences in air temperature between the cave and the surface. The results of 2021-2024 continuous monitoring (12- and 3-hour intervals) revealed a more complex variations in CO_2 concentrations which were influenced by both the chimney effect and meteorological events. The impact of bora wind was evidenced by abrupt decreases of CO_2 concentrations since bora amplifies the outflow of the CO_2-rich air from the cave. Intensive rains caused increases (although delayed) in CO_2 concentrations through infiltration of water through soil and epikarst into the cave and subsequent degassing of CO_2, particularly during the winter when there is a significant difference in partial pressure of CO_2 in cave air and drip water. Understanding the impact of meteorological events on CO_2 concentrations in Modrič Cave has had an implication on both scientific studies in the cave and cave management.

1. Introduction

Caves are integral parts of Earth Critical Zone (ECZ), a relatively thin but very heterogenous zone marked by the complex interactions between atmosphere, hydrosphere, biosphere and pedosphere. Interdisciplinary study of caves provides a window into the functioning of various mechanisms within the ECZ (BRANTLEY et al., 2007). The properties of the ECZ are predominantly determined by the surface climate which affects local hydrology and vegetation, key factors in modelling the atmosphere in caves. One of the features in which the cave atmosphere differs from the surface one (apart from quasi-constant cave air temperature) is carbon-dioxide concentration (CDC), which can be several tens of times higher in caves than on surface (FAIRCHILD & BAKER, 2012). Unlike the cave air temperature, the CDC show significant seasonal variations (BOURGES et al., 2001; SPÖTL et al., 2005; FAIMON et al., 2006). These variations can be linked with the ventilation of caves which is governed by cave morphology, connections with the surface and surface climate and weather (BAKER & GENTY, 1998; BOURGES et al., 2001; SPÖTL et al., 2005). In simple caves with one entrance and horizontal passages the ventilation is usually induced by the differences in air temperature (and density) between the cave and the surface. In areas with temperate climate (with significant variations in surface air temperature), this means that in warm season there will be an outflow of the air form the cave ($T_{cave}<T_{out}$) which will change to inflow during the cold season ($T_{cave}>T_{out}$) (CHRISTELLE et al., 2007). Such ventilation patterns, described as chimney effect, lead to seasonal variations of CDC in caves. The concentrations will increase during the warm period and decrease during the cold period. Apart from chimney effect, short-term weather events may also cause variations in CDC. Surface winds can amplify the chimney effect through increase or decrease of cave ventilation, and exceptionally strong wind episodes can even reverse the flow of air in caves (KUKULJAN et al., 2021). Precipitation amount and intensity is another feature that affects variations in cave air CDC (CAO et al., 2021). The impact of precipitation is particularly evident during short but intensive periods of rains when there is an abrupt increase in infiltration of water through epikarst where water is further enriched with CO_2 and then which can eventually lead to increase in cave CO_2 values through degassing if pCO_2 of percolating water is higher than pCO_2 of the cave air (CAO et al., 2021).

In this paper we present the results of CO_2 monitoring campaigns in Modrič Cave (Croatia) which indicate possible responses of cave air CDC variations to short-term meteorological events (mainly strong winds and intensive rains). The results of this study are valuable for future (palaeo)environmental and (palaeo)climatological research in the cave, as well as for the sustainable cave management because the Modrič Cave is a show cave.

2. Study site

Modrič Cave (44°15'24'' N; 15°32'14'' E; 32 m a.s.l.) is located on the seaward slope of the Velebit Mt. ca. 120 m from the coast (Fig. 1A). It has a simple morphology with two mostly horizontal passages with total length of 829 m and with 2-30 m thick overburden. The cave is formed along a wider fault line in Upper Cretaceous limestones which are heavily fractured. In the vicinity of Modrič Cave there are several smaller caves, coastal and submarine springs (*vruljas*) (KUHTA et al., 1999). Since 2004 the cave is open for public, however, the visitors are allowed only in the left passage in small guided tours with basic caving equipment. The annual number of visitors is low, up to 700 individuals (LONČARIĆ et al., 2023).

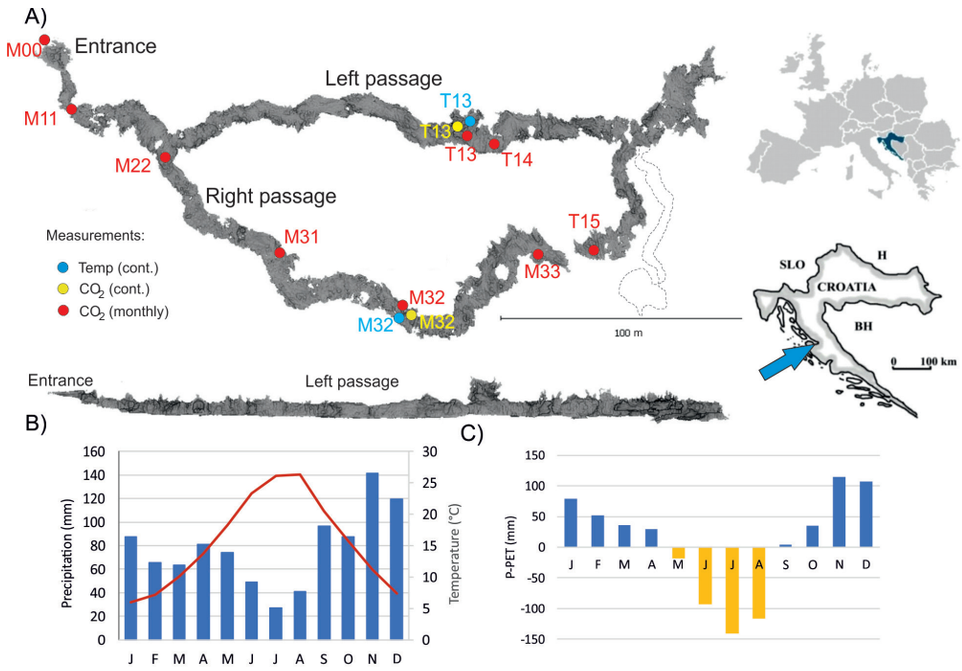


Figure 1 : *A) Location and layout of the Modrič Cave with measuring stations; B) mean annual average temperature and precipitation (1998-2024) for Novigrad meteorological station (8 km south of the cave); C) Potential evapotranspiration calculated using THORNTHWAITE (1948) calculation.*

The climate of the area is submediterranean (Cfa in Köppen-Geiger classification) with mean annual average temperature of 15.48° C and mean annual average precipitation of 914 mm (1998-2024) (CMHS, 2025). Although there is no true dry period (all moths have >60 mm precipitation), July is the driest month on average, while most precipitation occurs from September to December with a peak in November (Fig. 1B and 1C). Precipitation pattern shows less variability during the wet season when rain episodes, caused by frequent transition of low-pressure systems over the area, can last for several days. In contrast, precipitation during the "dry" period (summer) shows greater variability and it is not uncommon (although not regular) that rains are absent for several weeks. This absence of precipitation is caused by the presence of quasistationary Azores High over Adriatic, which prevents the circulation of cold and wet air from the Atlantic (CMHS, 2025). During the summer, very intensive precipitation sometimes develops in short-lived thunderstorms when large amounts of rain fall in short time frame, in extreme cases reaching 100 mm/day or even more. Particular feature of the Modrič Cave area is its exposure to strong *bora* wind, a katabatic wind which often reaches gale force (>200 km/h in short bursts) and occurs mostly during the cold part of the year when high-pressure area is located over central or southeastern Europe and low-pressure systems are moving across the Adriatic Sea or adjacent parts of the Mediterranean basin. Bora usually lowers the air temperature and relative humidity and enhances the evaporation which can leads to the disruption in both cave ventilation and drip water behavior. The intensity of bora is dependent, among others, on terrain morphology as mountain passes, canyons and valleys channel the air flow and increase the wind speed and the area around the Modrič Cave is well-known among the local population for its exceptionally strong wind gusts.

3. Materials and methods

The first program of monitoring CO_2 concentrations in Modrič Cave started in March 2017 and was based on monthly measurements of CO_2 concentrations using hand-held *AZ 7755* CO_2, temperature and relative humidity meter. Measurements were done at 8 locations inside the cave an on one location outside the cave (Fig. 1A). The CO_2 meter is able to register CO_2 concentrations up to 9999 ppm which proved to be inadequate for measuring the maximum concentrations of CO_2 in the cave's right passage where CDC regularly surpassed the upper limit of the instrument during late summer/early autumn. This fact, in conjunction with the necessity of determining fine-resolution temporal variations of CO_2 concentrations, required the setup of a new monitoring program. The second program began in November 2021 with continuous measurements of CO_2 concentrations using two Vaisala MI 70 data loggers connected to *GMP 252* CO_2 probes which have CO_2 measuring range from 0 to 20 000 ppm. Loggers were placed in the central parts of both passages (T13, M32) and they were initially recording the CO_2 concentrations with 12-hour intervals. The logging interval was later changed to 3 hours to better capture diurnal variations in CDC. Drip intensity was measured at two locations in each passage using Stalagmate® drip logger with 1-hour resolution. Air temperature and relative humidity were measured in front of the cave and inside each passage (T13, M32) with HOBO® ProV2 data loggers with 1-hour intervals. Meteorological and climatological data for Novigrad meteorological station (8 km S of the cave) were obtained from Croatian Meteorogical and Hydrological Service (CMHS). The data from continuous CO_2 measurements were correlated with the concurrent daily precipitation, drip rates of percolating water and surface air relative humidity and temperature which was used as indicators of the impact of meteorological events on cave CDC.

4. Results and discussion

The data obtained on monthly basis using the hand-held CO_2 meter (2017-present; for the detailed analysis of the 2017-2021 leg, see SURIĆ et al., 2021) showed spatial and temporal variations of CO_2 concentrations in both cave passages (Fig. 2). As expected, the CO_2 concentration

increases from the entrance towards the interior parts of the cave in both passages regardless of the season. The left passage showed significantly lower values of CO_2 concentrations in comparison with the right passage. At the T13 in the left passage values range from 480 ppm to 7448 ppm, while at the end of the left passage (T15) maximum values even surpassed the upper limit of the instrument (>9999 ppm). In the right passage minimum recorded values never dropped below 1000 ppm while values above instrument limit were regularly recorded on all three points in the channel (M31, 32 and 33). The difference in CDC between the two passages can be attributed to the differences in their morphology as the right passage is narrower and more confined, which reduces the ventilation and enables the build-up of the CDC. In both passages, the lowest values were recorded during the winter (January-March), while the highest values occur at the end of the summer and in early autumn (August-October) (Fig. 2). Interestingly, in the right passage in the summer 2024 values of >10 000 ppm occurred as early as July and continued until November. Based on these preliminary data, we concluded that the cave ventilation is primarily driven by the chimney effect with indications of the bora-induced airflow overprinting the dominant ventilation patterns (SURIĆ et al., 2021). However, the data obtained with hand-held CO_2 meter could not definitely corroborate meteorological impacts on variations of CO_2 which could be better detected by continuous measurements with higher temporal resolution.

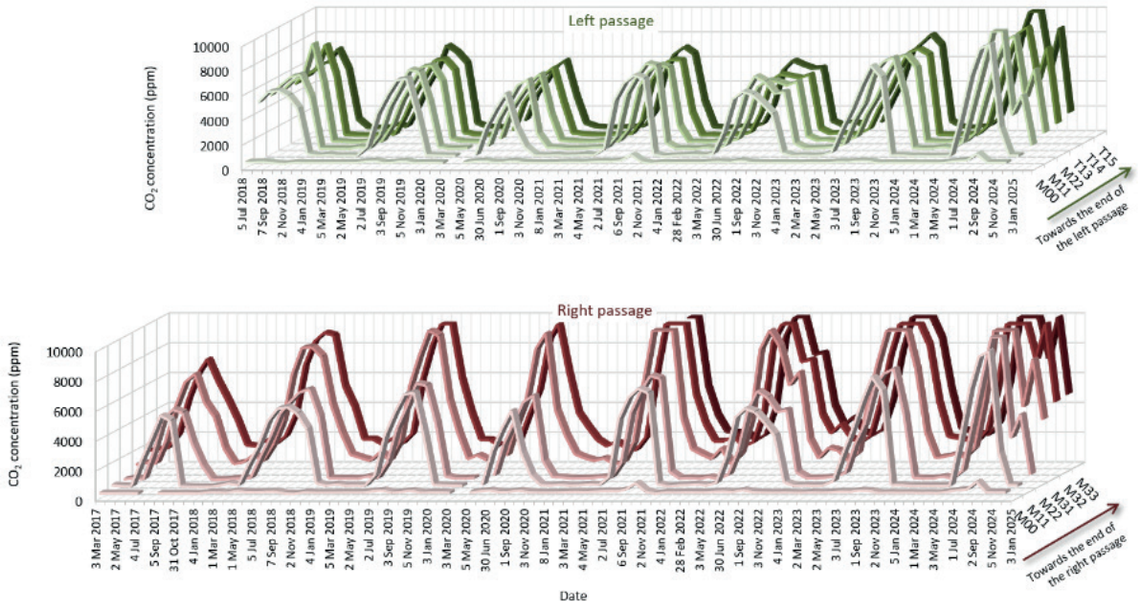


Figure 2: *Spatio-temporal variations of CDC in the Modrič Cave recorded on monthly basis between March 2017 and January 2025.*

Continuous measurements of CO_2 concentrations instigated in autumn of 2021 expectedly yielded a more detailed data series which provided a better insight into reaction of CO_2 to meteorological events. Since CO_2 probes had upper limit of 20 000 ppm we were able to reliably determine the maximum values of CO_2 concentrations, which in the right passage (M32) were regularly above 12 000 ppm during late summer/early autumn with absolute maximum of >15 000 ppm recorded in 2024 (Fig 3). Furthermore, continuous measurements confirmed not only our expectations about maximum values of CDC, but also about CDC variations on shorter time scale. Namely, the data showed that there are abrupt short-term variations of CDC which occur year-round and which might be connected to the meteorological events (Fig. 3).

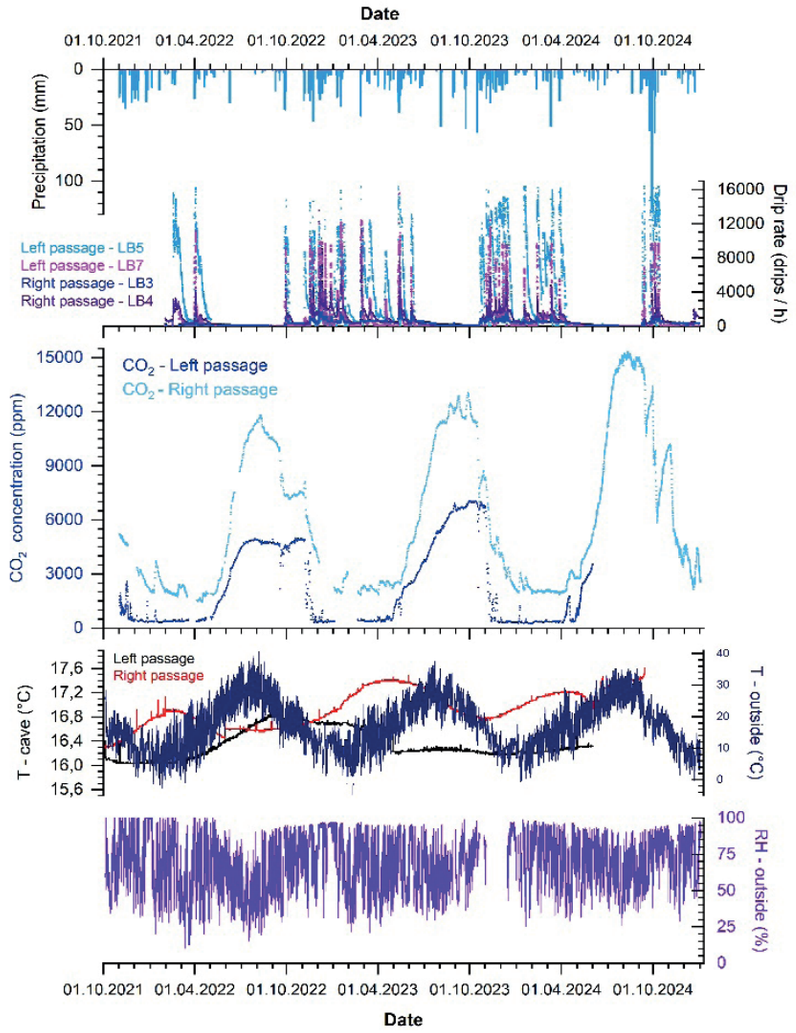


Figure 3: *Variations of CDC and its relation with precipitation, drip rate, cave temperature and outside temperature and relative humidity recorded from November 2017 to December 2024.*

Although we did not measure wind speed and direction on surface above the cave, we were able to detect the episodes of strong bora through the sudden decreases in surface air T and RH recorded with data logger in front of the cave. These are reliable indicators of bora, which originates from continental dry and cold air mass and therefore significantly reduces air T and RH. Some more evident bora episodes include those from March 2022, February 2023, January 2024 and April 2024.

Generally, during the spring/summer seasons there is an increase in CDC induced by more intensive bioactivity in soil horizon. Maximum values in CDC are reached in late summer/early autumn in both passages of the cave, followed by a period of abrupt transition towards lower winter values. This transition is caused by the change in the cave airflow when T_{out} decreases below T_{cave}, and outflow is replaced by inflow of the CO_2 depleted atmospheric air and CO_2 rich cave air is pushed out of the cave. Furthermore, this period of the year also marks the change in weather patterns caused by the weakening of the Azores High and subsequent increased number of low-pressure systems passing over the Adriatic Sea often causing intensive rains (as evident in autumn 2022, 2023 and 2024). Rains increase infiltration of CO_2 enriched water in the cave (data from drip loggers LB 3, 4, 5 and 7) and, through degassing, the increase of CDC. However, the response of cave CDC to rain events is not immediate as the data showed a delay, with peaks in CDC lagging about 15 days behind intensive rain events. The delay probably occurs because rain saturates the soil and epikarst above the cave which disrupts cave ventilation allowing steady increase of the gases inside the cave (LONČARIĆ et al., 2022). Despite the delay, rains temporarly halt the decreasing trend of cave CDC and cause short-term „peaks“ in gas concentration. These episodes of elevated CDC last until the next bora episode which usually follows shortly after the end of rain since both events occur within the same weather system. Namely, passing of the low-pressure systems over the Adriatic creates favorable conditions for both rain and bora wind. The most intensive rains are linked to the cold fronts which are rapidly moving inducing the inflow of cold air stream from the continent towards the Adriatic and the onset of bora. When rains end and bora starts, the decreasing trend in CDC continues until it reaches its minimum values in winter. The winter dynamics of the CDC is mainly governed by the rain events which leads to increases in CDC as the rainwater saturates the soil and blocks the fissures which temporarily suppresses the ventilation i.e. outflow of the CO_2 enrichhed air from the cave. However, since the bioactivity in the soil above the cave is very limited during the winter and the ventilation is intensive, the CDC values never reach the summer ones (SURIĆ et al., 2023).

It is worth mentioning that the recorded variations of CDC can be very indicative for the behavior of radon, a radioactive gas which is, similarly as CO_2, found in cave air in substantially higher concentrations than in the atmosphere. Radon is the main natural source of nuclear radiation and a leading natural cause of lung cancer, and therefore, the understanding spatial and temporal patterns of radon concentrations

is pivotal for responsible management of show caves. Although CO_2 and radon have different sources the two gasses exhibit similar variations in concentrations because CO_2 acts as carrier gas for radon. The study of radon behavior in the Modrič Cave (LONČARIĆ et al., 2022, LONČARIĆ et al., 2023, SURIĆ et al. 2023) demonstrated these relations in terms of the spatio-temporal variations in concentration of the gases and their responses on meteorological events.

5. Conclusions

The study of variations in CDC in the Modrič Cave revealed some site-specific patterns regarding spatial and temporal behavior of CO_2. The initial research proved that the chimney effect is the dominant mechanism driving the cave ventilation as could be expected for relatively shallow and simple caves in karst. Despite indications of weather impact on ventilation (primarily wind), long intervals between measurements (one month) and limit of the instrument (9999 ppm) could not confirm such impact. The continuous measurements (in initially 12-hour, later 3-hour intervals) of the CO_2 concentrations in both main passages of the cave confirmed the seasonal variations in CDC, and higher upper limit of the instrument (20 000 ppm) allowed us to determine absolute maxima of CDC in the cave which reached >15 000 ppm in the right passage. New data set proved that in certain situations the chimney-effect is affected by the meteorological events. A dry and cold bora wind amplifies the outflow of the CO_2 rich air, reducing the CDC, while intensive rains can cause rises in CDC, although the response of CDC to the rain events is somewhat delayed. The fact that intensive rains and strong bora episodes appear within the same weather systems can cause the abrupt changes in CDC visible as spikes on data chart. The data obtained during the CO_2 monitoring campaigns were used not only in paleoenvironmental and paleoclimatic studies, but also in cave management since CO_2 is a carrier gas for radioactive radon which is considered a significant health hazard for humans. Therefore, understanding the behavior of both gases helps to mitigate health risks for cave guides, visitors and scientists.

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Particulate matter monitoring: methodological guidelines based on the results of experiments in iron caves

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Abstract

Monitoring particulate matter (PM) and its effects on caves, particularly in mining areas, is a relatively new environmental licensing approach. PM dynamics in caves, including deposition, redispersion, and formation, remain poorly understood, and there is no standardized method for measuring or estimating PM dry deposition. Basic methods often use smooth horizontal plates and PTFE filters as collection devices. This study aimed to monitor PM deposition in iron caves in Minas Gerais, Brazil, focusing on three goals: improving analysis accuracy, evaluating tripod protection from external influences, and determining if exposure time affects PM accumulation. Three caves were sampled based on their vulnerability to PM: SAZ-0013, SAZ-0017 (highly vulnerable), and SAZ-0046 (low vulnerability). PM was collected using sanitized acrylic containers with PTFE filters, exposed at various points within caves for 30, 60, and 90 days. Protective tripods with roofs were tested. Filters were weighed pre- and post-sampling to measure PM accumulation. Results showed no significant differences in PM sedimentation rates between filters with and without tripods. Extended exposure times did not improve detection; however, increasing the number of collection devices provided more reliable monthly PM data. PM monitoring methods are adapted based on field conditions and past data for improved accuracy.

1. Introduction

Monitoring particulate matter (PM) and its effects on subterranean environments is a relatively new approach in environmental licensing, particularly within the context of mining activities. PM in caves poses a range of challenges affecting both ecosystems and human activity (WU et al. 2017, FAIMON et al. 2019). PM can accumulate on cave surfaces, altering natural microhabitats and disrupting nutrient cycles, which can have harmful effects on the diverse species that inhabit these sensitive environments, such as microorganisms, insects, and bats (CHANG et al. 2008, DREDGE et al. 2013). Chemical contamination from PM, especially if it carries heavy metals or other pollutants, further threatens cave biodiversity. Human health risks are another significant concern. Fine PM can degrade air quality in caves, leading to respiratory issues for workers, researchers, and tourists who frequent these areas (SCUNGIO et al. 2021).

The deposition of PM can also have a detrimental impact on cave aesthetics and cultural heritage (DREDGE et al. 2013). Accumulated PM may stain or corrode geological formations and cave art, compromising their visual appeal, cultural value, and preservation efforts. This is especially concerning in caves with significant historical or cultural artifacts, where even minor changes can cause irreparable damage (NAVA et al. 2010).

PM often originates from human activities such as mining, industrial processes, and tourism (SAIZ-JIMENEZ et al. 2011, DREDGE et al. 2013). Monitoring PM in caves is challenging due to unique environmental conditions, such as stable temperatures and air currents (DREDGE et al. 2013). There is a need for effective measures to minimize PM influx, using standardized monitoring techniques and mitigation strategies to protect these delicate environments. The dynamics of PM in caves, including deposition conditions, redispersion, and potential formation processes, are not well understood (DREDGE et al. 2013).

Current methods for analyzing PM deposition vary across environmental licensing projects and require further testing and refinement. To date, no standardized approach exists for directly measuring or estimating PM dry deposition (CHU et al. 2008), though basic methodologies generally employ smooth horizontal plates associated with polytetrafluoroethylene (PTFE) filters as collection devices (DREDGE et al. 2013). In this study, we employed an experimental method to monitor PM deposition in iron caves with three main objectives: (i) to enhance the accuracy of analysis and statistical assessments by calculating intrinsic methodological error, (ii) to evaluate the protective effect of a tripod against dripping, insects, and falling organic matter, and (iii) to determine if device exposure time influences PM accumulation.

2. Materials and methods

The caves sampled are located in the Tico-Tico Mine area, covering the municipalities of Igarapé, Brumadinho, and São Joaquim de Bicas in Minas Gerais, Brazil. Three caves were chosen based on their speleometric features, structural characteristics, and vulnerability to atmospheric PM accumulation: two highly vulnerable caves (SAZ-0013, SAZ-0017) and one with low vulnerability (SAZ-0046). We used sanitized acrylic containers (1.5 cm in height and 5 cm in diameter) with PTFE filters inside, dried at 40°C for 120 minutes, as collection devices and wrapped them in plastic film to prevent contamination during transportation. After analyzing each cave, devices were installed based on PM presence, deposition extent

(entrance, medial, or distal), maximum distance from the entrance, surface type, temporal deposition indication, PM layer thickness, and material characterization (color and granulometry). The experiment involved exposing three sets of collection devices at each of three monitored points (located near the entrance, suspended, and/or on the floor) within selected caves, with each set comprised a container with a filter and one without, both mounted on 12 cm stainless steel rods side-by-side (Figure 1). Each set was exposed for 30, 60, and 90 days, respectively. In the highly vulnerable caves, stainless steel tripods (20 cm) with protective roofs were placed at two points, each equipped with two containers holding filters. Filters were weighed before and after oven-drying and sampling to measure weight differences. Sampling took place from May to July 2021. Data from seven previous campaigns were used as a baseline. After each sampling, devices were carefully sealed, wrapped in plastic film, and sent for laboratory analysis.

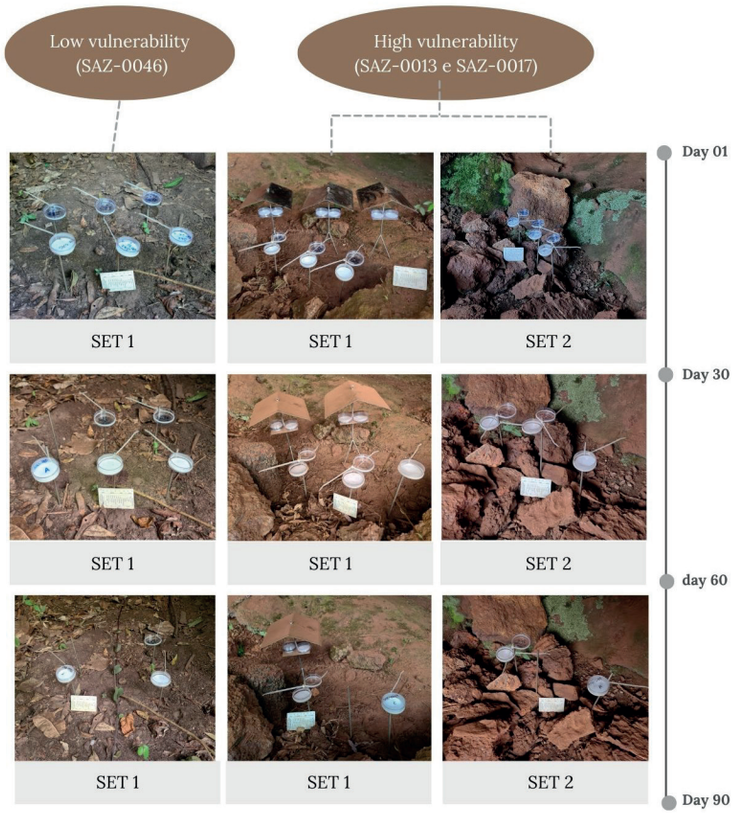


Figure 1: *Distribution pattern of containers in caverns with low vulnerability to particulate matter deposition (SAZ-0046) and caverns with high vulnerability to particulate matter deposition (SAZ-0013 and SAZ-0017) and the temporal evolution in the arrangement of equipment.*

3. Results

For the campaigns in which the filters were weighed before and after passing through the stove, an assessment of the differences between these two moments was performed. Below is the estimated mean difference in weights (post-stove – pre-stove) for each campaign and each time (pre-field and post-field). It can be noted that for all campaigns and periods, except one, the confidence intervals cross the zero value, indicating that there was no significant difference in the weights before and after passing through the greenhouse (Figure 2). As an exception, the results of the 3-month exposure experiment are characterized, since passing through the stove significantly increased the mean weight of the filters by 0.00506 g.

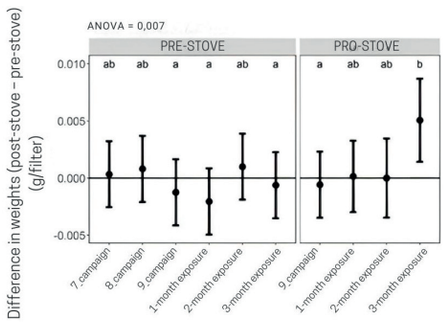


Figure 2: *Estimation of the average difference in weights (post-stove – pre-stove) for each campaign and each laboratory stage.*

For all combinations tested, no differences were found in the average sedimentation rates between the filters placed on the tripods and the filters without the tripod (Figure 3). The aforementioned result confirms that the use of the protective tripod did not significantly influence

the reduction of sediment deposition in the containers over the three months analyzed and, therefore, can be applied for protection against drips, insects and falling organic matter. The methodology using a longer exposure time, combined with a greater number of containers per point, allows for more reliable monthly sedimentation rate values, exceeding the limits of expanded uncertainty. In this way, it is possible to quantitatively interpret the deposition of solid PM based on laboratory weighings and subsequent statistical manipulations.

When performing the overall analysis of the results, a marginally significant difference was found in the number of months of exposure factor (p-value = 0.060, Figure 4). On the other hand, it is worth noting that the number of filters factor was significant (p-value < 0.001, Figure 5). The first way presents the variation in the mean deviations (post-field – pre-field) for each month of exposure, separately for the number of filters evaluated together. The second way shows the variation in the mean deviations (post-field – pre-field) for each number of filters evaluated together, separately for each month of exposure (Figure 4).

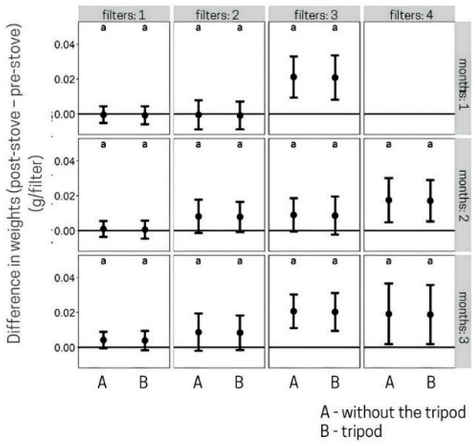


Figure 3: *Assessment of the average difference in weights (post-stove – pre-stove) for the use or not of the tripod to support the containers.*

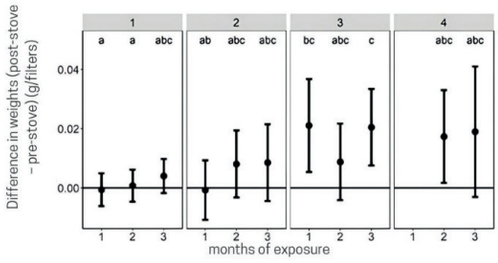


Figure 4: *Evaluation of the results obtained by months of exposure.*

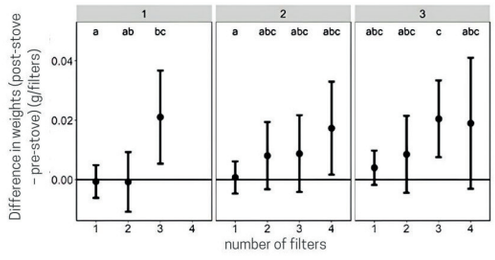


Figure 5: *Evaluation of results obtained by number of filters.*

It is noted that there is no clear increase in deviations with the increase in months (Figure 4). There is a visible subtle drop from the 1st to the 2nd month of exposure, with 3 filters. The increase in deviation is clear and follows the increase in the number of filters, except between 1 and 2 filters for the 1st month of exposure (Figure 5). This result shows that the most optimized strategy is to increase the number of filters in each campaign, to the detriment of the exposure time. Additionally, a statistical model was applied to the complete results, where 1,000 bootstrap estimates of the average sedimentation rate were performed for 3 and 4 filters and considering only one month of exposure (Figure 6). The estimates were divided by 3 and 4, respectively, in order to obtain the estimate per filter. Estimates below the uncertainty limit (0.0085 g) were discarded. Estimates for only 1 and 2 filters were not considered, as these had estimated means below the expanded uncertainty (0.0085 g). Furthermore, only the estimate for 1 month was considered, because no linear trend of increasing values over time was observed, which would allow the application of standardization.

From the 1000 estimates, it was possible to obtain an empirical distribution of the values, as well as to estimate the mean value and the 95% confidence percentile interval. The histogram below shows that the distribution of the values presented a slightly positively asymmetric distribution. The estimated mean was 0.00444 g per filter per month with a 95% confidence percentile interval between 0.00245 g and 0.00677 g per filter per month.

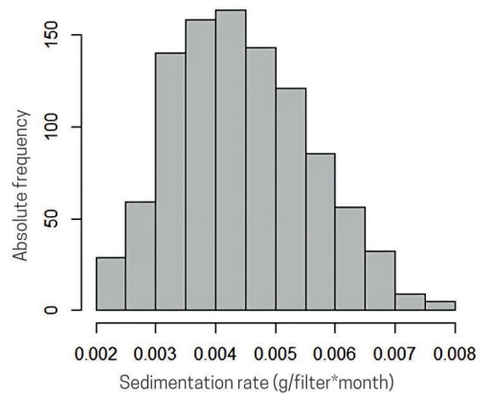


Figure 6: *Bootstrap estimate for three and four filters, considering a one-month exposure interval.*

4. Discussion

None of the studied caves showed significant changes in particulate matter (PM) levels during monitoring. The monitoring methodology is continually adapted based on field observations and statistical analyses from previous campaigns. The experimental method was valid, with six measurements exceeding the uncertainty limit in the second month, based on data from all filters in each cave. Longer exposure times did not necessarily lead to more detectable PM deposition, indicating that increasing the number of filters is more effective than extending exposure. A thin layer of brownish to reddish clayey sediment found in containers without filters was a positive result for the method. New automated measurement techniques, using grain counting and proprietary algorithms, are under development and will be detailed in future reports. The use of protective tripods showed no significant impact on reducing sediment deposition, but they can help protect against drips, insects, and falling organic matter.

5. Conclusion

No significant differences were found in average PM sedimentation rates between filters with and without tripods. Methods with extended exposure times, combined with increased numbers of collection devices per sampling point, provided more reliable monthly PM sedimentation rates, surpassing expanded uncertainty limits. No PM-related changes were observed in any cave, and extended exposure did not improve PM detection using current methods. Increasing the number of devices was more effective than longer exposure times, and PM monitoring methods are continuously adapted based on field conditions and past data.

Acknowledgments

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The cave voice: acoustic monitoring of floods in purga Delle Cadene (Italy)

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Abstract

Spurga delle Cadene is a cave situated in the Lessini Mountains, on the left bank of the Adige River. It shows unique hydraulic characteristics during floods events. The internal stream in normal conditions does not reach the exit but is drained by a fault in the lower channel, ca. 150 meters from the entrance located 7 m higher. During floods, loud sounds can be heard from considerable distances. To investigate the hydrogeological role of the cave stream, a 4-month monitoring study was conducted, documenting nine floods. The data revealed that atmospheric pressure within the cave chambers, isolated by the rising water levels, acts as the primary mechanism driving the "Plunger Effect," which governs cave behavior during flood events. Using a bioacoustic sensor it was possible to record the sounds produced during flood events revealing that the low-frequency intensity spectrum remained the same across all flood episodes analyzed. Generated sounds are solely dependent on water height and the cave's morphology. Moreover, the distance between specific peaks in the spectrum correlates with the rate of increase in water levels, while the maximum intensity of certain peaks corresponded to the rate of water level rise and consequently, with appropriate calibration, to flood discharge.

1. Introduction

The Spurga delle Cadene is one of the most spectacular karst caves in the Lessini Mountains of Verona, with an explored length of approximately 1,250 meters extending in an east-northeast direction. It opens with a large portal on the orographic left side of the Adige Valley at an altitude of 525 meters above sea level, developed within the core of a significant syncline in the Calcari Grigi Formation.

The Lessini Mountains, the southernmost extension of the eastern South Alpine domain, are considered the foreland, weakly deformed by the Neogene-Quaternary South Alpine Chain. Thus, Lessinia is located within the South Alpine domain, characterized by south-verging structures (DOGLIONI & BOSELLINI, 1987).

The cave functions as a large temporary karst spring, with water emerging from its entrance only during periods of flood, which coincide with intense precipitation in the recharge area (Fig.1). On such occasions, water flows out of the entrance portal at high pressure, with discharge rates in the order of several hundred liters per second. During dry periods, instead, the perennial stream within the cavity is entirely drained by an open fault intersecting the cave 150 meters from the entrance (ARTONI & REBESCO, 1990).

The cave's most peculiar feature lies in its name, given a long time ago, which reflects the sounds emanating from the cave, resembling "*Cadene*," that means "chains." The locals named the cave this way due to its characteristic production of loud noises, audible even from a large distance, during periods of flood.

To investigate the hydraulic functioning of the karst cavity and to explore potential explanations for the origin of these sounds, continuous monitoring of various parameters including water T, level and pH, air T and P, and sounds, was deemed necessary.



Figure 1: *Comparison between flood and dry periods in the entrance portal of the Spurga delle Cadene (Photo: E. Nicolini).*

2. Materials and methods

The Spurga delle Cadene is a rarity within the panorama of Italian caves, exhibiting unique characteristics that have never before been thoroughly studied. The hydraulic and physical features of the cave result from its distinctive morphology, characterized by a difference in elevation between two distinct sectors of the cave.

As is evident at the entrance, the first 60 meters of the cave develop along a plane coplanar to the axial plane of the syncline (ROSSI & ZORZIN, 2011). This section, known as the "upper channel," is traversed by water only during flood events. Approximately 60 meters from the entrance, the cave crosses a primary regional fault that marks the boundary of the heavily deformed block to which the syncline belongs. From this fault onward, the morphology of the cavity changes. The conduit descends by 7 meters through a narrow, sloping corridor to reach the Hanging Lake, where it meets the perennial stream. At this point, the conduit intersects a second fault, located 150 meters from the entrance, which serves as the primary drainage path for the internal stream during base level flows. This section is referred to in the present study as the "lower channel". Beyond the Hanging Lake, following the subterranean stream upstream, one reaches the Hall of Wonders.

To interpret and provide a physical explanation for the sounds observed, as well as to understand the hydraulic functioning of the cave spring, an acoustic and hydrogeological monitoring campaign was designed. This monitoring involved various instruments installed within the conduit over a period of four months, from September 2023 to January 2024.

The parameters measured and the instruments deployed within the Spurga delle Cadene during this monitoring effort were as follows (see Figure 1 for location of sensors):

Water level measurements of the perennial stream. Two HOBO pressure transducers (HOBO 1 and 2), model U20L, were installed for this purpose, with sensitivity limits of 9 meters and 4 meters of water, respectively. The instruments were configured to record one measurement every 15 minutes for the entire monitoring period. They were positioned above and below the Hanging Lake. An additional HOBO U20L pressure transducer (PA1) was placed in the Hall of Wonders to measure atmospheric pressure and its fluctuations.

Sounds occurring within the cavity before, during, and after floods. For this purpose, a bioacoustic recorder specialized for extreme environments was installed in an area safe from water flow (Microphone in Fig. 2). The microphone, manufactured by Wildlife Acoustics (model Song Meter SM4), is waterproof and equipped with two integrated microphones designed for high-quality recordings. The instrument was positioned in the White Hall, where it was able to clearly capture sounds emanating from the depths of the cave while minimizing the risk of being swept away by flood currents.

The huge quantity of recorded sounds was subsequently processed and transformed into usable, analyzable data for this study, at the Laboratory of Applied Bioacoustics at the Polytechnic University of Catalonia in Barcelona (LAB) (ANDRÉ et al., 2011).

For the purposes of this project, three of the lowest frequencies recorded by the microphone were selected for detailed analysis: <10 Hz, 15.8 Hz, and 31.6 Hz.

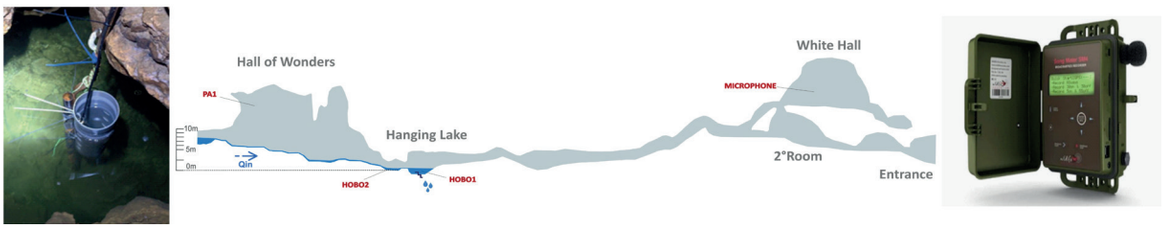


Figure 2: *Cave long profile with location of the installed monitoring equipment. Left, one of the HOBO sensors, protected by a tube ; right, the bioacoustic monitoring device.*

3. Results

The pressure transducer installed in the Hall of Wonders was designed to monitor atmospheric pressure variations occurring in this particular chamber within the karst network. During periods of normal hydraulic inflow and outflow, the pressure exhibits minor fluctuations that can be easily attributed to meteorological and climatic variations. In contrast, during each recorded flood period, very pronounced positive pressure peaks are observed, reaching values several hundred mmHg higher than those recorded during ordinary periods. The atmospheric pressure and water level height show coinciding growth phases (Fig. 3).

The atmospheric pressure exhibits very similar and cyclical fluctuations across different flood pulses: it shows an initial rise with a variable maximum peak coinciding with the arrival of the flood in the upper channel, followed by a decreasing phase and the restoration of ordinary values. The return to standard atmospheric pressure conditions is then followed by a depressurization phase, with values 30–40 mmHg lower than usual, which coincides with the end of the flood and the cessation of water flow in the upper channel. Additional pressure fluctuations can be observed during flood events, consisting of smaller increases and decreases that correlate with variations in the water level. Flood events display similar and cyclical atmospheric pressure and water level height curves.

An analysis of the acoustic recording data shows that the intensity of the sampled frequencies increases very rapidly with the rising height of the water column, while during the falling phase, it tends to decrease more slowly. The behavior of the various curves appears consistent, with all showing a period of intense oscillation in intensity that precedes and follows the flood; during the flood itself, the intensity curves exhibit varying changes between events, corresponding to fluctuations in the water column.

Frequency intensities, apart from normal minor fluctuations of a few decibels during any recorded period, show two periods of high variability corresponding to the rising and falling phases. During the rising limb of a flood, the graphs reveal distinct variations with sharp peaks where intensity values even double. Similarly, during the descending limb, a marked disturbance is observed, characterized in this case by prolonged peaks of high intensity.

4. Discussion

The hydrogeological monitoring of the Spurga delle Cadene aimed, among its primary objectives, to interpret the mechanism governing the cave during flood events. A simplified model of the cave was constructed to more clearly demonstrate and explain the results obtained. When precipitation in the recharge area is abundant, water reaches the Hanging Lake within a few hours, raising the piezometric surface level. Consequently, the inflow increases, transitioning from Qin1 to Qin2, as the surplus water coming from upstream cannot be completely discharged through the fracture beneath the Hanging Lake (Fig.4). The hydraulic level rises, and the rate of this phase is strongly dependent on the volume of incoming water.

By analyzing the data collected during all flood events, it was observed that the arrival of the flood wave in the upper channel consistently coincides with the peak atmospheric pressure measured in the Hall of Wonders. A more detailed analysis of what occurs in the Hall of Wonders reveals that during the rising phase, the water level increases and isolates the Hall by obstructing the narrow passage connecting it to the Hanging Lake, thereby compressing the air trapped within the chamber. This sudden increase in the water column height consequently raises the atmospheric pressure in the Hall, a mechanism clearly evident in all flood events previously analyzed.

The hypothesis proposed in this discussion is that atmospheric pressure, upon reaching a sufficient value, is the engine that initiates the flood event. The driving force of the mechanism is the pressure exerted by the compressed air pockets on the water, explained by Pascal's Law and the Principle of Communicating Vessels. According to these physical laws, the water—continuing to rise—experiences an additional pressure due to the compressed air in the Hall of Wonders, which in a short period of time, allows it to reach the height necessary to overcome the obstacle posed by the elevation difference with the upper channel. This principle has been termed the "Plunger Effect" in the present study, and its consistency has been mathematically verified.

Once the threshold is overcome, the flood wave flows with a notably vigorous discharge through the upper channel, eventually exiting as a pressurized jet from the cave's entrance (Fig. 1). In this context, the inflow is Qin3, and there are two outflows: Qout3a, which infiltrates through the fault located beneath the Hanging Lake, and Qout3b, significantly more abundant, which exits through the cave's entrance. Once triggered, the mechanism continues until the water level in the Hall of Wonders falls below the discharge level represented by the cave entrance.

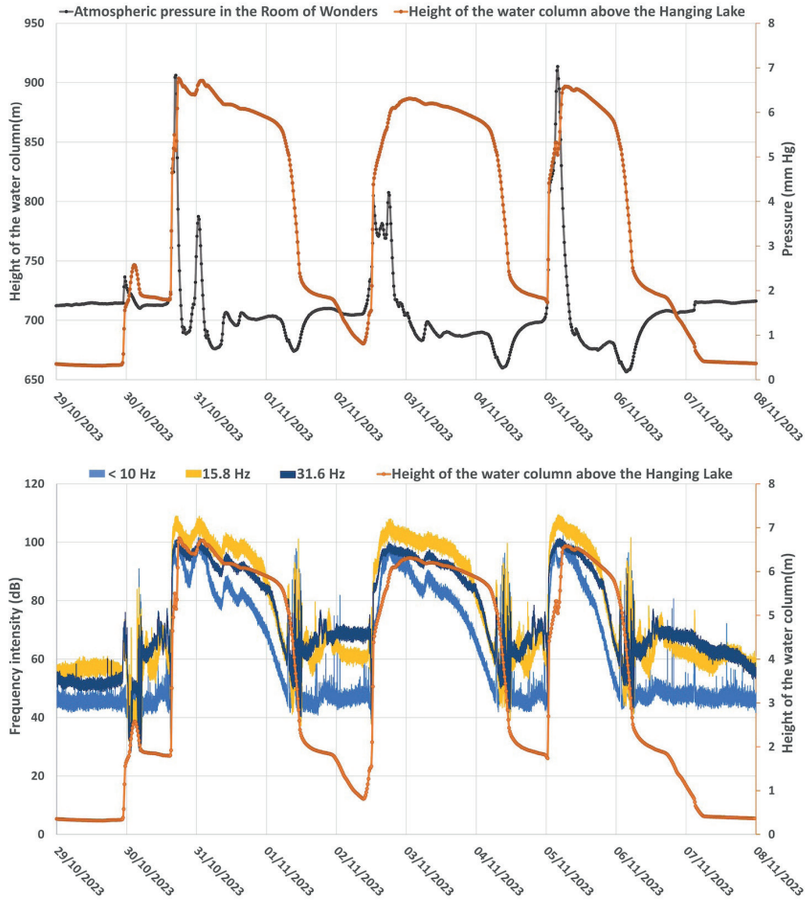


Figure 3: *Example of water level changes, pressure, and sound frequency intensities (low frequencies <10 Hz, 15.8 Hz, and 31.6 Hz) for three flood events between end of October to November 8, 2023.*

The negative pressure peak recorded is instead a consequence of the expansion of the air trapped in the Hall of Wonders during the phase of piezometric level decline. The trapped air, partially expelled during the loading phase, is now present in a reduced quantity compared to its initial volume. Therefore, during the level drop, it has more space to occupy, creating depressurization. The graphs provide an illustration of the acoustic data recorded by the microphone, showing that high-intensity sounds precede, follow, and accompany all flood events (Fig. 5).

During the rising stage, across various flood pulses, intensity spectra with consistent characteristics were recorded for all considered frequencies. Detailed analysis of the collected data revealed that variability between the graphs is attributable to differences in the rate of piezometric level rise. It can be concluded that there is a recurring intensity pattern during the flood's loading phase, reproduced in each event due to the interaction between the rising water level and the morphology of the karst cavity. The exact composition of the spectrum, particularly the adjacency and spacing between intensity peaks, is thus highly dependent on the rate of piezometric level rise.

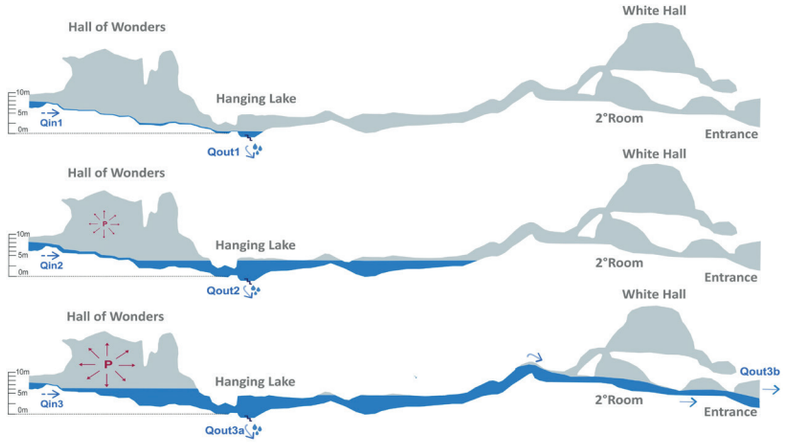


Figure 4: *Model of the Spurga delle Cadene with focus on 3 progressive phases during the rising of a flood episode.*

Regarding the falling stage, the graphs show that the observed floods exhibit a nearly identical frequency intensity pattern. The minimal variability in intensity curves observed during the falling stage across different events is also due to the amount of water coming from upstream, which can slightly affect the rate of decline. While the rising stage exhibits significant variations in speed, the falling stage shows only marginal differences, typically within decimal orders of magnitude. This is because, once the flow through the upper channel has ceased, the rate of piezometric level decline depends solely on the capacity of the fractures beneath the Hanging Lake to drain the water. Frequency analysis during the falling stage yielded unexpected results, highlighting the recurrence of a consistent spectral signature (Fig.5). Intensity peaks form during each flood at the same water column height, indicating that the only variable affecting the sequence is the rate of piezometric level rise or fall, which can alter the duration of the intensity pattern.

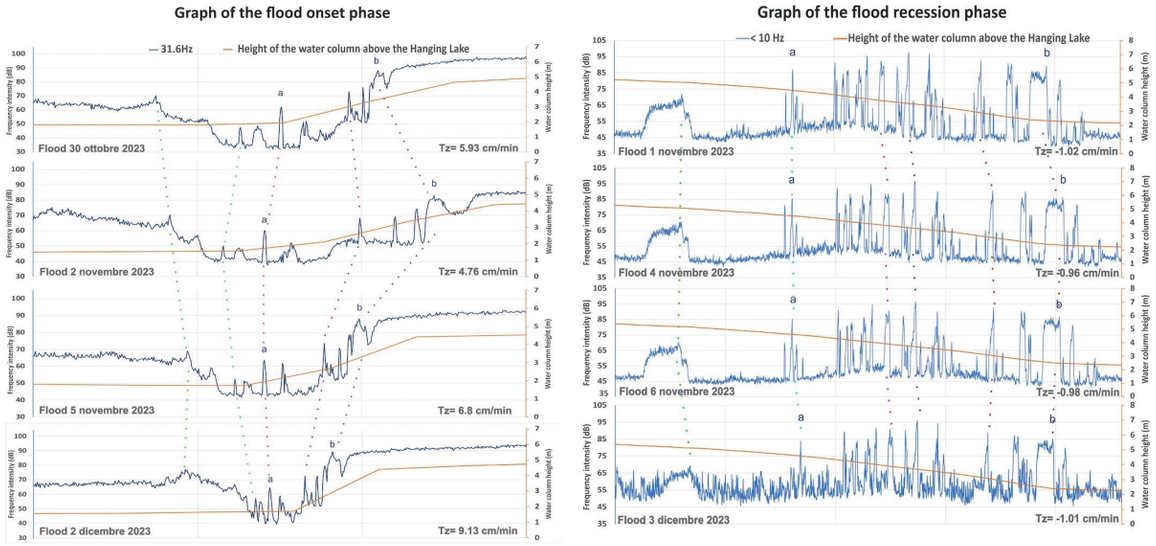


Figure 5: *Rising and falling stage water level changes, and sound frequency intensities (low frequencies 31.6 Hz (left) and <10 Hz (right), for four flood events between end of October to December 3, 2023.*

The most striking characteristic highlighted by this study is the cyclic and reproducable nature of the noise produced, a hybrid between sound and noise. We refer to it as the "voice" of the cave, which depends on the morphology of the cave; every chamber and fissure influences the final sound, creating a unique fingerprint for the cave. The spectrum, cleaned of interference from sporadic and random noises, repeats itself over time, and is identical during both the rising and falling stages of each flood. The only variable is the playback speed of the "voice", which depends on the rate of piezometric level rise or fall. During floods, particularly during the falling stage, the cave emits its "voice," repeating the same acoustic spectrum for the sampled frequencies. The sound during the rising stage is hypothesized to result from the isolation of fractures and domes within the conduits, accompanied by relative compression and rapid displacement of air masses through fractures. The unloading phase operates similarly but in the reverse sequence: as the water level decreases, previously submerged chambers and passages are exposed, emitting gurgling sounds due to the release of trapped and pressurized air. During this phase, major and minor chambers are subject to depressurization; as the water level declines, fractures and fissures reopen, leading to air exchanges, suction through fractures, and pressure movements, which generate intense and often prolonged noises. Some low-frequency sounds and probable tremors recorded within the cavity are hypothesized, during the falling stage, to be attributable to the phenomenon of cavitation.

5. Conclusion

The mechanism governing the Spurga delle Cadene during flood events is the "Plunger Effect". While this mechanism is peculiar to this cave, it is plausible that it may also serve to explain the behavior of numerous other cavities worldwide.

During floods, the Hall of Wonders becomes isolated due to the rise in the piezometric level, compressing the air trapped within the chamber. This rising atmospheric pressure, together with other overpressures present within the conduit, applies, according to Pascal's principle and the principle of communicating vessels, a supplementary pressure on the water volume. This pressure is sufficient to allow the water to overcome the seven-meter elevation difference with the upper channel.

The Plunger Effect is thus governed by the overpressures that develop within the conduit, with the Hall of Wonders acting as the principal driver. When the water level reaches 4.3 meters above the Hanging Lake, the flood begins to flow through the upper channel and exits the cave under pressure via the entrance portal. Once the inflow from upstream—and consequently the piezometric level—decreases, the flood flow in the upper channel subsides until it no longer possesses sufficient hydraulic head to continue. At this point, the decline in the water level is attributed, as far as currently known, solely to the drainage of fractures located below the Hanging Lake.

During the decrease in piezometric level, the air trapped within the Hall of Wonders tends to expand, resulting in a depressurization of the atmospheric pressure recorded within the room.

The acoustic monitoring conducted within the cave has yielded innovative results. As demonstrated, the spectral signature of sounds recorded during the rising and falling water level stages of flood events in the Spurga delle Cadene is consistent across all events. These sounds are attributable to the geometry of the cave, and it has been demonstrated that intensity peaks occur, without exception, at the same water level values.

The sounds originate from volumes of air trapped within the cave, which, during the rising and falling stages, generate noises due to the pressure differences. This conclusion is supported by the repetition of

identical spectra, indicative of a phenomenon governed by the only feature that remains constant: the morphology of the conduit.

The only hydrological variable capable of altering the intensity spectrum is the rate at which the piezometric level rises or falls. Indeed, as the rate increases, the spectra become more compressed, with peaks occurring closer together. The rates are significantly more variable during the rising phase than during the falling phase. This variability is a consequence of the incoming water from upstream being highly dependent on the precipitation occurring within the recharge basin. This difference in rate also explains the greater similarity of spectra recorded at the conclusion of flood events compared to those recorded at their onset.

Acknowledgments

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Quente ou frio? Como o entorno, sazonalidade e água atuam na termorregulação de cavernas ferríferas

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Abstract

Ferruginous geosystems host unique geological and ecological formations, including caves of great biodiversity importance. This study analyzed thermal patterns in three ferruginous caves in the Serra de Carajás (PA) and their relationship with the epigean environment. Using 22 dataloggers, we monitored internal and external temperatures from June 2018 to April 2019, covering both dry and rainy seasons. We identified distinct thermal zones within the caves, which became more homogeneous during the rainy season. In the dry season, cave temperature closely followed external variations, whereas in the rainy season, there was a one-hour delay in this relationship. This delay is likely due to water saturation, which acts as a thermal buffer. Our results indicate that external thermal influence on subterranean habitats is significant only up to approximately 70 meters from the cave entrance. These findings highlight the role of seasonality in the climatic dynamics of ferruginous caves and the importance of humidity in regulating cave environments. This study contributes to understanding climatic processes in tropical caves and provides valuable insights for conservation strategies.

1. Introdução

Os geossistemas ferruginosos amazônicos abrigam paisagens únicas, além de minerais de grande importância para economia mundial, como minério de ferro, ouro, cobre e níquel (PILÓ et al. 2015). São conhecidos também pelo elevado número de cavernas (~2000 registradas), que se distribuem ao longo do relevo e possuem grande importância tanto do ponto de vista geológico quanto ecológico (CARMO F. & KAMINO L.H 2015; PILÓ L.B. & AULER A.S. 2009). Tais cavernas geralmente apresentam pequenas dimensões, com cerca de 70% dessas possuindo projeções horizontais entre 20 e 30 metros. Ainda assim, há muitas espécies estritamente subterrâneas (troglóbias) e elementos físicos singulares conhecidos apenas nesses locais (FERREIRA et al. 2018, PILÓ et al. 2015).

O ambiente cavernícola é caracterizado por sua estabilidade climática, com temperatura constante próxima à média externa anual, umidade relativa próxima da saturação e ausência permanente de luz (POULSON & WHITE, 1969). Essa estabilidade, porém, depende dos fluxos térmico, hídrico e gasoso, que podem gerar variações microclimáticas em resposta a alterações externas (BOURGES et al., 2006). Em contraste, as zonas de entrada das cavernas apresentam maior variabilidade, com mudanças diárias e sazonais na temperatura, umidade e luminosidade (SERENA & MELUZZI, 1997; CULVER & PIPAN, 2009). Estudos realizados em diversos países têm contribuído para identificar zonas microclimáticas específicas no ambiente subterrâneo (STOEVA & STOEV, 2005). Em regiões tropicais, os estudos sobre caracterização da dinâmica climática em cavernas, considerando uma escala temporal e espacial refinadas, ainda são escassos.

Nesta perspectiva, avaliamos os padrões de temperatura de três cavidades ferruginosas e sua interface com o ambiente de superfície circundante. De forma específica, procuramos responder as seguintes questões: a) As cavernas ferruginosas apresentam zonas distintas de temperatura ao longo de sua extensão?; (b) Tais zonas diferem no período chuvoso e seco?; (c) Qual o tempo necessário para que mudanças térmicas em superfície sejam percebidas nas cavernas?; e (d) Até que distância observamos influência externa sobre a temperatura cavernícola? Como hipóteses, esperamos identificar zonas térmicas distintas em caverna ferruginosas, as quais deverão se diferenciar entre os períodos seco e chuvoso, dadas mudanças estacionais externas. Acreditamos que mudanças de temperatura em superfície sejam imediatamente detectadas no interior das cavernas, devido a limitada extensão da matriz rochosa entre esses ambientes. Por fim, prevemos que a influência externa deverá estar restrita ao entorno imediato às cavernas (<100m), com temperatura similar ao observado nas florestas que circundam as entradas principais.

2. Materiais e Métodos

Área de Estudo

Conduzimos o presente estudo em três cavernas ferruginosas (N4E_0022, N4E_0023 e N5SM2_0035) localizadas na Serra de Carajás, estado do Pará, Brasil (Figura 1). Essa região é mundialmente conhecida

pela produção de minério de ferro, ouro, níquel e cobre. O clima regional caracteriza-se por temperatura média entre 23 °C a 25 °C e precipitação anual em 2.400 mm (Piló et al. 2015). No entanto, a distribuição das chuvas é irregular, com a estação chuvosa ocorrendo entre outubro e abril (160 a 340 mm/mês) e período seco que se estende de maio a setembro (10 a 90 mm/mês) (SAHOO et al. 2016).

Procedimentos

Utilizamos 22 *dataloggers* (12 HOBO U23 e 10 HOBO MX2301; exatidão 0,01ºC, precisão ±0,20ºC) para mensurar a temperatura do ar nas três cavernas e paisagem adjacente. Em cada caverna, dispomos esses equipamentos conforme dimensão do habitat e morfologia, de forma a amostrar a temperatura em diferentes regiões, com distância mínima de 20 metros entre eles (Figura 1, A; B). Instalamos cinco *loggers* na N4E_0022, cinco na N5SM2_0035 e dois na N4E_0023. Na paisagem epígea, estabelecemos dois transectos, sendo um ao sul (com 200m de extensão) e outro a leste (250m) da caverna N4E_0022, com quatro e seis *loggers*, respectivamente (Figura 1.B). No ambiente externo, os *loggers* distaram 50m entre si. Programamos todos os equipamentos para mensurar continuamente a temperatura, em intervalo horário, no período entre 01/06/2018 e 30/04/2019, abrangendo os picos do período seco e chuvoso dessa região.

Análise dos dados

Organizamos e revisamos as séries temporais obtidas para cada equipamento para remoção de registros inválidos (ex. valores negativos) e/ou tendências de diminuição ou aumento súbito nos parâmetros (± 10°C em 24 horas), os quais advém de erro de leitura pelos sensores dos equipamentos. Selecionamos os *data loggers* centrais de cada caverna (A4 na N4E_0022, B1 na N4E_0023 e C4 na N5SM2_0035) e um externo (L3) para representar graficamente a variação dos dados nos locais de amostragem. A organização dos dados e conseguintes análises foram realizadas no *software* R (versão 4.1.2).

Dada tendência à autocorrelação em séries temporais de temperatura, submetemos as séries à transformação pela segunda diferença previamente aos testes estatísticos. Para cada cavidade, analisamos as séries obtidas internamente através da correlação de *Spearman* (função *chart.correlation*, pacote *PerformanceAnalytics*) para identificarmos aquelas com valores e tendência similares (quando $rho > 0,70$, $p < 0,05$). Posteriormente, submetemos essas séries a testes de correlação cruzada (CCF; função *ccf*, pacote *tseries*) para avaliar a influência da temperatura em um determinado setor da caverna sobre os demais. Consideramos tais associações significativas e representativas quando $p < 0,05$ e CCF > 0,15. Expressamos os resultados pela força de interação (CCF, varia entre 0 e 1) precedidos pelo tempo de resposta (lag) (ex. t=0; indica que as temperaturas avaliadas apresentam correspondência simultânea; t+1 indica que o primeiro fator atua com atraso de uma hora sobre o segundo fator). Realizamos essas análises considerando todo o período amostral e sazonalmente: estação seca (01/07/2018 a 30/09/2018) e estação chuvosa (01/01/2019 a 31/03/2019).

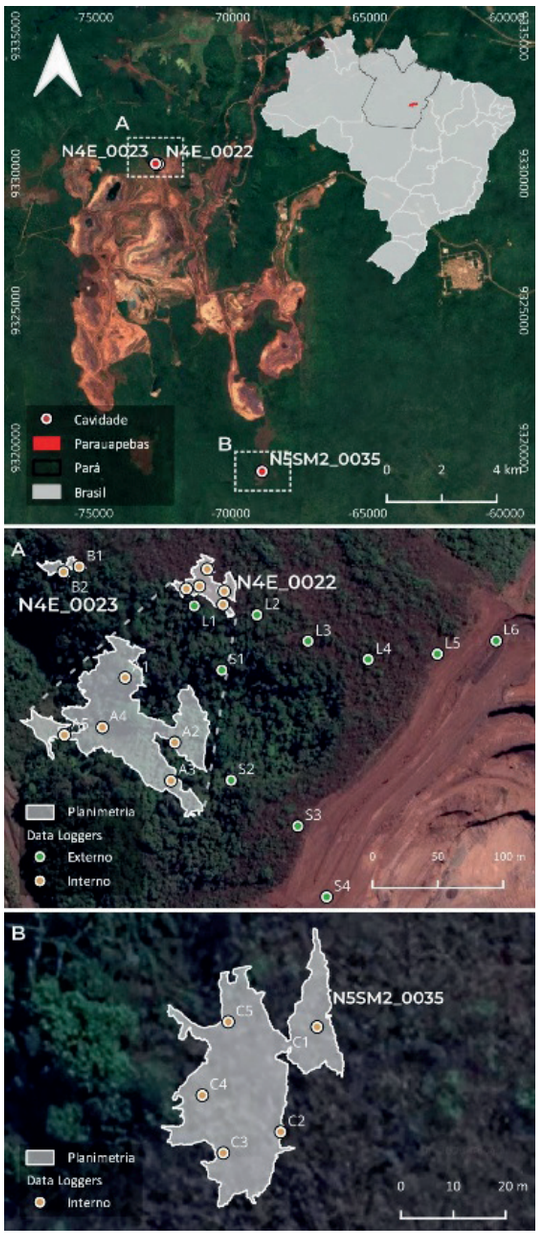


Figura 1: *Localização da área de estudo, com destaque para o município de Parauapebas, no estado do Pará, Brasil. (A) Cavidades N4E_0022 e N4E_0023, com os data loggers instalados. (B) Cavidade N5SM2_0035 e os data loggers instalados.*

Determinamos as zonas térmicas a partir da autocorrelação (*Spearman*) e correlação cruzada (CCF) entre as séries de temperatura mensuradas nas diferentes regiões de cada caverna. Consideramos que a autocorrelação entre as séries resulta na elevada similaridade dos valores e tendência de temperatura entre os locais avaliados, indicando que pertencerem a mesma zona térmica. De forma similar, consideramos que as séries independentes ($rho < 0,70$), mas com CCF representativo (CCF > 0,15) e correspondência simultânea (t=0), estão sob mesma zona térmica, dada oscilação concomitante e em mesmo sentido entre os locais. Indicamos séries independentes ($rho < 0,70$), com CCF < 0,15 ou t > 0 como pertencentes a zonas térmicas distintas, dada ausência de interinfluência entre as temperaturas desses locais. As zonas térmicas foram expressas considerando todo período amostrado e sazonalmente (estação seca e chuvosa).

Posteriormente, utilizamos as séries temporais da N4E_0022 e aquelas provenientes dos transectos na paisagem para avaliar se as

temperaturas mensuradas na caverna se correlacionam às mudanças climáticas de superfície. Novamente, submetemos tais séries a testes de correlação cruzada (CCF; função *ccf*, pacote *tseries*) para obtermos a força de interação (CCF) e o tempo de resposta (*lag*) entre os pares.

Por fim, aplicamos modelos lineares generalizados (GLM's) para avaliar se a distância é fator determinante para correlação climática entre a paisagem e caverna. Nesta análise, utilizamos os valores de correlação cruzada (CCF) das séries temporais da caverna N4E_0022 e transectos externos como variável resposta. Obtemos a distância para-a-par entre os *loggers* na N4E_0022 e aqueles externos a partir das coordenadas geográficas. Agrupamos os valores de CCF's em três categorias de distâncias: até 70m, 150m e 260m. Para a análise, utilizamos a distribuição gaussiana com função de ligação logística e avaliamos o nível de significância através do teste de Wald (função *summary*, $p < 0,05$). Conduzimos teste de contrastes ortogonais em pares para indicar se há diferenças entre as categorias de distância (função *pairs*, pacote *graphics*). Expressamos o resultado em gráficos de *boxplot*, sendo considerados significativos quando $p < 0,05$.

3. Resultados

A temperatura na paisagem próxima às cavidades variou entre 18,14 °C e 36,59 °C (Figura 2). As cavidades apresentaram, em média, registros térmicos próxima àquelas mensuradas na paisagem, porém com menor amplitude.

Observamos diferentes zonas térmicas nas três cavernas (Figura 5). Na N4E-0022, a temperatura nas duas entradas da cavidade (representadas pelos equipamentos A5 e A3) influenciam instantaneamente a área central (A4), com maior contribuição da entrada a oeste (A5), porém a região A1 não apresenta influência representativa para os demais. Para a cavidade N4E-0023, o padrão aleatório para a correlação cruzada entre a temperatura no interior da cavidade e aquela próxima à entrada demonstra ausência de influência entre estas, caracterizando duas zonas térmicas distintas. Em relação à N5SM2-0035, a temperatura na região distal do principal conduto (C3) apresenta variação similar à mensurada na entrada principal (C5). Ambas as regiões atuam sobre a temperatura no conduto principal da cavidade (C2 e C4). Entretanto, o atraso de uma hora entre o C5 para os demais (C2 e C4) demonstra que há zonas térmicas distintas na entrada e região distal do conduto. Para o salão à nordeste (onde localiza-se o lago, C1), a temperatura não apresenta relação significativa com entrada principal, e é pouco expressivo para o C2 (CCF < 0,15). Entretanto, atua sobre o C3 com atraso de uma hora na resposta.

Sazonalmente, apesar do padrão geral observado para a cavidade, as zonas térmicas apresentam dinâmica distintas em resposta à precipitação (Figura 5). De forma geral, as distinções entre as zonas térmicas tendem a ser mais expressivas no período seco e amenizadas no período chuvoso, com a temperatura similar por quase toda extensão das cavidades.

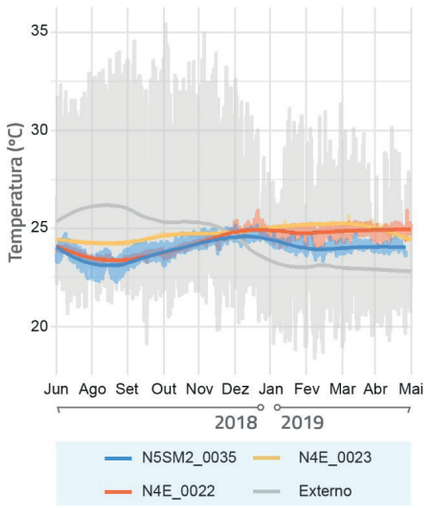


Figura 2: *Séries temporais de temperatura obtidas por data loggers nas três cavidades e ambiente externo. Em cinza, a temperatura em superfície na área de estudo como referência.*

O tempo de defasagem (lag) difere entre as estações, sendo que a temperatura na cavidade evolui simultaneamente com a epígea durante a seca e, durante as chuvas, há um atraso de uma hora nesta relação (Figura 3). Desta forma, a saturação promovida pela água impede atuação imediata da temperatura externa sobre os habitats subterrâneos. A exceção é o L1, localizado muito próximo à principal entrada da cavidade, o qual apresenta atraso de uma hora em ambas as estações. Isto sugere que o entorno imediato se caracteriza como zona ecotonal à temperatura, estando sob influência do microclima subterrâneo e epígeo.

A correlação entre as temperaturas epígeas e hipógeas diminuem com o aumento da distância (Figura 3; 4). Tal resultado demonstra que a temperatura epígea que atua sobre os habitats subterrânea advém localmente. Os dados agrupados indicam que, para a N4E-0022, há influência significativa da temperatura externa sobre aquela mensurada no subterrâneo em até 70 metros da cavidade (Figura 4). A partir deste limiar, os valores de CCF decaem significativamente em ambas as estações.

Logger epígeo	Logger hipógeo	CCF(ES)	Lag(ES)	CCF(EU)	Lag(EU)	Distância entre os loggers (m)
L1	A5	0,358	t+1	0,751	t+1	14,32
L2	A5	0,361	t=0	0,737	t+1	57,58
L3	A5	0,324	t=0	0,664	t+1	101,24
L4	A5	0,297	t=0	0,706	t+1	149,12
L5	A5	0,286	t=0	0,729	t+1	198,40
L6	A5	0,229	t=0	0,673	t+1	240,35
L1	A4	0,358	t+1	0,349	t+1	15,52
L2	A4	0,361	t=0	0,267	t+1	49,19
L3	A4	0,324	t=0	0,273	t+1	93,02
L4	A4	0,297	t=0	0,340	t+1	140,63
L5	A4	0,286	t=0	0,320	t+1	189,28
L6	A4	0,229	t=0	0,362	t+1	230,85
L1	A3	0,358	t+1	0,241	t+1	22,02
L2	A3	0,361	t=0	0,269	t+1	27,20
L3	A3	0,324	t=0	0,173	t+1	70,77
L4	A3	0,297	t=0	0,220	t+1	118,68
L5	A3	0,286	t=0	0,216	t+1	168,34
L6	A3	0,229	t=0	0,151	t+1	210,87
S1	A5	0,401	t=0	0,736	t+1	67,62
S2	A5	0,326	t=0	0,665	t+1	149,91
S3	A5	0,303	t=0	0,708	t+1	199,96
S4	A5	0,287	t=0	0,695	t+1	258,21
S1	A4	0,401	t=0	0,345	t+1	66,22
S2	A4	0,326	t=0	0,340	t+1	149,93
S3	A4	0,303	t=0	0,326	t+1	197,77
S4	A4	0,287	t=0	0,331	t+1	256,08
S1	A3	0,401	t=0	0,208	t+1	50,01
S2	A3	0,326	t=0	0,182	t+1	134,13
S3	A3	0,303	t=0	0,231	t+1	178,35
S4	A3	0,287	t=0	0,189	t+1	236,58

Figura 3: *Resultados das correlações cruzadas (CCF) entre as temperaturas (ºC) obtidas por data loggers no ambiente epigeo e na caverna N4E_0022 conforme a estação. As séries foram diferenciadas (2ª ordem) para as análises de correlações cruzadas. Na tabela são indicados os valores de CCF e lag (defasagem, em horas) para os maiores picos de correlação. É informado também a distância entre os loggers para cada correlação.*

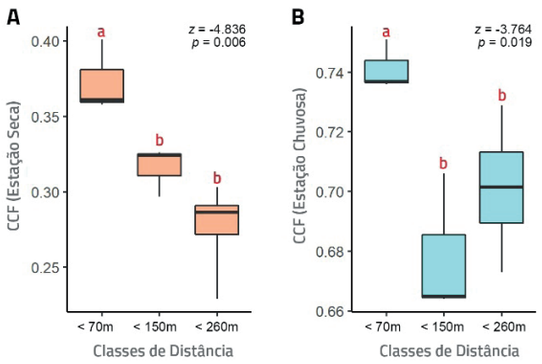


Figura 4: *Valores de CCF para as correlações cruzadas conforme a estação: (A) Estação Seca; (B) Estação Chuvosa. Os modelos lineares generalizados (GLM) informam quando houve diferenças significativas ($p < 0,05$) e os valores de z. Nos boxplots, as áreas em azul se referem ao intervalo de confiança (95%) em torno da média observada (traço central em preto) e as barras representam o desvio padrão. As letras sobre os boxplots indicam as diferenças por pares avaliadas pelo teste de contrastes ortogonais.*

4. Discussão

As hipóteses que prevemos no presente estudo foram parcialmente corroboradas. Quanto as zonas térmicas, confirmamos a existência de zonas distintas nas cavernas ferruginosas estudadas. Ainda, tais zonas são influenciadas sazonalmente: no período seco, apresentaram maior distinção térmica, com maior amplitude de variação, enquanto no período chuvoso, elas se tornaram mais homogêneas, devido à saturação hídrica. Diferente do que previmos, o tempo de resposta para que mudanças térmicas de superfície sejam percebidas nas cavernas difere entre as estações. Observamos ainda que a influência epígea sobre a temperatura dos habitats subterrâneos é local e limitada, limitando-se a 70m a partir da caverna.

As variações sazonais observadas nas zonas térmicas das cavernas ferruginosas refletem a interação entre a regulação térmica subterrânea e os processos ambientais externos. Durante o período seco, a maior distinção térmica entre as zonas pode estar relacionada à menor umidade relativa do ar e à redução da capacidade de retenção de calor no ambiente subterrâneo, permitindo uma maior amplitude térmica. Já no período chuvoso, a saturação hídrica do substrato e do ar atua como um estabilizador térmico, reduzindo as oscilações de temperatura dentro da caverna. Esse efeito ocorre porque a água presente no ambiente subterrâneo absorve calor lentamente e o libera de forma gradual, diminuindo a resposta imediata às flutuações externas (POULSON & WHITE 1969). Assim, a umidade desempenha um papel crucial na atenuação das influências epígeas sobre o microclima cavernícola, tornando os habitats subterrâneos relativamente mais estáveis durante a estação chuvosa (CIGNA 2002).

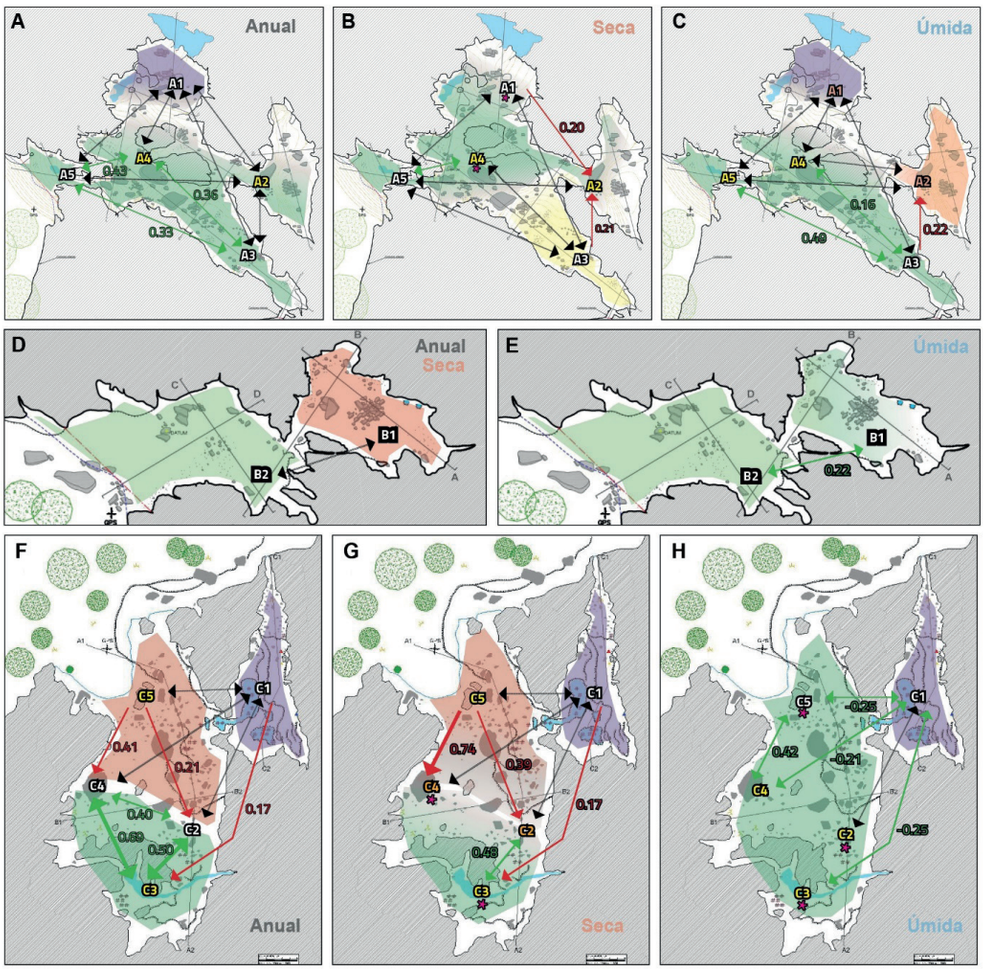


Figura 5: *Determinação das zonas térmicas nas cavidades N4E-0022 (A-C), N4E-0023 (D-E) e N5SM2-0035 (F-H). A análise estatística dos dataloggers revela as relações térmicas entre diferentes regiões da cavidade. As áreas destacadas em amarelo laranja e/ou com asterisco rosa indicam séries temporais autocorrelacionadas (rho > 0,70, p < 0,05), com variações térmicas semelhantes. As setas representam correlações cruzadas entre pares independentes, as linhas verdes indicam correlações simultâneas significativas (CCF > 0,15, p < 0,05) e as linhas vermelhas refletem correlações com atraso de uma hora (lag = +1). As linhas tracejadas em preto indicam correlações não significativas (CCF < 0,15 e/ou p > 0,05). As zonas térmicas independentes são representadas por cores distintas. As figuras A, D e F ilustram zonas térmicas identificadas no padrão anual. As figuras B, D e G destacam as zonas durante o pico da estação seca (junho a agosto de 2018). Por fim, as figuras C,E e H destacam as relações térmicas durante o pico da estação chuvosa (janeiro a março de 2019).*

O tempo de resposta diferenciado entre as estações sugere que o fluxo de calor entre a superfície e a caverna não ocorre de maneira uniforme ao longo do ano. Esse fenômeno pode estar relacionado às variações na condutividade térmica da rocha, que depende diretamente do teor de umidade do substrato e das propriedades físicas do maciço (BADINO 2010). Além disso, a limitação da influência epígea a aproximadamente 70 metros da entrada reforça a ideia de que a penetração do calor na caverna é fortemente modulada pela circulação de ar e pela morfologia do sistema subterrâneo (DE FREITAS & LITTLEJOHN 1987). Em cavernas com ventilação restrita, a troca de ar com o meio externo ocorre de forma mais lenta, aumentando a estabilidade térmica nas regiões mais profundas (GABROVŠEK 2023). Esse padrão é consistente com estudos que indicam que a variação climática externa influencia principalmente os primeiros metros das cavernas, sendo rapidamente amortecida conforme se avança para áreas mais internas (HOWARTH 1980). Assim, a limitação espacial da influência epígea sugere que, em cavernas ferruginosas, os processos de dissipação térmica são altamente localizados, com impactos concentrados nas áreas próximas à entrada.

5. Conclusão

Nosso estudo destaca a importância da água e da paisagem no entorno imediato na manutenção da dinâmica microclimática de cavernas ferruginosas. Ainda, contribui diretamente para o manejo adequado desses habitats, delimitando espacialmente o entorno necessário para conservação de sua dinâmica térmica.

Para estudos futuros, sugerimos limitar a amostragem de dados aos picos sazonais, por serem representativos das diferentes condições que o sistema pode assumir ao longo do ano.

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Comparing different methods for measuring cave airflow

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Abstract

Precise measurements of airflow within caves are increasingly demanded to assess heat and mass transfers and their impacts on the karst environment, including subsurface ecosystems, hydrochemistry of karst water and secondary mineral precipitates. This study compares different methods for measuring airflow in ventilated caves. Airflow estimates from gauging tests using an artificial tracer are compared with direct measurements from hand-held anemometers and digital airflow meters equipped with dataloggers. The tests generally yield similar results, although the comparison reveals some discrepancies, with differences of up to 50% in small conduit cross-sections. Deployment of three digital flowmeters along a 300 m ventilated cave indicated either a potential air leak or more likely the upper and lower bounds of the estimated airflow. This comparison underlines that the use of different methods for estimating airflow should be a welcome practice when monitoring ventilated caves, to derive a range of plausible airflow rates that accurately reflect actual conditions.

Résumé

Des mesures précises du flux d'air dans les grottes sont de plus en plus demandées pour évaluer les transferts de chaleur et de masse et leurs impacts sur l'environnement karstique, y compris les écosystèmes souterrains, l'hydrochimie des eaux karstiques et les précipités minéraux secondaires. Cette étude compare différentes méthodes de mesure du flux d'air dans les grottes ventilées. Les estimations de flux d'air provenant de tests de jaugeage utilisant un traceur artificiel sont comparées à des mesures directes réalisées avec des anémomètres portatifs et des débitmètres numériques équipés de dataloggers. Les tests effectués donnent des résultats comparables, bien que la comparaison ait révélé certaines divergences, avec des différences atteignant jusqu'à 50 % dans les sections transversales de petits conduits. Le déploiement de trois débitmètres numériques le long d'une grotte ventilée de 300 m indique soit une fuite d'air potentielle, soit plus probablement les limites supérieures et inférieures du flux d'air estimé. Cette comparaison souligne l'importance d'utiliser différentes méthodes d'estimation du flux d'air lors de la surveillance des grottes ventilées, afin de dériver une gamme de débits d'air plausible qui reflète avec précision les conditions réelles.

1. Introduction

Caves, complex and dynamic environments, are characterized by airflows that influence the distribution of heat, gases, and particles therein. Precise monitoring of these flows is crucial for understanding the hydrochemistry of karst waters (Jeannin et al., 2017), the formation of secondary minerals (Spötl et al., 2005), the distribution of subterranean ecosystems (Mammola et al., 2019) and paleoenvironmental reconstructions (Fairchild and Baker, 2012; Rau et al., 2015). Cave ventilation, often driven by the chimney effect (Badino, 1995; Lismonde, 2002; Luetscher and Jeannin, 2004; Gabrovšek, 2023), plays a fundamental role in regulating temperature and thermal exchanges, thus long airflow data series in caves are of interest to assess e.g. the associated energy exchanged therein (Luetscher et al., 2008; Obleitner & Spötl, 2011). Various anemometer types are available, including analogue, hotwire, and ultrasonic models, each differing in cost and measurement quality. While suited to specific monitoring ranges, they have limitations: analogue devices suffer from low resolution and mechanical inertia, hotwire anemometers lack airflow direction detection, and both hotwire and ultrasonic models require a high power supply. Nowadays, ultrasonic anemometers are widely used in caves (e.g. Pflitsch and Piasecki, 2003; Obleitner and Spötl, 2011; Gomell and Pflitsch, 2022), however, they could suffer cave climatological conditions (temperature, humidity and lack of sunlight), failing during long term monitoring. Nevertheless, technological advancements continue to improve their performance (Pastore et al.,2024a; Wang et al., 2021; Fan et al., 2018; Leoni et al., 2018).

Airflow in ventilated caves can be assessed with direct measurements (i.e. with anemometers) or with gauging tests using a tracer gas. Direct measurements with anemometers provide the air velocity at specific locations. To estimate the volume flow rate (m^3/s), these velocities need to be integrated over the cross-section. In Pastore et al. (2024a) it was demonstrated that this procedure may be associated with uncertainties related to the velocity distribution across the cross-section. In a second work by Pastore et al. (2024b), CO_2 was used as an artificial tracer and it was demonstrated to be a reliable method for assessing airflow rates within ventilated conduits. Therefore, the comparison between different methodologies to assess the airflow rate is essential for understanding the uncertainties associated with each approach and for obtaining accurate estimates of airflow. This work aims to compare results obtained using gauging tests with CO_2 as a tracer (Pastore et al., 2024b), and flow rates estimated with both a hand-held anemometer and a digital flowmeter used for long-term monitoring (Pastore et al., 2024a), adding insights into the comparison between these different methods.

2. Materials and methods

The first method applied was gauging the airflow by injecting CO_2 as a tracer. This method relies on the mass conservation equation $Q = \frac{m}{\int c(t)dt}$ [Eq.1], where Q is the airflow rate [m³/s], m is the known mass of the injected tracer [g], and c is the measured concentration [ppmv] at time t [s]. More details about the method applied to the airflow are given in Pastore et al. (2024b). To assess the airflow, tracer mass conservation is always assumed to solve Eq. 1 (no gas leakage along the conduit). The second method consisted of manual measurements of flow velocity across the conduit cross-sections, carried out with a Testo 425 hand-held hotwire anemometer (from now on Testo; accuracy ±0.03 m/s +5% of reading). The volume flow rate (m³/s) is derived by the integration from 3 to 6 velocity measurements (based on the cross-sectional surface area) averaged over 30 s per monitored cross-section. As a third method, we installed a digital device such as the Sensirion SFM3003-300-CE (from now on SFM) flow meter which allows recording airflow time series. In (Pastore et al., 2024a), we provided a reliable calibration for this device and a rating curve to convert the measured Standard Litre per Minute (SLM) into m/s. The accuracy of this instrument is ±5% of the measured value for velocities above 0.50 m/s and ±26% for velocities <0.50 m/s. The high instrumental precision (±1%) and reproducibility were verified between different SFM devices (Pastore et al., 2024a). The SFM can be connected to a data logger and deployed to record the flow speed at a specific location in the conduit. Thus, the volumetric flow rate (m³/s) can be derived from the integration of the measured airspeed in the conduit cross-section. External temperatures were measured with a ReefNet Sensus Ultra device (accuracy ±0.3 °C, resolution 0.01 °C).

The tests were conducted in two different sites which are naturally ventilated conduits (chimney effect): 1 mine and 1 cave (the latter in Figure 1), both in the Swiss Jura Mountains (the test dates, cross-section sizes and distances from the CO_2 injection point of each station are given in Table 1). The first test site is Baulmes Mines, where we carried out spot measurements with Testo and two gauging tests with CO_2 (during upward and downward ventilation, see Table 1). The measurements were carried out at station B3 (Table 1), located within a 360 m-long, sub-horizontal tunnel that provides access to the lowest mine level before connecting to the main mining network. Indeed, this tunnel serves as a lower entrance for the chimney effect. The geometry is typical of a mining tunnel: flat ground (except for some local collapses), vertical walls, a barrel-vaulted ceiling and homogeneous cross-sectional areas. No air inlets or outlets are observed along the select tunnel, except for the main entrance. The survey and more details of this testing site can be found in Pastore et al. (2024b). The second test site is Longeaigue cave, where we conducted two gauging tests and measurements using both the Testo and SFM devices. We carried out supplementary measurements with Testo and SFM without performing CO_2 tests (see the last two periods in Table 1). Longeaigue cave is a vertical cave (Figure 1). Here, we carried out the gauging tests and measurements at three stations along the 300 m-long conduit that connects the upper and lower entrances. The stations are close to the cave's upper entrance (station Lo_UE), lower entrance (station Lo_LE) and in a cave transect between the previous (station Lo_M) (Figure 1 and Table 1). Moreover, a perennial lake between the two entrances, whose level is controlled by external precipitations, temporarily stops the airflow when the level rises high enough to close the air passage (mainly in winter).

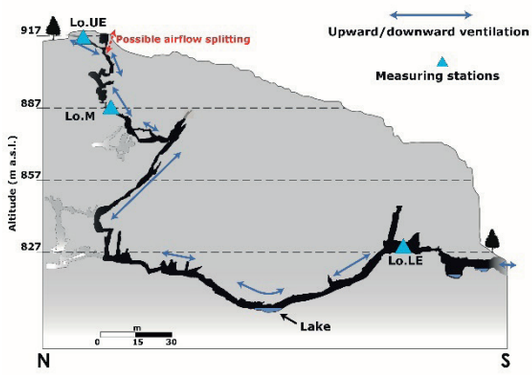


Figure 1: *An excerpt of the Longeaigue Cave survey, showing the ventilated conduit (300 m long and 100 m deep). Modified after Jeannin (2018) and Pastore et al. (2024b).*

3. Results

Site	Station	Distance [m]	Cross-section [m²]	Q_{CO2} [m³/s]	Q_{Testo} [m³/s]	Q_{SFM} [m³/s]	$(Q_{Testo}-Q_{CO2})/Q_{CO2}$	$(Q_{SFM}-Q_{CO2})/Q_{CO2}$	$(Q_{SFM}-Q_{Testo})/Q_{Testo}$
Baulmes (upward) 15/02/2023	B3	128	4.5	2.3	2.3	-	0%	-	-
Baulmes (downward) 02/05/2023	B3	232	4.5	3.8	4	-	5%	-	-
Longeaigue (upward) 13/12/2022	Lo_UE	294	0.5	1.5	0.79	1.00	-47%	-33%	27%
	Lo_M	239	1.2	1.5	1.76	-	17%	-	-
	Lo_LE	0	3.1	-	1.63	1.50	-	-	-8%
Longeaigue (downward) 17/06/2022	Lo_UE	0	0.5	-	0.89	0.90	-	-	1%
	Lo_M	55	1.2	1.1	1.64	1.60	49%	45%	-2%
	Lo_LE	20	3.1	1.1	1.27	1.40	15%	27%	10%
Longeaigue (downward) 09/08/2022	Lo_UE	0	0.5	-	0.64	0.51	-	-	-20%
	Lo_M	55	1.2	-	1.10	1.18	-	-	7%
	Lo_LE	20	3.1	-	1.40	1.29	-	-	-8%
Longeaigue (downward) 09/06/2023	Lo_UE	0	0.5	-	0.69	0.84	-	-	22%
	Lo_M	55	1.2	-	0.87	-	-	-	-
	Lo_LE	20	3.1	-	0.97	0.70	-	-	-28%

Table 1: *The grey columns show the geometrical characteristics of the monitoring stations. Orange columns show the airflow rate estimated with the three methods. Green columns show the ratio between them.*

The SFM measurements are available only for Longeaigue. The relative deviation between SFM and CO_2 tests is between 27% and 45% (Table 1). Between SFM and Testo measurements, the deviation constantly stays below 30% (Table 1), showing sometimes higher values for SFM (negative % in Table 1) and sometimes for Testo (positive %). Figure 2 presents the time series obtained with SFMs at the three monitoring stations in Longeaigue compared with the flow rates estimated with gauging tests and the Testo device at the same locations, in the periods 16 to 22 of June 2022 (Figure 2.a, downward flow) and 10 to 12 of December 2022 (Figure 2.b, upward flow). The positive and negative values on the flow rate indicate downward and upward ventilation, respectively. For both ventilation modes, the airflow time series show similar patterns but with different amplitudes between the three stations and also strong daily fluctuations following the external temperatures during the downward flow (Figure 2.a). In the same Figure 2.a, the flow rate at Lo_UE (orange line) shows constantly lower values ($0<Q<1.3$ m³/s) than the other two devices. In contrast, the device positioned at Lo_LE (blu line) generally displays the highest values ($0.3<Q<1.5$ m³/s), while the device placed at Lo_M (green line) measured an airflow generally comprised between the previous two. However, certain flow peaks in the SFM time series and manual measurements at station Lo_M exceed those recorded at station Lo_LE, reaching 1.6 m³/s at Lo_M during the measurement period shown in Figure 2.a.

During the upward flow (Figure 2.b), periods constantly at 0 m³/s at the beginning and end of the graph are due to the lake closure during external rainfall (Figure 1). Therefore, the upward ventilation was active for about 4 days, before the lake closed the air passage again. When the ventilation was active the airflow rate at Lo_UE stabilised between 1.3 and 1.1 m³/s, while at Lo_LE oscillated between 1.5 and 1.1 m³/s. The flow rate of 1.5 m³/s estimated at Lo_LE with manual measurements fits with SFM time series and with the airflow yielded by CO_2 tests along the cave. The absence of daily fluctuations relates to low fluctuations of external temperatures, which stayed between -11°C and -6 °C (Figure 2.b). Figures 2.c and 2.d show two supplementary periods (see the last two periods in Table 1) where manual measurements are compared with the SFM time series at the three stations in Longeaigue. The measurements confirm that the airflow estimated at Lo_LE is generally the highest, in contrast with the lowest airflow estimated at Lo_UE, while measurements from Lo_M are in between.

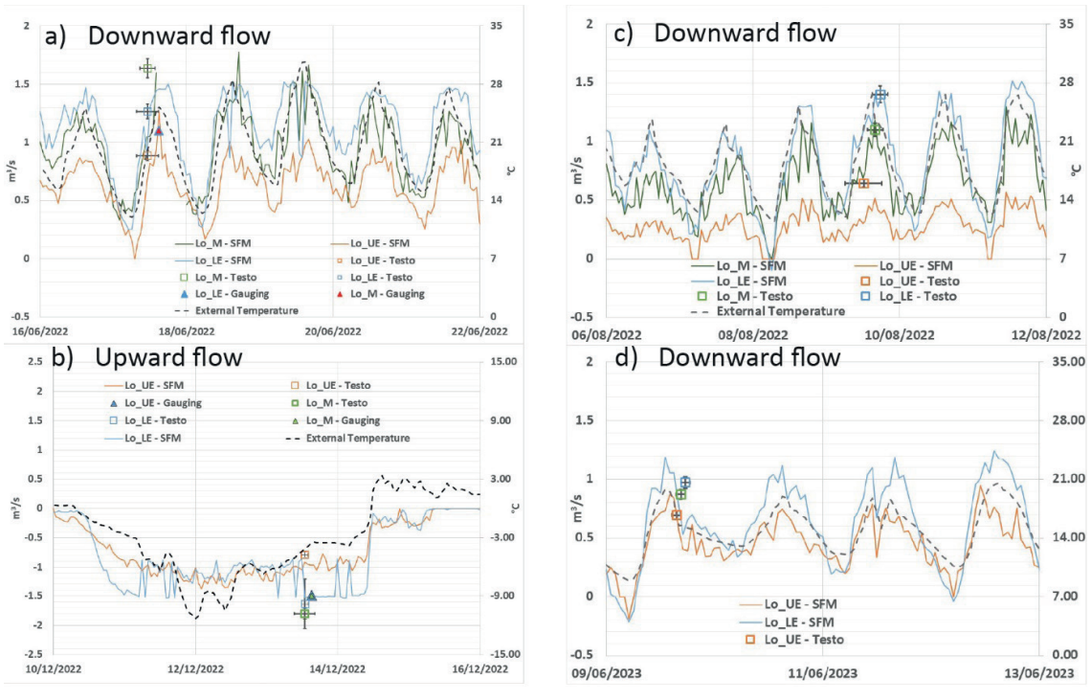


Figure 2: *Air flow rates estimated with the three methods at the three stations in Longeaigue during a) downward and b) upward ventilation. In c) and d) air flow rates were estimated only with Testo and SFM at the three during downward ventilation. Dates are dd/mm/yyyy.*

4. Discussion

The tests conducted aimed to compare different methods for measuring cave airflow. The chosen methods are gauging tests with an artificial tracer (CO_2 in this case), and measurements with both a hand-held anemometer (Testo) and in-place digital flowmeters (SFM). These tests were carried out in one cave (Longeaigue) and one mining tunnel (Baulmes), both naturally ventilated by a chimney effect (Pastore et al., 2024b). Gauging tests are a reliable method to assess volume flow rates along ventilated conduits (Pastore et al., 2024b; Widiatmojo et al., 2015; Standish, 1988; Thirnonsl and Kissel, 1974). The method does not require an integration of the velocity over a cross-section, as the airflow is derived from the mass conservation equation [Eq.1] and yields reliable flow rates even at low air speeds. In the following, flow rates assessed with this method, when available, will be used as reference values. The results indicate that the measurements performed manually (Testo) and those obtained with the digital flow meter (SFM) are comparable, with differences between the two that stayed below 30% (last column of Table 1). In contrast, the comparison between the gauging tests and most of the direct measurements at Longeaigue cave reveals more significant discrepancies than in Baulmes (Table 1). Moreover, time series from SFM and manual measurements (Figure 2), seem to indicate an increase in the flow rate from the upper (Lo_UE, Figure 1) to the lower station in the cave (Lo_LE, Figure 1). Different reasons may determine these differences. The first possible reason for the deviation between direct measurements and CO_2 tests can be

related to an unknown inlet/outlet along the conduit, or in other words that the assumption of air mass conservation along the conduit [Eq.1] is not true. To determine the airflow with gauging tests, this basic assumption has to be verified, otherwise the gauged airflow may be unreliable. If in Baulmes the absence of air divergences is warranted, it is not possible to say the same for Longeaigue. The relative difference between direct measurements (SFM and Testo) and CO_2 gauging tests (Table 1) shows values that suggest a possible air leak between the upper and lower entrances. Our field observations identified a divergence located between Lo_M and Lo_UE (red arrow in Figure 1) which may sometimes provoke a secondary airflow reducing/increasing the airflow between these two stations. This possible leak would remain undetected through the CO_2 tracing alone since mass conservation is assumed. The presence of an air splitting could be checked with the air tracing if a logger is deployed along the possible leakage, to confirm or not the passage of the injected tracer. Further investigation will be necessary to clarify this point.

When working with anemometers (e.g. Testo) or flowmeters (e.g. SFM), the volume flow rate is calculated based on the estimation of an average air velocity derived from one or several punctual measurements within the cross-section. Therefore, another reason possibly causing the discrepancy between gauging tests and direct measurements involves errors stemming from the estimation of this average. In caves, the spatial variability of the cross-section can be significant and a turbulent flow is typically observed (Lismonde, 2002). Thus, in a turbulent field, the stochastic error related to the sampling may impact the measurements (Finkelstein and Sims, 2001; Mauder and Zeeman, 2018). Moreover, because of the nonuniformity of the cave walls, the distribution of velocity fields varies as the flow rate and its direction change, creating high and low-speed zones (Pastore et al., 2024a). Manual measurements that have shown sometimes higher (49%) and sometimes lower (-47%) values than those from gauging tests were observed in Longeaigue cave at Lo_M and Lo_Ue, respectively. In contrast, estimations made at Lo_LE and Baulmes mines have shown smaller differences (Table 1). During measurements with hand-held devices (e.g. Testo), the presence of the operator in narrow conduits may affect the flow velocity within the conduit. The stations Lo_UE and Lo_M, are located within crawling passages with reduced cross-sections (0.5 and 1.2 m^2, respectively; Table 1). Performing measurements at these stations obliges the operator to lie down on the conduit floor, possibly affecting the measurements, although this is likely to cause a lower flow estimate, as for Lo_UE, rather than higher values, as for Lo_M. Instead, stations Lo_LE and B3 have much larger cross-sections (3.1 and 4.5 m2, Table 1) and may be less affected by the presence of the operator who can stay outside the main airflow.

Another explanation for differences between CO_2 tests and direct measurements (with SFM and Testo) could be related to the unmatching time between the manual measurements (horizontal error bars in Figure 2), the gauging tests and SFM logging times. The temperature difference between the cave and the outside temperature, which drives the airflow inside the cave by a chimney effect (Pastore et al., 2024b), may change during the experiment likely causing a transient flow rate. The low temperature variation outside the cave shown in Figure 2.b does, however, not support this possibility for the upward flow (Pastore et al., 2024b). Instead, the external temperature varied and increased during the duration of the measurements (3 to 4 hours) shown in Figure 2.a/c/d (downward flow). We always took measurements going from Lo_UE to Lo_M, then to LO_LE. The external temperature variations during the time needed to move from one station to the other may explain the different airflow measured at the three stations. In fact, since these manual measurements were taken at subsequent times, they should be seen as a part of a time series. The increasing airflow on the manual measurements is supported by the actual airflow time series from SFM devices (Figure 2), which also show peaks at the same time.

However, there must be another reason explaining the fact that SFM time series from different parts of the cave show different airflow amplitudes at the same time. Comparing time series from the three stations along the cave (Figure 2) airflow increases up to 50% from Lo_UE (upper station) and Lo_LE (lower station). This could indicate again the presence of a supplementary inlet/outlet as discussed before. However, it also appears that the airflow rate measured at Lo_M is in between the Lo_UE and Lo-LE flow rates, and does not support the presence of an unknown inlet along the cave. As stated before, stations Lo_UE and Lo_M are crawling passages. Here, SFM devices were positioned at a few centimetres from the conduit walls to facilitate the transit of cavers. Instead, the device deployed at station Lo_LE was positioned in the middle of the 3.1 m^2 cross-section. This suggests that the instruments close to the wall (Lo_UE and Lo_M) could have measured a lower velocity than the actual average speed of the cross-section, while the SFM positioned at Lo_LE was far from the walls, and could have yielded higher values for the average flow rate. If, with a hand-held device, one can take measurements at several points across the cross-section to average the flow velocity, the location of a single device is crucial for providing a good assessment of the average air velocity.

Long airflow data series in caves are of interest to study e.g. the air dynamics (e.g. Faimon & Lang, 2013; Gomell & Pflitsch, 2022) and the associated energy exchanged therein (Luetscher et al., 2008; Obleitner & Spötl, 2011). When an instrument is installed at a specific point within the cross-section, it is important to note that the device may be measuring an airspeed that does not necessarily represent the average velocity across the entire cross-section (Pastore et al., 2024a). In Pastore et al. (2024a), we deployed simultaneously three SFMs within a 1.2 m^2 cross-section (the same location as Lo_M). We have shown with field data and a numerical model that the position of the instruments within the same cross-section can produce high uncertainties (up to ±50%) in the estimation of the airflow. Moreover, if an anemometer is placed in a high-speed zone, there is a high possibility of overestimating the airflow. Conversely, positioning it close to the wall may result in an underestimation of the flow.

Therefore, by comparing the results from the different tests, the airflow estimated close to the wall at Lo_UE is likely to represent the lower uncertainty bound, while the airflow estimated in the centre of Lo_LE cross-section represents the higher uncertainty bound of the actual cave airflow.

5. Conclusion

Each of the methodologies applied for measuring an airflow (gauging tests, spot measurements with a hand-held anemometer and airflow time series) offers specific advantages depending on the type of measurement required. Spot measurements can help to identify airflow differences along a conduit due to airflow deviations (i.e. airflow splitting into different flow paths) since they can be carried out all along a ventilated conduit, whereas airflow time series provide insights into airflow dynamics (e.g. airflow variations and direction related to external conditions). Among these, the gauging test with a tracer is likely the most accurate method to assess a one-time airflow rate since it does not require velocity integration over a cross-section. Nevertheless, the assumption of air mass conservation can be a limitation of the method, especially over long distances and in complex systems, where it may be difficult to verify this requirement. Despite a general consistency in measured airflow among the three methods, uncertainties inherent to each technique affect accuracy. Factors such as instrument placement, external variability (e.g., temperature fluctuations), the number of measurement points used to average air velocity, and environmental

constraints (e.g. small cross-sections) contribute to these uncertainties. As a result, airflow measurements are rarely more precise than 20–30%, with uncertainties often reaching 50%. To address these uncertainties, several approaches can be used to improve the accuracy of measurements. In the case of manual measurements to estimate the airflow, one approach could be to increase the number of measurement points to assess an average velocity value that is as representative as possible of the velocity fields across the cross-section. It is crucial to cover the entire cross-section and avoid disturbing the airflow with the operator's presence. Moreover, to decrease the stochastic error due to flow turbulences, punctual measurements of air velocity should last long enough to compensate for this error due to turbulence (e.g. 30 s per measuring point). Another approach could be to measure airflow in three or more different cross-sections along the same conduit. Another key challenge is selecting an appropriate instrument position for long-term monitoring. The field tests and the 3D model of air velocity distributions within a cave cross-section presented by Pastore et al. (2024a) suggest that there is no clear position to deploy a single anemometer within a cross-section. To achieve greater precision, multiple devices should be used in a single cross-section to asses the average air velocity. If only one instrument is available, the measurement point should be selected after conducting manual measurements with a hand-held anemometer to assess the velocity distribution. The fixed anemometer should be placed in a velocity zone that closely represents the average velocity, avoiding both high-speed and low-speed areas. Gauging tests with an artificial tracer, performed under varying airflow conditions (i.e. different directions and flow rates), can provide a rating curve for in-place devices to account for site-specific discrepancies. Long-term monitoring with a single instrument is unlikely to provide a fully accurate airflow rate (Pastore et al., 2024a), so it is crucial to determine a plausible range of airflow uncertainties. High-precision airflow measurements are challenging to achieve in caves, not only due to methodological uncertainties but also because of the difficulty in precisely determining the instrument's position within the velocity fields of a measuring cross-section. Therefore, comparing different methods can help establish the order of magnitude of the flow and its variations. This approach will allow for the estimation of upper and lower bounds of the flow rates, which are essential for the calculation of e.g. energy balance and aerosol transport modelling.

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Geotecnologias aplicadas ao monitoramento da sazonalidade da Lagoa do Sumidouro, Minas Gerais, Brasil

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Resumo

O presente estudo aborda o comportamento sazonal (compreendido entre os anos hidrológicos 2000-2001 e 2019-2020) da Lagoa do Sumidouro, na região do Carste de Lagoa Santa, em Minas Gerais,Brasil, através da utilização de imagens derivadas do satélite Landsat (5,7 e 8) obtidas no catálogo *JRC Water Monthly History* no Google Earth Engine e dados de precipitação do CHIRPS obtidos na mesma plataforma. A Lagoa do Sumidouro é a maior lagoa cárstica do território do Carste de Lagoa Santa e está integralmente no Parque Estadual do Sumidouro. Contudo, a bacia hidrográfica do Córrego Samambaia, a qual pertence a Lagoa do Sumidouro possui quase dois terços sem qualquer proteção, configurando assim uma grande ameaça aos recursos hídricos, uma vez que atividades agropecuárias, silvicultura, urbanização e mineração são comuns no território. Além das ações antrópicas, sistemas climáticos de larga escala atuam na região definem o quadro das precipitações durante o ano hidrológico. Contudo, anomalias climáticas durante os verões dos anos hidrológicos de 2012-2013 e 2016-2017 propiciaram a diminuição das precipitações abaixo da média e o consequente aumento da utilização das águas subterrâneas pelas atividades humanas que levaram a Lagoa do Sumidouro ao completo ressecamento.

Abstract

Geotechnologies applied to monitoring the seasonality of Lagoa do Sumidouro, Minas Gerais,Brazil. he present study examines the seasonal behavior (covering the hydrological years 2000-2001 to 2019-2020) of Lagoa do Sumidouro, located in the Carste de Lagoa Santa region in Minas Gerais,Brasil, through the use of images derived from the Landsat satellites (5, 7, and 8) obtained from the JRC Water Monthly History catalog on Google Earth Engine, as well as precipitation data from CHIRPS acquired from the same platform. Lagoa do Sumidouro is the largest karstic lagoon in the Carste de Lagoa Santa region and is entirely within the Sumidouro State Park. However, the watershed of the Samambaia Stream, to which Lagoa do Sumidouro belongs, has nearly two-thirds of its area unprotected, posing a significant threat to water resources, as agricultural, forestry, urbanization, and mining activities are common in the region. In addition to anthropogenic actions, large-scale climate systems influence the region and determine the precipitation patterns throughout the hydrological year. However, climate anomalies during the summers of the 2012-2013 and 2016-2017 hydrological years led to a decrease in precipitation below the average and a consequent increase in the use of groundwater for human activities, ultimately causing the complete drying up of Lagoa do Sumidouro.

Resumen

El presente estudio aborda el comportamiento estacional (comprendido entre los años hidrológicos 2000-2001 y 2019-2020) de la Laguna do Sumidouro, en la región del Carste de Lagoa Santa, en Minas Gerais, Brasil através del uso de imágenes derivadas del satélite Landsat (5, 7 y 8) obtenidas del catálogo JRC Water Monthly History en Google Earth Engine y datos de precipitación de CHIRPS obtenidos en la misma plataforma. La Laguna do Sumidouro es la mayor laguna kárstica del territorio del Carste de Lagoa Santa y se encuentra completamente dentro del Parque Estatal do Sumidouro. Sin embargo, la cuenca hidrográfica del arroyo Samambaia, a la cual pertenece la laguna, tiene casi dos tercios de su área sin ningún tipo de protección, lo que representa una gran amenaza para los recursos hídricos, ya que actividades agropecuarias, silvicultura, urbanización y minería son comunes en la región. Además de las acciones antrópicas, sistemas climáticos de gran escala actúan en la región y definen el régimen de precipitaciones durante el año hidrológico. No obstante, anomalías climáticas durante los veranos de los años hidrológicos 2012-2013 y 2016-2017 redujeron las precipitaciones por debajo del promedio, aumentando el uso de aguas subterráneas por actividades humanas, lo que llevó al completo agotamiento de la Laguna do Sumidouro.

1. Introdução

Os recursos hídricos são vitais para o funcionamento dos sistemas naturais e, por conseguinte para as atividades humanas. As diferentes paisagens sobre a superfície terrestre apresentam distintas capacidades de recepção, armazenamento e distribuição dos recursos hídricos. Isto se deve ao fato que as paisagens são resultantes de um conjunto de elementos abióticos e bióticos que interagem entre si, regidos pelo

antagonismo das forças endógenas e exógenas ao longo do tempo geológico. Essa diversidade paisagística e mutável, contudo, imperceptível à escala do tempo humano, propicia também a distribuição da diversidade biológica (que também varia conforme a escala do tempo geológico). Dentre as várias paisagens existentes sobre a crosta terrestre, as cársticas destacam-se como importantes ambientes ligados à história do Planeta e também da humanidade. A conformação estrutural do carste propicia a presença das águas, geralmente em abundância, sobretudo em subsuperfície, além da presença de águas superficiais em drenagens de baixa densidade que comumente são capturadas por sumidouros fazendo com que se tornem subaéreas (drenagem criptorreica). Algumas paisagens cársticas ainda apresentam ambientes lacustrinos associados, que são extremamente importantes para o funcionamento do sistema hidrológico do carste, uma vez que, através destes é possível fazer inferências sobre a quantidade de água disponível no sistema, além das mesmas serem essenciais aos processos geoecológicos e biogeográficos.

O Carste de Lagoa Santa, localizado cerca de 30 km ao norte da capital do Estado de Minas Gerais, na Região Metropolitana de Belo Horizonte, é um bom exemplo da presença de lagoas associadas ao carste. Dentre as várias lagoas, destaca-se a do Sumidouro, a maior de toda a região e com grande importância no contexto geográfico, geomorfológico, biogeográfico, historiográfico e científico, iniciado com os estudos do eminente dinamarquês Peter W. Lund (1801- 1880), no século XIX e é de grande importância ao contexto regional do Carste de Lagoa Santa. Por ser a maior lagoa do Carste de Lagoa Santa e por estar em uma área de intensa pressão antrópica (ainda que esteja dentro de uma unidade de conservação de uso integral, o Parque estadual do Sumidouro (PESU)), compreender a dinâmica sazonal da Lagoa a partir do uso das geotecnologias é de grande importância para o gerenciamento dos recursos hídricos do carste regional, pois, as lagoas refletem em certa medida a disponibilidade hídrica no sistema.

2. Materiais e Métodos

Para a realização do estudo objetivou-se a pesquisa por coleções de imagens da área que contivessem dados acerca da presença de água no ambiente, nos espaço temporal compreendido entre os anos hidrológicos 2000-2001 e 2019-2020. A plataforma utilizada para a busca foi o Google Earth Engine (GEE), da Google©. GORELICK et al.(2017) apontam que a ciência dos dados cada vez mais está amparada em supercomputadores e, estes não estão acessíveis para muitos pesquisadores e o público em geral. O GEE é uma plataforma baseada em dados de diferentes coleções de imagens e produtos derivados das imagens (como índices de vegetação, água, temperatura, classificação de usos e cobertura da terra, etc). Para a obtenção dos dados a coleção selecionada foi a *JRC Monthly Water History* v.1.4 (PEKEL et al.,2016). A coleção possui dados em escala global para a ocorrência de águas continentais derivad (resolução espacial de 30m) as da classificação de imagens dos satélites da série Landsat 5, 7 e 8, entre os anos de 1985 e 2021, com freqüência mensal.

Na plataforma GEE foi criado um *script* em linguagem Java para a obtenção das imagens do período compreendido entre outubro de 2000 a setembro de 2020. Foram obtidas 240 imagens que posteriormente foram analisadas e tratadas individualmente para avaliar a sua elegibilidade. Para tal foi utilizado o *software* de SIG livre e gratuito QGIS v.3.22.10. Inicialmente todas as imagens foram reprojetadas do *Datum* WGS84 – EPSG 4326 – para o *Datum* oficial do território brasileiro SIRGAS 2000 (Sistema de Referência Geodésica da América do Sul) para o fuso 23 Sul (EPSG 31983). Após a reprojeção das imagens foi selecionado um raio útil de 2000 m a partir da porção central da imagem de representação da Lagoa do Sumidouro para garantir assim que toda a superfície de representação da lagoa fosse contemplada. Assim, foi criado um *buffer* em formato shapefile utilizado para o recorte de todas as imagens.

A etapa seguinte consistiu no processamento digital das imagens, com a aplicação do filtro de preenchimento dos pixels sem dados do pacote GDAL de análise raster no QGIS v.3.22.10. Tal ação foi necessária, pois, as imagens produzidas pelo satélite *Landsat 7* a partir de fevereiro de 2003 passaram a apresentar linhas de falhas do sensor em que as imagens produzidas posteriormente foram derivadas. O algoritmo do filtro faz uma análise de vizinhança próxima e realiza o preenchimento. As imagens foram convertidas para o formato vetorial (*shapefile*) com criação de duas classes: (0) 'não-água' e (1) água. Os polígonos da classe (0) 'não-água foram descartados e os polígonos da classe (1) água foram suavizados minimamente para a retirada do efeito '*pixelizado*' gerado nas bordas dos mesmos em função da conversão *raster-vetor.* Para a elaboração do perfil de precipitação para os anos analisados, foi realizado o levantamento dos dados de precipitação através conjunto de dados orbitais e de estações meteorológicas CHIRPS disponíveis na plataforma GEE.

3. Resultados

O Carste de Lagoa Santa está sob sazonalidade marcada por dois períodos distintos: um chuvoso, entre os meses de outubro e março e outro seco, entre os meses de abril a setembro, com médias anuais entre os anos de 1985 e 2020 (CHIRPS, 2022) em torno de 1266 mm. Conforme IBAMA (1998) já houve anos com totais de precipitação superiores a 2000 mm, muito chuvosos e anos com totais inferiores a 500 mm, muito secos. Para a análise dos resultados levou-se em consideração o ano hidrológico da região, com seu início em 1º de outubro do ano civil corrente e seu término em 30 de setembro do ano civil seguinte. A análise pelo ano hidrológico faz mais sentido em função da sazonalidade e do *continuum* apresentado pelo ambiente lacustrino do Carste, FIGUEIRA et al. (2020) apontam que após o período chuvoso, em poucas semanas a maioria das lagoas podem secar completamente ou no intervalo de poucos meses podem ainda apresentar alguma água, o que dependerá essencialmente da extensão e profundidade da depressão cárstica a qual a lagoa se encontra, bem como das conexões com as águas superficiais e as encontradas no endocarste. AULER (1995) associou as lagoas cársticas de Lagoa Santa com tal comportamento, quando estas se encontram nas porções de menor altitude no relevo, com baixo gradiente hidráulico e sob influência do nível de base regional, nesse caso, o Rio das Velhas. A Lagoa do Sumidouro apresenta tais características e, por ser a maior lagoa do conjunto regional são notáveis os seus ciclos de cheia e vazante.

É inegável o papel da precipitação na dinâmica hídrica do carste, seja pelo abastecimento dos aquíferos e reabastecimento das nascentes cársticas (surgências) que dependem exclusivamente do endocarste, uma vez que a densidade da drenagem das águas superficiais é extremamente baixa. O trabalho de TAVARES (2020) que consistiu na caracterização da bacia hidrográfica do Samambaia, apontou que a principal entrada de água no sistema (limites fisiográficos da bacia e nascentes fora dos limites) na qual está contida a Lagoa do Sumidouro são as águas meteóricas (24,18 milhões de m3/ano), seguido pela contribuição das nascentes cársticas (4,12 milhões de m3/ano), com algumas encontradas fora dos limites fisiográficos da bacia. TAVARES (2020) destacou que as nascentes apresentam respostas rápidas a eventos de chuvas não superiores a um dia.

No período analisado, compreendido entre os anos hidrológicos de 2000-2001 e 2019-2020, a média do total anual de precipitação foi de 1.222,6 mm, com os anos hidrológicos mais chuvosos: 2001-2002

(1.528,8 mm), 2011-2012 (1.490,39 mm), 2002-2003 (1.459,2 mm), 2003-2004 (1.456,8 mm), 2004-2005 (1.428,5 mm) e 2008-2009 (1.441,7 mm). Os anos hidrológicos menos chuvosos foram: 2000-2001 (1.046,9 mm), 2015-2016 (1.031,7mm), 2014-2015 (994,26 mm), 2012-2013 (895,4 mm), 2013-2014 (856,5 mm) e 2016-2017 (855,8 mm). Com relação aos anos hidrológicos mais secos da série analisada, os compreendidos entre 2012-2013 e 2015-2016 merecem destaque. COELHO et al. (2016) apontam que a seca na região Sudeste nos referidos anos se deu a partir de condições convectivas anômalas geradas na porção norte da Austrália, desencadeando uma sequência de processos que conectaram as regiões tropicais e extratropicais do Pacífico Sul ao Atlântico Sul, afetando assim as condições atmosféricas na região Sudeste, uma vez que a Alta Subtropical do Atlântico Sul (ASAS), que é um sistema de alta pressão que atua de forma distinta no verão e no inverno, teve seu posicionamento alterado, no verão, impedindo assim a ação da Zona de Convergência do Atlântico Sul (ZCAS), responsável pelo transporte de umidade no sentido Noroeste-Sudeste e por conseguinte formadora de chuvas.

Os meses mais chuvosos, novembro (média 196,5 mm), dezembro (média 277 mm) e janeiro (média 225,3 mm) concentram a média de 57,1 % do total pluviométrico dos anos hidrológicos. No período analisado, o trimestre mais chuvoso (dos meses mais chuvosos) foi o do ano 2001-2002 com 1104,5 mm (75,7% do total pluviométrico do ano hidrológico). Os meses mais secos são junho (média 5,01mm), julho (média 8,74mm) e agosto (média 7,73mm) concentram 1,75% da média do total pluviométrico dos anos hidrológicos analisados. Quando separamos as médias totais pelos dois períodos do ano hidrológico: chuvoso (outubro a março) e seco (abril a setembro) são encontradas as seguintes contribuições das médias dos totais pluviométricos: outubro a março (chuvoso) – 88,6%; abril a setembro (seco) – 11,4%. O que corrobora com os trabalhos de AULER (1995) e FIGUEIRA et al. (2020) sobre o cessar das chuvas e o esvaziamento das lagoas e, neste caso o da Lagoa do Sumidouro. Contudo, dentro da série analisada há algumas hipóteses que devem ser postas no cenário ambiental da Lagoa.

4. Discussão

Na série estudada, entre os anos hidrológicos 2012-2013 e 2016-2017, as chuvas ficaram abaixo da média histórica da série, o que acarretou na ruptura gradativa dos ciclos plurianuais a partir de outubro de 2012. O verão de 2013 foi marcado pela diminuição das médias das chuvas em toda a região Sudeste do país (em função do sistema climático de larga-escala oriundo da Austrália e que se repetiu nos verões seguintes). NOSHANG (2014) apud IGAM (p.59, 2020) indica que as alterações climáticas são prejudiciais às águas subterrâneas, uma vez que podem interferir diretamente na recarga dos aqüíferos a partir de períodos de estiagem mais prolongados. A combinação da ausência de chuvas e, por conseguinte a redução da disponibilidade das águas dos aqüíferos cársticos decretou o secamento da Lagoa do Sumidouro, principalmente nos anos em que a média das chuvas ficou muito abaixo da média histórica. IGAM (2018) destaca em relatório anual sobre a gestão dos recursos hídricos, que o período compreendido entre os anos de 2014 e 2017, a região Central do Estado de Minas Gerais (assim como as demais regiões) apresentou anomalias negativas em relação às médias de precipitação, o que acarretou um aumento na demanda de água para diferentes usos. Historicamente a região do Carste de Lagoa Santa e, por conseguinte a bacia do Córrego Samambaia apresenta-se altamente modificada pelos diferentes usos da terra, sobretudo, pela pecuária extensiva de corte e também pela agricultura de subsistência, pela implementação da silvicultura de eucalipto nas últimas décadas e pela atividade minerária, que sabidamente promove o rebaixamento do nível freático para a explotação de minério de calcário.

Outro ponto a ser considerado é a especulação imobiliária e um novo movimento presenciado nos últimos anos na região do Carste de Lagoa Santa: o aumento dos condomínios e também do novo ordenamento das áreas rurais: a busca pela tranqüilidade nas áreas rurais próximas à capital. Há uma demanda muito grande por água e também há uma estrita dependência pelas águas subterrâneas, o que é muito comum a perfuração de poços. Contudo, há relatos que muitos poços são perfurados sem qualquer tipo de licenciamento. Mesmo que a Lagoa do Sumidouro esteja inserida totalmente em uma Unidade de Conservação de uso integral, quase dois terços da bacia de contribuição não possuem qualquer tipo de proteção, o que pode ser uma grave ameaça aos ciclos plurianuais da Lagoa do Sumidouro. Associado a isto, a recorrência de eventos climáticos extremos e/ou de longa duração podem fazer com que o quadro ambiental da Lagoa dos períodos de cheias e de vazantes seja duramente alterado. Em um comparativo entre o ano hidrológico 2001-2002, o mais chuvoso e o ano hidrológico 2013-2014, o mais seco da série temporal estudada, em que já ocorre a atuação do sistema climático de larga-escala oriundo da Austrália, que gerou o deslocamento da ASAS e a anulação da ZCAS, os cenários são completamente distintos.

O trimestre mais chuvoso (NDJ) do ano hidrológico 2001-2002 superou os 1.100 mm, justamente pela intensa atuação da ZCAS. A ZCAS é o sistema atmosférico mais relevante formador de chuva da região sudeste (logo, da área de estudo) durante os meses mais quentes (meses finais da primavera e verão austral). A repetição de eventos da ZCAS promove a ocorrência de chuvas intensas que auxiliam na recarga dos aqüíferos, assim como a recepção direta dentro das bacias de contribuição. No caso da Lagoa do Sumidouro, a grande quantidade de chuvas no período propiciou a 'perenidade' de suas águas até pelos meses mais secos do ano. Geralmente, quando os meses mais chuvosos do ano hidrológico ficam com a precipitação acima da média para o período, é este excedente que parece garantir a presença do espelho d'água nos meses mais secos (abril a setembro). Por fim, cabe destacar que a Lagoa do Sumidouro é um importante corpo hídrico da região cárstica de Lagoa Santa, pois, a partir de estudos hidrológicos de maior duração será possível criar modelos preditivos a respeito das águas regionais.

5. Conclusão

A Lagoa do Sumidouro é a maior e mais importante do sistema lacustrino da região cárstica de Lagoa Santa. O presente estudo do comportamento hídrico da Lagoa através da utilização das geotecnologias foi de suma importância para a compreensão da dinâmica da lagoa em função da sua sazonalidade marcante associada, sobretudo à precipitação, que além da entrada direta das águas nos limites da bacia de contribuição, também contribui diretamente para a recarga dos aquíferos cársticos, que retornam parte de suas águas às surgências do Córrego Samambaia, a principal drenagem que abastece a Lagoa do Sumidouro. Diante das mudanças climáticas e o aumento da pressão antrópica, a bacia do Samambaia, logo a Lagoa do Sumidouro, fica evidente a criação de planos voltados à sustentabilidade socioambiental, uma vez que proteger apenas a Lagoa do Sumidouro (no âmbito do PESU) significa apenas adiar o colapso das águas da Lagoa.

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Proposição de método para monitoramento de polígono de influência de cavidades

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Resumo

Este estudo apresenta os resultados alcançados no monitoramento de polígono de influência, executado no âmbito do Monitoramento Espeleológico realizado na área da Mina de Miguel Burnier (Ouro Preto, Minas Gerais, Brasil), de propriedade da Gerdau Açominas. Utilizando imagens de LIDAR e de drone as principais alterações na paisagem foram mapeadas e confrontadas com o potencial de perda de biodiversidade do ambiente. O resultado dessa análise resultou em um zoneamento das áreas do polígono de influência que estão mais suscetíveis a perturbações em sua dinâmica ecológica. Tal resultado pode se tornar uma ferramenta para o planejamento das atividades que serão desenvolvidas no entorno do polígono de influência.

Abstract

Proposal of a method for monitoring caves influence polygons. This study presents the results achieved in the monitoring of a polygon of influence, carried out within the scope of the Speleological Monitoring carried out in the area of the Miguel Burnier Mine (Ouro Preto, Minas Gerais, Brazil), owned by the mining company Gerdau Açominas. Using LIDAR and drone images, the main changes in the landscape were mapped and compared with the potencial for loss of biodiversity in the environment. The result of this analysis resulted in a zoning of the areas of the polygon of influence that are most susceptible to disturbances in their ecological dynamics. This result can become a tool for planning the activities that will be developed in the surroundings of the polygon of influence.

1. Introdução

Segundo o artigo 2, inciso 4 do Conselho Nacional do Meio Ambiente 347/2004 a área de influência de uma cavidade é definida como a "área que compreende os elementos bióticos e abióticos, superficiais e subterrâneos, necessários à manutenção do equilíbrio ecológico e da integridade física do ambiente cavernícola". Uma vez estabelecido, o seu monitoramento tem como objetivo identificar possíveis alterações no equilíbrio e na paisagem da área de influência da caverna. Esse equilíbrio refere-se a dinâmica sedimentar, hidrológica, macro alterações ecológicas e processos mecânicos de deslizamento que podem alterar o sistema ecológico que dá suporte ao funcionamento e desenvolvimento da cavidade. Na Mina de Miguel Burnier, de propriedade da mineradora Gerdau Açominas, foram definidos cinco polígonos de influência (BRANDT, 2020), já validados pelo órgão ambiental (SUPRAM), que estão sob monitoramento. A Mina de Miguel Burnier está localizada no estado de Minas Gerais, município de Ouro Preto, sul da província geológica do Quadrilátero Ferrífero (Brasil). Este estudo irá apresentar e discutir o método desenvolvido para executar o monitoramento dos polígonos de influência supracitados, e apresentar os resultados alcançados em um dos polígonos durante as duas campanhas executadas. Além de identificar as possíveis alterações no equilíbrio ecológico do polígono de influência, foram mapeadas as áreas onde este equilíbrio está sob maior risco, tendo como base análises de uso do solo e a resiliência do ambiente.

2. Materiais e Métodos

Para acompanhar a evolução da paisagem no entorno do polígono de influência foi utilizada a análise comparativa de imagens. Para tal foi utilizada uma ortofoto produzida com o sensor LIDAR (Light Detection and Ranging), que permitiu maior detalhamento da paisagem; esta ortofoto constituiu a base para a análise comparativa do uso do solo. Posteriormente, em cada campanha, foram realizados voos de drone, e as imagens resultantes foram comparadas à ortofoto, possibilitando mapear a evolução de quaisquer alterações no uso do solo no interior e na borda dos polígonos. Partindo das feições mapeadas, a próxima análise foi determinar como o meio responde as alterações. Para isso foi utilizado o conceito de Unidades Funcionais (WEBER, 2019) que consistem em unidades com características paisagísticas e ambientais homogêneas (BRANDT, 2020). Desta forma foi considerado o potencial de perda de biodiversidade de cada Unidade Funcional.

Crepani et al. (1996; 2001) desenvolveram uma metodologia para expressar a susceptibilidade/potencialidade/vulnerabilidade de elementos ambientais através da atribuição de valores numéricos para cada atributo da paisagem analisado. Para o monitoramento foi feita uma adaptação desta metodologia considerando as variáveis "uso" e "unidades funcionais", para daí executar um mapeamento de risco cujo objetivo é mapear as áreas do Polígono de Influência (PI) que estão mais expostas a perturbações e classificar a intensidade do risco em cada uma das áreas. Para tal dividiu-se a soma das variáveis (100%=10) de acordo com a relevância de cada uma para a alteração do PI. Em seguida

para cada atributo das variáveis consideradas foram estabelecidas três classes de risco, sendo que a classe com peso1 representa o menor risco, o peso 2 com risco intermediário e o peso 3 com maior risco de alterações. Após a classificação das variáveis, a análise foi conduzida em ambiente GIS através da álgebra de mapas onde foi executada a fórmula seguinte: [(Uso*6) + (Unidades Funcionais*4)]/10 = Risco. As figuras 1, 2 e 3 apresentam os pesos considerados para a execução da álgebra de mapas para o monitoramento:

Variáveis	Peso
Uso do solo	**6**
Unidade Funcional	**4**

Figura 1: *Escala de potencialidade atribuída as variáveis consideradas na análise.*

Uso do solo	Peso	Risco de alteração
Acessos	**2**	**Médio**
Feições erosivas	**3**	**Alto**
Terraplanagem	**2**	**Médio**
Ferrovia	**1**	**Baixo**
Mineração	**3**	**Alto**
Área não antropizada	**1**	**Baixo**
Escorregamento	**2**	**Médio**

Figura 2: *Escala de potencialidade atribuída a variável «uso» [Fonte: Imagens Drone DJI Phantom 4 Pro, 2023/2024].*

Unidade Funcional	Peso	Risco de alteração
Estruturas de mineração em atividade ou terraplenagens	**1**	**Baixo**
Campo limpo de cerrado secundarizado	**2**	**Médio**
Silvicultura extensiva	**1**	**Baixo**
Campo sujo em regeneração arbustivo-arbóreo	**2**	**Médio**
Capoeira de FESD altamente antropizada	**2**	**Médio**
FESD mais avançada	**3**	**Alto**
Campo Rupestre	**3**	**Alto**
Escarpas em meio florestal	**3**	**Alto**

Figura 3: *Escala de potencialidade atribuída a variável «Unidades Funcionais» [Fonte: Brandt, 2020].*

3. Resultados

O resultado do monitoramento do polígono influência mostrou, através do mapa de risco (Fig. 4), que a maior fragilidade do polígono de influência está em suas bordas, devido a pressão do avanço das atividades antrópicas. Deve-se considerar que neste estudo o termo ‘’borda’’ é utilizado aqui para definir uma zona de contato entre dois ambientes (MILAN, MORO, 2016) e o efeito de borda se refere às perturbações que esse contato pode sofrer. Quanto a extensão desses efeitos não há uma largura fixa para sua influência, podendo variar de acordo com os aspectos considerados (RODRIGUES, 1998).

A existência de áreas de “FESD mais avançada”, que são paisagens mais consolidadas em sua composição ecológica e portanto mais sensíveis a alterações ambientais do que aquelas que já passaram por intensa perturbação. De acordo com a análise realizada 3,88% da área do polígono de influência alvo desse estudo apresentou alto risco de sofrer alterações que afetem seu equilíbrio, 7,56% da área apresenta médio risco e 88,56% apresenta baixo risco.

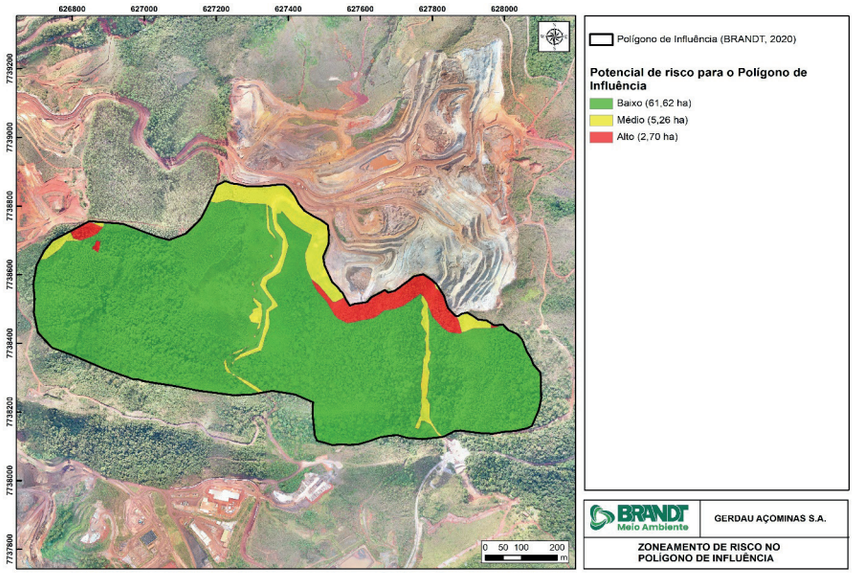


Figura 4: *Resultado do zoneamento de risco elaborado pa partir do monitoramento do Polígono de Influência [BRANDT, 2024].*

4. Discussão

Foram executadas duas campanhas do monitoramento (período seco e período úmido) do polígono de influência, durante as quais a evolução do uso do solo foi mapeada. A Fig. 5 mostra as feições antrópicas que evoluíram ou foram desencadeadas durante as duas campanhas.

Foram mapeados quatro cenários que podem pressionar o polígono de influência:

1. Expansão de estruturas da mina
2. Expansão das atividades minerárias no limite norte do polígono de influência
3. Acesso
4. Cicatriz de escorregamento

A Fig. 6 mostra as Unidades Funcionais que ocorrem no polígono, alvo deste estudo. A maior área do polígono é coberta pela unidade "FESD mais avançada" que é caracterizada por conservar alguns de seus atributos originais, logo é uma unidade mais exigente quanto a recursos e dinâmica ecólogica, desta forma possui maior potencial de perda em termos de biodiversidade.

A análise do potencial de alteração de cada feição antrópica frente ao potencial de cada Unidade Funcional permitiu mapear as zonas de risco, ou seja, áreas que estão mais suscetíveis a sofrerem perturbações em sua dinâmica ecológica.

Apesar do mapa de risco resultar de uma operação quantitativa, o valor dos pesos conferidos a cada um dos usos do solo e a cada uma das Unidades Funcionais não é absoluto, ou seja, possui caráter qualitativo, uma vez que depende das características físicas e bióticas da área e da dinâmica ecológica do polígono de influência frente a possíveis alterações antrópicas. Os estudos anteriores realizados para determinar o polígono de influência foram fundamentais para entender a dinâmica local e orientaram a determinação dos pesos.

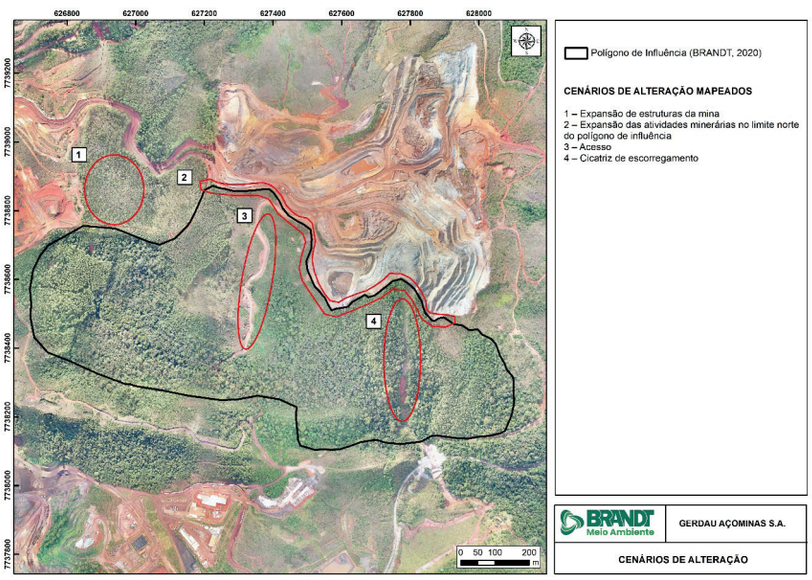


Figura 5: *Cenários com potencial de alteração mapeados [BRANDT, 2023; 2024].*

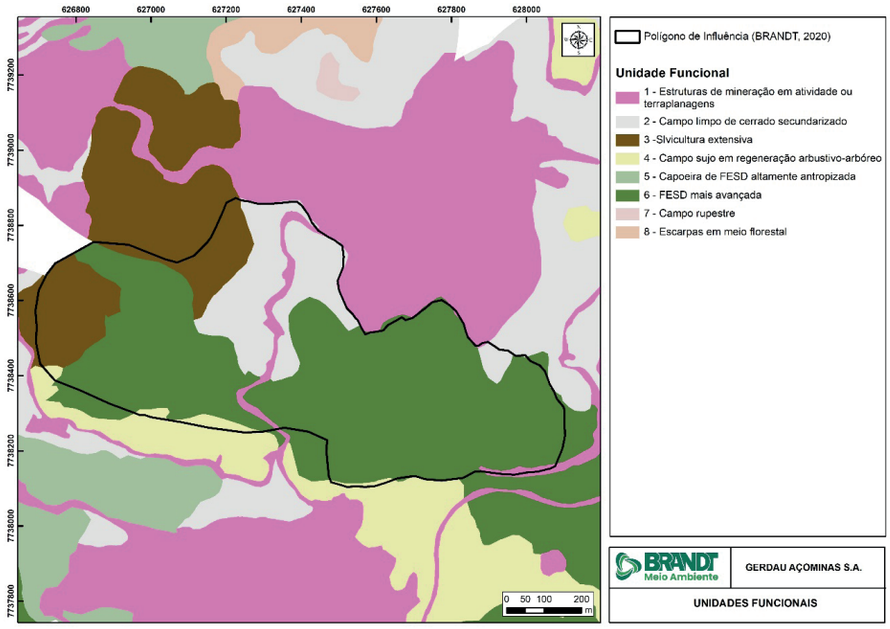


Figura 6: *Unidades Funcionais mapeadas [BRANDT, 2019].*

5. Conclusão

O monitoramento de polígono de influência tem como objetivo identificar e acompanhar as possíveis alterações na paisagem e no equilíbrio ecológica da área de influência cavernícola. O método aplicado neste estudo resultou em um mapa de risco que permitiu indicar em quais áreas a dinâmica ecológica está mais suscetível a pressão de perturbações antrópicas.

Esse resultado permite que medidas preventivas e mitigadoras possam ser planejadas, podendo constituir uma ferramenta para o planejamento das atividades de engenharia, por exemplo, logo fica evidente a necessidade da continuidade do programa de monitoramento para acompanhar a evolução da paisagem.

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Climate change footprint in Modrič Cave (Croatia) data set

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Abstract

Twenty years of various researches in Modrič Cave (Croatia) included multi-year monitoring of different parameters above and within the cave. Although often with intention to assess the average values, it was inevitable to capture the overall increasing trends of certain parameters. Along with surface air temperature rise (at the rate of ~0.4 °C per decade), we recorded the trend of the cave air temperature increase of around one tenth of the surface one. Increase of atmospheric CO2 had just a miniscule portion in much higher CO_2 increase inside a cave which is, actually, the consequence of global warming, local reforestation and modification in cave ventilation pattern. Time series of the cave air radon concentration is still quite short, but observed rise is probably linked to the increase of the concentration of its carrier gas, CO_2. Finally, also short-term, but noticeable 4-year trends in rain and dripwater $\delta^{18}O$, i.e. isotopical enrichment, is most likely the result of global warming trend, although the source effect probably affects that signal, as well. Taking everything into account, such clear response of the subterranean microclimate is most likely sustained by the current acceleration of the global warming trend.

1. Introduction

Caves are considered as relatively isolated from intensive and abrupt atmospheric events, and many surface processes and features are averaged or buffered in the deep cave interior. However, it appears that even within them, climate changes, especially global warming, can be traced (e.g. BADINO, 2004; DOMINGUEZ-VILLAR ET AL., 2015; ŠEBELA & TURK, 2021; OBLEITNER et al., 2024). From climatological point of view, caves can be treated differently from the surface where the official climate normals represent mean values in 30-year periods (defined by the World Meteorological Organization; WMO, 2017). With their quasi-constant air temperature year round, climatological approach could be similar to that of the equatorial regions (with low intra- and interannual variability of air temperature and absence of distinct seasons) where the reliable climate normals can be obtained already after 10 years of measurement or even less. In that sense, we can discuss the climate change at much shorter data sets, but, of course, having in mind thermal inertia of the underground (DOMINGUEZ-VILLAR ET AL., 2015; MAMMOLA et al., 2019).

Similarly as numerous caves worldwide, Croatian karst caves might play important role in one of the most current topics – prediction of the ongoing (and future) climate change based on the palaeoenvironmental records. One of such cave is Modrič Cave (44°15'24'' N; 15°32'14'' E; 32 m a.s.l.) which has been investigated from multiple perspectives for more than 20 years, providing valuable environmental data sets. Modrič Cave was formed in Upper Cretaceous heavily fractured limestone on the seaward slopes of the Velebit Mt, on the eastern Adriatic coast. It consists of two horizontal passages with total length of 829 m covered with 2-30 m thick overburden. During the last decade, research was focused on the speleothem-based palaeoenvironmental reconstruction in which characterization of the karst environment is essential, so several microclimate and hydro(geo)logical parameters has been monitored (SURIĆ et al., 2010; 2018; 2020; 2021; RUDZKA et al., 2012; LONČARIĆ et al., 2023). One of the prerequisites for the reliable interpretation of the speleothem stable isotope ($\delta^{18}O$, $\delta^{13}C$) record is calcite deposition in isotopic equilibrium with drip-water in stable cave environment (HENDY, 1971; MCDERMOTT, 2004), for which we monitored cave air temperature and relative humidity, and analyzed isotopic composition of precipitation and drip water. Besides, since CO_2 controls deposition of speleothem calcite, we also measured cave air CO_2 concentrations and additionally, intrigued with quite high CO_2 values, we initiated radon concentration measurements, as well. Here we present some of the time series which directly and indirectly point to the overall environmental changes, mostly related to the recent global warming.

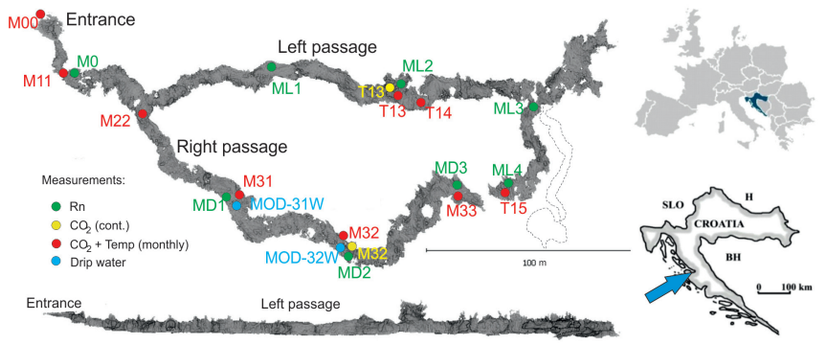


Figure 1: *Modrič Cave survey with marked monitoring (air temperature, CO_2 and radon concentration) and sampling (drip water) sites.*

2. Materials and methods

Surface air temperature was provided by official Croatian Meteorological and Hydrological Service (CMHS) from the meteorological stations located in Starigrad Paklenica (8 km NW from the cave) and Novigrad (8 km to the south), while in deep interior of the cave (M32 and T13) we employed temperature and relative humidity loggers *HOBO® Pro v2* to decipher variation and/or stability of the cave air temperature at the 1-hour resolution (Figure 1). During the previous researches, cave air temperature was measured by different devices (*3M TL20, LOG32, Tinytag*) at various time intervals, and as sort of back up, from 2017 on, once per month we conduct spot measurements with handheld *AZ 7755* device at 8 locations along the both cave passages and in front of the cave entrance. The same device is used for cave air CO_2 monthly readings, which is unfortunately limited by the device measuring CO_2 range of 0-9999 ppm. Thus, in 2021 we enforced continuous logging by two *Vaisala MI 70* devices connected to *GMP 252* CO_2 probes, located at the mid-part of the both passages (M32 and T13). Furthermore, instigated by high CO_2 concentrations, between 2018 and 2022 measurement of radon concentrations in cave air was performed by solid-state nuclear track-etched detectors *LR115 type II*, and between 2020 and 2023 we set up *TSR3* radon detectors for continuous radon concentration monitoring at 7 locations in the cave (Figure 1). From 2014 to 2018, composite water samples were collected on a monthly basis: precipitation (MOD-R) 0.5 km from the cave and dripwater from two drip sites in the right passage (MOD-31W and MOD-32W). Oxygen and hydrogen stable isotope analyses were performed on 141 water samples in total, as reported in SURIĆ et al. (2018).

3. Results and discussion

Cave air temperature

The 24-year (1994-2017) meteorological data sets from Starigrad, and 27 years of measurement (1998-2024) in Novigrad defined the Cfa climate type in Modrič region, with mean annual air temperatures of 16.17 °C and 15.48 °C, respectively (CMHS, 2024). Both stations recorded long-term trend of warming at rate of 0.39 °C in Starigrad and 0.35 °C per decade in Novigrad. Meanwhile, the average cave air temperature measured in previous campaigns were 15.64 °C during 2009-2010 (RUDZKA et al., 2012), 16.58 °C during 2014-2015 (SURIĆ et al., 2018) and 16.65 °C during 2014-2017 monitoring period. The longest in-cave data set (2017-2024) is given in Figure 2a, showing increasing temperature trend in all parts of the cave, superimposed on seasonal variations. However, in the heterothermic zone closer to the entrance (M11 and M22) with more expressed seasonal variations, the warming trend is more evident than in the homothermic zone deeper into the cave (M31 and M32) where the seasonal temperature oscillations are reduced, and the warming trend is attenuated, but still noticable. At the site M32, with the most consistent cave conditions, calculated warming trend is 0.018 °C within 5 years, which is only around one tenth of the surface trend. 20-year data set (2000-2020) from Alpine caves displayed trends of the cave temperature increase which are about half of those observed outside, i.e. 0.2 vs. 0.5 °C per decade (OBLEITNER et al., 2024). Apparently, in comparison with the eastern Adriatic coast, Alpine environment is more impacted in terms of warming both on the surface (0.3 °C per decade, while the global rate was 0.2 °C) and underground where the loss of cave ice has a feedback effect on cave temperatures (OBLEITNER et al., 2024). At this point we must partly refrain from absolutely precise values since our data rely on monthly readings with handheld instrument. Though, due to the relatively simple Modrič Cave morphology without pit-like channels that can act as a 'cold air trap', and due the absence of any water fluxes or icing, these spots can be representative sites for continuous logging of the microclimate parameters and their responses to the concurrent atmospheric changes. One of the features that is governed by the temperature, in particular by the differences between surface (T_{out}) and cave air temperature (T_{cave}), is cave ventilation which governs the variation of the concentration of the cave air gasses, such as CO_2 and radon.

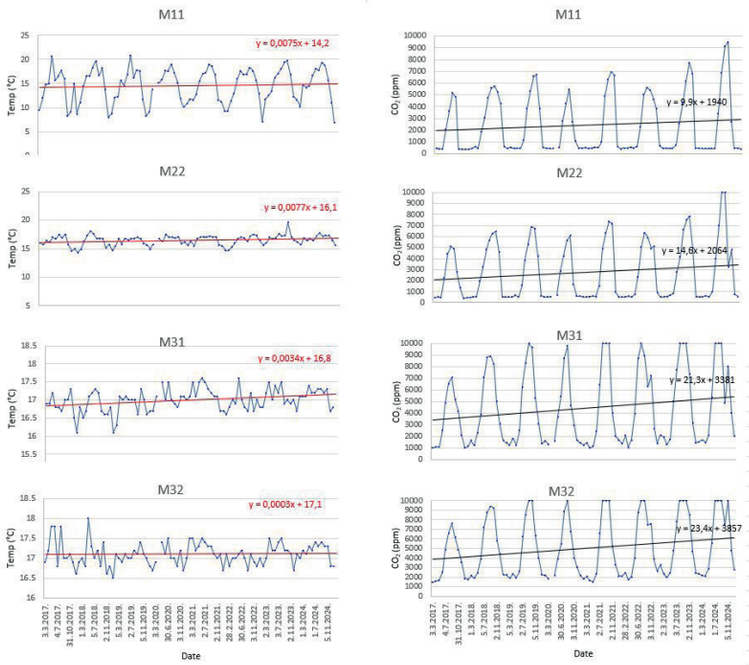


Figure 2: *Monthly readings of the cave air temperature (a) and CO_2 concentration (b), at four sites from the entrance and through the right passage (see Fig. 1). Note the different scale of temperature axes due to the dampened seasonal signal in the deep interior of the cave, opposite to the CO_2 concentrations with the differences amplified inward. Device has limit at 9999 ppm CO_2 concentration, so all the episodes of higher concentrations are given as 10,000 ppm values.*

Cave air CO_2

Measurement of the cave air CO_2 concentration (along with collection of modern calcite) in Modrič Cave was initiated in order to determine speleothem (non)depositional periods, and eventually resulted with identifying unique spatio-temporal variations of CO_2 concentration controlled by multiple factors (SURIĆ et al., 2021). As an addition, and superimposed on seasonal variations, we recorded multi-year increase in cave air CO_2 concentration in all parts of the cave. Though, since there were portions of the cave where CO_2 concentrations rose beyond the device limit (e.g. at the sites M31 and M32), we further discuss only those with maximum concentration <10,000 ppm (i.e. M11 and M22) and also uncorrupted with the vicinity of very entrance (like M00) (Fig. 2b). Their trendlines (M11: y = 9.9x + 1940; M22: y = 14.6x + 2064) show increase of almost two orders of magnitude in comparison to the surface trend. Namely, according to NOAA (2025), in the same period (2017-2024) globally averaged marine surface monthly mean atmospheric CO_2 data had a trend of ~0.2 ppm per month (y = 0.1979x + 404.38) (LAN et al., 2024). Of course, absolute concentrations of CO_2 in the underground are 2-20 times higher with respect to the standard atmosphere (FORD & WILLIAMS, 2007) which is currently ~420 ppm (420.26 ppm in September 2024, NOAA accessed on 2nd January 2025) since there are many different sources of the underground CO_2. In Modrič Cave, the main sources of the CO_2 are: i) microbial- and plant-derived CO_2 produced in the pedosphere by root respiration and organic matter decay which is transported downward, and ii) in-cave CO_2 degassing of the drip water, while the main CO_2 sink is ventilation-driven dilution of the cave air with outside air (SURIĆ et al., 2021). Correspondingly, increasing trend of in-cave CO_2 concentration is indirectly governed by temperature rise which partially control vegetation activity, as well as the ventilation patterns. According to 2014-2023 data for the Modrič microlocation (unpublished data for 2014-2023 by CMHS and Pljusak.com), there is no evident decrease in precipitation amount, which in combination with ongoing reforestation above the cave (SURIĆ et al., 2021) and global temperature increase, supports enhanced soil CO_2 production and accumulation due to the inhibited ventilation during the warm part of the year (Tout > Tcave). Given such input and winter (Tout < Tcave) ventilation with atmospheric air which is constantly enriched by CO_2, a further increase in both winter and summer CO_2 values is expected. Similar scenario with increased CO_2 concentrations, although sometimes with different background plays out in many caves, e.g. in Belgian caves it was recorded already for 1966-2020 period (EK et al., 2022), in Chauvet Cave (France) during 1998-2012 period (BOURGES et al., 2014), in Samograd Cave (Croatia) during 2021-2024 (BUZJAK et al., 2024) while for Altamira Cave models include period from 1950 to 2100 (SAEZ et al., 2024).

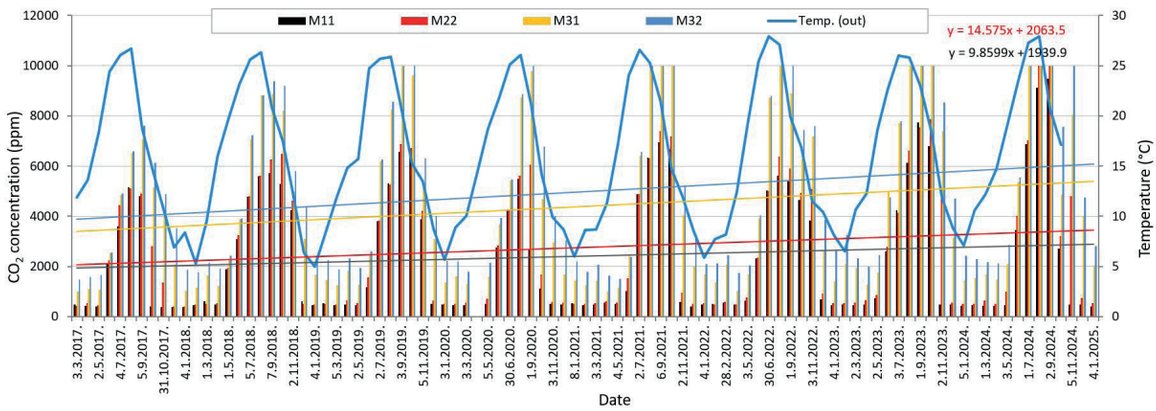


Figure 3: *Cave air CO_2 concentrations at four sites (see Fig. 1) along with outside temperature (Novigrad CMHS station).Note the lag between surface temperature rise and gradual CO_2 built up, followed by sudden decrease of CO_2 concentration upon the ventilation activation as soon as T_{out} falls below T_{cave}.*

Radon in cave air

Time series of cave air Rn concentration in Figure 4 presents continuous measurement between 3/2020 and 3/2023 performed in left (ML4) and right (MD3) passages which are characterized by significantly different absolute Rn values (LONČARIĆ et al., 2023). However, they both show positive trend. Radon is not directly climate related, but since CO_2 acts as its carrier gas (ETIOPE & MARTINELLI, 2002), it significantly controls distribution of radon within the karst underground. On the other hand, radon concentration is also controlled by cave ventilation dynamics, which is again temperature-dependant. Regardless of the absolute concentrations, in Modrič Cave we identified covariance of radon and CO_2 concentration on the seasonal scale, suggesting that both gases have a mutual source (the subsurface karstified zone) and dynamics (LONČARIĆ et al., 2023). However, due to quite short time series, the quasi-constant increase of Rn concentration (tied to the global warming) is still at the speculative level, but it might be indicative and worth monitoring and comparing in the future.

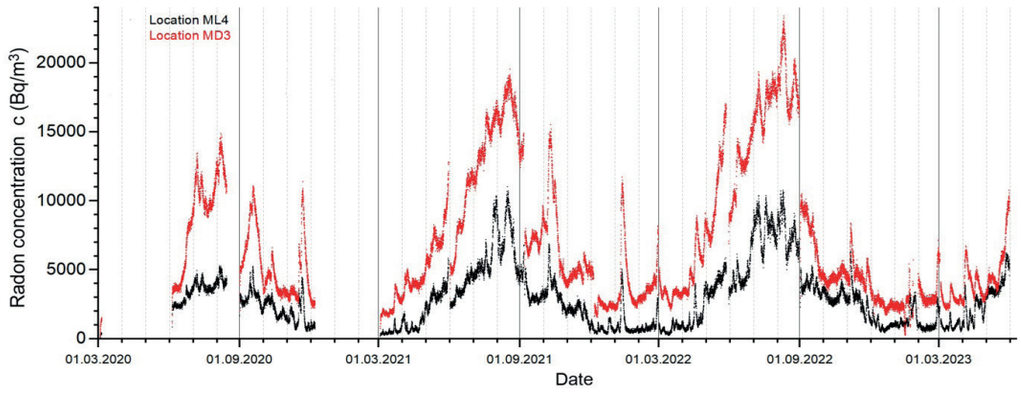


Figure 4: *Cave air Rn concentration in the middle part of the left (ML4) and right passage (MD3).*

$\delta^{18}O$ in dripwater

Analyses of isotopic ($\delta^{18}O$, $\delta^{2}H$) composition of precipitation and drip water are essential for the characterisation of the karst aquifer. It controls the homogenisation of the seasonally marked precipitation infiltrated within epikarst, being crucial for modification and/or preservation of palaeoclimate signal in the speleothems. Thus, from 2014 to 2018, two drip sites (MOD-31W and MOD-32W) supplied significantly homogenized dripwater with almost completely dampened seasonal pattern that rainwater (MOD-R) contains (Fig. 5). Calculated trend lines of all three time series (MOD-R: y=0.042x-6.1; MOD-31W: y=0.0127x-6.3; MOD-32W: y=0.004x-6.3) indicate a slight 4-year positive trend, i.e. isotopical enrichment, which is more pronounced in rainwater, and the most buffered in the slow-dripping MOD-32W. That can be broadly attributed to the increase in temperature (as we actually observed) and probably enhanced evapotranspiration. Still, given such a short sequence, we do not draw definite conclusions, especially considering that similar Mediterranean sites in France have additionally modified isotopical signal due to the shifting vapour source (Zhang et al., 2025), which is also susceptible to climate change.

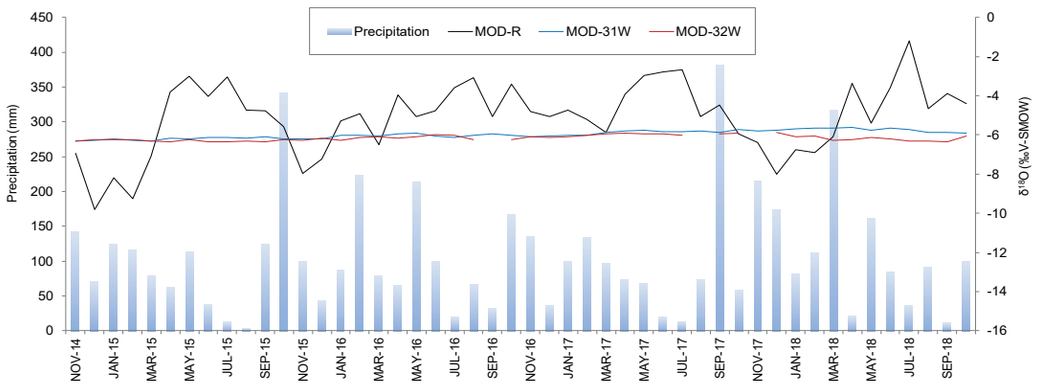


Figure 5: *Monthly precipitation amounts and $\delta^{18}O$ of precipitation (MOD-R) and dripwater from two drip sites (MOD-31W and MOD-32W) in Modrič Cave right passage. While the rainwater keeps the seasonal signal, dripwater is homogenized.*

4. Conclusion

Global warming, as a key feature of the global climate change has been 'accidentally' captured during the long-term monitoring of the spatio-temporal variations of subterranean microclimate parameters in Modrič Cave. Undoubtedly, the increase of cave air temperature is a consequence of atmosphere warming, with the trends (outside and in-cave) different from some other regions (e.g. Alpine), while other features indirectly transfer the rising temperature signal: CO_2 follows the improvement of the surface vegetation and probably the change of cave ventilation pattern, radon concentration rise is linked to an increase of his carrier gas CO_2, while stable isotope enrichment in water follows mainly the temperature increase. However, fully aware that couple of years of certain measurements (e.g. Rn concentration or dripwater isotopic composition) cannot indicate the global climate change, we presume that prolonged monitoring will align with already confirmed trends, which carry the signal of recent accelerated global warming rate.

Acknowledgments

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Virtual Tours for Monitoring Physical Changes in Ferriferous Caves: A Comparison with Traditional Photographic Methods

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Abstract

This study examines 360-degree virtual tours (VTs) as a complementary tool for monitoring cave stability in Serra Sul, Pará, Brazil, a region with active mining operations. We developed a methodology to create immersive virtual experiences and compared the advantages and limitations of this technique with traditional photographic methods. Criteria such as coverage angle, image resolution, and equipment costs were assessed. Our results show that VTs offer significant time and cost savings, enhanced spatial understanding, but are limited by lower resolution and the need for multiple light sources. Despite these challenges, virtual tours offer a valuable tool for cave monitoring, especially when combined with traditional methods. Future technological advancements may enhance their utility in environmental monitoring and speleological studies.

1. Introduction

Nowadays, technologies are undergoing constant development, urging people to adapt and reshape their lives. Our reality has severely shifted, and many innovative tools that once seemed futuristic and far-fetched are now common, deeply integrated into our everyday existence. This new reality can be virtual, defined by content-rich and highly interactive digital environments. Virtual tours (VTs) are examples of such immersive experiences, allowing users to explore locations in a simulated space from anywhere. But what exactly are virtual tours and how are they currently applied across various fields, particularly in areas related to speleology?

Virtual tours are engaging digital experiences that render 360-degree panoramic views of real-world environments, such as museums, open landscapes, or exhibitions, often featuring responsive functionalities like selecting specific locations or adjusting the viewing angle to simulate the feeling of physical presence (SHIKHRI et al. 2021).

Virtual tours have become a prominent tool in various sectors, including real estate, education, and tourism (SAMALA et al. 2024). Matterport, an online platform for creating 3D models of physical spaces, was highlighted by SULAIMAN et al. (2020) as an innovative marketing tool for real estate during the COVID-19 pandemic, noted for its hyper-realistic 3D virtual tours, precise measurements, and efficiency in producing virtual property replicas. In the education sector, web-based VT applications enable users to virtually explore university campuses and access detailed information about facilities and services, with the potential to transform marketing approaches, boost student engagement, and reshape campus visit practices (SAMALA et al. 2024). As for the tourism industry, the application of virtual environments has been widely observed in cultural heritage initiatives, with studies underlining the potential of virtual reality to deliver robust interactive experiences while enhancing cultural asset understanding and educational outcomes (CHENG & LEE 2024, YANG & KARNCHANAPAYAP 2024).

Concerning the use of virtual tours in subterranean environments, caves have been digitized to promote interactive and educational exploration of cultural heritage sites, fostering knowledge dissemination, public awareness, and a deeper understanding of the spatial context (HAN et al. 2019, KARKAZI et al. 2024). Leveraging cutting-edge 3D technology, KARKAZI and colleagues (2024) developed a highly immersive Virtual Museum of the Petralona Cave, a renowned natural and cultural landmark in Greece celebrated for its significant archaeological and paleontological discoveries.

In this study, we adopted virtual tours as a complementary tool to photographic monitoring in ferriferous caves. To this end, we developed a methodology specifically tailored for cave environments, identified the additional assessments enabled by this approach in comparison to conventional photographic monitoring techniques, and outlined the advantages and limitations of applying virtual tours to subterranean systems. We anticipate that this innovative tool will prove effective and valuable in identifying and interpreting potential physical changes in caves near mining operations.

2. Materials and methods

Study Area

We conducted this study in 14 iron ore caves located in Serra Sul, in the municipality of Canaã dos Carajás, Pará State, Brazil (Figure 1). This region forms part of the Carajás Mineral Province (CMP), globally recognized for its vast mineral wealth, including iron ore, gold, nickel, and copper. Serra Sul, in particular, hosts the world's largest open-pit iron ore mine, with an estimated annual production of 90 million tons (MATLABA et al. 2017). The caves selected for this study are under continuous monitoring for their physical integrity due to their proximity to active mining operations (BIOESPELEO 2022).

Tools and Procedures for Data Collection

Fieldwork was conducted in May 2024 at selected caves in Serra Sul. Within each cave, fixed camera stations were established and identified using a sequential numbering system (Figure 2). The number of stations varied depending on the cave's dimensions and specific topographic characteristics. Each station was equipped with a GoPro MAX camera mounted on a tripod and illuminated by up to four LED panels positioned on the ground (Figure 2). The LED panels were arranged in approximately 90-degree angles relative to one another to ensure even lighting, where spatial conditions allowed.

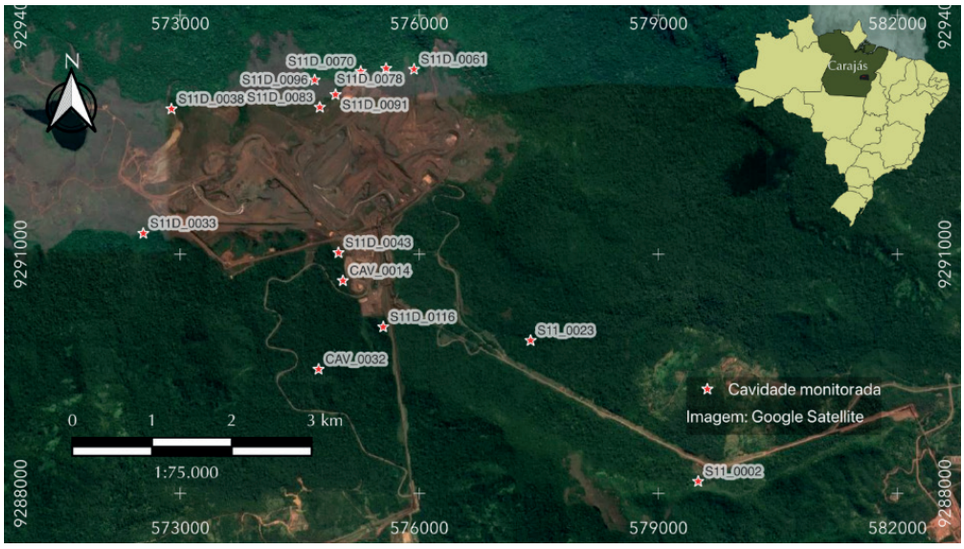


Figure 1: *Map of Serra Sul (Pará, Brazil), showing the distribution of caves selected for the monitoring program.*



Figure 2: *GoPro MAX camera set up in cave S11_0023 within a dimly lit environment. The detail in the top left corner shows a numbered plate used to identify stations inside the cave and in the surrounding area.*

The GoPro MAX camera features dual wide-angle lenses (focal length: 8.9 mm) that provide a 360-degree field of view, paired with a 16.6 MP sensor capable of capturing images at a resolution of 5760 x 2880 pixels. The camera was operated in automatic ISO mode (100–800), and the panoramas were stored in JPEG format.

For aerial 360-degree images, a DJI Mavic Air II drone was employed. The drone operated at altitudes ranging from 30 to 80 meters above ground level to capture the external topography and surrounding landscape.

The morphological and lithostructural characteristics of the monitored environment were documented using electronic devices, including tablets and, occasionally, mobile phones. These records detailed the precise positioning of the camera stations based on the caves' topographic maps, along with the height of the tripods and the arrangement of the LED panels.

Creation of Virtual Tours

Before the creation of the virtual tours for each cave, the 360-degree panoramic images were edited using GIMP. Through subtle adjustments to color, brightness, and contrast, we enhanced the visibility of fine details in each image, such as wall and floor textures.

The virtual tours were developed using Theasys (https://www.theasys.io/), an online platform for building 360-degree virtual tours. The software provides a variety of customization tools that facilitate the creation of interactive virtual experiences. Each tour begins with an aerial panorama captured via drone. Users can then access the cave environment through a hotspot, a clickable feature that enables navigation within the tour.

To facilitate movement between different locations within both the interior and exterior of the caves, we incorporated directional arrows as hotspots to guide users toward the next point. Additionally, a custom floor plan of the cave was included to provide spatial context, allowing users to track their position in real time as they navigate the virtual environment.

For visualizing data from the monitored caves, we created a custom map using Google's free digital mapping tool, My Maps. Location data and links to the virtual tours were imported directly from a Google Sheets spreadsheet.

Comparison Between 360-Degree and Traditional 2D Photography

We analyze the distinct characteristics of the GoPro MAX and the 24 MP Nikon with a 14 mm lens—the standard camera previously used in monitoring activities employing conventional repeat photography techniques—focusing on their differences in field application. A quantitative approach was adopted to facilitate evaluation across the following criteria: coverage angle (°), color scale placement, image resolution (MP), operation time (minutes), and equipment cost (USD).

Analysis of the Advantages and Limitations of Virtual Tours

After developing the virtual tours and assessing the equipment used, we identified key advantages and limitations of this technique for speleological monitoring.

3. Results

Access to virtual tours

Virtual tours for each cave can be accessed by scanning the QR code in Figure 3, which allows users to explore a custom map featuring monitored caves. On Google Maps, clicking a location marker opens an info window displaying a screenshot from the cave's virtual tour, its coordinates in decimal degrees, and a link to access the tour (Figure 4).

Differences between 360-degree and traditional 2D photography

The GoPro MAX captures a significantly broader field of view, offering an almost seamless spatial representation of the monitored environment. In contrast, a standard camera requires approximately 13 images (three horizontal shots plus five each for the ceiling and floor) to achieve full coverage of an underground space, substantially increasing data collection time. Capturing an entire scene at a monitoring station using conventional methods takes approximately 195 minutes (around three hours), whereas a 360-degree camera completes the process in just 15 minutes (Figure 5). Additionally, when using the GoPro MAX, only two walks are required—one to position the scale at the designated spot and another to return to the starting point for image capture. In contrast, employing the 24 MP Nikon necessitates 26 walks to accomplish the same task. Finally, the 24 MP Nikon entails higher operational costs.



Figure 3: *Custom map created with Google My Maps, showing an info window on the left that displays the coordinates of cave S11D_0043 and a link to its virtual tour. Scan the QR code in the bottom-right corner to explore.*

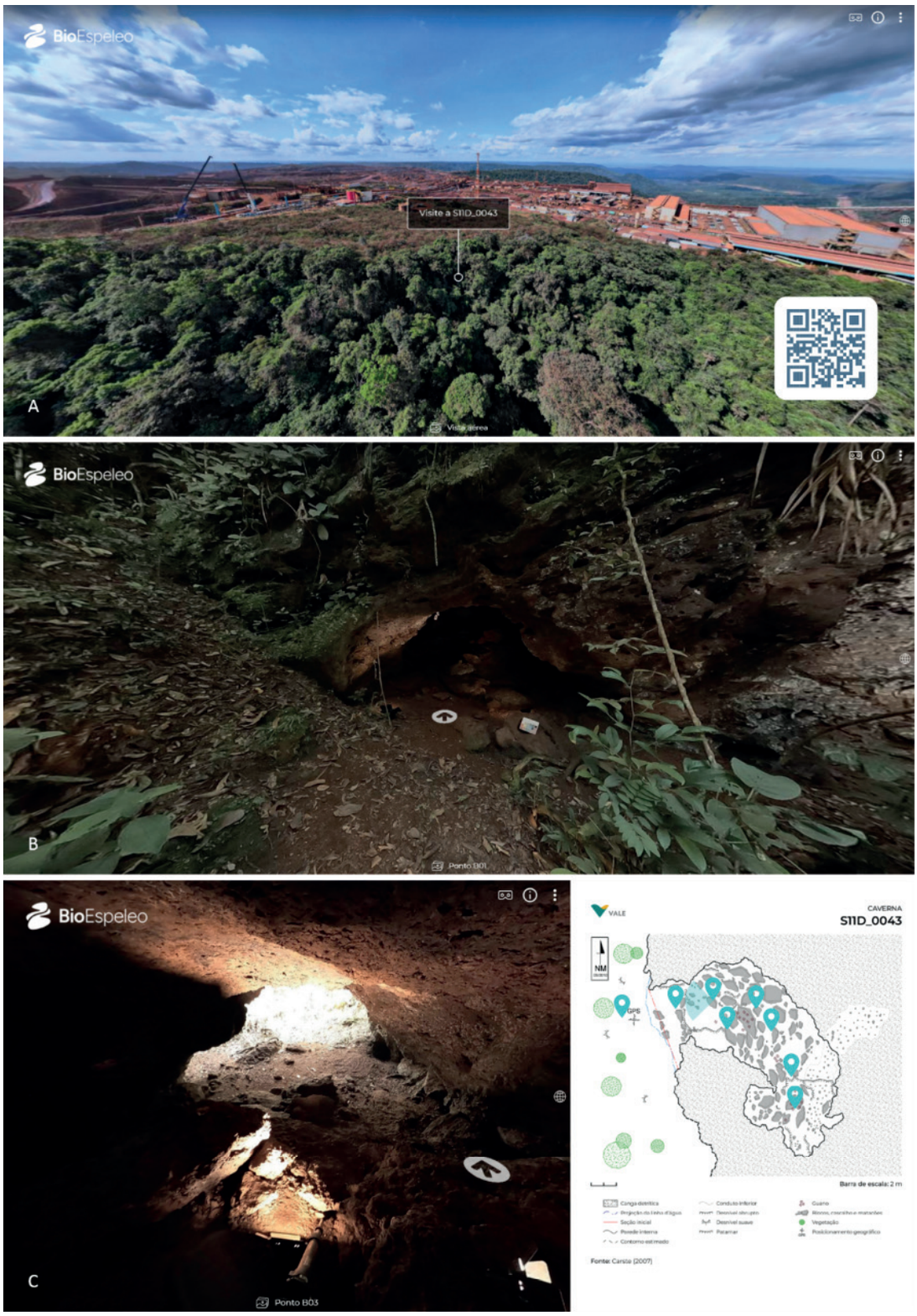


Figure 4: *A) Starting panorama of cave S11D_0043's virtual tour. B) View of the cave's entrance. C) View of station B03 with the floor plan tab open on the right. Each marker represents a camera station, and when clicked, displays a radar indicating the user's viewing perspective.*

Feature	GoPro MAX	Nikon (24 MP/14 mm)
Coverage angle (°)		
Horizontal angle	360	114
Vertical angle	340*	84
Setting up the IFRAO color scale		
Number of walks	2	26 (2 × 13)
Image resolution (MP)	16.6	312 (24 × 13)
Operational time per monitoring station (minutes)	15	195 (15 × 13)
Equipment cost (USD)		
Camera	649	1,396
Lenses	-	249
Supplementary lighting	556 (139 × 4**)	296 (flash)
Total	1,205	1,941

*During virtual tour shoots, the tripod obstructs the view when the camera is angled downward, limiting the ability to capture all perspectives. As a result, we cannot claim that the vertical view amounts to 360 degrees.

**We multiply the price by four, as four LED panels were used to ensure proper lighting inside the cave.

Figure 5: Comparison between an omnidirectional camera (GoPro MAX) and a conventional camera (24 MP Nikon). Note: By dividing the camera angles of view and multiplying the resulting values, it was determined that a single image from the GoPro MAX is equivalent to approximately 13 images from the 24 MP Nikon. This ratio was used in all subsequent calculations in the table.

Advantages and limitations of the application of virtual tours

We outlined five key advantages and limitations of integrating virtual tours into monitoring programs in karst environments (Figure 6).

Advantages
Enhanced understanding of spatial relationships
Cost-effective
Time-saving
Minimized operational risks
Immersive experiences
Limitations
Lower image resolution
Reliance on digital devices to access outcomes
Dependence on at least four continuous light sources for proper lighting
Potential steep learning curve associated with virtual tour applications
User experience challenges with 360-degree navigation

Figure 6: Key benefits and challenges associated with the use of virtual tours in monitoring cave environments.

4. Discussion

This research introduces 360-degree panoramic photography as an innovative approach to monitoring the physical stability of caves in Serra Sul. By integrating the captured images into an online virtual tour platform, we developed a streamlined process for creating engaging and interactive experiences. However, how valuable is the use of virtual tours for monitoring activities in caves near mining operations?

Undoubtedly, 360-degree panoramas provide a clearer understanding of spatial context while significantly reducing operational time, as they capture the entire environment in both horizontal and vertical planes in a single image. However, omnidirectional cameras typically produce results with lower resolution compared to conventional cameras, which can make it challenging to identify finer details. The reduced pixel density limits the ability to detect minor signs of erosion or fractures in rock surfaces, which are crucial for assessing cave stability.

Nonetheless, it is important to point out that using a 360-degree camera for monitoring caves in Serra Sul was not only a cost-effective and time-saving strategy, but also helped reduce operational hazards. The conventional repeat photography method used in previous monitoring campaigns involved multiple displacements between locations inside the caves to assess fracture spacing and movement. In contrast, the novel approach using the GoPro MAX relies on fewer monitoring stations, which accelerates the process and significantly reduces sediment compaction and other potential impacts associated with survey operations.

Virtual tours can provide highly realistic and immersive experiences; however, depending on the application, the learning curve may pose a limitation for many users, particularly those without technical expertise. For instance, creating or managing a virtual tour may require mastering complex interfaces, integrating multimedia elements (such as images, videos, or audio), and setting up interactive hotspots. While some platforms offer simplified interfaces, tutorials, and more user-friendly features, those seeking fully customizable or highly specialized tours may still encounter significant challenges due to the complexity involved. Additionally, viewers may find 360-degree navigation unintuitive, especially if they are unfamiliar with interactive media.

Another limitation related to the digital aspect of virtual tours is their dependence on electronic devices (and often an internet connection) to access the results. Flat images can be disseminated through printed media; however, while 360-degree panoramas could be printed, they would not fulfill their original purpose.

One more factor to consider when choosing virtual tours over traditional 2D photography is the requirement for at least four continuous light sources during shoots to ensure adequate lighting. The demand for multiple light sources stems from the fact that 360-degree cameras capture images from all angles simultaneously. To avoid harsh shadows

and overexposed areas, a balanced distribution of light is necessary. Using only a few light sources can lead to uneven lighting, where certain parts of the scene may be overly bright while others remain too dark. Achieving the right lighting balance requires precise positioning of the lights and careful control of their intensity. In contrast, standard cameras typically only require a single flash or light source to achieve proper illumination for a shot. The flash provides a burst of light that illuminates the subject for a moment, which works well for capturing still images from a specific angle. Since standard cameras don't capture a 360-degree view, the lighting challenges are less complex, and one flash is often sufficient to achieve even exposure.

Overall, factoring in the prior analysis of the benefits and drawbacks of adopting virtual tours for monitoring operations, it is evident that these tours offer a valuable tool for cave monitoring, providing a more immersive and spatially accurate representation of subterranean environments compared to traditional methods. However, the limitations discussed underscore the importance of a balanced approach. Virtual tours should be viewed as a complementary tool to 2D photography, rather than a complete replacement. By integrating both methods, it is possible to maximize the benefits of detailed visual documentation and operational efficiency while continuing to leverage the advantages of traditional monitoring techniques. Looking ahead, continued advancements in virtual tour technology, along with improved accessibility and user-friendly features, could further enhance their role in environmental monitoring.

5. Conclusion

In conclusion, 360-degree virtual tours offer a valuable tool for cave monitoring, enhancing spatial understanding and streamlining operations. However, limitations like lower image resolution and technical requirements highlight the need for a complementary approach. Integrating virtual tours with traditional methods can create a more efficient monitoring system, with future technological advancements likely expanding their applications in environmental studies.

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Session 15

SPECIAL TOPICS

Integração de Inteligência Artificial no EspeleoVale: Um Sistema SaaS para Análise de Dados Espeleológicos

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Abstract

Speleology, as a multidisciplinary field, increasingly benefits from technology and data analysis. This paper presents an innovative proposal for the integration of Artificial Intelligence (AI) with a Software as a Service (SaaS) called EspeleoVale, dedicated to the management and analysis of speleological data. Through the application of generative AI and machine learning algorithms, the system aims to optimize the collection, storage, and interpretation of data related to caves and underground ecosystems. The software development will be discussed in three main stages: first, the technological update of the existing system to connect with generative and predictive AI models; second, the implementation of AI models that allow the prediction of speleological phenomena and the identification of patterns that may go unnoticed in traditional analyses; and, finally, the creation of a user-friendly interface that facilitates access and visualization of data for researchers and managers. The expected results include a significant improvement in the decision-making capacity in cave conservation and exploration projects, in addition to promoting greater collaboration among research institutions. This work not only demonstrates the potential of technology in speleology but also proposes a scalable model that can be adapted to different contexts and needs.

1. Introdução

A espeleologia é uma ciência multidisciplinar que estuda as cavidades naturais e os ecossistemas subterrâneos (Wei-Hai, 2006). A coleta e a análise de dados espeleológicos são fundamentais para a compreensão desses ambientes e para a definição de estratégias de conservação (DI SANTO & HAMILTON, J.,2020). Com o avanço da tecnologia, novas ferramentas têm surgido para auxiliar nesse processo, como a utilização de Sistemas de Informação Geográfica (GIS) e bancos de dados especializados (REDDY, G ,2018).

A utilização de um Software as a Service (SaaS) para a gestão de dados já é uma realidade (TSAI & HUANG ,2014). O EspeleoVale é um exemplo de sistema que centraliza informações sobre cavernas, permitindo o cadastro, a consulta e o compartilhamento de dados. No entanto, a integração de Inteligência Artificial (IA) a esse tipo de sistema ainda é pouco explorada, representando uma grande oportunidade de avanço na área (CAHYANINGRUM, Y. ,2024).

Este artigo propõe a conexão do EspeleoVale a ferramentas de IA generativa e a outros modelos de aprendizado de máquina, visando aprimorar a análise de dados espeleológicos. A IA pode auxiliar na identificação de padrões, na previsão de fenômenos e na geração de insights que seriam difíceis de obter por meio de métodos tradicionais (LEDDY & MCCREANOR ,2023).

A integração de IA ao EspeleoVale pode trazer benefícios significativos para a espeleologia, como a otimização do tempo de análise, a melhoria da precisão das previsões e a geração de novos conhecimentos sobre os ecossistemas subterrâneos (SHIYING DI et al., 2021). Além disso, a solução proposta é escalável e pode ser adaptada a diferentes contextos e necessidades, contribuindo para a conservação e o manejo adequado desses importantes ambientes naturais.

Este artigo está organizado da seguinte forma: a seção 2 apresenta a arquitetura da solução proposta, detalhando os componentes e as conexões entre eles; a seção 3 descreve os modelos de IA que serão utilizados; a seção 4 aborda a interface do usuário e as ferramentas de visualização de dados; a seção 5 discute os resultados esperados e as métricas de sucesso; e a seção 6 apresenta as considerações finais e os trabalhos futuros.

2. Materials and methods

A solução proposta integra o EspeleoVale a ferramentas de IA por meio de uma arquitetura em camadas, que permite a comunicação entre os diferentes componentes do sistema. A Figura 1 ilustra a arquitetura proposta.



Figure 1: *Integração do EspeleoVale com ferramentas de IA.*

O EspeleoVale é um sistema SaaS existente que atua como um repositório central de dados espeleológicos. Ele permite o cadastro de informações sobre cavernas, como localização, dimensões, características geológicas, dados biológicos e registros de expedições. O sistema possui uma interface web que permite aos usuários acessar e gerenciar os dados, seguindo padrões de usabilidade e acessibilidade.

A camada de integração é responsável por fazer a conexão entre o EspeleoVale e os modelos de IA. Ela é composta por um conjunto de APIs (Application Programming Interfaces) que permitem a troca de dados entre os sistemas, seguindo o padrão RESTful (FIELDING, 2000). A camada de integração também é responsável por fazer a conversão dos dados para um formato compatível com os modelos de IA, como JSON ou CSV (CHOLLET, 2018).

A camada de IA é composta pelos modelos de IA generativa e preditiva. Esses modelos são responsáveis por processar os dados espeleológicos e gerar insights. A camada de IA também inclui ferramentas para treinamento e validação dos modelos, utilizando técnicas como validação cruzada e otimização de hiper parâmetros (GM HARSHVARDHAN et al.,2020).

A camada de apresentação é a interface do usuário. Ela permite que os usuários interajam com o sistema, visualizem os dados e os resultados das análises de IA. A camada de apresentação inclui ferramentas de visualização de dados, como gráficos e mapas interativos, facilitando a compreensão dos resultados (SHUWEN ZHOU et al, 2024).

2.1. Conexões e Justificativas

2.1.1. EspeleoVale ↔ Camada de Integração

A conexão entre o EspeleoVale e a camada de integração é feita por meio de APIs. O EspeleoVale disponibiliza APIs que permitem que a camada de integração acesse os dados espeleológicos. A camada de integração também pode enviar dados para o EspeleoVale, como resultados de análises de IA.

Justificativa: A utilização de APIs permite uma comunicação eficiente e segura entre os sistemas, seguindo padrões amplamente adotados na indústria de software (FIELDING, 2000). Além disso, as APIs permitem que a camada de integração seja independente do EspeleoVale, o que facilita a manutenção e a evolução do sistema, permitindo a integração com outros sistemas e fontes de dados no futuro.

2.1.2. Camada de Integração ↔ Camada de IA

A troca de informações entre a camada de integração e a de IA ocorre por meio de chamadas de função. Dessa forma, a camada de integração envia dados espeleológicos aos modelos de IA e recebe os resultados das análises (VASWANI et al., 2017).

Justificativa: Chamadas de função propiciam comunicação rápida e eficiente, viabilizando a execução da camada de IA em um servidor dedicado. Isso melhora o desempenho e possibilita a escalabilidade horizontal, caso necessário (CHEN; GUESTRIN, 2016).

2.1.3. Camada de IA ↔ Camada de Apresentação

A conexão entre a camada de IA e a camada de apresentação se dá por meio de um barramento de mensagens, pelo qual a camada de IA envia resultados que são exibidos aos usuários (GOODFELLOW et al., 2016).

Justificativa: O barramento de mensagens possibilita comunicação assíncrona, de forma que os usuários não precisam aguardar a conclusão das análises de IA para continuar utilizando o sistema (NIELSEN, 1993). Adicionalmente, essa abordagem permite a atualização em tempo real dos resultados na camada de apresentação, enriquecendo a experiência do usuário.

2.2. Ferramentas e tecnologias

2.2.1. EspeleoVale

O EspeleoVale foi desenvolvido em Golang e Javascript e utiliza o banco de dados PostGres/PostGIS. Atualmente, está hospedado em servidores na nuvem, podendo ser acessado via navegador web, numa abordagem condizente com a filosofia SaaS (CHOLLET, 2018).

2.2.2. Camada de integração

A camada de integração será desenvolvida em Python, devido à larga adoção em projetos de IA e à disponibilidade de bibliotecas para comunicação via APIs e processamento de dados (BROWN; GEIGER, 2020). Para tanto, serão usadas as bibliotecas *requests* (para comunicação com APIs), *pandas* (para manipulação de dados) e *json* (para conversão de dados).

2.2.3. Camada de IA

A camada de IA será responsável por processar os dados provenientes do EspeleoVale, gerando insights a partir de modelos de linguagem natural e algoritmos de aprendizado de máquina. Para IA generativa, serão adotados os modelos disponibilizados pela OpenAI e pela Meta:

Modelos da OpenAI: A família de modelos GPT oferece recursos avançados de geração de texto e compreensão de contexto, com capacidade de produzir descrições detalhadas sobre cavernas, relatórios de expedição e resumos científicos (VASWANI et al., 2017). A OpenAI disponibiliza APIs que permitem o acesso e a integração dinâmica dos modelos às aplicações SaaS, viabilizando um fluxo de trabalho automatizado.

LLama (Large Language Model Meta AI): Desenvolvida pela Meta, a família LLama traz modelos de linguagem que empregam arquiteturas inspiradas em Transformers, mas com foco em maior eficiência computacional. Ela permite executar inferências em ambientes de hardware mais modestos, mantendo resultados de boa qualidade em tarefas como análise de textos espeleológicos, classificação de documentos e geração de relatórios (BROWN; GEIGER, 2020).

Para IA preditiva, modelos como Redes Neurais Recorrentes (RNNs) ou algoritmos de ensemble (ex.: Random Forest) ainda podem ser utilizados em paralelo, dependendo da natureza dos dados envolvidos (HOCHREITER; SCHMIDHUBER, 1997; CHEN; GUESTRIN, 2016). Dessa forma, a camada de IA combinará modelos generativos avançados e técnicas de previsão, oferecendo um conjunto abrangente de ferramentas para análise de dados espeleológicos.

2.2.4. Camada de apresentação

A camada de apresentação será desenvolvida com tecnologias web modernas como HTML, CSS e JavaScript (SHNEIDERMAN, 1998). O uso

de bibliotecas como React ou Vue.js possibilita a criação de interfaces dinâmicas e responsivas. Para visualização de dados, serão utilizadas bibliotecas como D3.js ou Chart.js, que permitem a confecção de gráficos e mapas interativo.

3. Results

3.1. Implementação dos Modelos de IA

Os modelos de IA selecionados serão treinados com dados históricos armazenados no EspeleoVale. O processo de treinamento seguirá etapas de metodologias consolidadas de aprendizado de máquina (GOODFELLOW et al., 2016):

Pré-processamento dos dados: Limpeza, normalização e conversão para formatos adequados (CHOLLET, 2018).

Divisão dos dados: Separação em conjuntos de treinamento, validação e teste, na proporção usual de 80-10-10 (BROWN; GEIGER, 2020).

Treinamento dos modelos: Utilizando o conjunto de treinamento (HOCHREITER; SCHMIDHUBER, 1997).

Validação dos modelos: A partir do conjunto de validação (DEVLIN et al., 2019).

Teste dos modelos: Com o conjunto de teste para avaliar o desempenho real (CHEN; GUESTRIN, 2016).

3.2. Avaliação do Modelos de IA

Os modelos de IA serão avaliados por métricas como precisão, revocação, F1-score e acurácia, dependendo do tipo de modelo e da tarefa (GOODFELLOW et al., 2016). Os resultados serão comparados com métodos tradicionais de análise de dados espeleológicos, estabelecendo um referencial para medir possíveis avanços.

3.3. Exemplos de aplicação

Alguns exemplos que demonstram o potencial da integração proposta:

Previsão de inundações: A partir de dados históricos de precipitação, nível d'água e características da caverna, um modelo de IA pode estimar probabilidades de inundações, tornando expedições mais seguras (HOCHREITER; SCHMIDHUBER, 1997).

Descoberta de novas cavidades: Ao analisar dados geológicos, geomorfológicos e de prospecção, é possível identificar áreas com maior probabilidade de abrigar novas cavernas (CHEN; GUESTRIN, 2016).

Classificação automática de espeleotemas: Modelos de IA podem reconhecer padrões em imagens de formações rochosas e classificá-las (BROWN; GEIGER, 2020).

Geração de relatórios automatizados: Com base nas informações coletadas em expedições, a IA pode produzir relatórios que descrevam as cavernas, descobertas e recomendações para pesquisas futuras (VASWANI et al., 2017).

Análise de fauna e flora: Modelos especializados podem identificar espécies de plantas e animais em imagens capturadas no interior das cavernas, contribuindo para o monitoramento da biodiversidade (GOODFELLOW et al., 2016)

Monitoramento de estabilidade estrutural em cavernas: Por meio de técnicas de visão computacional aplicadas a sequências de imagens ou dados de sensores de deformação (geofones, extensômetros, entre outros), a IA pode detectar sutilmente fissuras, rachaduras ou deslocamentos de rochas em cavernas. Esses algoritmos preditivos fornecem alertas antecipados sobre possíveis riscos de colapso ou instabilidade, auxiliando na adoção de medidas preventivas em planos de conservação e segurança das expedições.

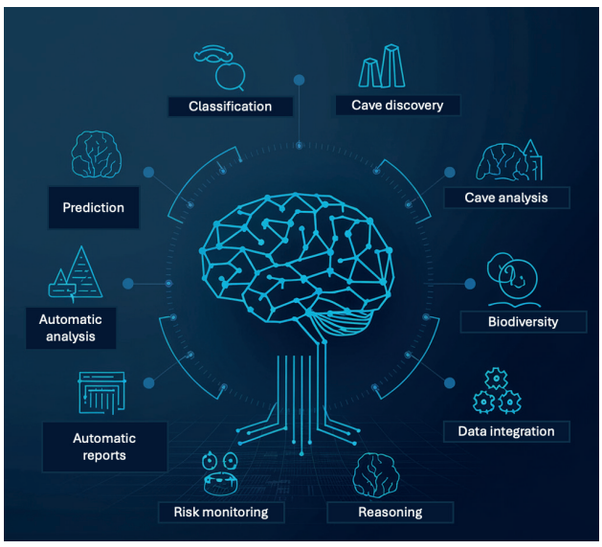


Figure 2: *Fluxo de dados e processamento de IA no EspeleoVale.*

4. Discussion

A incorporação de IA ao EspeleoVale representa um salto qualitativo na forma de analisar dados espeleológicos. Modelos de IA generativos e preditivos potencializam a extração de informações valiosas, muitas vezes imperceptíveis pelos métodos convencionais, ao mesmo tempo que automatizam tarefas e identificam padrões complexos (BROWN; GEIGER, 2020).

Os resultados deste trabalho ressaltam o papel da IA na tomada de decisões relacionadas à conservação e exploração de cavernas (CHEN; GUESTRIN, 2016). A capacidade preditiva e analítica da IA permite iniciativas mais proativas, com gerenciamento baseado em evidências e assegurando a sustentabilidade dos ecossistemas subterrâneos.

A solução proposta caracteriza-se pela escalabilidade e adaptabilidade, pois a arquitetura em camadas permite a inserção de novos modelos de IA e o uso de diferentes fontes de dados, garantindo sua relevância a longo prazo (GOODFELLOW et al., 2016). No entanto, é fundamental sublinhar que a IA não substitui o conhecimento especializado dos espeleólogos. Embora a IA auxilie na análise de dados, a interpretação final e a tomada de decisão devem permanecer sob responsabilidade de profissionais experientes (FORD; WILLIAMS, 1989).

5. Conclusion

Este artigo apresentou uma proposta inovadora para integrar IA ao software EspeleoVale, com vistas a aprimorar a análise de dados espeleológicos. A arquitetura em camadas viabiliza a comunicação entre diversos componentes e a inclusão de novos modelos de IA, proporcionando interoperabilidade e escalabilidade (CHEN; GUESTRIN, 2016).

Os modelos de IA discutidos mostram amplo potencial para identificar padrões, prever fenômenos e gerar resultados relevantes a partir de grandes volumes de dados. Além disso, a interface de fácil utilização e as ferramentas de visualização de dados tornam as análises de IA acessíveis a uma audiência mais ampla (VASWANI et al., 2017).

Dessa forma, a incorporação de IA ao EspeleoVale representa não apenas um avanço tecnológico para a espeleologia, mas também um importante passo na conservação e gestão sustentável desse patrimônio natural (FORD; WILLIAMS, 1989). A solução proposta, por sua escalabilidade, pode atender a diferentes contextos e continuar evoluindo, contribuindo para o progresso da ciência e da preservação das cavernas.

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Software para gerenciamento de dados espeleológicos: estudo de caso de duas cavidades de máxima relevância

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Resumo

As cavernas são cruciais para entender processos geológicos, climáticos e biológicos, além de abrigarem biodiversidade e patrimônios culturais únicos, sendo fundamental o registro e controle padronizado dos dados espeleológicos para sua conservação e manejo sustentável. A gestão de dados espeleológicos enfrenta desafios significativos, como a dificuldade de integrar diferentes bases de dados devido à falta de padronização, financiamento limitado e escassez de recursos técnicos qualificados. Este estudo visa demonstrar as vantagens do software EspeleoVale no gerenciamento de dados espeleológicos ao empregar tecnologias de software livre e de código aberto. A caracterização e os estudos das cavidades da região de Tutámeia, em propriedade localizada na Serra da Calçada foram essenciais para a Vale S.A. no processo de compensação ambiental espeleológica para o licenciamento de empreendimentos minerários, uma vez que o levantamento dos atributos das cavidades e sua sistematização no sistema EspeleoVale auxiliaram na escolha de áreas de preservação permanente como medida compensatória para impactos irreversíveis, especialmente no contexto do projeto de Ampliação da Mina de Abóboras, no Complexo Vargem Grande, localizados nos municípios de Nova Lima e Rio Acima (MG). Dessa maneira acredita-se ser plausível afirmar que o EspeleoVale se destaca como um repositório e ferramenta de gerenciamento e gestão de dados espeleológicos.

Abstract

Caves are crucial for understanding geological, climatic and biological processes, as well as being home to unique biodiversity and cultural heritage; therefore, standardized recording of speleological data is essential for their conservation and sustainable management. The management of speleological data faces significant challenges, such as the difficulty of integrating different databases due to a lack of standardization, limited funding and a shortage of qualified technical resources. This study aims to demonstrate the advantages of the EspeleoVale, a software in managing speleological data by employing free and open-source software technologies. The characterization and studies of the caves in the Tutámeia region in the Serra da Calçada were essential for Vale S.A. in the process of environmental compensation for the licensing of mining projects, since the survey of cavity attributes and their systematization in the EspeleoVale system helped in the choice of permanent preservation areas as a compensatory measure for irreversible impacts, especially in the context of the Abóboras Mine expansion project, in the Vargem Grande Complex, located in Nova Lima and Rio Acima (MG). We therefore believe that EspeleoVale stands out as a repository and management tool for speleological data.

1. Introdução

As cavernas desempenham um papel de suma importância na compreensão de processos geológicos hidrológicos,climáticos e biológicos, também comportam uma biodiversidade e patrimônios histórico-culturais únicos. O registro integrado e padronizado dos dados espeleológicos é essencial para a conservação e o manejo sustentável dos ambientes em que estão inseridas, apresentando informações sobre localização, formação, estrutura, entorno, riscos e ameaças. Inventários nacionais integrados, como por exemplo, o Cadastro Nacional de Informações Espeleológicas (CANIE) no Brasil, são fundamentais para a centralização desses registros, permitindo e facilitando o acesso a pesquisadores e gestores (ICMBIO, 2024). Um exemplo que demonstra como dados sistematizados são importantes para tomadas de decisão para a preservação e o manejo sustentável das áreas foi realizado por CUNHA et al. (2022), onde é destacado o desenvolvimento de um sistema de monitoramento microssísmico que utiliza como objeto de estudo agrupamentos de cavidades naturais na região da Serra Norte, no Pará. Outra iniciativa como o Karst Information Portal (KIP) demonstra a importância da cooperação internacional na centralização e no compartilhamento de informações espeleológicas, contribuindo para decisões mais informadas e sustentáveis (FLEURY et al 2008).

A proteção de cavidades é garantida por lei específicas em diversos países, tanto por seu valor ecológico, geológico, histórico e cultural. No Brasil, de acordo com o Decreto Federal 99.556/1990, alterado pelo decreto 6.640/2008 e do disposto na Instrução Normativa do Ministério

do Meio Ambiente IN-MMA 02/2017, considerando que o Decreto Federal 10.935/2022, encontra-se parcialmente suspenso pelo Supremo Tribunal Federal (STF) até a presente data, e a Resolução CONAMA nº 347/2004 estabelecem normativas para o licenciamento ambiental em áreas que contenham cavidades naturais subterrâneas, onde são exigidos estudos espeleológicos como parte do processo (BRASIL, 1990; CONAMA, 2004). Em contexto global, a International Union for Speleology (UIS) expõe a necessidade de políticas integradas que levem em consideração os dados espeleológicos como base para decisões sustentáveis, o que traz contribuições para a gestão eficiente e conservacionista de sistemas cársticos (UIS, 2024). Estudos como o de Moraes et al. (2020), que demonstra uma abordagem a aplicação de modelagem 3D para a visualização e o planejamento em áreas de mineração, mostram como avanços tecnológicos recentes podem ser utilizados conjuntamente a essas normativas para promover a conservação.

A gestão de dados espeleológicos é um outro ponto que, apesar de sua importância, apresenta desafios que precisam ser superados, como a dificuldade para integrar diferentes bases de dados, causado em considerável parte pela falta de padrão nos dados cadastrados, por vezes acarretada pela limitação de financiamento e a falta de recursos técnicos qualificados para as atividades. Além disso, as questões envolvendo segurança e acesso aos dados ainda são pontos centrais na discussão, especialmente em contextos em que informações sensíveis precisam ser protegidas (MATTHEWS, 2019).

CUNHA et al. (2022) trazem um exemplo de otimização do gerenciamento de dados de monitoramento microssísmico, e como essa atividade pode ser implementada para a detecção precoce de instabilidades em cavernas e ainda mitigar os riscos.

Apesar de não serem acessíveis em todos os contextos, tecnologias mais recentes vêm melhorando a forma como os dados espeleológicos são coletados, armazenados, analisados e demonstrados. Uma aplicação que vem revolucionando o estudo de cavidades é a utilização de LiDAR, que junto à fotogrametria digital e modelagem 3D, tem permitido a criação de mapeamentos extremamente detalhados das cavernas, facilitando estudos e a exploração (JOURNAL OF CAVE AND KARST STUDIES, 2024). Plataformas como QGIS e ArcGIS vem sendo utilizadas para solucionar problemas de integração de dados espeleológicos com outros bancos ambientais, possibilitando análises espaciais mais abrangentes e embasadas a múltiplos parâmetros. MORAES et al. (2020) também relatam a aplicação prática de tecnologias de mapeamento 3D para identificar áreas de risco e planejamento ambiental, destacando os benefícios da adoção de soluções tecnológicas avançadas no manejo de cavernas. Além de contribuírem com a gestão de cavernas, esses movimentos auxiliam também em questões educacionais e no engajamento da sociedade civil sobre a importância desses ecossistemas.

Portanto, este estudo tem como objetivo mostrar o uso de um software como serviço (SaaS), denominado EspeleoVale, para exemplificar as vantagens que um sistema pode exercer no gerenciamento de dados espeleológicos. No presente caso demonstraremos o uso da solução por meio de duas cavernas preservadas (cavidades testemunho).

2. Materiais e métodos

O EspeleoVale emprega tecnologias de software livre e de código aberto para fornecer um sistema abrangente de gerenciamento de dados espeleológicos. Hospedado na Amazon (AWS), sua arquitetura principal utiliza linguagens de script de código aberto, como JavaScript, HTML, CSS, Golang e SQL. Os componentes e estruturas da plataforma incluem AngularJS, sistema de gerenciamento de banco de dados relacional (RDBMS) PostgreSQL com a extensão PostGIS e Mapstore2 integrado ao Geoserver (ASSUNCAO, 2024).

No EspeleoVale, tem-se a possibilidade de empresas cadastrarem cavidades e suas respectivas informações, coletadas em campo e relatórios técnicos ou tramitadas em órgãos ambientais, além da possibilidade da empresa responsável pela contratação dessas empresas, no caso a Vale S.A, validar essas informações. Esses registros são armazenados em um repositório de dados espeleológicos que organiza a documentação dos principais estudos sobre as cavidades, incluindo prospecção, mapeamento e topografia, geoespeleologia, bioespeleologia, patrimônio cultural e relevância. Além dos estudos, existem módulos para o gerenciamento dos dados que permitem estabelecer correlações, possibilitando uma visão global do nível de conhecimento acerca daquela cavidade e de todas as outras presentes em uma determinada região ou projeto. O banco de dados, devido sua estrutura relacional, permite análises avançadas acerca dos dados cadastrados e possibilita a publicação de informações que alimentam painéis (*PowerBI*) e recursos de visualização web (*WebGIS*), auxiliando stakeholders a conhecerem e gerenciar o conteúdo espeleológico. Tal arquitetura amplifica ações de desenvolvimento sustentável, mediante o equilibro entre o desenvolvimento econômico e a preservação do meio ambiente (ARAUJO, 2011).

O atributo testemunho, segundo a IN MMA nº 02/2017, diz respeito "testemunho de processos ambientais ou paleoambientais expressivos ou cavidade com grau de relevância alto apontada como salvo conduto para liberação de impactos a outra cavidade". Para o presente estudo o EspeleoVale foi consultado para demonstrar informações de duas cavidades testemunho, sendo elas as cavidades TUTA_0007 e TUTA_0014.

3. Resultados

Na porção oeste do município de Nova Lima (MG) próximo à divisa com o município de Brumadinho (MG), cerca de 1 Km da BR-356 e do condomínio Miguelão estão localizadas as cavidades objeto de estudo. Denominadas TUTA_0007 e TUTA_0014, estão inseridas na unidade espeleológica Quadrilátero Ferrífero e unidade geomorfológica Quadrilátero Oeste, que compreende as Serras do Curral, Moeda e do Itabirito. As duas cavidades encontram-se localizadas em áreas de litologia de rochas ferríferas, pertencentes ao grupo Itabira. Também estão localizadas no Monumento Natural (MONA) Serra da Calçada, uma unidade de conservação de jurisdição municipal e de proteção integral, que de acordo com a Lei Sistema Nacional de Unidades de Conservação da Natureza (SNUC), "têm como objetivo preservar sítios naturais raros, singulares ou de grande beleza cênica." Embora localizada em um vetor de crescimento urbano da região metropolitana de Belo Horizonte e na região do Quadrilátero Ferrífero que historicamente é conhecida pela extração de minérios, a MONA da Serra da Calçada faz parte de um conjunto de unidades de conservação que apresentam certa conectividade de áreas protegidas com importância estratégica para a proteção ambiental e ecológica da região (Figura 1).

No contexto de compensação ambiental espeleológica para o licenciamento ambiental dos empreendimentos minerários, a caracterização e os estudos acerca das cavidades da região de Tutámeia na Serra da Calçada foi de suma importância. O levantamento dos atributos ecológicos, biológicos, geológicos, hidrológicos, paleontológicos, cênicos, histórico-culturais e socioeconômicos das cavidades, assim como o cadastro e sistematização dos resultados desses estudos no sistema EspeleoVale, representam importante fase de estruturação da informação, e contribuem para a escolha de cavidades testemunho como medida compensatória para impactos negativos irreversíveis, em acordo com o Artigo 4º do Decreto nº 6.640 de 7 de novembro de 2008. Neste caso,

objetivando a compensação de cavidades localizadas próximas a áreas de exploração mineral do projeto de Ampliação da Mina de Abóboras, localizada no Complexo Vargem Grande, Nova Lima e Rio Acima (MG). (BRASIL, 2008).

As cavidades foram identificadas em 2012 através de prospecção espeleológica por empresa contratada e tiveram sua localização e ficha de prospecção adicionadas ao EspeleoVale. Foram identificadas as principais características das cavidades como estado de conservação e medidas espeleométricas estimadas. Os estudos de prospecção mencionam a ocorrência das cavidades em litologia ferrífera com blocos abatidos na região interna, presença de invertebrados, morcegos e raízes. Em 2014, outra empresa foi responsável pela fase de topografia, etapa de caracterização e elaboração de mapeamento com a morfologia das cavidades. Na ficha de topografia foram adicionadas informações espeleométricas, e mapas topográficosdas cavidades foram anexados (formato .dwg), a saber, TUTA_0007 apresenta projeção horizontal de 14,1 metros e área de 29,6 m² e TUTA_0014 apresenta projeção horizontal de 26 metros e área de 91,9 m². A ficha de topografia juntamente com as fichas de geoesepeleologia, bioespeleologia e histórico-cultural, fornecem atributos para caracterizar e classificar a relevância das cavidades. Esses diagnósticos compõem o protocolo dos estudos iniciais no processo de licenciamento e dos estudos de relevância realizados sob a vigência do Decreto Federal nº 99.556/1990, alterado pelo Decreto Federal nº 6.640/2008 e do disposto Instrução Normativa IN-MMA 02/2017 do Ministério do Meio Ambiente, vigente durante a apresentação dos estudos aos órgãos licenciadores.

Os atributos de enfoque local das cavidades TUTA_0007 e TUTA_0014 identificados são a presença de táxons novos. Para a cavidade TUTA_0007 foram identificados *Pseudosinella* sp.1 (Collembola: Entomobryidae) e Gen. nov. 2 ca. *Gisinurus* sp.1 (Collembola: Sminthuridae) e para a cavidade TUTA_0014, *Pseudosinella* sp.1 (Collembola: Entomobryidae). Quanto a presença de espécie troglomórfica, encontrou-se a *Pseudosinella* sp.1 (Collembola: Entomobryidae) nas duas cavidades. Em hidrologia foi identificado água de percolação.

No enfoque regional as cavidades apresentam riquezas e diversidade de espécies, como *Phalangopsini* sp2, *Endecous* sp1; *Phalangopsini* sp1; e *Pseudonannolene* sp1. Quanto ao atributo troglóbios que não sejam considerados raros, endêmicos ou relictos, que considera a presença de espécies de ocorrência restrita a ambientes subterrâneos que ocorrem em outras localidades do Quadrilátero Ferrífero, as espécies Tisentnops mineiro (Araneae: Caponiidae),aff. Ochyrocera sp.1 (Araneae: Ochyroceratidae) e Pseudosinella sp.1 (Collembola:Entomobryidae) são encontradas nas duas cavidades. Em espeleometria, TUTA_0007 destaca-se por volume e projeção horizontal, TUTA_0014, por sua vez, destaca-se pelos quatro atributos físicos analisados: projeção horizontal, volume, área e desnível. A partir da avaliação dos atributos presentes no enfoque regional, observa-se que ambas as cavidades apresentaram importância acentuada (com base no Anexo III da IN MMA nº 02/2017), de acordo com a quantidade de grupos pontuados. A classificação de importância acentuada sob enfoque regional já estabelece o grau alto de relevância para as cavidades conforme chave de classificação do grau de relevância que integra o Anexo IV da IN MMA nº 02/2017.

Durante o licenciamento de ampliação da Mina de Abóboras, a autorização para impacto negativo irreversível em quatro cavidades foi solicitada aos órgãos competentes. A Vale S.A apresentou no termo de compromisso de compensação espeleológica (TCCE) a proposta de preservação das cavidades TUTA_0007 e TUTA_0014 e suas áreas de influências como compensação para a cavidade ABOB_0018 de alta relevância e atributos similares às duas cavidades testemunho. Deferida no ano de 2024 pelo órgão ambiental de Minas Gerais, através de parecer único de licenciamento, as cavidades TUTA_0007 e TUTA_0014 passaram a ser consideradas como Testemunho, atributo que classifica as cavidades como de máxima relevância.

Todas as informações apresentadas acima e as verificações dos status das fichas foram consultadas no EspeleoVale, conforme exemplificado na Figura 2.

Exemplificando o uso e integração disponível no EspeleoVale, a Figura 3 traz informações das cavidades apresentadas neste estudo e suas respectivas áreas de influência definidas e aprovadas pelo órgão ambiental. Além da representação espacial, o usuário pode consultar os atributos, baixar informações e realizar interpretações a partir de outros dados espaciais ou imagens de satélite (*Basemap*).

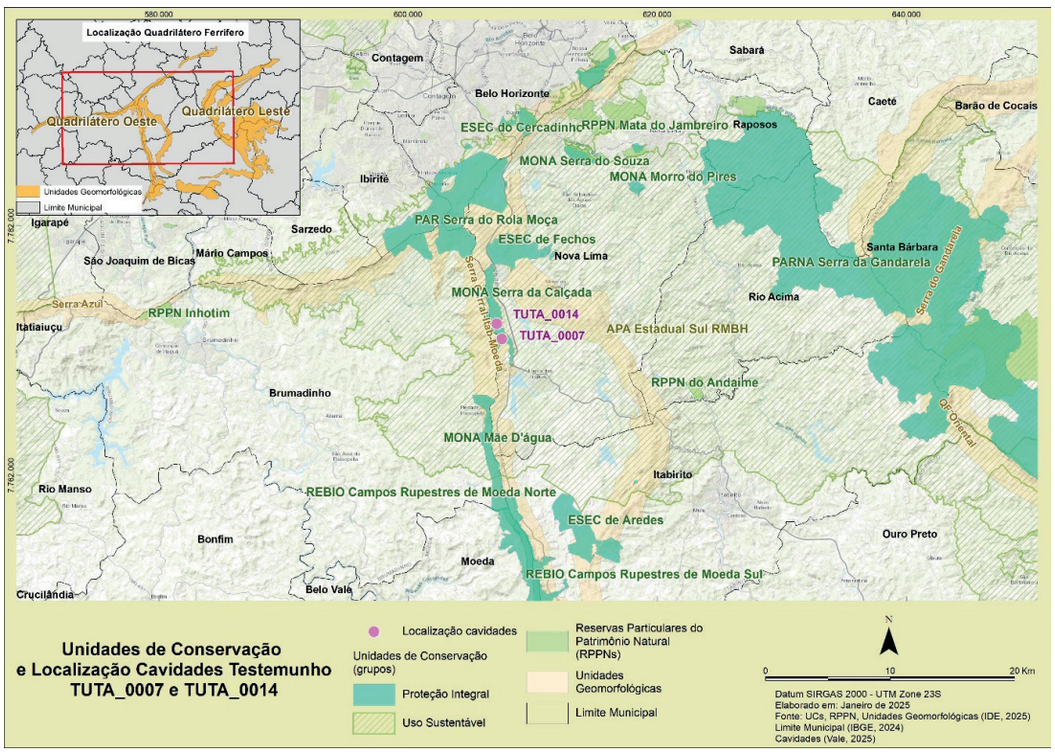


Figura 1: *Mapa de localização e contextualização ambiental das cavidades testemunho TUTA_0007 e TUTA_0014.*

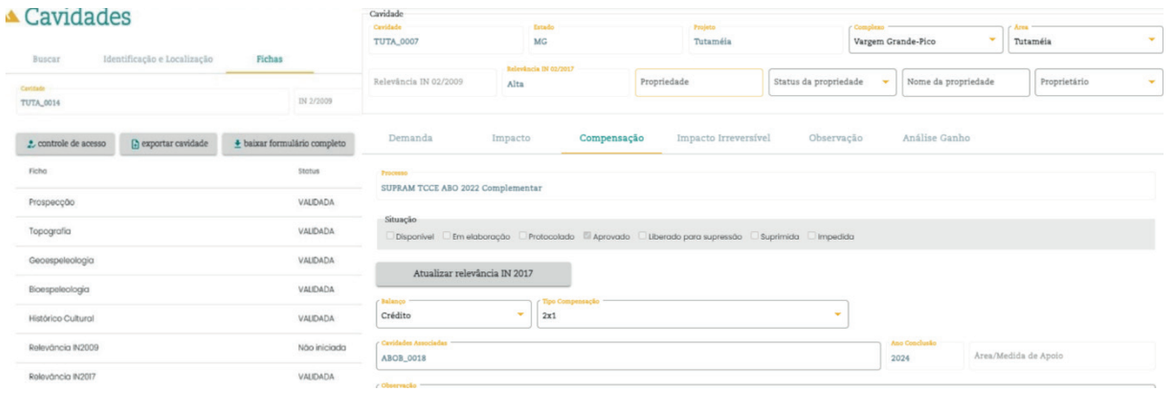


Figura 2: *Módulo de apresentação e consulta das fichas cadastradas para cada cavidade (imagem à esquerda) e Módulo de cadastramento de informações de compensação ambiental (imagem à direita) - EspeleoVale.*

4. Discussão

O uso de bancos de dados para o gerenciamento de dados espeleológicos oferece capacidade de armazenamento de grandes conjuntos de dados em um repositório central, permite atualizações e backups, possibilita pesquisas e consultas personalizadas em diversas áreas, suporta vários formatos de saída, e integra-se à outras tecnologias e facilita o acesso remoto e as atualizações por meio de plataformas baseadas na Web (MATTHEWS, 2019).

O armazenamento centralizado de dados apresenta facilidade no gerenciamento e manutenção. Ao consolidar os dados em um único local, organizações podem se beneficiar de processos simplificados de governança e conformidade de dados (RAFIQUE et al., 2015; MEZNI et al., 2018). Além disso, os sistemas centralizados podem aproveitar as economias de escala, reduzindo os custos associados ao armazenamento e ao gerenciamento de dados em comparação com os sistemas descentralizados (OJALA, 2013). SAVAGE et al (2018) por exemplo utilizaram um modelo de gerenciamento de dados estruturado para aprimorar a eficiência de desenvolvimento de uma mina subterrânea.

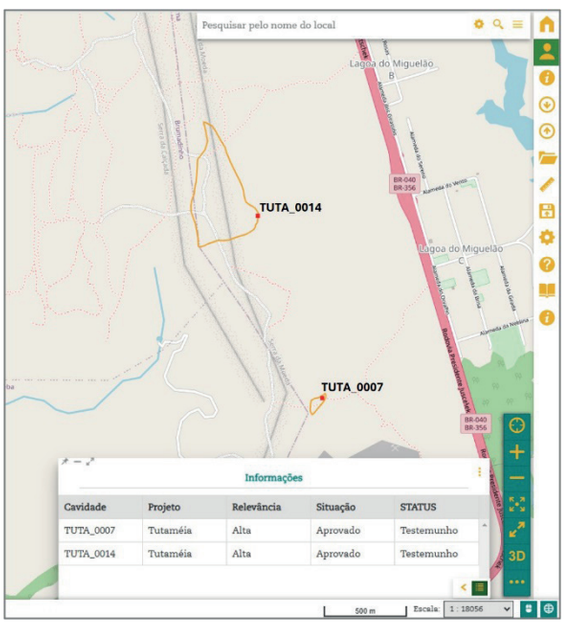


Figura 3: *WebGIS (MapsEspeleo) exibindo informações alfanuméricas e representações espaciais, presentes no EspeleoVale, das cavidades TUTA_0007 e TUTA_0014 e suas áreas de influência definidas.*

Além disso, a organização e estruturação do armazenamento de dados espeleológicos permitem a realização de análises sofisticadas e a compatibilidade com outras tecnologias, como GIS, dashboards, e linguagens de programação. Em contrapartida, métodos baseados em papel são propensos a inconsistências e impraticáveis para consultas complexas, o que limita sua utilidade em aplicativos modernos e orientados por tecnologia (MATTHEWS, 2019). GAO et al (2002) demonstra a integração de dados espeleológicos da região do estado do Minnesota-EUA com ambientes SIG Desktop. Neste trabalho, essa integração é demonstrada por meio de utilização de recursos de visualização *Web*, explorando os avanços e as vantagens de se utilizar um repositório de dados espeleológicos que permite a publicação e a atualização das informações para visualização em um ambiente compartilhado.

O controle de acesso é outra ferramenta essencial para o gerenciamento de dados espeleológicos, garantindo uma atribuição de permissão segura, simplificada e flexível que se adapta à dinamicidade de equipes que se dividem em trabalhos de campo e trabalhos de escritório, além de proteger a integridade dos dados e impedir o acesso não autorizado (PEREIRA, 2006). O EspeleoVale, por exemplo, conta com usuários que podem cadastrar informações, fiscais com conhecimento técnico em cada temática que podem avaliar informações cadastradas e administradores que possuem maior controle para o cadastro de empresas, liberação de acessos e atribuições à usuários.

FLEURY et al (2008) mencionam que a administração de cavidades e ambientes cársticos demandam acesso a diferentes análise e informações. Com isso, os autores criaram um portal, denominado Karst Information Portal, para que usuários pesquisem publicações, pesquisem e publiquem dados sobre ambientes cársticos, o que favorece um desenvolvimento colaborativo e compartilhamento de ideias entre pesquisadores. O EspeleoVale é um exemplo de repositório aplicado à iniciativa privada, que traz assertividade nas análises estratégicas, e eficiência na gestão de informações espeleológicas.

5. Conclusão

O propósito principal deste trabalho foi de apresentar a aplicação de um *software* como serviço (SaaS) - EspeleoVale, destacando os benefícios que um sistema pode oferecer na gestão de dados espeleológicos.

O EspeleoVale é um software em constante aperfeiçoamento que visa atender de forma ágil e eficiente as demandas dos diferentes usuários para diversos fins, como consulta de dados espaciais, cadastramento e alimentação de fichas espeleológicas, dentre outros. Os ganhos obtidos através da organização dos dados espeleológicos em plataforma única garantem o acesso e integridade, o que potencializa a assertividade das análises.

No sistema estão registradas todas as cavidades que precisam passar por análises e serem administradas pela companhia. Portanto, o gerenciamento dos dados das cavidades desde o período de prospecção, perpassando por todas as etapas de caracterização como levantamento topográfico, estudos de bioespeleologia e geoespeleologia, histórico-cultural, além da relevância da cavidade contribuem para tomada de decisão embasada na totalidade de informações. A indicação das cavidades testemunho, por exemplo, passa por análises criteriosas que, a partir da consulta facilitada aos dados espeleológicos, atribuem eficiência e assertividade na tomada de decisão.

A caracterização e os estudos das cavidades na região de Tutámeia, Serra da Calçada, foram essenciais para a Vale S.A. no contexto de compensação ambiental espeleológica para o licenciamento de empreendimentos minerários. O levantamento dos atributos ecológicos, biológicos, geológicos, hidrológicos e outros, além do cadastro no sistema EspeleoVale, ajudou na escolha de cavidades testemunho para compensar impactos irreversíveis, especificamente no projeto de Ampliação da Mina de Abóboras. As cavidades TUTA_0007 e TUTA_0014, identificadas em 2012 e caracterizadas em 2014, apresentaram características significativas, como a presença de táxons novos e diversidade de espécies. Ambas foram classificadas como de alta relevância, e a Vale S.A. propôs sua preservação como compensação para outra cavidade de alta relevância.

De posse às referências bibliográficas apresentadas e estudo de caso das cavidades TUTA_0007 e TUTA_0014, acredita-se na substancialidade do EspeleoVale como repositório, ferramenta de gerenciamento e gestão de dados espeleológicos. O constante aperfeiçoamento da ferramenta em acordo com o atendimento de demandas identificadas pelos diversos perfis de usuários garante sua atualização contínua e sobrevida ao longo do tempo.

Agradecimentos

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The importance of harmonized terminology for the protection of caves and karst landscapes

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Abstract

The sustainable protection of caves and karst landscapes is a challenge that includes not only ecological but also social and economic aspects.

Experiences from various construction projects have shown that misunderstandings between project participants, such as developers, contractors, authorities, environmental organizations, speleologists, and other stakeholders, often prevent the development of meaningful, sustainable, and effective protection measures due to different terms and concepts being used. One of the fundamental prerequisites for effective protection is the establishment of a standardized and accurate karst nomenclature.

This paper examines the need for a standardized nomenclature and identifies the consequences that misunderstandings in terminology can have for the protection of caves and karst landscapes.

The paper shows that a common understanding of the phenomena and processes in karstified rock mass is based on a common language. A nomenclature that is used and understood in the same way by everyone involved in a project is a major challenge. Therefore, a German-language karst nomenclature for engineering geologists and civil engineers has been proposed. This provides all stakeholders involved in a project with standardised, coherent terminology based on current and scientifically sound concepts. The precise nomenclature is the basis for a common understanding of the hazards related to the karstified rock mass and allows an adequate understanding of the relationship between rock mass, building, construction methods, and environmental aspects by all participants of a construction project. Fundamental misunderstandings are avoided. This is a prerequisite for a common understanding and elaboration of sustainable solutions for the protection of caves and karst landscapes.

Résumé

La protection durable des grottes et des paysages karstiques est un défi qui comprend non seulement des aspects écologiques, mais aussi sociaux et économiques.

L'expérience de divers projets de construction a montré que les malentendus entre les participants au projet, tels que les promoteurs, les entrepreneurs, les autorités, les organisations environnementales, les spéléologues et les autres parties prenantes, empêchent souvent l'élaboration de mesures de protection significatives, durables et efficaces en raison de l'utilisation de termes et de concepts différents. L'une des conditions préalables à une protection efficace est l'établissement d'une nomenclature standardisée et précise du karst.

Ce document examine la nécessité d'une nomenclature normalisée et identifie les conséquences que les malentendus terminologiques peuvent avoir pour la protection des grottes et des paysages karstiques.

L'article montre qu'une compréhension commune des phénomènes et des processus dans les masses rocheuses karstifiées est basée sur un langage commun. Une nomenclature utilisée et comprise de la même manière par toutes les personnes impliquées dans un projet est un défi majeur. C'est pourquoi une nomenclature karstique en langue allemande a été proposée pour les géologues et les ingénieurs civils. Elle fournit à toutes les parties prenantes d'un projet une terminologie standardisée et cohérente, basée sur des concepts actuels et scientifiquement fondés.

La nomenclature précise est la base d'une compréhension commune des risques liés à la masse rocheuse karstifiée et permet une compréhension adéquate de la relation entre la masse rocheuse, le bâtiment, les méthodes de construction et les aspects environnementaux par tous les participants d'un projet de construction. Les malentendus fondamentaux sont évités. C'est une condition préalable à une compréhension commune et à l'élaboration de solutions durables pour la protection des grottes et des paysages karstiques.

1. Introduction and issue

Karst landscapes are fragile landscapes that can suffer irreparable damage from human activities, often unintentionally. This damage usually results from an insensitive or inadequate understanding of the karstified rock mass, rather than a lack of regulations or resources. Instead, «inappropriate actions» are often due to a lack of understanding of the unique characteristics of the karstified rock mass and/or differing understandings of the hazard situation among the involved stakeholders within a construction project.

From a civil engineering point of view, karstified ground harbours hazards that are absent or less pronounced in other types of ground. A key feature is that construction projects are not only threatened by karst phenomena (such as collapsing of karst voids) but also pose a risk by themselves to the karst landscape and karst groundwater (like groundwater pollution). This dual risk requires an interdisciplinary approach

to manage the karst hazard adequately and sustainably. As Alija et al. (2013) concluded: "It is important to highlight that the karst phenomenon is one of the most difficult problems to solve in [construction], due to the great diversity of circumstances that may come up, and especially because of the variability of their occurrence".

The realization involves various, and during the time, changing stakeholders in the different project phases like planning, approving, construction, operating, and dismantling a structure. Typically, this includes the client, authorities, planners, geologists, contractors, speleologists, environmental groups, and other stakeholders (Figure 1). Each group has different goals and, more importantly, different approaches and understandings of the karstified rock mass and its hazards. As Day (2004) already noted, the common understanding of the specifics of karst ground is crucial for a successful realization of a construction project.

The experiences of various construction projects showed that misunderstandings between the stakeholders involved in a project, due to the different use and understanding of karst-related expressions, have often prevented the elaboration of solution-orientated, sustainable and effective protection measures. It can be concluded that the establishment of a standardized and precise karst nomenclature is one of the fundamental prerequisites for effective protection of caves and karst landscapes.

The systematic analysis of such misleading projects allowed us to identify the following nomenclature-related issues (the following examples are taken 1:1 from various construction projects to illustrate the issues):

- Use of the term 'karst' as a generic term for 'karst landscape', 'karst cavity', 'karst aquifer', 'karst hazard', etc.
    - Original: 'Karst was encountered three times during construction.
    - Probably meant: 'Three karst voids were encountered during construction.'
    - Original: 'Karst is to be expected.' Presumably meant: 'Karstified rock is to be expected.'
    - Original: 'The dynamics of karst lead to considerable challenges.'
    - Presumably meant: 'The dynamics of the karst aquifer lead to considerable challenges.'
    - Original: 'The karst was larger than predicted.'
    - Probably meant: 'The karst void was larger than predicted.'
- Use of misleading definitions.
    - Original: 'Caves are to be expected during construction.' Better would be: 'Karst voids are to be expected during construction.'
- Mixing of terms from different concepts (Figure 2).
    - Original: 'The tunnel crosses an extensive shaft zone before entering the phreatic zone.'
    - Better would be: 'The tunnel crosses an extended speleogenetic shaft zone before entering the horizontal cave zone.' or 'The tunnel crosses an extended vadose zone before entering the phreatic zone.'
- Disregarding the hierarchy of terms.
    - Original: 'The motorway crosses an area with depressions and collapse dolines.'
    - Better would be: 'The motorway crosses an area with solution and collapse dolines.' or more generic: 'The motorway crosses a karstified area with depressions.'
    - Original: 'Karst voids and caves are to be expected.'
    - Better would be: 'Karst voids are to be expected.'
- Use of terms that are used differently in different geological disciplines.
    - Original description by the sedimentologist: 'Caverns were observed in several sections of the borehole.'
    - Better: 'Karst voids were encountered in several sections of the borehole.'
- Misunderstandings due to anglicisms.
    - This category includes terms that were 'creatively' translated and then lost their meanings.
- Use of project-specific definitions.
    - The use of project-specific terms. These were often not used or understood by everyone involved in the project.

It was also interesting to realize that the use of 'outdated' concepts and understanding of karstification often led to fewer structural engineering consequences compared to the consequences of a misunderstanding of terminology. However, the use of outdated concepts generally led to greater forecasting uncertainty and more costs during execution.

The evaluation is based on construction projects whose documentation was available in German, English or French. It can be assumed that the same or similar misunderstandings also exist in other languages.

We assume that when terms are misused, it is often not only a question of the purely semantic ambiguity of terms, but also of the actual understanding of the term and ultimately the understanding of the underlying theoretical and conceptual constructs.

We are convinced that a common understanding of the karst problem is based on a common nomenclature and represents a major challenge for all project participants. In this context, a German-language karst nomenclature for civil engineers and engineering geologists was proposed. This provides all stakeholders involved in a construction project with standardized, coherent terminology based on current and scientifically sound concepts. The precise nomenclature is the basis for a common understanding of problems and systems by all project participants. This avoids misunderstandings. This is the prerequisite for defining and implementing common, meaningful project-related goals for cave and karst protection and sustainable measures. We are convinced that the standardized use of terminology across all projects will improve the structural handling of karst problems.



Figure 1: *Paleo-karst landscape exposure in a quarry in Apricena (Italy) as an example of the complex issues involved in describing a karstified rock mass for engineering purposes.*

2. Karst nomenclature for civil engineers, engineering geologists, karst specialists and cavers

The aim of the 'Karst Nomenclature for Civil Engineers and Engineering Geologists' (Filipponi et al. 2022), is to provide practical definitions that are based on established concepts. The nomenclature is intended as a recommendation for the standardised use of karst-related terms in engineering geology practice. It pursues the following objectives:

- A basis is created for standardized karst hazards related communication between all stakeholders involved in the construction project.
- The understanding of the geological-hydrogeological processes of the rock mass conditions encountered in a karstified rock mass is promoted.
- A basis is created for objective, reproducible and adequate descriptions of the karst-relevant rock conditions.
- The formulation of adequate rock mass models for karstified ground is made possible.
- The systematic derivation of comprehensible hazard patterns for karstified subsoil is promoted.
- The formulation and development of suitable investigation and exploration objectives as well as appropriate methods for karst-related hazards is promoted.
- The planning and implementation of suitable and sustainable construction or protection measures with regard to karst hazards are promoted.
- The karst nomenclature aims to bridge the gap between speleology and construction practices.
- The definitions are based on today's established concepts and understanding of karstification processes.

Around 200 relevant karst-related terms were selected for the nomenclature, which play a role in the everyday work of engineering geologists and civil engineers working in karstified rock masses. Accordingly, the nomenclature does not claim to be complete. The focus was clearly on practical suitability and not on 'academic' completeness.

When compiling the definitions, previously published nomenclatures (e. g. Trimmel 1965; Monroe 1972; Unesco 1971; Field 1999; Gunn 2003) and the extensive scientific literature (e. g. Palmer 2012; Klimchouk 2000; Bögli 1978; de Waele & Gutierrez 2022; Stevanović 2015; Filipponi et al. 2012.) were consulted, as well as the experiences of the construction projects. The compilation work showed that there is no standardized definition for many terms in the literature. This is partly due to the fact that the understanding of karst landscape and aquifer development has evolved significantly over the last decades. Therefore, new terms have been introduced to explain the new concept. Furthermore, already existing terms have also been redefined. Others have been replaced and still others have become obsolete.

The proposed nomenclature is divided into chapters that allow the terms to be defined via thematic contexts. Such topics include, for example, general, superordinate terms, spatial delimitations, genetic processes, geomorphological descriptions, hydrogeological functions and processes, properties of karst voids and their fillings. Conceptual approaches such as the concept of inception horizons, the speleogenetic zones, and stages of karst aquifer development are also introduced. A special focus was given to the particular role of speleological terms and cave exploration by speleologists. The terms were defined, the definitions justified, and the underlying concepts explained. The book attempts to create a relevant practical reference with instructive graphics and 'practical tips' emphasizing the everyday use for engineering geologists and civil engineers.

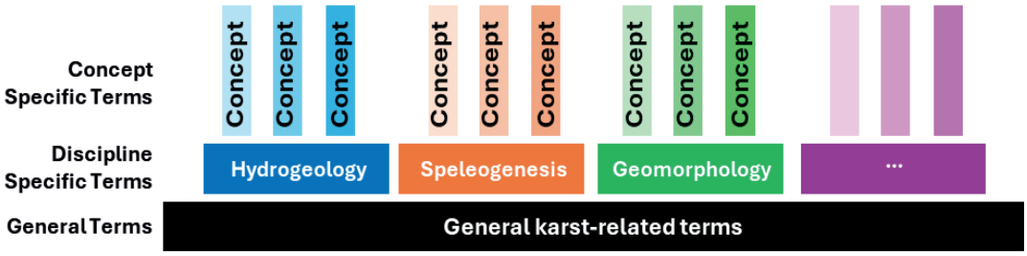


Figure 2: Karst-related terms can belong to a specific discipline or even within specific concepts within a discipline. It is recommended, do not mix up terms belonging to different concepts.

Some 'radical' decisions were also made. For example, the recommendation that the term 'karst' should no longer be used as a generic term for 'karst landscape', 'karst cavity', 'karst aquifer' or 'karst hazard'. 'Karst' should only be used on its own if it explicitly refers to the geographical region of the Karst. When analyzing the nomenclature of the construction projects, we found that the use of the term 'karst' as a generic term often leads to ambiguities, even when the project-related context should actually be given.

Figure 3 shows a typical example of the karst nomenclature for the conceptual approach to defining void types in karstified rock mass. It illustrates the meaningfulness of the delimitation of voids according to genetic aspects and size. Furthermore, it illustrates that not all voids in karstified rock are karst voids, as well as that not all dissolution voids are karst voids.

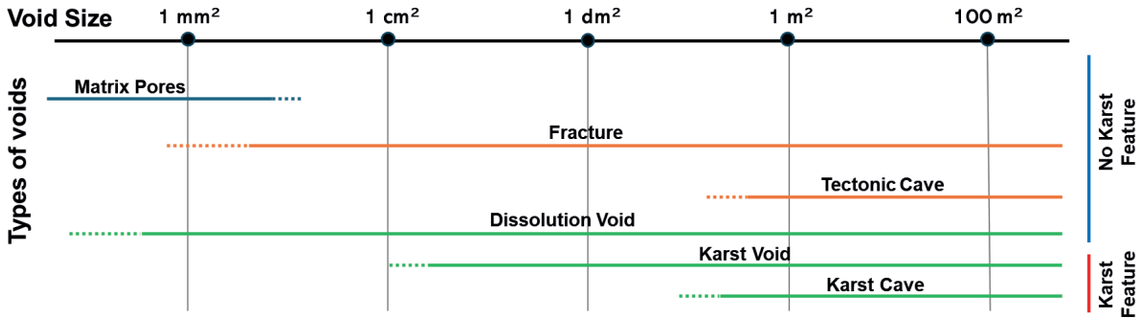


Figure 3: Classification of different voids in a karstified rock mass according to size and genetic aspects.

3. Effect of the nomenclature in practice

The first feedback from engineering geologists and engineers using the proposed 'Karst nomenclature for engineering geologists and civil engineers' has been positive. It is still too early to judge whether and how the terms will become established in practice. However, the reactions show that there is a need for a practical and coherent nomenclature. It can be stated that the publication has raised awareness of karst-specific hazards and problems to a certain extent. The proposed nomenclature has initiated a discussion about the practical description and interpretation of karstified rock mass and, in this sense, also about the protection of karst landscapes, karst aquifers and caves.

A translation of the nomenclature into other languages is currently not foreseeable. However, as a first step in this direction, a translation of the term into English and French has been provided (www.bauen-im-karst.info).

The provision of a consistent, practicable karst nomenclature is an important first step towards a common understanding of the challenges of building in karstified rock mass. Next, it would be desirable for this to be applied as far as possible in everyday practice. This presupposes that:

- all participants understand the terms and the associated concepts,
- terms from different concepts are not mixed up,
- the hierarchy of terms is respected,
- the introduction of project-specific terms is avoided.

The authors are aware that this will take time. However, the first feedback and observations are encouraging.

Acknowledgments

We would like to thank our co-authors of the 'Nomenclature' Ullrich Joerin and Gorgio Höfer-Öllinger as well as all our colleagues who discussed and criticized with us the karst nomenclature for practical use in the construction sector.

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Transformação digital na espeleologia profissional com a análise de risco por aplicativo - Speleosafety

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Resumo

Este trabalho aborda o desenvolvimento do SpeleoSafety, um aplicativo voltado para a análise de risco de tarefas, desempenhadas em estudos espeleológicos no mercado profissional brasileiro. Criado inicialmente utilizando tecnologias de realidade aumentada (AR) e virtual (RV), com o objetivo de visualizar previamente as cavernas, à partir de uma experiência imersiva, o projeto transformou a ART – Análise de Risco de Tarefa, que é um documento comum de ambientes corporativos para a liberação de atividades críticas, em uma ferramenta dinâmica, podendo ser acessada em qualquer smartfone, de maneira simples e eficiente, uma vez que torna comum o conhecimento dos riscos identificados nas cavidades, difundindo-os para todas as pessoas que utilizam a aplicação.

Abstract

This paper addresses the development of SpeleoSafety, an application aimed at analyzing the risk of tasks performed in speleological studies in the Brazilian professional market. Initially created using augmented reality (AR) and virtual reality (VR) technologies, with the aim of previously visualizing caves through an immersive experience, the project transformed the ART – Task Risk Analysis, which is a common document in corporate environments for the release of critical activities, into a dynamic tool that can be accessed on any smartphone in a simple and efficient way, since it makes common knowledge of the risks identified in the cavities, disseminating them to all people who use the application.

Resumen

Este trabajo aborda el desarrollo de SpeleoSafety, una aplicación destinada a analizar el riesgo de las tareas realizadas en estudios espeleológicos en el mercado profesional brasileño. Inicialmente creado utilizando tecnologías de realidad aumentada (RA) y realidad virtual (RV), con el objetivo de visualizar previamente las cuevas a través de una experiencia inmersiva, el proyecto transformó el ART – Análisis de Riesgo de Tarea, que es un documento común en entornos corporativos para la liberación de actividades críticas, en una herramienta dinámica a la que se puede acceder en cualquier teléfono inteligente de forma sencilla y eficiente, ya que hace de conocimiento común los riesgos identificados en las cavidades, difundiéndolos a todas las personas que utilizan la aplicación.

1. Introdução

A espeleologia ao explorar e estudar cavernas, apresenta desafios únicos e riscos significativos, exigindo metodologias rigorosas de segurança e prevenção de riscos. A transformação digital, marcada pelo uso de tecnologias inovadoras, oferece uma oportunidade ímpar para revolucionar a maneira como esses riscos são analisados e gerenciados. O SpeleoSafety foi inicialmente desenvolvido para atividades espeleológicas na Vale, evoluindo para a ART Digital, expandindo seu escopo para atender diversas operações e setores. Este trabalho explora essa transformação e os benefícios resultantes, baseando-se na Análise de Risco da Tarefa (ART) que é um documento comum de ambientes corporativos para a liberação de atividades críticas (Fig. 1).

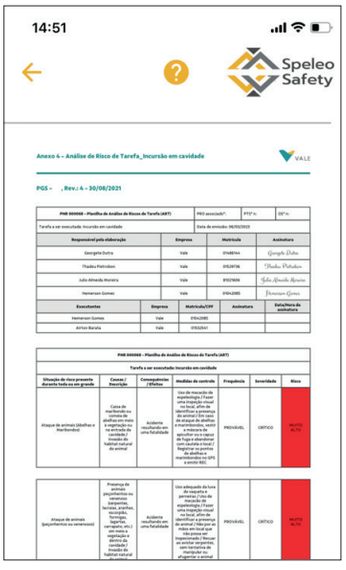


***Figura 1:**- Análise de Risco de Tarefa.*

2. Materiais e Métodos

A metodologia para o desenvolvimento do SpeleoSafety envolveu a colaboração entre especialistas em tecnologia, segurança do trabalho e espeleologia. O processo começou com a identificação dos requisitos de segurança específicos das atividades de campo, seguido pela integração de tecnologias de AR e RV para desenvolver simulações detalhadas das cavidades. Além disso, a plataforma foi projetada para ser intuitiva, permitindo fácil acesso e uso por parte dos trabalhadores em campo, o que foi fundamental para sua rápida adoção e eficiência (Fig. 2).



Figura 2: *Aparência da página inicial da aplicação Speleo Safety.*

O desenvolvimento da aplicação foi realizado utilizando *Flutter*, permitindo sua execução tanto em dispositivos móveis (Android e iOS) quanto na web. Para garantir uma experiência imersiva, foi integrado um módulo desenvolvido em *Unity*, responsável por renderizar cavidades em 3D dentro da aplicação. A comunicação entre *Flutter* e *Unity* foi estabelecida por meio de um pacote específico que facilita a incorporação e interação do módulo 3D, garantindo um desempenho fluido e uma integração eficiente entre as tecnologias. Dessa forma, os usuários podem visualizar e interagir com as cavidades tridimensionais de forma intuitiva, independentemente da plataforma utilizada (Fig. 3).

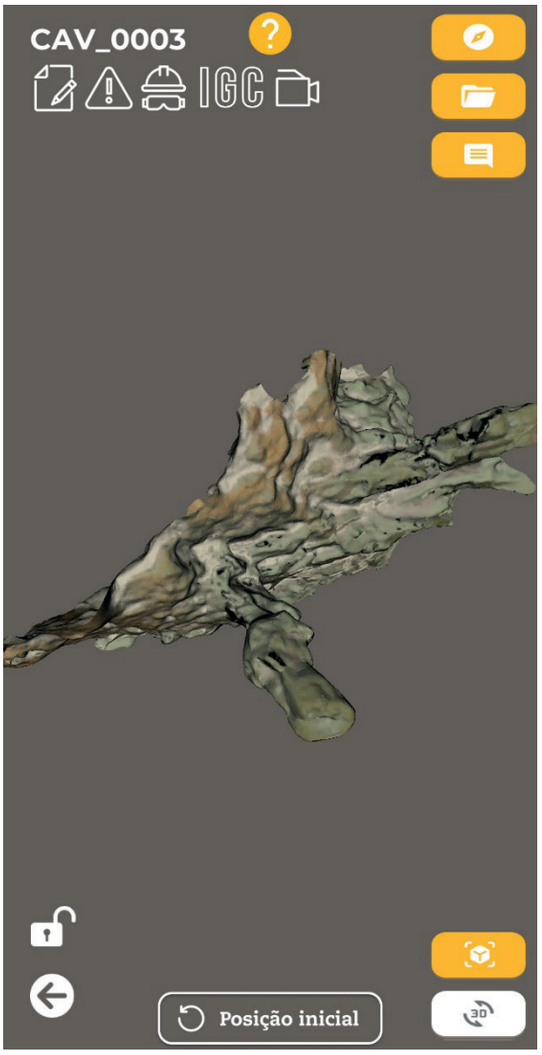


Figura 3: *Ferramenta de realizadade virtual incorporada no aplicativo.*

Além da visualização 3D, a aplicação também incorporou a biblioteca do Google Maps para criar um ambiente personalizado onde os usuários podem inserir riscos georreferenciados encontrados durante as atividades espeleológicas (Fig. 4).



Figura 4: *Ferramenta de geolocalização de riscos.*

Com essa funcionalidade, é possível adicionar marcadores e registrar informações relevantes diretamente no mapa, tornando a aplicação ainda mais interativa e útil para análise de riscos. Para armazenar e gerenciar todos os dados, foi utilizado o *Supabase*, um banco de dados baseado

em *PostgreSQL* que oferece suporte a autenticação, armazenamento e APIs em tempo real. A aplicação se comunica com o *Supabase* para salvar informações dos usuários, registros de interação com os modelos 3D, bem como os dados inseridos no mapeamento de riscos. Essa escolha possibilitou uma infraestrutura escalável e segura, permitindo que a aplicação funcione de maneira eficiente tanto em dispositivos móveis quanto na web, integrando diferentes tecnologias para oferecer uma solução completa e acessível em diversas plataformas.

3. Resultados

O SpeleoSafety transformou o processo manual e burocrático da ART em um sistema digital dinâmico, permitindo o usuário realizar uma reciclagem contínua através de um *Quiz* com os riscos inerentes as atividades espeleológicas. Através da realidade aumentada, os usuários podem visualizar os riscos potenciais em um ambiente controlado, permitindo uma melhor compreensão e preparação para as condições reais de campo.

A realidade virtual foi utilizada para treinar os funcionários em procedimentos de segurança sem expô-los a riscos reais, além de ter um planejamento prévio das atividades, uma vez que o mapa de riscos da cavidade é integrado a ferramenta, bem como as condições geotécnicas da cavidade em geral.

A padronização dos processos de ART através da plataforma digital resultou em uma gestão de riscos em tempo real, de forma consistente e colaborativa, uma vez que os riscos são compartilhados com todos os usuários assim que cadastrados. O feedback dos usuários indicou uma alta satisfação com a facilidade de uso do aplicativo e a eficácia do treinamento interativo.

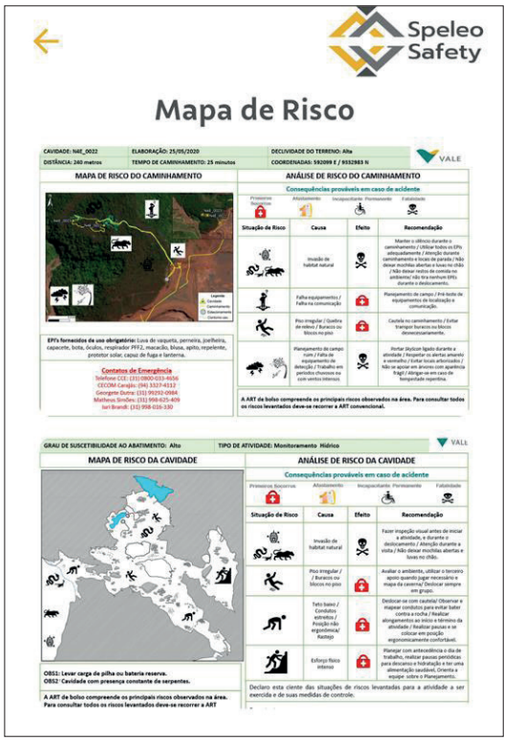


Figura 5: *Mapa de riscos da cavidade da ferramenta de realidade virtual.*

4. Conclusão

A ART Digital (APP SpeleoSafety) mostrou potencial para o gerenciamento de risco das atividades espeleológicas em um ambiente profissional, podendo ainda ser expandida para outras áreas de risco elevado, como mineração subterrânea e construção civil. A adaptação da plataforma para diferentes setores pode facilitar a difusão da cultura de segurança de forma dinâmica e abrangente, devido a sua aparência intuitiva e a substituição de formulários de papel, que são muitas vezes tratados como processos burocráticos. Portanto, a digitalização da ART é um passo fundamental para a modernização das práticas de segurança de Espeleologia e para a promoção de ambientes de trabalho mais seguros. Essa rotina de gerenciamento de riscos por aplicativo, bem como a proposição de melhorias no sistema será mais bem avaliada quando da sua adoção em maior escala.

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Tomografia sísmica aplicada a perfilagem e identificação de cavidades em litologias ferríferas

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Resumo

O presente trabalho visa entender o comportamento geoespeleológico e estratigráfico das rochas itabiríticas, mediante a utilização de métodos indiretos (mapeamento microssísmico) em ambientes favoráveis à presença de cavidades. A utilização dos métodos indiretos em zonas itabiríticas, permitem após o processamento dos dados, uma interpretação geológico-geotécnica das informações obtidas nos levantamentos in loco. Desta forma, a avaliação dos dados adquiridos no Quadrilátero Ferrífero permitiu identificar as estratificações dos BIFs, bem como uma interpretação tridimensional do contexto geoespeleológico da área de estudo, além de definir as características geotécnicas, parâmetros de resistência e índices geomecânicos para entendimento do maciço, a partir das informações disponibilizadas pela tomografia sísmica realizada com imagens de alta resolução.

Abstract

This study aims to understand the geospeleological and stratigraphic behavior of itabiritic rocks by using indirect methods (microseismic mapping) in environments favorable to the presence of cavities. The use of indirect methods in itabiritic zones allows, after data processing, a geological-geotechnical interpretation of the information obtained in the on-site surveys. Thus, the evaluation of the data acquired in the Iron Quadrangle allowed the identification of the stratifications of the BIFs, as well as a three-dimensional interpretation of the geospeleological context of the study area, in addition to defining the geotechnical characteristics, resistance parameters and geomechanical indices for understanding the massif, based on information provided by seismic tomography performed with high-resolution images.

Resumen

Este estudio tiene como objetivo comprender el comportamiento geoespeleológico y estratigráfico de las rocas itabiríticas mediante el uso de métodos indirectos (mapeo microsísmico) en ambientes favorables a la presencia de cavidades. El uso de métodos indirectos en zonas itabiríticas permite, después del procesamiento de los datos, una interpretación geológico-geotécnica de la información obtenida en los estudios in situ. Así, la evaluación de los datos adquiridos en el Cuadrángulo del Hierro permitió la identificación de las estratificaciones de los BIF, así como una interpretación tridimensional del contexto geoespeleológico del área de estudio, además de definir las características geotécnicas, parámetros de resistencia e índices geomecánicos para el conocimiento del macizo, con base en la información proporcionada por la tomografía sísmica de alta resolución.

1. Introdução

O entendimento dos aspectos geológicos de uma área de estudo se faz necessário para a compreensão e previsão do comportamento das ondas sísmicas no meio de análise, o que permite contextualizar a ambiência geotécnica na qual a área está inserida. O estudo tem por objetivo a realização de um imageamento de alta resolução através da microssísmica aplicada (tomografia sísmica), permitindo ter conhecimento tridimensional do comportamento geológico estrutural em relação à integridade do maciço e a presença de cavidades na região do estudo.

A área de estudo em questão está localizada no município de Barão de Cocais, estado de Minas Gerais, estando geográfica e geologicamente associada a evolução da porção NE do Quadrilátero Ferrífero, sendo observado no local uma cobertura eluvionar detrito-laterítica como unidade aflorante, representada litologicamente pela canga detrítica, formada a partir de processos de intemperismo das formações ferríferas bandadas.

Do ponto de vista geotectônico, a área investigada está inserida na porção sul do Cráton do São Francisco, sob contexto do Quadrilátero Ferrífero ALMEIDA (1977). A localidade guarda uma complexa gama de rochas e estruturas, cuja evolução segue em debate no meio acadêmico.

O mapa da Figura 1 mostra o Quadrilátero Ferrífero, lugar onde foram realizados os monitoramentos de microssísmica.

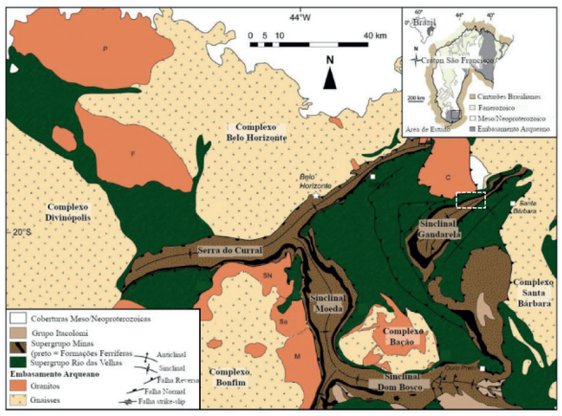


Figura 1: *Mapa geológico regional do Quadrilátero Ferrífero. O retângulo tracejado, em branco, destaca a localização da área investigada. Traduzido de Faria et al 2016.*

Quanto à estratigrafia, a área investigada pertence ao Supergrupo Minas e a estrutura geológica mais proeminente a nível regional, é o Sinclinal Gandarela (Fig. 2).

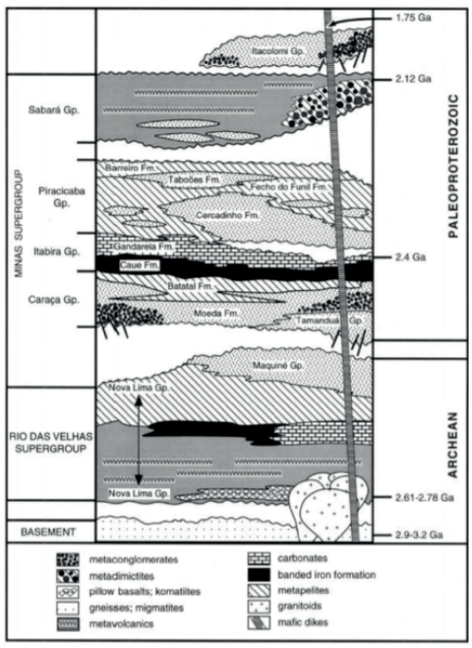


Figura 2: *Coluna estratigráfica do Quadrilátero Ferrífero. Retirado de Alkmim & Marshak (1998).*

2. Materiais e Métodos

A metodologia utilizada para a realização do estudo consiste na microssísmica aplicada, a qual possui duas abordagens conceituais: a microssísmica convencional e a passiva. O método convencional é baseado na medição de eventos sísmicos, em escala reduzida, nos quais os eventos são consequências de estímulos de origem natural, como o reequilíbrio de tensões no maciço, ou aqueles induzidos, como os gerados pelos eventos de detonação em uma operação de mineração GALLETI & CURTIS (2012).

Esta investigação utilizará principalmente a segunda abordagem (passiva) através da interferometria sísmica ou tomografia sísmica. A premissa da microssísmica passiva é a interferometria, que em resumo, é baseada na utilização de ruído (ambiente), como fonte sísmica, ou seja, o ruído ambiente, assume a função de ferramentas que usualmente são utilizadas como estíulos na superfície para estudos sísmicos, como os explosivos ou um caminhão vibroseis, por exemplo.

A Figura 3. apresenta um exemplo dos contrastes na velocidade de propagação das ondas sísmicas no meio, em função da profundidade. Embora este exemplo seja no contexto de uma investigação submarina, o mesmo princípio pode ser aplicado em investigações continentais.

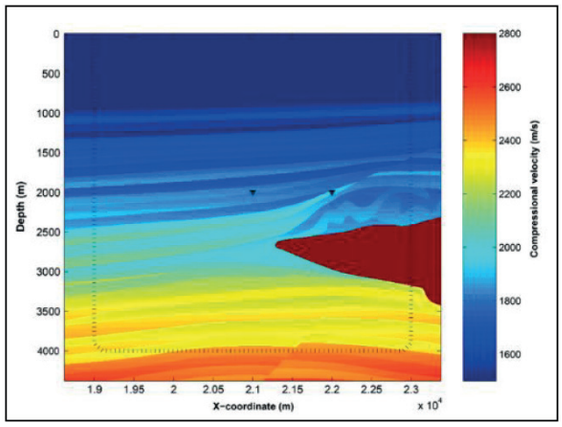


Figura 3: *Contrastes na velocidade de propagação das ondas sísmicas e associação com variações de profundidade. Retirado de Galleti & Curtis, 2012.*

Na atual investigação, será utilizado o método de correlação cruzada. O produto gerado após aplicação do método é uma tomografia e através da combinação entre os contrastes identificados por ocasião do imageamento mais a avaliação dos aspectos geológicos, serão obtidas as características geotécnicas do maciço em subsuperfície bem como a existência de vazios ou de água subterrânea.

Para tanto, durante o levantamento neste estudo foram utilizados 27 geofones móveis, dispostos em uma configuração de 4 linhas na área de estudo (Fig. 4).

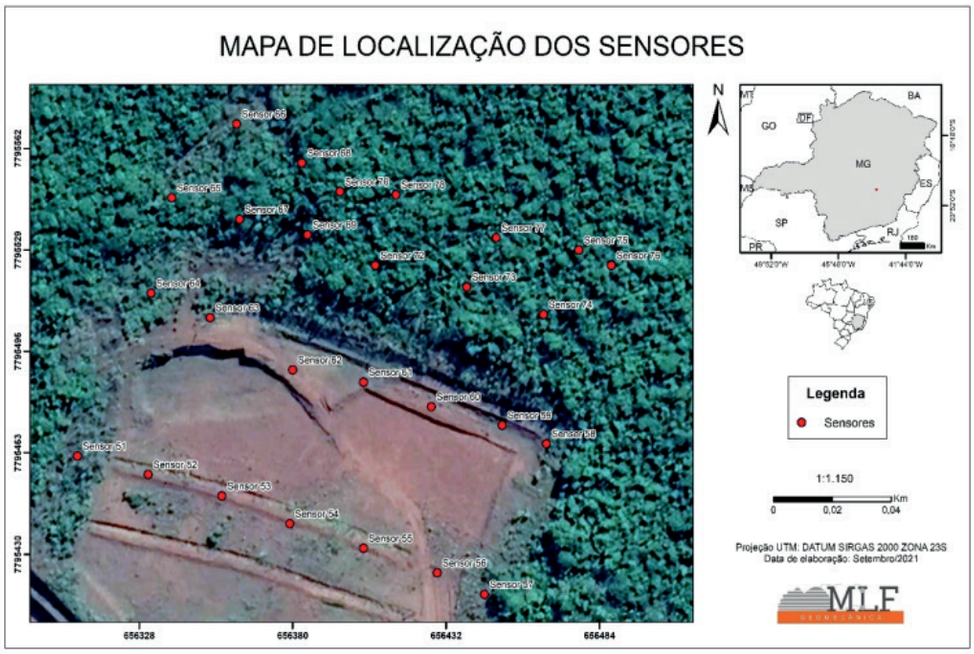


Figure 4: *Arranjo dos sensores distribuídos na região, através de 4 linhas de aquisição (Linha 1, Linha 2, Linha 3 e Linha 4).*

3. Resultados

A Figura 5 apresenta as camadas em individualizadas em subsuperfície, através do contraste de velocidade das ondas S. A escala flutua entre 360m/s e 1500 m/s. As cores quentes representam os maiores valores de velocidade (m/s) e as cores frias representam os menores valores. No total, foram identificadas em torno de 6 camadas individualizadas com espessuras que variam entre 7 e 21 metros. Observa-se que os menores valores associados, estão concentrados nas porções mais superficiais, da ordem de ~380 e 360 m/s. À medida em que se migra para as camadas mais profundas, observa-se a tendência de crescimento de velocidade de propagação das ondas S. Estes contrastes podem ser justificados em função das alterações de condições do maciço e de suas propriedades reológicas que em função do aumento das velocidades conferem redução do volume de vazios, do padrão de fraturamento do grau de compactação da coesão etc. ou seja comprovam a melhoria das condições do maciço em profundidade.

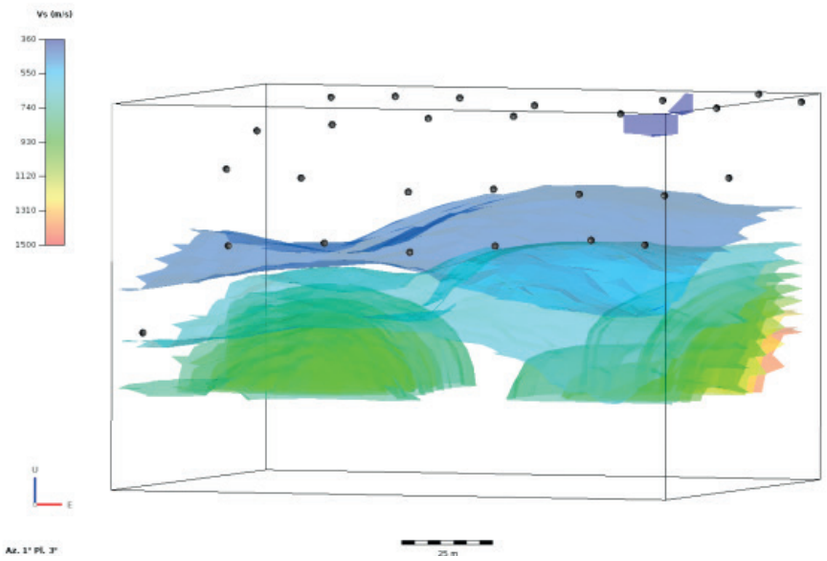


Figure 5: *Modelo tridimensional em subsuperfície, destacando o contraste entre as camadas a partir da diferença de velocidade de propagação das ondas sísmicas.*

A Figura 6 apresenta um modelo topográfico da área investigada, assim, observa-se que a profundidade atingida pela investigação foi de aproximadamente 40m. Ainda inclui as zonas de alta velocidade sísmica, identificadas na seção anterior. A escala de cores representa as diferenças de elevação, onde as cores frias (menores valores) correspondem às menores elevações. Enquanto as cores quentes correspondem às maiores elevações.

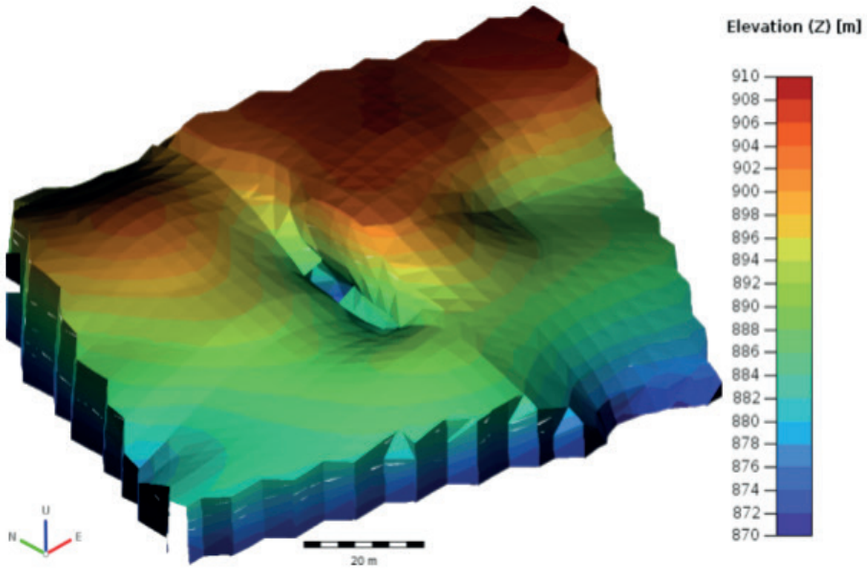


Figure 6: *Modelo com a topografia da área, considerando a região com alta velocidade de propagação de ondas sísmicas. A escala de cores representa as diferenças de elevação.*

4. Conclusão

Em linhas gerais, o imageamento de subsuperfície pela tomografia sísmica alcançou resolução suficiente para identificar os estratos típicos de um perfil de alteração no contexto de formação de crostas lateríticas, sendo possível obtermos interpretações de perfilagem estratigráfica e estrutural do maciço, a partir da utilização do método microsísmico.

A utilização desta metodologia, permite também a identificação de vazios quando aplicado uma maior distribuição de geofones. No caso da área de estudo, um índice de vazios mais acentuado foi observado apenas no estrato superficial, diminuindo gradativamente com o aumendo da velocidade sísmica nos estratos inferiores.

Os resultados demonstram que a microssísmica pode ser aplicada como uma ferramenta de investigação para o entendimento tridimensional do maciço que suporta as cavidades, não se limitando ao monitoramento das estruturas frente a atividades antrópicas.

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University Speleology: Diversity, Renewal, and Funding

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Resumo

Os grupos espeleológicos universitários desempenham um papel crucial na introdução de novos pesquisadores à espeleologia e na produção científica. Esta pesquisa analisa as dinâmicas de diversidade, renovação e financiamento desses grupos, com base em dados coletados dos Espeleo Grupos CAVUS (UNICAMP) e Espeleo Grupo Rio Claro (UNESP). A pesquisa revelou uma predominância de homens cisgênero e pessoas brancas, evidenciando a falta de diversidade de gênero e étnica, o que reflete desafios significativos relacionados à inclusão nos grupos universitários de espeleologia. Além disso, a escassez de recursos financeiros influencia diretamente as atividades realizadas, limitando a aquisição de equipamentos e a realização de trabalhos de campo. Enquanto o EGRIC se concentra na prospecção e mapeamento de cavernas, o CAVUS prioriza a extensão universitária e a divulgação científica. A alta rotatividade de membros e a predominância de jovens nos grupos reforçam sua importância para a renovação da espeleologia como ciência, mas também evidenciam desafios estruturais, como a necessidade de financiamento contínuo. A pesquisa destaca a importância do apoio institucional e de políticas inclusivas para garantir a existência e produção científica destes grupos.

Abstract

University speleological groups play a crucial role in introducing new researchers to speleology and in scientific production. This research analyzes the dynamics of inclusion, renewal, and funding of these groups, based on data collected from the CAVUS Speleology Group (UNICAMP) and the Rio Claro Speleology Group (UNESP). The research revealed a predominance of cisgender men and white individuals, highlighting a lack of gender and ethnic diversity, which reflects significant challenges related to inclusion within university speleology groups. Additionally, the scarcity of financial resources directly influences the activities carried out, limiting the acquisition of equipment and the execution of fieldwork. While EGRIC focuses on cave prospecting and mapping, CAVUS prioritizes university extension and scientific outreach. Constant member renewal and the predominance of young individuals in the groups reinforce their importance for the renewal of speleology as a science but also highlight structural challenges, such as the need for continuous funding. The research underscores the importance of institutional support and inclusive policies to ensure the existence and scientific production of these groups.

1. Introdução

Os grupos espeleológicos universitários são formados principalmente por estudantes, e ocasionalmente, incluem funcionários e professores, que se dedicam ao estudo e à prática de atividades relacionadas à espeleologia, ou seja, a exploração e o estudo de cavernas. Esses grupos podem estar vinculados a departamentos acadêmicos e têm como objetivo principal promover a pesquisa científica, divulgar a educação ambiental e a conservação do patrimônio espeleológico. Os grupos espeleológicos universitários têm características intrínsecas como: i) Alta rotatividade de membros; ii) Ser o primeiro contato com a espeleologia e iii) Membros jovens.

Grupos espeleológicos podem ser de diferentes naturezas, assim tendo características, objetivos e problemas diferentes. Clubes espeleológicos ou grupos não vinculados a outras entidades podem ter um caráter mais esportivo e exploratório, além de incluir profissionais de outras áreas que não abrangem o estudo de cavernas, no entanto, este não é um impeditivo para produção acadêmica sobre espeleologia.

Este estudo tem como objetivo destacar a relevância dos grupos universitários de espeleologia e, em especial, a diversidade de seus membros, que contribuem significativamente para o desenvolvimento e aprimoramento dessa área do conhecimento. Entender e incentivar a diversidade de gênero, de idade e raça é fundamental para o desenvolvimento de uma ciência inclusiva e menos enviesada. A espeleologia, como ciência multidisciplinar, beneficia-se da variedade de perspectivas e habilidades trazidas por estudantes, pesquisadores e profissionais de diferentes áreas e identidades.

Outra análise realizada ao longo deste trabalho envolve o perfil econômico dos grupos e de seus integrantes. Essa análise visa entender como as restrições econômicas nas atividades práticas, de extensão e/ou de materiais e equipamentos afetam a produção científica e acadêmica dos grupos espeleológicos universitários, tornando-se um empecilho para sua continuidade.

Os objetos em estudo são baseados nas características de dois grupos universitários do estado de São Paulo. O Espeleo Grupo Rio Claro (EGRIC), criado em 1979 por estudantes de graduação da Universidade Estadual Paulista (UNESP) de Rio Claro, possui uma diretoria organizada em cargos que mantém uma linha horizontal de poder. Ao longo dos seus 45 anos de existência, o grupo já realizou diversas atividades, principalmente visando a prospecção e mapeamento de cavidades com foco na proteção do patrimônio espeleológico brasileiro. Muitas dessas atividades de pesquisa foram realizadas fora do estado de São Paulo, no entanto, é dentro do estado que se encontra a maior concentração de estudos, com destaque para pesquisas desenvolvidas no Parque Estadual Turístico do Alto Ribeira (PETAR) e na Serra do Itaqueri. Além das atividades de prospecção e mapeamento, o grupo conta com uma

seção especial para prática e aprendizado de técnica de espeleo vertical, denominada Seção de Espeleo Vertical Erva Mate (SEVEM).

Diferentemente do outro grupo universitário em análise, o Espeleo Grupo CAVUS foi formado apenas no final do ano de 2023, por estudantes do Instituto de Geociências (IG) da Universidade Estadual de Campinas (UNICAMP). A gestão é organizada com base nos cargos de diretoria, que incluem presidente, vice-presidente e secretário-geral, desempenhando funções semelhantes às do EGRIC.

Acerca das atividades realizadas, o grupo atuou, majoritariamente, no campo da extensão universitária e divulgação científica. Ao longos dos últimos anos, foram preparados materiais didáticos para a participação em eventos focados na comunidade externa, como o Unicamp Portas Abertas (UPA) e o Museus da Unicamp de Portas Abertas (MUPA), ambos em 2024 e que proporcionaram trocas de experiências e conhecimentos sobre espeleologia com os visitantes. Para o ano de 2025, foi programada uma disciplina de extensão ministrada pelo CAVUS, professores do IG e voluntários do Grupo Pierre Martin de Espeleologia (GPME), em que todos os estudantes de graduação da UNICAMP podem se matricular.

2. Materiais e Métodos

Ao longo de todo o desenvolvimento deste trabalho foi realizada a contínua revisão bibliográfica com o objetivo de consolidar os fundamentos teóricos acerca da relevância da diversidade social e econômica para a produção científica. Durante as pesquisas de material de referência, o escopo foi direcionado ao campo das geociências, em consequência da ausência de estudos específicos acerca da diversidade na espeleologia.

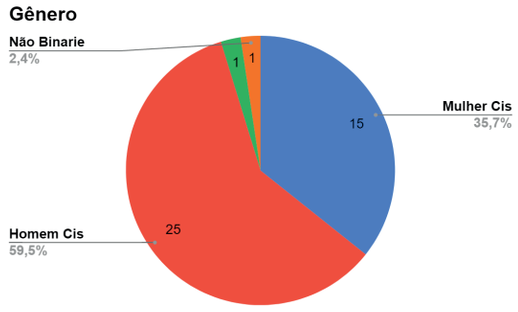
A execução do trabalho é embasada nas experiências relatadas por dois grupos universitários (CAVUS e EGRIC), caracterizando fontes empíricas, isto é, observações e vivências dos próprios grupos universitários. De modo a quantificar e fundamentar as questões apresentadas no trabalho, foi aplicado um formulário online, em que os membros de ambos os grupos responderam ao que foi solicitado. As perguntas, de formato objetivo, perpassam tópicos como identidade de gênero, identidade racial, faixa etária e posse de equipamentos espeleológicos.

3. Resultados

O questionário ficou disponível no período de 11 a 31 de janeiro de 2025, com divulgação frequente nos grupos de *whatsapp* dos dois grupos espeleológicos participantes. No total, foram recebidas 42 respostas anônimas, das quais 27 correspondem a integrantes do EGRIC e 15 do CAVUS. A pesquisa contou com a participação tanto de membros ativos quanto de membros inativos dos grupos.

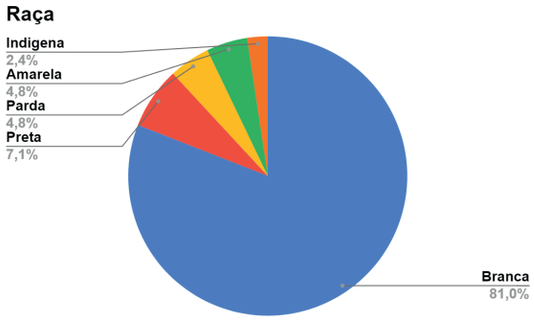
A partir dos dados coletados, foi possível traçar um perfil racial e de gênero dos grupos universitários em estudo. Entre os membros ativos, 25 (59,5%) se declaram homens cis, 15 (35,7%) mulheres cis, 1 (2,4%) homem trans e 1 (2,4%) como não binarie (Gráfico 1).

Gráfico 1: *Diversidade de Gênero nos Grupos EGRIC e CAVUS.*



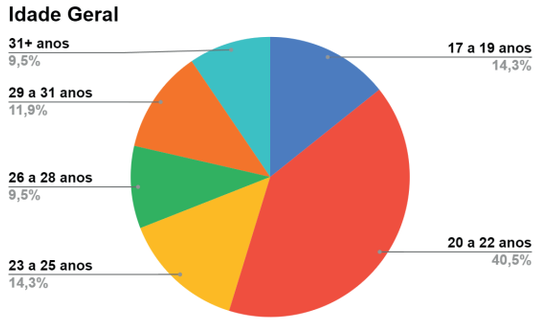
Quanto à composição racial, dos 42 integrantes que responderam a pesquisa, 34 (81,0%) se autodeclararam brancos, 3 (7,1%) pretos, 2 (4,8%) pardos, 2 (4,8%) amarelos e 1 (2,4%) indígena (Gráfico 2).

Gráfico 2: *Composição Racial dos Integrantes do EGRIC e CAVUS.*



Em relação à faixa etária, entre os participantes do estudo, há membros com idades entre 17 a 31 anos, sendo as principais faixas etárias 20 a 22 anos (40,5%), 23 a 25 anos (14,3%) e 17 a 19 anos (14,3%), como é possível observar no Gráfico 3.

Gráfico 3: *Idade dos membros dos grupos espeleológicos CAVUS e EGRIC.*



Os dados obtidos por meio do formulário evidenciam que ambos os grupos são compostos, predominantemente, por homens e mulheres cis autodeclarados brancos com idade entre 20 a 22 anos. Embora esses números não representem a totalidade dos membros de grupos universitários brasileiros de espeleologia, eles oferecem um panorama significativo dessa realidade. A desigualdade de gênero também é refletida em dados nacionais. Segundo o censo mais recente da Sociedade Brasileira de Espeleologia (SBE), realizado entre 2018 e 2019, as mulheres representavam apenas 27% (163 espeleólogas) da comunidade espeleológica brasileira.

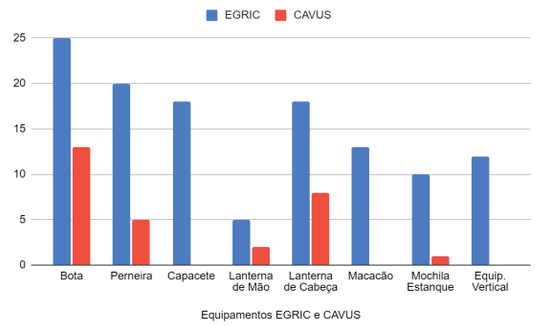
Considerando a importância de traçar um perfil detalhado dos espeleólogos universitários em questão e compreender os recursos disponíveis para os grupos em análise, foram coletados dados acerca dos Equipamentos de Proteção Individual (EPIs), como botas, capacetes, lanternas e perneiras, e outras ferramentas comumente utilizadas por espeleólogos na exploração de cavernas. Além disso, a análise incluiu outros itens que evidenciam o nível técnico dos grupos e o investimento pessoal dos integrantes em seus equipamentos.

A partir dos dados coletados, observou-se que todos os participantes da pesquisa possuem pelo menos um EPI, sendo as botas de campo e os capacetes os itens mais comuns. No entanto, o grupo EGRIC se destaca por possuir uma quantidade significativamente maior de equipamentos

de proteção individual e itens adicionais, como macacões espeleológicos, mochilas estanques e equipamentos para atividades verticais.

Essa disparidade está ilustrada nos Gráfico 4, que mostram as proporções e quantidade total de cada tipo de equipamento por grupo. É importante destacar que o equipamento de vertical é exclusivamente utilizado pelo EGRIC, o que reforça sua melhor estruturação em termos de disponibilidade de recursos.

Gráfico 4: *Disponibilidade e tipos de equipamentos por grupo (EGRIC e CAVUS).*



A diferença na quantidade e diversidade de equipamentos reflete também nas condições operacionais de cada grupo, o que pode influenciar tanto a segurança quanto a eficiência das atividades de campo realizadas por cada um. Entretanto, é relevante observar que o CAVUS é um grupo recente, com foco predominante em divulgação científica e extensão universitária. Por outro lado, o EGRIC, com mais de 40 anos de experiência, concentra suas atividades na prospecção espeleológica e mapeamento de cavernas.

4. Discussão

De acordo com Wenlong Yang e Yang Wang (2024) a reorganização e inclusão de membros em grupos de pesquisa são um caminho para atingir resultados mais disruptivos e multidisciplinares. Além disso, membros mais jovens e com menos experiência podem contribuir com maior criatividade para os projetos.

Os espeleo grupos universitários possuem características intrínsecas que favorecem a produção de ciência inovadora, especialmente relevante para a espeleologia, uma área que demanda ampla interdisciplinaridade e frequentemente cruza as fronteiras entre diferentes campos do conhecimento. Estas características são:

- Alta rotatividade de membros: à medida que o ciclo do ensino superior se encerra, novos integrantes entram todos os anos, enquanto outros deixam o grupo ou se tornam menos ativos ao concluírem a graduação ou pós-graduação. Dessa forma, as novas combinações de equipes provocam conflitos construtivos, o que é positivo, e também evitam a repetição de gestores, isso impede a reprodução de padrões e a resistência à transformação, que seriam prejudiciais.

- Membros jovens: segundo o Censo da Educação Superior de 2022, a idade média dos alunos em cursos presenciais é de 26 anos, com 50% dos alunos com até 23 anos. Isso se reflete na idade dos membros de grupos espeleológicos universitários, onde 69,1% dos membros do CAVUS e do EGRIC têm até 25 anos (Gráfico 3), estimulando a renovação etária na espeleologia, essencial para manter a continuidade de qualquer segmento da ciência e manter um ambiente propício para soluções criativas.

- Primeiro contato com espeleologia: os grupos universitários cumprem a função de introduzir a espeleologia para pessoas que nunca tiveram contato com a área. Para muitos pode ser só uma curiosidade passageira, mas para os integrantes do grupo pode se tornar objeto de pesquisa, profissão ou hobbie. Abrindo caminho para novas gerações de espeleólogos.

Por outro lado, outros fatores importantes para a ciência são os processos iterativos e a experimentação que só são possíveis com subsídio e infraestrutura, ou seja, com os recursos limitados, comuns em espeleo grupos universitários, perde-se um elemento crucial para produção e inovação científica.

A Espeleologia, apesar de ser uma ciência que não demanda uma formação específica, tem certa concentração de pesquisas relacionadas principalmente à Biologia, Geociências, Turismo, Ciências Ambientais, História e Arqueologia (FIGUEIREDO, 2017). Porém, é um campo pouco explorado, dada a falta de registros publicados. Ainda assim, a ausência de inclusão de diversos grupos étnicos, principalmente pretos, pardos e indígenas nos trabalhos científicos é marcante (OLIVEIRA, 2022). Isso ocorre devido a uma questão estrutural, influenciada logo no início da formação superior dos indivíduos, dado que, de acordo com o Instituto Nacional de Estudos e Pesquisas Educacionais (INEP), alunos autodeclarados brancos ainda representam a maioria nos cursos mencionados.

Neste sentido, para além de uma ciência pouco explorada no âmbito dos registros científicos e acadêmicos, a espeleologia também se mostra uma ciência pouco diversa quando se trata do perfil dos estudantes que a praticam. Para atestar essa afirmação e aplicá-la a um exemplo prático, o presente projeto trabalhou com dados raciais sobre os participantes dos grupos EGRIC e CAVUS, a fim de entender o impacto da estrutura racial presente nos ambientes acadêmicos e científicos no estudo espeleológico. Dessa forma, a porcentagem de pessoas autodeclaradas pretas, pardas e indígenas, respectivamente falando, é de 7,1%, 4,8% e 2,4%, enquanto a de alunos autodeclarados brancos é de 81%, valores muito discrepantes.

A falta de diversidade também se manifesta quando analisamos os dados de gênero com 59,5% autodeclarados homem cis, 35,7% mulher cis, 2,4% não binarie e 2,4% homem trans e nenhuma mulher trans. Como já amplamente explorado por SOUSA & TOJA (2022) a espeleologia é apresentada como uma área que ainda enfrenta desigualdade de gênero e é considerada pouco representativa, segundo o censo da Sociedade Brasileira de Espeleologia (SBE) dos anos de 2018-2019, apenas 27% da comunidade espeleológica é composta por mulheres e isso agrava dificuldades que as mulheres enfrentam, como o machismo em diversos ambientes relacionados à espeleologia, além da descredibilidade e oportunidades perdidas por serem mães. Dentro do EGRIC e do CAVUS a desigualdade entre homens e mulheres é ligeiramente menor, para saber se isso é uma tendência entre grupos universitários é necessário maior quantidade de dados.

Outro ponto a se pensar é o tipo de atividade que é realizada pelos grupos espeleológicos e como as condições econômicas escassas deles influenciam isso. Para se interpretar os resultados obtidos no formulário, é preciso antes caracterizar e diferenciar a estrutura financeira dos dois grupos universitários em análise. O EGRIC, embora seja composto majori-

tariamente por universitários, não tem apoio nem ligação formal com a UNESP, assim, apenas utiliza os espaços da universidade de maneira não vinculada, mantendo sua sede e realizando reuniões na instituição. Tem como forma de aquisição de verba o autofinanciamento, proveniente de doação, mensalidade, realização de cursos e eventos, empréstimo de equipamento e editais publicados por órgãos que fomentam o estudo da espeleologia. Há também, a venda de produtos como camisetas e adesivos, esses que acabam sendo uma ajuda secundária para o caixa. Com o problema do grupo não ter um financiamento grande, a falta de equipamento acaba afetando alguns membros que não têm a possibilidade de comprar seu EPI próprio. Contudo, aqueles que têm a possibilidade de adquirir, emprestam seu equipamento caso haja necessidade.

Por outro lado, a principal arrecadação monetária do CAVUS parte da venda de produtos, sendo camisetas, bottons e adesivos, não havendo nenhum tipo de patrocínio. Mesmo sendo uma organização sediada na universidade, o apoio financeiro é um dos principais desafios na realização de atividades, já que os materiais disponibilizados pela instituição pública não são suficientes ou até mesmo adequados, a exemplo dos capacetes disponíveis para trabalhos de campo. Por se enquadrar como um grupo de extensão, surgem oportunidades para a participação em editais de apoio financeiro, mas que são focados apenas na realização de atividades a curto e médio-prazo, não possibilitando a compra de equipamentos permanentes para o grupo, como os mencionados no formulário aplicado para os membros. Logo, cabe aos participantes do grupo buscar outras formas de financiar os recursos, como nas vendas citadas anteriormente, na criação de rifas ou por recursos pessoais.

A partir do levantamento de dados realizado com ambos os grupos, é possível observar que o EGRIC e o CAVUS, respectivamente, realizam muitas atividades relativas à prospecção e mapeamento de cavidades e trabalhos de campo para regiões com grande concentração de cavernas, e atividades de formação, como o Curso Básico de Cavernas (CBC), bem como atividades de extensão.

Todas atividades que demandam custos pessoais (ex: EPI) e coletivos (ex: transporte, combustível, alojamento), sem vínculo de suporte financeiro há maior liberdade e menos burocracia para suas escolhas, porém essa liberdade é cerceada dentro das limitações financeiras do grupo. Principalmente quando pensamos em trabalhos de campo distantes, exploração de ambientes que exigem equipamento complexo de mapeamento ou locomoção. Dessa forma, ambos sediam atividades que demandam materiais, equipamentos e condições financeiras que permitam experiências adequadas e de qualidade para seus integrantes, além de permitir produções científicas que se adequem ao perfil das universidades. Ainda, neste mesmo levantamento, extraiu-se que ambos os grupos não possuem verbas pela universidade, sendo o autofinanciamento a principal forma de aquisição de bens.

5. Conclusão

Em conclusão, os grupos universitários de espeleologia apresentam características intrínsecas que os configuram como ambientes propícios para a geração de conhecimento inovador e disruptivo. A rotatividade de membros, a presença de jovens com perfis criativos e a função de introduzir a espeleologia para novos integrantes são fatores que impulsionam a renovação e a diversidade de perspectivas, essenciais para o avanço de uma área tão interdisciplinar.

Contudo, esses grupos enfrentam um desafio estrutural significativo: a carência de recursos financeiros e de infraestrutura adequada. Diante disso, torna-se imperativo a implementação e incentivo de ações específicas para apoiá-los, seja por meio de iniciativas institucionais das universidades, seja por meio de colaborações com entidades externas, órgãos ambientais ou empresas do setor de recursos naturais. Tais investimentos são essenciais para potencializar o impacto desses grupos, assegurando não apenas a continuidade de suas atividades, mas também a consolidação e o avanço da espeleologia como campo científico no Brasil.

Os resultados apresentados até aqui representam uma contribuição significativa para a compreensão do papel dos grupos universitários dentro da espeleologia. No entanto, reconhecemos a necessidade de ampliar e aprofundar a pesquisa, buscando dados adicionais tanto de grupos universitários quanto de grupos não universitários, a fim de compreender melhor as dinâmicas específicas de cada tipo de grupo e estabelecer comparações mais robustas para ampliar o escopo do estudo. Essa continuidade permitirá uma visão mais abrangente e detalhada do cenário espeleológico, fortalecendo as bases para políticas de apoio e investimento que garantam o desenvolvimento dessa área do conhecimento.

Se por um lado os os espeleo grupos universitários têm particularidades importantíssimas para o progresso científico, este trabalho também revela que o EGRIC e o CAVUS, apresentam uma brutal falta de representatividade que enfraquece o método científico e a resolução de problemas.

Essas desigualdades refletem um cenário mais amplo, já que, conforme destacado por SOUSA & TOJA (2022), a espeleologia como um todo enfrenta desafios significativos de equidade, especialmente no que diz respeito à representatividade de gênero e ao acesso a oportunidades. No entanto, as disparidades observadas nos grupos universitários não são uniformes, e compreender suas nuances é essencial para identificar pontos de melhoria e estratégias de fortalecimento.

A ampliação da pesquisa, incluindo a análise de grupos não universitários, permitirá uma comparação mais abrangente, elucidando se essas desigualdades são mais ou menos pronunciadas em diferentes contextos. A partir desses dados, será possível traçar caminhos mais assertivos, como a elaboração de políticas específicas para cada tipo de grupo, o direcionamento de recursos financeiros e a promoção de práticas inclusivas.

Agradecimentos

Agradecemos profundamente a todos os membros do CAVUS e do EGRIC que dedicaram seu tempo para responder ao formulário e compartilhar suas experiências. Suas contribuições foram essenciais para a realização deste trabalho, e cada resposta trouxe insights valiosos que enriqueceram nossa pesquisa. Que este estudo seja um pequeno reflexo do compromisso e da paixão que vocês dedicam à espeleologia.

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Da superfície ao subterrâneo: aplicação de modelagem digital para definir bacias hidrológicas de cavernas

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Abstract

This study addressed the use of a digital elevation model to define the upstream topographic boundaries of the watershed of the S11_0028 cave, located in the Carajás region, Pará. The QGIS software (v. 3.36.2) was used for analyses based on a free 30 m resolution SRTM raster image. The definition of the upstream topographic boundaries was performed using the r.watershed tool to generate watersheds through automated modeling. Flow segment models and flow direction models were used for the manual refinement of the watershed perimeters. Morphometric parameters such as hypsometry, slope, and the Topographic Wetness Index were extracted from the raster model using the r.slope.aspect and r.flow tools. The presented data demonstrate how these tools can be applied to define and understand the geomorphological characteristics of the hydrological contribution areas of ferruginous caves.

Resumo

Este estudo abordou a utilização de um modelo digital de elevação na definição dos limites topográficos de montante da bacia hidrográfica da caverna S11_0028, localizada na região de Carajás, no estado do Pará. Foi utilizado o software QGIS (Quantum Geographic Information System) versão 3.36.2 para análises a partir do Modelo de Digital de Superfície (MDS) SRTM, de acesso gratuito, com resolução espacial de 30 m. A definição dos limites topográficos de montante foi realizada com o uso da ferramenta *r.watershed*, para a geração de bacias hidrográficas por modelagem automática. Modelos de segmentos de fluxo e direção de fluxo foram utilizados para o refinamento manual dos perímetros da bacia. Parâmetros morfométricos de Hipsometria, Declividade e Índice Topográfico de Umidade foram extraídos do modelo *raster* com o uso das ferramentas *r.slope.aspect* e *r.flow*. Os dados apresentados mostram como estas ferramentas, podem ser utilizadas para definição e conhecimento das características geomorfológicas das áreas de contribuição hídrica de cavernas ferríferas.

1. Introdução

As cavernas estão em constante e, em muitos casos, lenta modificação natural de seus componentes bióticos e abióticos. Ainda que os processos espeleogenéticos relacionem-se à escala de tempo geológica, interligando fatores geológicos, climáticos, hidrológicos, sedimentares, além de biológicos, seus resultados são notáveis e, por isso, precisam ser preservados. Os elementos da paisagem do entorno da caverna, sejam eles naturais ou antrópicos, constituem fator determinante em sua evolução.

Agentes hídricos estão intimamente ligados aos processos erosivos e dissolutivos, que levam ao surgimento e alargamento das cavidades naturais subterrâneas, embora movimentos tectônicos, agentes eólicos, gravitacionais e biológicos também exerçam influência nesses processos. Considerando a água como principal agente na gênese e evolução das cavernas, análises que visem a manutenção da dinâmica evolutiva dessas feições devem, por isso, garantir a manutenção das condições hidrológicas naturais que envolvem a presença de drenagens (alóctones ou autóctones), os processos de infiltração e percolação, além da relação desses com o entorno e o sistema subterrâneo.

A atividade hídrica relaciona-se à dinâmica sedimentar do ambiente subterrâneo, influenciando fortemente a entrada e a retirada de materiais clásticos e orgânicos, além da deposição química. Assim, é essencial entender o funcionamento hidrológico da cavidade, bem como analisar a origem dos sedimentos e a correlação desses com o meio externo, a fim de manter a dinâmica evolutiva das feições espeleológicas.

A delimitação de uma área que salvaguarde a dinâmica evolutiva de uma caverna pode ser bastante complexa em ambientes cársticos, muitas vezes requerendo técnicas e materiais que permitam mapear as rotas de escoamento subterrâneas. Em terrenos pouco carstificados como os ferríferos, onde as cavernas se inserem como elementos isolados na paisagem, em sua grande maioria desconectadas de águas subterrâneas - nível freático, a definição da área de contribuição hídrica / sedimentar máxima, delimitada por divisores topográficos mostra-se suficiente na preservação de seus processos naturais de desenvolvimento.

O método clássico de delimitação de bacias hidrográficas pela identificação dos interflúvios, utilizado com ferramentas SIG em modelos digitais de elevação, tem se mostrado solução eficaz na definição e melhor entendimento desse sensível recorte da paisagem de entorno das cavernas. Nosso objetivo é apresentar como essas ferramentas podem ser utilizadas na definição dos limites topográficos e na obtenção de dados morfométricos da área de montante de uma caverna.

2. Materiais e Métodos

Para exemplificar os métodos tratados neste resumo foi utilizada a área de entorno da caverna S11_0028 situada na região de Serra Sul, município de Canaã dos Carajás, no estado do Pará (Fig. 1).

A Serra Sul é um planalto residual localizado na extremidade sul da Província Mineral de Carajás. A superfície tem o relevo ondulado sustentado por cobertura laterítica, com altitudes entre 650 e 900 m. No topo, colinas com vertentes côncavas e convexas são frequentemente interrompidas por rupturas da cobertura laterítica que marcam os limites do planalto residual na forma de imponentes escarpas erosivas. Denominadas, de modo genérico, como bordas de platô esses locais abrigam as maiores concentrações de cavernas e marcam a transição entre o planalto residual e a depressão interplanáltica, com altitudes entre 200 e 300 m (PILÓ et al. 2015).

A caverna S11_0028 está localizada na encosta do planalto residual. Com 370 m de altitude, está posicionada em baixa vertente na calha de uma drenagem, abaixo de uma queda d'água. Suas dimensões são de 29,2 m de projeção horizontal, 2,1 m de desnível, 73,1 m² de área e volume de 125 m³. Formada no jaspilito friável por um salão sub-retangular com maior extensão no eixo NW-SE. Possui uma surgência com escoamento perene que drena em direção à entrada, na extremidade sudeste (Carste 2010).

Diferentes ferramentas SIG para análises morfométricas de Modelos Digitais de Elevação (MDE) podem ser utilizadas para a identificação dos limites topográficos de uma bacia hidrográfica ou mesmo de um ponto ou área (RENNÓ & SOARES, 2001; RENNÓ et al., 2008).

No presente estudo buscamos os limites topográficos da bacia de uma caverna. O recorte resultante será aqui denominado: Área de Contribuição Hídrica / Sedimentar Máxima (ACHM).

Foi utilizado o software QGis na versão 3.36.2. As análises foram feitas a partir de dados raster SRTM, de acesso livre, disponibilizados pelo USGS, com resolução de 30 m (UNITED STATES GEOLOGICAL SURVEY, 2000).

Trata-se de um modelo digital de superfície, não traduzindo a curvatura do terreno no nível do solo por correção da cobertura vegetal.

A definição da ACHM foi realizada com o uso da ferramenta *r.watershed*, (adotando como padrão a direção de fluxo único - D8), com a qual foram gerados três modelos raster:

1. Bacias hidrográfica por modelagem automática
2. Segmentos de fluxo (linhas de drenagem)
3. Aspecto (direção de drenagem)

Tendo como referência a planimetria da caverna, a identificação dos limites topográficos da área de montante foi realizada por análise comparativa. Foram utilizadas as bacias hidrográficas geradas de modo automático, que tiveram seus perímetros ajustados com base nos modelos de segmentos de fluxo e direção de drenagem. O refinamento dos perímetros foi feito de modo manual, tendo sido retificado o traçado nos locais onde o resultado da modelagem automatizada mostrou incongruências quando comparado ao mergulho de uma determinada superfície.

Para a obtenção de dados morfométricos do ACHM foram gerados modelos raster de Hipsometria, Declividade e Índice Topográfico de Umidade (*TWI Topographic Wetness Index*). A ferramenta *r.slope.aspect* foi utilizada para gerar o modelo de declividade do terreno por classes de porcentagem. Por fim, com a ferramenta *flow acumulation* foi gerado um modelo de acumulação de fluxo, também denominado índice Topográfico de Umidade, bastante útil para se distinguir áreas propensas à acumulação de umidade de zonas melhor drenadas, como os interflúvios.

Os dados morfométricos foram extraídos por estatística zonal das camadas *raster* (Hipsometria, Declividade e TWI) recortada pelo perímetro da ACHM. Foram extraídos os parâmetros: i) média; ii) mediana; iii) desvio padrão; iv) mínimo e v) máximo. Os modelos são apresentados sobrepostos por curvas de nível com equidistância de 10 m e renderizados por mesclagem a relevo sombreado, ambos extraídos da imagem *raster* de entrada.



Figura 1: *Localização da caverna S11_0028 em Serra Sul na região de Carajás, Estado do Pará.*

3. Resultados

Delimitação da ACHM

Na Figura 2a é mostrado o resultado da extração de bacias hidrográficas em modo automático com o uso da ferramenta *r. watershed*. Neste mesmo recorte pode ser observada a camada de seguimento de fluxo que delimita as linhas de drenagem (talvegues).

A Figura 2b mostra o aspecto das superfícies (direção de drenagem) modelada pelo método D8. Elaborado por O'Callaghan e Mark (1984), o método atribui a direção do fluxo à célula vizinha (*pixel*) de declive mais íngreme, sendo determinada uma única direção de fluxo para cada célula (*single flow direction – SFD*). O resultado permite identificar para qual direção a superfície analisada mergulha. Para cada uma das oito direções é atribuída uma cor, como pode ser visto na legenda.

As bacias hidrográficas foram transformadas em camada vetorial (polígonos) para permitir o refinamento dos limites. A cavidade foi considerada como ponto exutório de todo o conjunto de bacias (como sua área é de pouco mais de 70m², optou-se por representá-la como ponto para fins de visualização). Deste modo, todas as bacias cujos segmentos de fluxo confluíam na direção da caverna foram unificadas (mescladas) em uma única feição. O passo seguinte foi refinamento manual dos limites topográficos de montante, tendo como referência as células do *raster* de direção de drenagem posicionadas próximas do perímetro da bacia unificada, gerando a ACHM (Figura 2c). Na Figura 2d pode-se observar a ACHM, após o refinamento do perímetro, sobreposta às bacias geradas de modo automático.

Extração de dados morfométricos

A Figura 3 apresenta a média, a mediana, o desvio padrão e os valores mínimos e máximos obtidos por meio dos rasters de hipsometria, decli-

vidade e Índice Topográfico de Umidade no interior da ACHM. Na Figura 4 são mostrados os modelos *raster* gerados para fins de interpretação e quantificação dos parâmetros morfométricos na ACHM da caverna.

Na Figura 4a é apresentado o mapa hipsométrico. Nele pode-se observar a conformação de um relevo resultante de forte controle litoestrutural, dividido por Boaventura & Narita (1974) em duas Unidades Morfoestruturais e Morfoclimáticas: o Planalto Dissecado do Sul do Pará e a Depressão Periférica do Sul do Pará. A primeira unidade é representada pelas cores mais quentes atribuídas às cotas mais elevadas, situadas acima dos 600 m, com pontos culminantes a sudeste, no platô de S11, onde atinge a altitudes superiores a 800 m. A Depressão Periférica, no recorte apresentado, mostra um caimento de norte para sul / sudeste, onde atinge as cotas mais baixas, na faixa dos 230 m. Nos limites da ACHM nota-se que os interflúvios estão situados, majoritariamente, em cotas superiores a 600 m nos topos de platôs e cristas. Apenas nas extremidades sul e leste os interflúvios estão em cotas mais baixas, na casa dos 450 m no topo de cristas dissecadas.

A declividade, mostrada na Figura 4b, está expressa em porcentagem de acordo com as classes de relevo definidas pela Embrapa (1979). Nota-se que todas as seis classes estão presentes na área, cujo relevo varia de Plano (com inclinação de até 3%) a Forte Montanhoso (>75%). As classes Plano e Suave Ondulado (3 a 20%) predominam tanto na depressão periférica como nos topos do planalto dissecado. As classes Ondulado (8 a 20%) e Forte Ondulado (20 a 45%) tendem a se concentrar nas encostas do planalto residual que tem suas faces voltadas para norte e noroeste, enquanto que as faces voltadas para sul e sudoeste são mais escarpadas, relevo Montanhoso (47 a 75% e Forte Montanhoso (>75%).

A Figura 4c apresenta o Índice Topográfico de Umidade da área abordada. O índice expressa em cores as diferentes propensões de determinadas zonas à saturação hídrica. É possível notar que as classes não obedecem a uma hierarquia topográfica, ou seja, valores altos e baixos estão distribuídos tanto no planalto residual como na depressão periférica.

De acordo com Lopes (2012) valores mais elevados do índice são atribuídos a áreas que recebem maior contribuição do escoamento superficial. No recorte analisado os maiores índices são observados nas vertentes de perfil côncavo e nas zonas de baixa declividade. Já os valores mais elevados foram atribuídos aos interflúvios (independentemente da escala) e às zonas maior declividade, notadamente nas encostas de geometria linear-convexa.

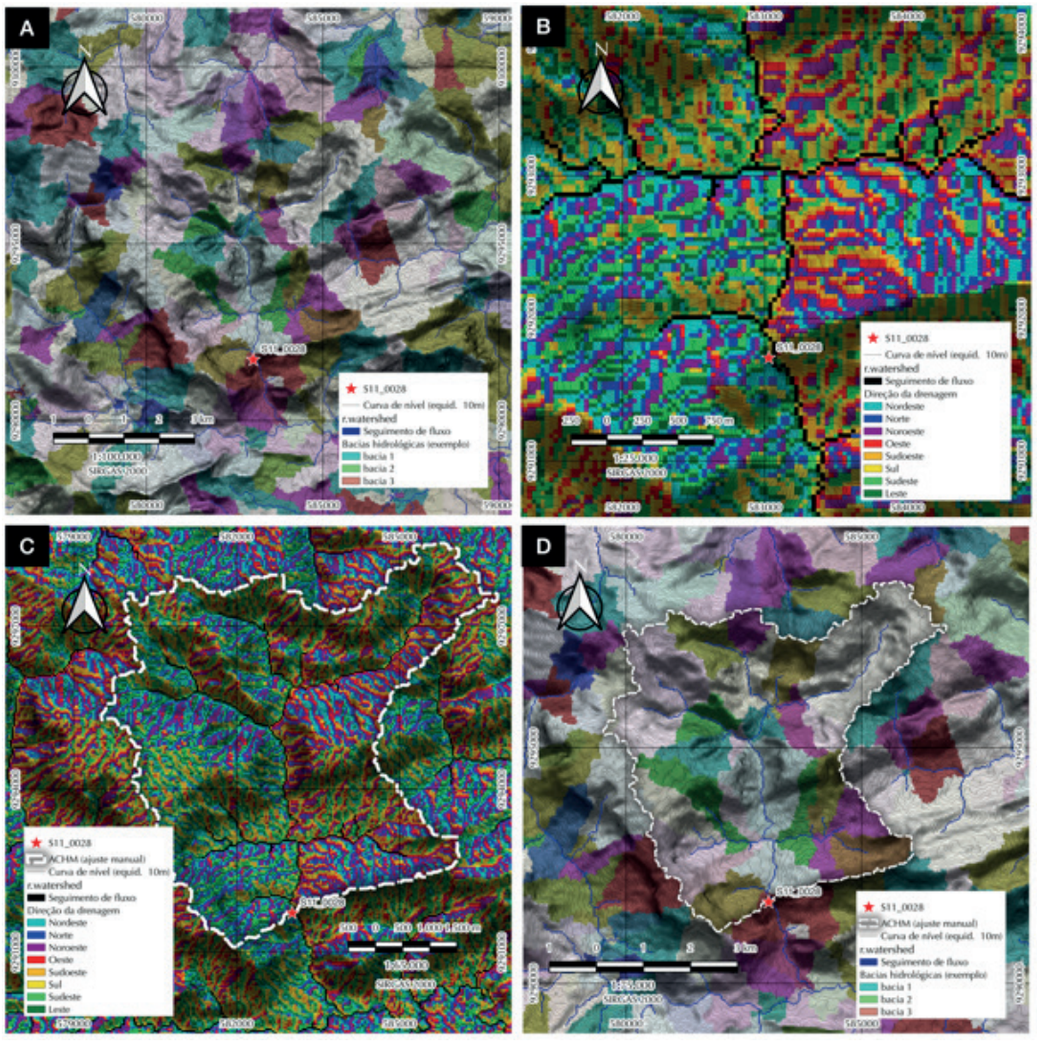


Figura 2: *Modelos raster utilizados para a definição do limite topográfico de montante da caverna. Em (A) bacias hidrográficas e seguimentos de fluxo (talvegues) gerados de modo automático; (B) modelo de direção de drenagem, que indica a direção de mergulho das superfícies a partir de oito classes; (C) sobreposição do limite da ACHM para ajuste manual do perímetro com base no modelo de direção de drenagem e; (D) sobreposição da ACHM com as bacias hidrográficas geradas de modo automático.*

ACHM	3077,4 hectares				
Camada *raster*	Média	Mediana	Desvio padrão	Mínimo	Máximo
Hipsometria	570,87 m	565 m	107,79 m	370 m	750 m
Declividade	24,66º	20,44º	17,74º	0º	>75º
TWI	6,53	5,97	2,23	2,07	19,16

Figura 3: *Tabela de parâmetros morfométricos de hipsometria, declividade e propensão a acúmulo de água em superfície (Índice Topográfico de Umidade - TWI) na área de contribuição hídrica / sedimentar da caverna S11_0028.*

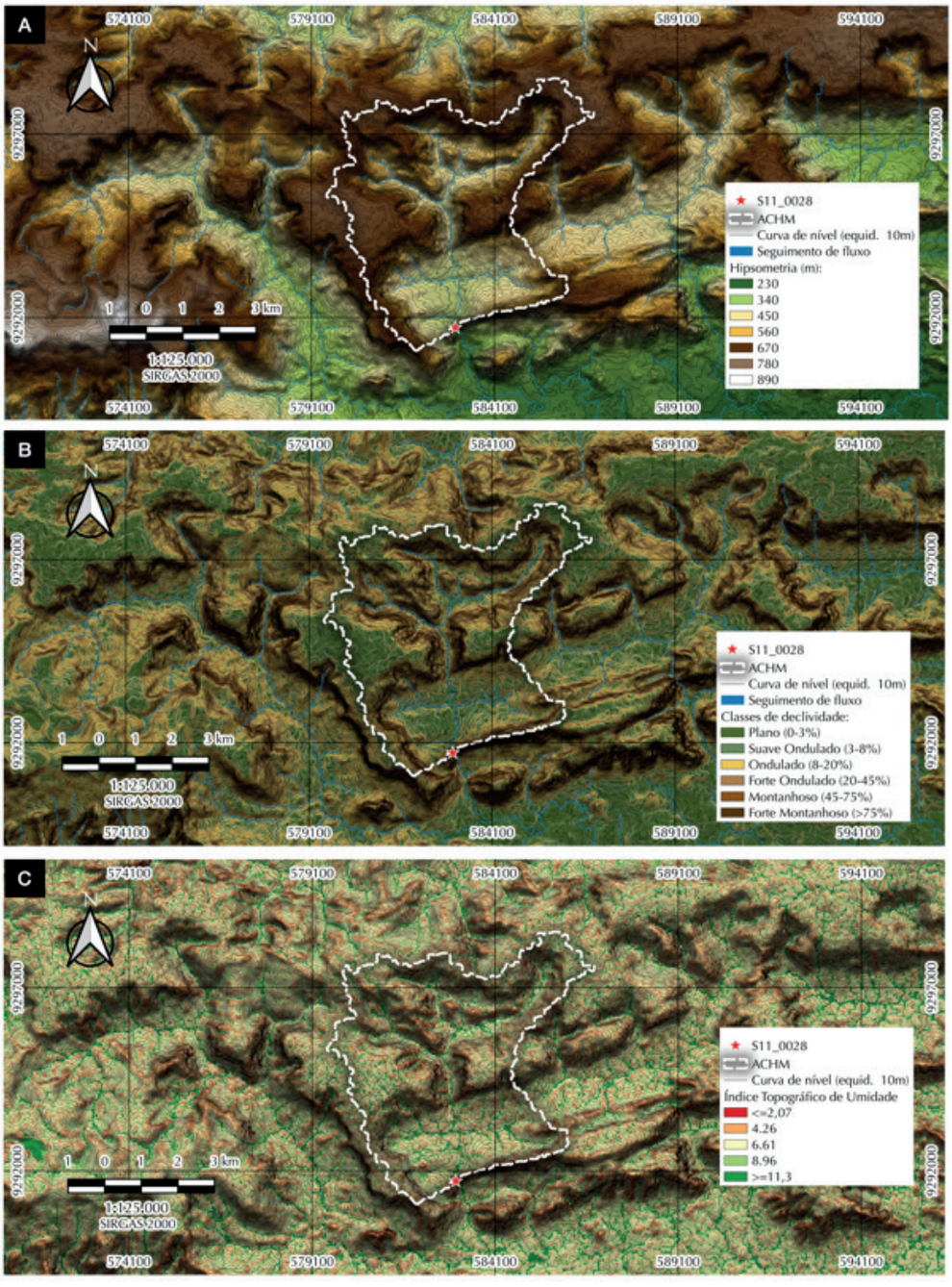


Figura 4: *Área da ACHM e entorno vista sobre os modelos raster: A) hipsometria; B) classes de declividade em porcentagem (Embrapa 1979) e; C) Índice Topográfico de Umidade.*

4. Discussão

Os resultados aqui apresentados mostram como o modelo digital de elevação pode ser utilizado para definição dos limites topográficos de montante da área de uma caverna e para a extração de parâmetros morfométricos que permitem interpretar melhor a geomorfologia dentro desses limites. Importante mencionar que a utilização de modelos digitais de terreno, por representar a superfície do solo, oferecem maior precisão nas análises pois não estão sujeitos a falsas interpretações, muitas vezes ocasionadas pela cobertura vegetal. Os exemplos trazidos na Figura 3 possibilitaram a extração, de modo simplificado, de dados estatísticos de altimetria, declividade e propensão do terreno a acúmulo de umidade. Parâmetro este, bastante útil na identificação de áreas de risco de alagamento e que pode contribuir para melhor gestão das áreas de montante das cavernas.

Diversos outros parâmetros morfométricos podem ser extraídos a partir de modelos digitais de elevação com o uso de ferramentas específicas do QGIS. A ferramenta *r.param.scale* por exemplo, permite a criação de um mapa geomorfológico pela parametrização de formas com base nos dados altimétricos das células do *raster*. A utilização desses dados de modo conjunto com informações do meio físico como geologia, pedologia, entre outros, se mostra uma ferramenta poderosa para análises que permitam a conservação das áreas de entorno de cavernas.

5. Conclusão

O estudo de caso demostrou como o processamento de dados altimétricos extraídos de um modelo digital de elevação, utilizando o software de código livre QGis, permitiu a delimitação da área de contribuição hídrica e sedimentar de uma caverna na região de Carajás a partir dos limites topográficos de montante. Também foram extraídos dados morfométricos que podem ser utilizados para melhor compreensão da área.

Diferentemente da maior parte das cavernas ferríferas, a caverna aqui analisada possui uma bacia de montante com mais de 3.000 hectares. Muitas das cavernas situadas no topo e nas bordas do planalto residual estão em interflúvios, com áreas de montante bastante restritas. Nestes casos, a utilização das ferramentas aqui abordadas em modelos digitais de terreno de alta resolução (<10 m) podem trazer resultados bastante precisos na delimitação e na obtenção de dados morfométricos que possibilitem a definição de planos de conservação dessas áreas sensíveis do entorno das cavernas ferríferas.

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Detection of microplastics in Cueva Tallonal at Arecibo, Puerto Rico

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Abstract

Microplastics are a serious environmental problem that has percolated through the karst ending up in caves and aquifers affecting the water quality and damaging the habitat of some organisms. However, the study of microplastics on karts has been limited for different reasons. This study aims to detect the presence of microplastics at Cueva Tallonal in Arecibo, Puerto Rico. We conduct this research by adapting the methodology of other's previous work on caves. To perform the study, we collected and processed water and sediment samples in the laboratory. The water sample was directly filtered, and the sediment sample was processed through density separation before the filtration. The suspicious particles were observed and visually analyzed by a digital microscope to classify the particles by aspect. Some suspicious particles with the morphology of microplastics were found in the cave, which have limited access. Interestingly, the locations they were found contradicts previous works in other caves. Our results showed that we were able to identify some suspicious particles in a restricted access cave that correspond to microplastics cubes and fiber cloths.

1. Introduction

Puerto Rico is an island that has a complex geology since part of the island was formed by volcanic and tectonic activity. As ROSE (2023) mention Puerto Rico has three karst regions, mainly limestone: northern, southern, and dispersed.

This research was conducted on northern karst region at Cueva Tallonal located in the municipality of Arecibo. DOWNEY (2020) indicated that this cave is a formation of Aymamon limestone and is approximately 60m long passage without side passages and it can be over 6m wide (Fig, 1). DOWNEY et al. (2022) remark that this cave has a stream controlled and used for private water supply, the water percolates through the karst formation from upward flowing and flows downstream onto the entrance. The purpose of this study is to detect any particles that may be microplastics and analyze the composition of the suspicious particle to clarify if is plastic fiber or another material. Microplastics (MPs) are small particles with approximately 5µm or less and with a density of >1.24kg/L. Microparticles are derived from plastic objects that with time degrade and become what are called microplastics. BARAZA & HASENMUELLER (2023) mention that previous studies determined that water sources are the main mode of transport for microplastics like rivers that play a major role in plastic transport. BARAZA & HASENMUELLER (2023) discuss that the remarkable presence of microplastics in water and land surfaces implies that these particles could be reaching subsurface ecosystems and underground water. These particles can put in danger these ecosystems. BARAZA & HASENMUELLER (2023) indicated that the main reason may be the fact that Karst formation is feature for having soluble rocks including caves and sinkholes that lead to the connection of surface to subsurface. HASENMUELLER et al. (2023) remark that the evidence of microplastics in the subsurface is scarce but the evidence of these suspicious particles in karst has been documented since the 1990s. The nature of the karst can make most caves vulnerable to microplastic contamination. BALESTRA & BELLOPEDE (2023) indicated that karst represents the major Earth's cave systems. Caves are one of the most important geological formations been a peculiar habitat for some organisms with interesting geologic adaptation, and also caves are rich in speleothems and minerals. BARAZA & HASENMUELLER (2023) explain that microplastics can badly affect the biology of the cave and have been demonstrated the ecotoxicity due to chemical additives. BALESTRA & BELLOPEDE (2022) presented that detection of Microplastics is essential because these contaminants can cause irreversible damage to quality and state of the water used for human consumption.

2. Materials and methods

The method used in this study was an adaptation of HASENMUELLER et al. (2023) study. We established 5 sites for the collection of water and sediment samples with approximated 30m per site. Starting with sampling site 1 at the entrance and sampling site 5 at the end as shown in Fig. 1. Before the sampling, the instruments used were sterilized to prevent sample contamination. Also, we mostly avoid the use of plastic material of unknowledge composition. To collect the water sample, 1L glass bottles were introduced first to the top of the bottle slowly in the water to mitigate the sediment presence in the water sample. The sediment samples were placed in polyethylene bags and glass bottles, the samples were left in the sampling sites due to the difficulties presented in a cave and collected in the return. The sediment samples were collected not deeper than 3cm with metallic trowel. To process the sediment sample, we dried them in an oven at 105° C for 48 hours. For the distribution of sediment size particles, the sediment was sieved using mesh sizes: #10 (2,000µm), #60 (250µm), #120 (125µm), and #230 (63µm). The sediment, possible clay, was gently broken into small pieces for the sift. The four different sizes of sediment were stored in polyethylene bags in a fridge until the density separation. For the density separation, we mixed each sediment sample in a 1L glass beaker with 1.20kg/L of NaCl solution. Most of the microplastics have densities < 1.40kg/L, using this solution we can create density separation for the microplastic detection. A magnetic agitator was used to break the clay particles and then the top of the beaker was covered with aluminum foil to let the sample rest while

the density separation occurred. Once the mixture was settled, the supernatant was slowly collected in a 50mL glass beaker with the help of a glass agitator to prevent spillage. The density separation process was triplicated to ensure all suspicious particles were retained. The triplicated supernatants were combined into one solution for filtration. To filtrate the sample, we used a nitrocellulose filter of 0.45µm. Each one of the samples were vacuum filtered, and the process was triplicated with each one of the samples. The water samples were directly vacuum filtered in the same way through the cellulose filter.

The filters of the sediment and water samples were visually inspected under a digital microscope to identify suspicious particles. Those particles that were different from the organic material in color or form were classified as suspicious material.

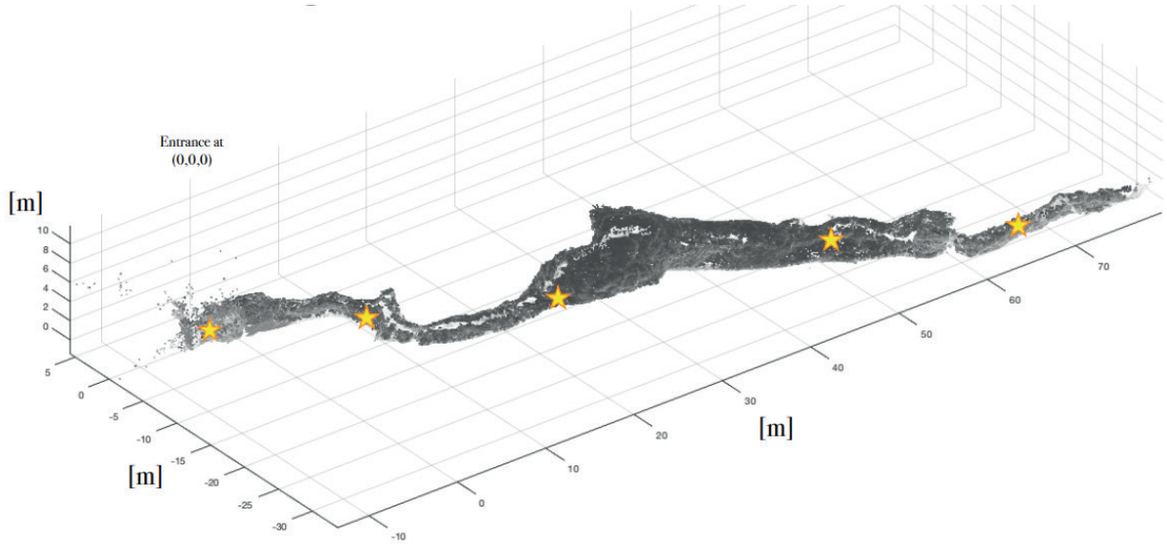


Figure 1: *Sites of sample collection starting with number 1 (left) at the entrance and number 5 at the end (right).*

3. Results

As preliminary results, suspected particles were found in the water samples in the 0.45µm filter. Microparticles were presented in 12 out of 17 filters for the sediments sample and 4 out 5 filters for water. We were able to observe some particles that may be fiber cloth. PEREZ et al. (2021) presented a table in with the characteristics to identified microplastics, i.e. fiber cloth. Examples of the fibers are presented in Figure 2 and Figure 3. As is shown, these fibers had a range of sizes and colors. Additionally, in some samples a cubic particle was found with a variety of colors but similar geometrical shape. Furthermore, some of those particles were transparent and identified as calcite minerals that comes from the erosion mechanisms of the cave.



Figure 2: *Suspicious particle in sediment sample identifies as Fiber/filament. The photo was taken from a digital microscope.*

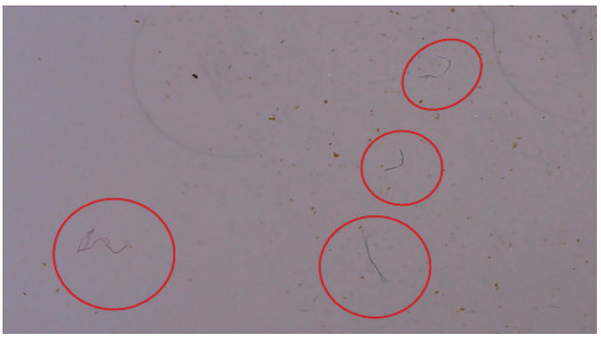


Figure 3: *Suspicious particle found I water sample identify as Fiber/filament. Photon taken from digital microscope.*

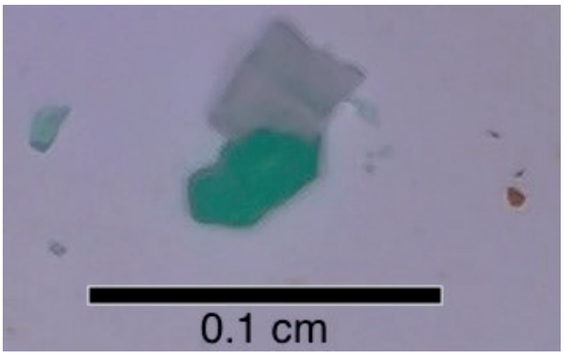


Figure 4: *Suspicious particle found I water sample classified as fragment. Photo taken from a digital microscope whit a scale of 0.1 cm.*

4. Discussion

The presence of microplastics in caves is a concern problem. But it is more concerning the fact that we found some suspicious particles that may be of plastic origin in a limited access cave that is not frequently visited. Usually, the main entrance of the cave is where most of the particles were found in other studies as indicated by PEREZ et al. (2021). For our study, in Cueva Tallonal, the entrance water sample did not have any suspicious particles. In the other 4 water sampling sites, suspicious particles were found (Fig. 3 and Fig. 4). The sediment samples were collected given the fact that microparticles over time are deposited in the sediment. A suspicious particle was found in the 5 sediment sampling sites. We noticed that the abundance of particles increased the deeper into the cave. Because sample 5 has more suspicious particles than sample 1. The particles found were visually classified for preliminary results with the list of most common particles found on water sources following PEREZ et al. (2021) classification by morphology color and size. All the particles that were found on the sample were >0.45µm. To determine the composition of the particles, a Fourier transform infrared spectroscopy can be used. The most common microplastics found in the environment are polymers, synthetic fiber, and pellets.

5. Conclusion

For this study, we were able to demonstrate the presence of some suspicious particles that correlates with microplastics. Additional spectroscopical methodology will provide us information about the exact type of plastic. As demonstrated, caves that aren't free open to humans can be contaminated by non-organic material. We also find more particles in sediment than in water due to the low-density particles do not remain much as supernatant. Since the highest contamination level was found at the deep regions of the cave, microplastics may percolate through the karst getting into the cave. This study shows that karst and cave systems can transport contaminants such as microplastics impacting the water quality and the ecosystem.

Acknowledgments

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Evolution of the SpeleoMedit Project

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Abstract

The SpeleoMedit (Mediterranean Speleology) project offers a unique and collaborative view of caves and karst systems across 24 Mediterranean countries. Initiated during the International Year of Caves and Karst (IYCK), the project aims to promote speleology and conservation efforts. Supported by Tetide APS and the Italian Speleological Society (SSI), it enhances communication among Mediterranean countries and fosters collaboration among research organizations. The project began with foundational elements like pocket cards, photographic exhibitions, and publications. In 2023, it evolved into "Speleological Italy," expanding its scope and introducing SpeleoMedit Interactive, which won the PNRR – TOCC Digital Transition award. This phase embraced digital innovation, offering tools for exploring and documenting caves. The project collected data through surveys, created detailed country-specific reports, and used interactive tools to engage a broader audience. It highlighted the ecological and cultural value of caves, promoting their protection and sustainable management. The project faced challenges like varying data availability but adapted through online platforms and multilingual resources. Future initiatives could include advanced technologies like 3D cave mapping and real-time biodiversity monitoring, enhancing policy development for cave and karst conservation.

Résumé

Évolution du projet SpeleoMedit. Le projet SpeleoMedit (Spéléologie Méditerranéenne) offre une perspective unique et collaborative sur les grottes et les systèmes karstiques de 24 pays méditerranéens. Lancé pendant l'Année Internationale des Grottes et du Karst (IYCK), le projet vise à promouvoir la spéléologie et les efforts de conservation. Soutenu par Tetide APS et la Société Spéléologique Italienne (SSI), il améliore la communication entre les pays méditerranéens et favorise la collaboration entre les organisations de recherche. Le projet a commencé avec des éléments de base tels que des cartes de poche, des expositions photographiques et des publications. En 2023, il a évolué en «Spéléologie Italienne», élargissant son champ d'action et introduisant SpeleoMedit Interactive, qui a remporté le prix de la Transition Numérique PNRR – TOCC. Cette phase a embrassé l'innovation numérique, offrant des outils pour explorer et documenter les grottes. Le projet a collecté des données via des enquêtes, créé des rapports détaillés spécifiques à chaque pays et utilisé des outils interactifs pour engager un public plus large. Il a mis en évidence la valeur écologique et culturelle des grottes, promouvant leur protection et leur gestion durable. Le projet a rencontré des défis tels que la disponibilité variable des données, mais s'est adapté grâce à des plateformes en ligne et des ressources multilingues. Les initiatives futures pourraient inclure des technologies avancées comme la cartographie 3D des grottes et la surveillance en temps réel de la biodiversité, renforçant le développement des politiques de conservation des grottes et des karsts.

1. Introduction

The SpeleoMedit project, initiated as part of the International Year of Caves and Karst (IYCK), seeks to promote speleology and the conservation of caves and karst systems across the Mediterranean. This initiative, supported by Tetide APS and the Italian Speleological Society (SSI), aims to enhance communication among Mediterranean countries, create a unified awareness of speleological practices, and strengthen ties among research organizations. Its core elements include comprehensive documentation of caves, the dissemination of environmental knowledge, and fostering collaboration for the protection of these vital ecosystems

The project began with foundational elements such as pocket cards providing detailed web-based information for each Mediterranean country, a photographic exhibition showcasing the diversity of caves through panels, and the publication of SpeleoMedit Mediterranean Speleology

which incorporated both general contributions and specific insights from all Mediterranean countries. These efforts laid the groundwork for fostering collaboration and raising awareness across the region.

In 2023, the project evolved into "Speleological Italy," expanding its scope to include national contributions that emphasized Italy's role in Mediterranean speleology. The initiative further advanced with the introduction of SpeleoMedit Interactive, which won the PNRR – TOCC Digital Transition award. This interactive phase embraced digital innovation, offering enhanced tools for exploring and documenting caves, thereby amplifying accessibility and engagement for both researchers and the public.

2. Materials and methods

Data Collection Tools: Google Sheets and surveys designed to gather data from 24 participating Mediterranean countries.

Publication Media: Pocket cards, photographic panels, and a special edition magazine, Mediterranean Speleology.

Visual and Digital Assets: Infographics, high-resolution photographs, and an interactive online platform.

Contributors: A network of speleologists, national organizations, and researchers collaborated to create detailed country-specific reports.

TOCC SpeleoMedit Interactive Tools: An interactive web portal featuring pictograms, quizzes, games, and podcasts, transforming SpeleoMedit into a dynamic platform. Podcasts aim to progressively convert the printed volume into an audiobook, making it accessible to a wider audience.

Data Compilation: Information was collected via structured questionnaires focusing on geomorphology, biodiversity, legal protections, and cultural significance of caves in each country.

Content Development: Each country provided a detailed "pocket card" with photographs, cave statistics, and speleological data. These cards were used for online dissemination and physical exhibits.

Exhibitions and Publications: A 53-panel photographic exhibition and a comprehensive magazine presented findings to the public and scientific communities.

Interactive Tools: The SpeleoMedit Interactive portal enables users to navigate Mediterranean caves through engaging multimedia content. This digital transformation supports cultural education and broadens public engagement.

Communication Strategy: The project leveraged web platforms, social media, and international events to engage diverse audiences and promote Mediterranean speleology.



Figure 1: *Book & 53-panel exhibition and conference. Photo Victor Ferrer.*

3. Results

Widespread Participation: Out of 24 invited countries, 23 actively contributed to the project. Each country's participation was represented through detailed pocket cards and photographs.

The SpeleoMedit project has made significant strides in outreach, effectively bridging the gap between scientific research and public engagement. By leveraging a variety of tools and platforms, the project has successfully disseminated knowledge about Mediterranean caves and karst systems to a wide audience. Key outreach efforts include the creation of detailed pocket cards, a touring photographic exhibition, and a special edition book, all of which highlight the ecological and cultural significance of these natural wonders. The introduction of interactive tools, such as a web portal with podcasts, quizzes, and games, has further enhanced public engagement, making speleological information more accessible and engaging. Additionally, the project has fostered collaborations among speleologists and strengthened connections with international organizations, amplifying its impact on both local and global scales. Through these comprehensive outreach initiatives, SpeleoMedit has raised awareness about the importance of cave conservation and promoted sustainable management practices, ensuring that the rich speleological heritage of the Mediterranean is appreciated and protected for future generations.

Knowledge Dissemination:

Pocket Cards: These were made available online and in exhibitions, summarizing critical data such as the number of caves, marine caves, and speleological organizations per country.

Photographic Panels: A touring exhibition showcased the diversity of Mediterranean caves, including iconic sites like Santa Barbara Cave (Italy) and Pas de Vallgornera (Spain).

Expo catalogue: describe the the SpeleoMedit exhibition created by Victor Ferrer with the contribution of dozens of authors composed of 56 rollups.

Special Edition BOOK: The publication compiled comprehensive analyses of Mediterranean karst geography, biospeleology, and cultural aspects.

Interactive Tools: The web portal launched under the TOCC initiative provides a new layer of interactivity, with podcasts and games engaging a broader audience while making speleological information more accessible.

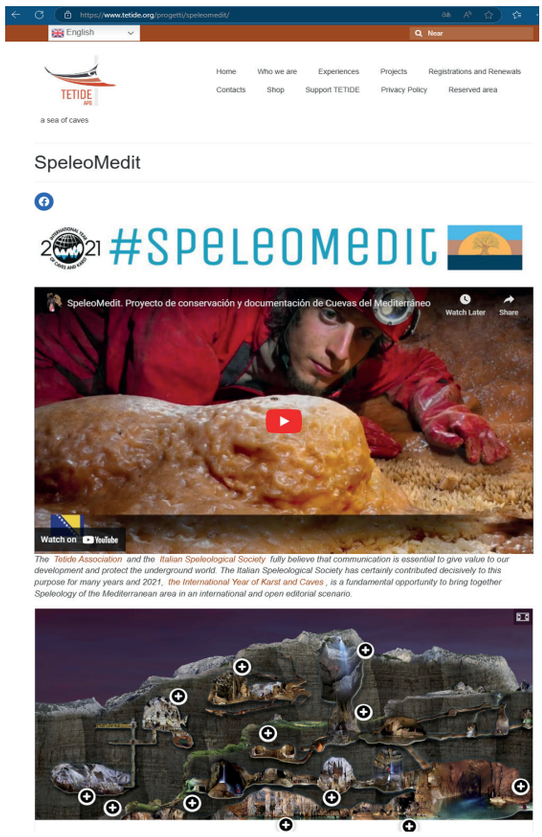


Figure 2: *The SpeleoMedit project portal. Photo: https://www.tetide.org/progetti/speleomedit/.*

Enhanced Networking: The project fostered collaborations among Mediterranean speleologists and strengthened links between local organizations and international bodies like UIS and FSE

New **stereoscopic 3D** video project in high definition. The main objective is to document caves that are exceptional for their conservation or difficult to access. This documentary base is important for geological studies or museums. Some completed examples are the Cova del Pas

de Vallgornera (Spain), Resseau Lachambre (France), Salt Caves (Spain) and the Cueva de los Chorros system (Spain.



Figure 3: *Stereoscopic 3D video for the Chorros cave museum (Albacete, Spain) Photo Ferrer V.*

SpeleoMedit expo on you tube video with music presented in 2023 duration 20:57 https://youtu.be/CFzjL_YcVec

Increased Awareness: The initiative highlighted the ecological and cultural value of caves, promoting their protection and sustainable management



Figure 4: *The SpeleoMedit expo brochure on ISSU: https://www.tetide.org/progetti/speleomedit/ .*

4. Discussion

The SpeleoMedit project effectively bridges the gap between science and public engagement, offering a unified platform for Mediterranean speleology. The detailed documentation and multimedia approach ensure accessibility for both experts and the public. By aligning with IYCK goals, the project has amplified the importance of caves and karst landscapes in the global conservation dialogue.



The introduction of SpeleoMedit Interactive under the TOCC Digital Transition framework has significantly enhanced the project's reach and utility. The portal's combination of quizzes, podcasts, and interactive maps offers an innovative way to engage users, promoting education and cultural awareness on a larger scale. This digital transformation ensures sustainability and positions SpeleoMedit as a forward-thinking initiative.

Key challenges included varying levels of data availability among countries and the need for ongoing updates to maintain relevance. However, the project's adaptability—through online platforms and multilingual resources—mitigated these challenges, ensuring broad participation and utility.

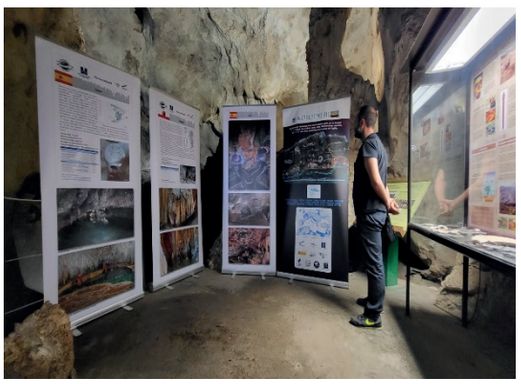


Figure 5: *SpeleoMedit exhibition at the Gruta de las Maravillas in Zuheros (Cordoba-Spain). 11 May 2022. Photo Ferrer V.*

Future initiatives could expand on these foundations by publishing the project in several languages, update info and incorporating advanced technologies like 3D cave mapping and real-time biodiversity monitoring. Furthermore, stronger governmental engagement could enhance policy development for cave and karst conservation.

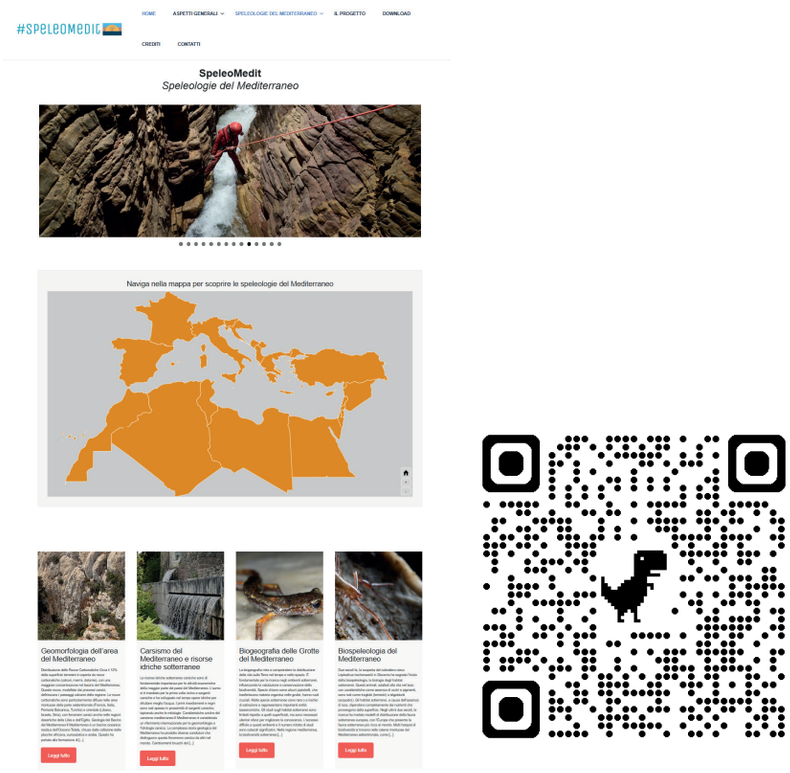


Figure 6: *TOCC web portal for audio book in Italian https://speleomedit.tetide.org/.*

5. Conclusion

The evolution of the Speleomedit project demonstrates its success in fostering collaboration, raising awareness, and documenting the rich speleological heritage of the Mediterranean. Through publications, exhibitions, and digital outreach, it has established a robust framework for future conservation and research efforts. The addition of SpeleoMedit Interactive highlights the project's commitment to innovation and inclusiveness, setting a benchmark for international speleological cooperation and speleology outreach.

Acknowledgments

We extend our gratitude to all contributing speleologists, national organizations, and research institutions. Special thanks to all the authors for photographic contributions and to the editorial team for their tireless efforts in realizing this project. We also acknowledge the support provided by the EU-TOCC Digital Transition program for enabling the digital transformation of SpeleoMedit.

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DIDONNA F., MAURANO F. & FERRER V #SPELEOMEDIT: Speleologie del Mediterraneo.(2023) Speleologia 87; 29-31

Vegetação associada aos neossolos litólicos do carste do Grupo Paranoá, Goiás

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Resumo

A composição florística do carste carbonático é diversa, refletindo características físico-químicas do substrato e ambiente. Além disso, estudos que relacionam a flora com diferentes compartimentos do ambiente cárstico são escassos no Cerrado goiano. Este estudo apresenta espécies botânicas no carste carbonático do Legado Verdes do Cerrado. A amostragem foi realizada em três afloramentos das cavernas do Tarzan, Timor e Val. Foram identificados 826 indivíduos, 30 famílias, 56 gêneros e 73 espécies. As famílias Fabaceae, Malvaceae e Vochysiaceae apresentaram maiores riquezas, assim como os gêneros *Ficus* e *Qualea*. *Cecropia pachystachya, Ficus calyptroceras* e outras dez espécies foram observadas nas três áreas. *Pilosocereus flexibilispinus* e *Piptadenia gonoacantha* podem ser consideradas espécies preferenciais e indicadoras das cavernas do Val e Timor, de acordo com a Análise de Componentes Principais (PCA). Sobre os afloramentos, foram identificadas espécies relacionadas ao cerradão, cerrado *sensu stricto*, mata ciliar e mata seca, assim como sete espécies presentes na lista protegida por Lei no Estado de Goiás e duas espécies "vulneráveis" na categoria de ameaça do CNCFlora (Centro Nacional de Conservação da Flora). A elevada diversidade da flora associada ao carste goiano, ocupando diferentes fitofisionomias do Cerrado ressalta a importância desse ecossistema a ser, especialmente, protegido de impactos.

Abstract

The floristic composition of carbonate karst is diverse, reflecting physicochemical characteristics of the substrate and environment. Furthermore, studies that relate flora to different compartments of karst environment are scarce in the Cerrado of Goiás. This study presents botanic species in carbonate karst of Legado Verdes do Cerrado. Sampling was carried out in three outcrops of the Tarzan, Timor and Val caves. 826 individuals, 30 families, 56 genera and 73 species were identified. The families Fabaceae, Malvaceae and Vochysiaceae showed greater richness, as did the genera *Ficus* and *Qualea*. *Cecropia pachystachya* and *Ficus calyptroceras*, and ten other species, were observed in the three areas. *Pilosocereus flexibilispinus* and *Piptadenia gonoacantha* can be considered preferential and indicator species of the Val and Timor caves, according to the Principal Component Analysis. On the outcrops, species related to cerradão, cerrado *sensu stricto*, riparian forest and dry forest were identified, as well as seven species present on protected by law list of State of Goiás and two "vulnerable" species in the threat category of the National Flora Conservation Center. The high diversity of flora associated with the Goiás karst, occupying different phytophysiognomies of the Cerrado, highlights the importance of this ecosystem being, especially, protected from impacts.

1. Introdução

O ambiente cárstico apresenta peculiaridades quanto a sua hidrologia, fertilidade e biodiversidade que conferem características e feições únicas como cavernas, dolinas, espeleotemas e habitat, além de fragilidades intrínsecas.

No Brasil, a cobertura vegetal do carste forma um mosaico de fitofisionomias, relacionadas à profundidade do solo e sua consequente capacidade de retenção de água, onde florestas predominam na base das encostas e capoeira seca e aberta no topo dos afloramentos (MELO et al., 2013; ESCHWEGE, 1979; WARMING, 1973).

Devido à ampla diversidade de substratos, condições de umidade e luminosidade, o carste promove o desenvolvimento de micro-habitats que sustentam diferentes tipos de vegetação, resultando num conjunto extremamente biodiverso e comumente com espécies restritas a estes ambientes (MELO et al., 2013). Apesar de haver muitos estudos sobre a flora do Cerrado brasileiro, poucos deles abordam especificamente a flora relacionada ao carste (FELFILI, 2004; MELO et al., 2013; MENINO et al., 2015).

A flora saxícola, por exemplo, é uma fitofisionomia particular do carste, pouco densa e associada aos microhabitats das partes mais dissecadas do relevo nos maciços calcários, como os lapiás, onde existam condições ambientais favoráveis ao estabelecimento de plantas (FERREIRA, 2020; MELO et al., 2013). Tais ambientes se encontram extremamente ameaçados, principalmente por ações antrópicas como mineração e agricultura ou indiretas (espécies invasoras) (FERREIRA, 2020).

No carste, em Goiás, autores como Rizzini (1997) verificaram a relativa pobreza de espécies herbáceas no sub-bosque das formações florestais decíduas sobre afloramentos calcários. Em Minas Gerais, entretanto, Melo et al. (2013) observaram a presença deste grupo em

um terço da riqueza total das espécies encontradas, associadas principalmente a terrenos cársticos, tendência que reforça a diversidade botânica associada ao carste.

A mata seca compõe outro tipo de fitofisionomia comum no carste devido à litodependência (RODRIGUES & TRAVASSOS, 2013), tendo seus estudos aprofundados negligenciados quando comparados a outros ambientes.

Conforme Ribeiro & Walter, a mata seca e a mata ciliar apresentam similaridade florística e o que as diferencia é a estrutura da vegetação da mata ciliar que é mais densa e mais alta do que a da mata seca devido à presença do curso d'água.

No Cerrado goiano, rochas carbonáticas intercaladas com quartzitos e filitos da Formação Córrego do Barreiro, Grupo Paranoá compõem o carste da porção centro-norte do estado (ZANCOPÉ et al, 2023). Os solos associados ao carste (epicarste) dessa região, especificamente no Legado Verdes do Cerrado, em Niquelândia, compõem a classe dos Neossolos Litólicos eutróficos próximos às aberturas das cavernas, com alta fertilidade natural e dos Latossolos Vermelho-Amarelo distróficos próximos às dolinas, com baixa fertilidade (BRANDÃO & MOMOLI, 2022; MIRANDA et al., 2022).

Estudo florístico realizado em diferentes fitofisionomias, como mata seca, cerradão, mata ciliar e cerrado sensu stricto no Legado Verdes do Cerrado amostrou 933 espécies arbóreas distribuídas em 154 espécies botânicas (Ferreira et al. 2021). O presente estudo busca contribuir com o levantamento de espécies vegetais associadas ao carste do Grupo Paranoá, em Goiás, e com a integração de dados bióticos e abióticos da paisagem cárstica.

2. Materiais e Métodos

Este estudo foi realizado no entorno de 3 cavernas no Núcleo Engenho da Reserva Legado Verdes do Cerrado (LVC), área privada de produção sustentável de propriedade das Reservas Votorantim/Companhia Brasileira de Alumínio CBA, em Niquelândia, norte do estado de Goiás (Figura 1). Na região do LVC podem ser encontradas diferentes fitofisionomias do bioma Cerrado: cerrado stricto sensu, cerrado rupestre, formações florestais e savânicas (REZENDE; ALVES, 2017). Segundo a classificação de Köppen, o clima é classificado como Savana (Aw), tropical com verões chuvosos e invernos secos, típico do bioma Cerrado, com temperatura média anual mínima de 19,5°C e máxima de 30,2°C e precipitação média anual de 1551 mm (REZENDE; ALVES, 2017).

Os terrenos na região do LVC são sustentados por rochas como metarritmitos que integram sucessões de quartzitos, filitos, ardósias, metacalcários, metadolomitos e mármores (CARVALHO; ALVARENGA, 2018; SERAINE et al., 2021) da Formação Córrego do Barreiro, Grupo Paranoá (CAMPOS et al., 2013; CORDANI et al., 2013; FUCK et al., 1988).

O relevo é fortemente dissecado pela erosão, com serras de topos aguçados e depressões estreitas e alongadas, com vales profundos e encostas íngremes (ZANCOPÉ et al., 2023), com altitude variando de 556 a 1.234 m e declividade entre 0 a 191%. As lentes de rochas carbonáticas propiciaram o desenvolvimento de relevo cárstico, com cavernas, dolinas e uvalas.

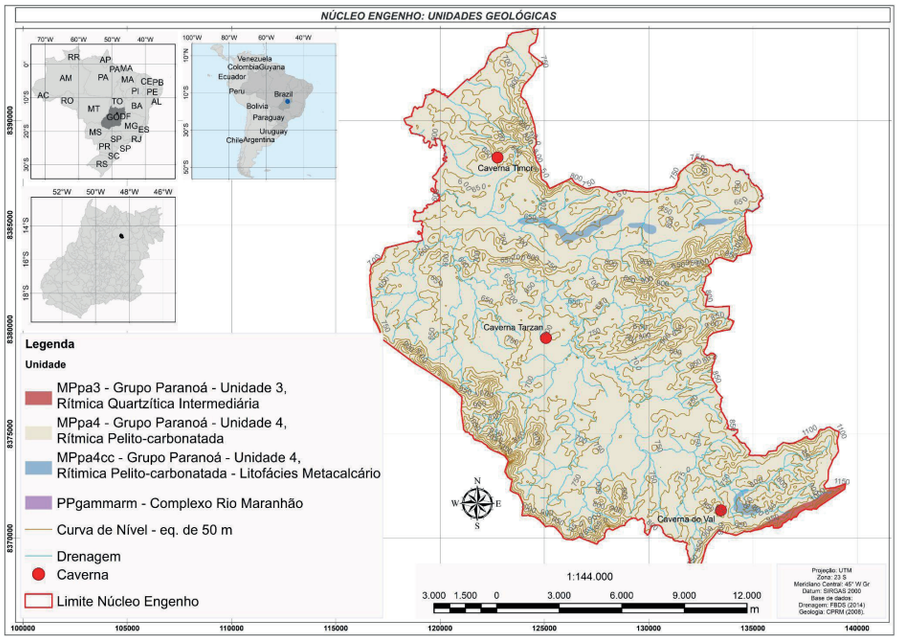


Figura 1: Localização das cavernas Tarzan, Timor e Val e unidades geológicas (Moreira et al., 2008) no Núcleo Engenho do Legado Verdes do Cerrado, Niquelândia, GO.

Os solos do entorno das cavernas Tarzan e Timor correspondem aos Neossolos Litólicos eutróficos, rasos, férteis (pH na ordem de 6,2; Ca e Mg: 8,3 e 2,8 respectivamente; CTC = 13 e V% = 84 (EMBRAPA, 2018; MOMOLI, 2021)) e com condutividade hidráulica (Ko) muito alta na camada superficial (0-20 cm), respectivamente 133,17 e 109,68 cm h^{-1}, de acordo com o sistema de classificação do Soil Survey Division Staff (2017). A elevada condutividade hidráulica está associada a elevada porosidade do solo, com média de 66,4%, e predomínio de macroporos, na ordem de 30,64% nas cavernas Tarzan e Timor (MIRANDA et al., 2022).

Para o presente estudo foram selecionadas três cavernas, situadas em diferentes posições topográficas e uso da terra no entorno: i) Tarzan, no fundo de um vale florestado com cultivo de soja no entorno, a montante; ii) Timor, numa encosta com vegetação de cerrado nativo a montante e cultivo de soja a jusante e; iii) Val, no topo da área mais elevada do LVC com vegetação de cerrado nativo e à beira de estrada vicinal (Figura 2).

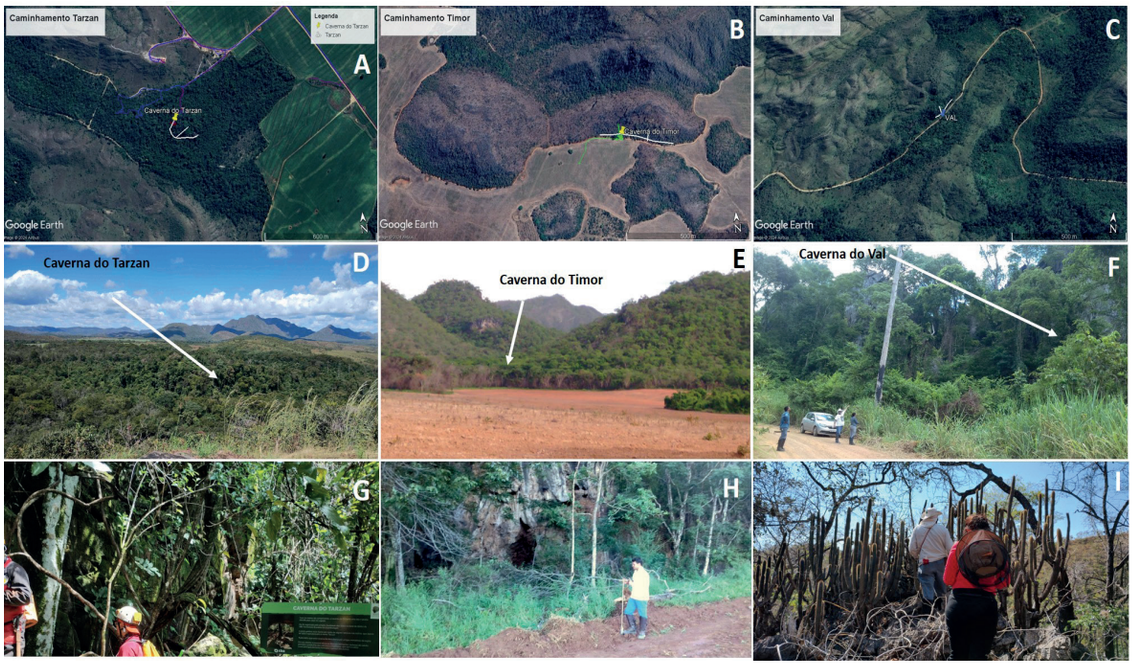


Figura 2: *Eixos de caminhamentos do levantamento da flora no entorno das cavernas do Tarzan, Timor e do Val (A, B e C), vista geral da paisagem do entorno das cavernas (D, E F) e aspectos da vegetação nos maciços do Tarzan, Timor e Val (G,H e I).*

3. Resultados

No que diz respeito ao levantamento florístico e identificação botânica, foram amostrados 826 indivíduos, distribuídos em 30 famílias, 56 gêneros e 73 espécies. As famílias mais representativas em termos de quantidade de espécies foram: Fabaceae (26 espécies); Malvaceae (sete espécies) e Vochysiaceae (quatro espécies). Os gêneros com maior riqueza de espécies foram: *Ficus* e *Qualea* (três espécies cada). Já as espécies mais abundantes foram *Terminalia argentea* (57 indivíduos); *Astronium urundeuva* e *Dilodendron bipinnatum* (55 indivíduos cada); *Luehea paniculata* (52 indivíduos) e *Pilosocereus flexibilispinus* (50 indivíduos).

A caverna que apresentou maior riqueza florística foi a do Timor (41 espécies), seguida pela do Val (38 espécies) e por último a do Tarzan (37 espécies). As três áreas apresentaram em comum a ocorrência das seguintes espécies: *Astronium fraxinifolium, A. urundeuva, Cecropia pachystachya, Dilodendron bipinatum,, Ficus calyptroceras, Guazuma ulmifolia, Luehea paniculata, Piptadenia gonoacantha, Sterculia striata* e *Terminalia argentea*. É importante ressaltar também a ocorrência de espécies presentes na lista protegida por Lei no Estado de Goiás como: *A. fraxinifolium; A. urundeuva; P. gonoacantha; Tabebuia roseoalba; T. aurea; Handroanthus impetiginosus* e *H. ochraceus*. Além dessas, outras espécies amostradas como *Cedrela fissilis* e *Apuleia leiocarpa* são consideradas "vulneráveis" na categoria de ameaça do CNCFlora (Centro Nacional de Conservação da Flora).

Pela Análise de Componentes Principais/PCA (PC1 = 70,1% e PC2 = 20,8% da variância, respectivamente) (Figura 3) foram encontradas espécies preferenciais e indicadoras das cavernas do Val e Timor, especialmente *P. flexibilispinus* (Cactaceae) associada à caverna do Val, seguida de *P. gonoacantha* (Fabaceae).

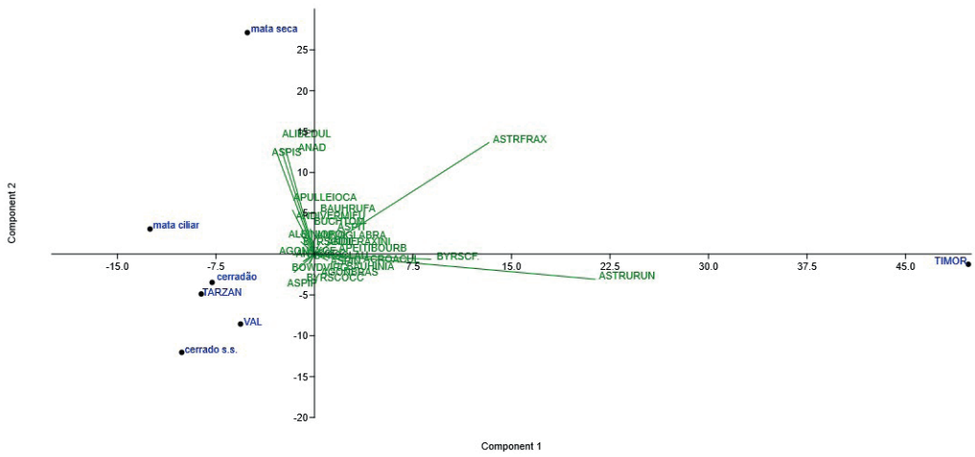


Figura 3: *Análise de Componentes Principais/PCA da distribuição das espécies em relação aos sítios do Tarzan, Val e Timor presentes na Reserva Particular de Desenvolvimento Sustentável Legado Verdes do Cerrado, Niquelândia Goiás.*

Na caverna Timor, as espécies preferenciais e indicadoras foram *A. urundeuva* e *A. fraxinifolium* (Anacardiaceae), *Luehea divaricata* e *Sterculia striata* (Malvaceae), *Terminalia argentea* (Combretaceae), *Dilodendron bipinatum* (Sapindaceae), *Guettarda viburnoides* (Rubiaceae). Não foram encontradas espécies indicadoras em Tarzan, ficando este sítio em posição intermediária entre Val e Timor, com espécies em comum. A grande maioria das espécies apresentaram ocorrência comum nas três áreas, ficando posicionadas ao centro do diagrama da PCA. A análise PCA foi realizada com as 181 espécies encontradas nas três áreas, utilizando matriz de variâncias e covariâncias.

4. Discussão

A flora arbórea-arbustiva associada aos afloramentos cársticos do LVC, em Niquelândia, Goiás, apresentou relativa riqueza de espécies, em contraponto ao constatado por Rizzini (1997) sobre a relativa pobreza de espécies herbáceas sobre os afloramentos carbonáticos goianos.

Outro aspecto relevante sobre a flora do cerrado no carste, de forma geral, é que esta exibe uma grande amplitude de ecossistemas, tanto na escala de fitofisionomias quanto de biomas.

Por exemplo, o presente trabalho no LVC identificou espécies sobre o carste típicas de cerradão, cerrado *sensu stricto*, mata seca e mata ciliar, enquanto Melo et al. (2013) detectaram, sobre o carste de Minas Gerais, a presença de espécies encontradas em outros domínios fitogeográficos além do Cerrado, como Mata Atlântica, Amazônia, Caatinga, Pampa e Pantanal. MENINO et al. (2015), ao investigarem a flora do carste do Parque Nacional das Cavernas do Peruaçu, em Minas Gerais, se depararam, também com ampla diversidade de espécies de Floresta Estacional Decidual em diferentes ambientes como uma encosta, caatinga arbórea e no ecótono com o Cerrado. Na região cárstica do Parque Estadual da Terra Ronca, em Goiás, foram identificadas espécies compatíveis com os biomas Cerrado e Caatinga sobre os solos arenosos da região (TEIXEIRA et al., 2016).As espécies encontradas no presente levantamento arbóreo, sobre o carste carbonático do Grupo Paranoá no LVC, revelou a presença de espécies observadas em levantamento anterior, realizado na RPDS-LVC entre 2018-2020 (Ferreira et al. 2021), em outros ambientes e diversas fitofisionomias, em especial na mata seca (vegetação típica do carste), na mata ciliar e em menores proporções no cerradão e cerrado *sensu stricto*. o No carste do LVC, além das espécies citadas como preferenciais e indicadoras na PCA, as paineiras (gênero *Ceiba*), figueiras e cactos foram amostradas com exclusividade nas três cavernas estudadas, sendo as demais espécies consideradas comuns a outros ambientes. Dessa forma, quando comparado ao levantamento florístico de Ferreira et al. (2021), nota-se que as espécies dos gêneros *Ficus, Ceiba, Cereus* e *Pilosocereus* não foram amostradas em outras áreas do LVC, podendo, portanto, serem consideradas típicas desses ambientes. A presença de espécies de porte arbóreo sobre solos rasos, a princípio incapazes de sustentar o sistema radicular robusto e profundo das árvores, indica que há sobre estes afloramentos rochosos, solos com condições favoráveis para tal desenvolvimento radicular. Solos rasos com pavimento rochoso próximo à superfície costumam ter problemas de baixa permeabilidade à água, resultando em stress hídrico e baixa disponibilidade de nutrientes, ou seja, restrições físicas e químicas. Os solos do carste, contudo, apresentam peculiaridades que, literalmente, dissolvem essas restrições. Fisicamente, a permeabilidade à água sobre a rocha carbonática é alta, visto que apresenta porosidade elevada. E quimicamente, os solos do carste, apesar de pouco desenvolvidos, em profundidade, apresentam boa disponibilidade de nutrientes devido ao elevado conteúdo de cálcio e magnésio das rochas carbonáticas, resultando em pH próximo à neutralidade e V% acima de 50% (índice que indica alta fertilidade ou eutrofia) (BRANDÃO & MOMOLI, 2022; MIRANDA et al., 2022).

5. Conclusão

O caste das cavernas Tarzan, Timor Val no LVC apresenta riqueza florística considerável, variando de 37 a 41 espécies. Algumas espécies demonstram ter preferência pelo ambiente cárstico quando comparadas a outras no interior da Reserva (RPDS-LVC), sendo encontradas apenas sobre o carste e podendo ser consideradas típicas desses ambientes. As paineiras e figueiras (gêneros Ficus e Ceiba), se repetiram com frequência nas três cavernas, enquanto cactáceas (gêneros Cereus e Pilosocereus) se concentraram apenas no topo do afloramento da caverna do Val.

A maioria das espécies observadas pode ser encontrada em diferentes fitofisionomias como mata seca, mata ciliar e cerradão devido às transições e compartilhamento de espécies que ocorrem entre essas fitofisionomias. Já no cerrado *sensu stricto*, as espécies em comum observadas foram sobretudo aquelas consideradas de ampla ocorrência, ou seja, sua presença pode ser observada em várias fitofisionomias do Cerrado, como é o caso de *Curatella americana*.

Além do carste carbonático representar uma "ilha de fertilidade" para a vegetação nativa de diversas fitofisionomias do Cerrado, na RPDS-LVC ele abriga sete espécies protegidas por Lei no Estado de Goiás e duas espécies "vulneráveis" na categoria de ameaça do CNCFlora (Centro Nacional de Conservação da Flora). Representa, assim, um importante geoecossistema para o desenvolvimento vegetal, produção de biomassa e sequestro de carbono.

O presente estudo corrobora a premissa que a flora associada ao carste costuma apresentar elevada diversidade na sua composição, suporta espécies de diferentes fitofisionomias e geoambientes, secos e ensolarados, úmidos e sombreados, sobre solos rasos e profundos. Logo, compõe um importante ecossistema a ser, especialmente, protegido de impactos e usos degradadores, conferindo elevado valor agregado aos ecossistemas.

Agradecimentos

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Considerações sobre a distribuição de cavidades em rochas graníticas, granito - gnaisse e granitóides e ígneas diversas em Minas Gerais - Brasil

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Resumo

Este artigo faz uma contribuição ao estado da arte do conhecimento sobre a distribuição e do conhecimento de cavidades ou cavernas em rochas granito-gnáissicas, graníticas, vulcânicas ou litotipos correlatos no Estado de Minas Gerais. Traz um apanhado a partir dos cadastros conhecidos (CANIE – CECAV ; CNC_SBE), trabalho de mapeamento individual de grupo de espeleologia, informações de alguns licenciamentos indicados pelos órgãos ambientais (públicos – URA Leste ; FEAM) e estudos atuais da empresa Vale, com base no conhecimento adquirido em cavidades encontradas nos processos de licenciamentos e de espeleologia em geral.

Abstract

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Resumen

Este texto te permite redactar tu artículo completo para las actas de la Conferencia Científica 19 th. Los artículos deben ser entregados en su forma definitiva (listos para impresión) en formato *.doc, *.odt o preferiblemente en *.docx. Su extensión será de 6 páginas, incluyendo figuras, fotos y tablas. La longitud del resumen será de 200 palabras como máximo. No se permiten palabras clave. Para el resumen, escribe en una sola columna. Si el artículo está escrito en inglés, se recomienda un resumen en francés, pero no es obligatorio. Si el artículo está escrito en un idioma diferente al inglés, es obligatorio incluir un resumen en inglés (con el título en inglés al principio del resumen). Usa la fuente Calibri de 9 pts.

1. Introdução

Cavernas formadas por rochas graníticas, ígneas, granitóides, metaígneas, granito-gnáissicas e gnáisses – também chamadas de rochas magmáticas ou plutônicas – são aquelas originadas em altas temperaturas à partir da solidificação do magma, que foram soerguidas por processos diversos desde o grande continente Gondwana. Elas constituem formações geológicas altamente resistentes e com elevado nível de dureza, sendo importantes para a obtenção de minérios para construção civil e produção de materiais derivados de sua composição. No Brasil, nos últimos 20 anos são mencionadas cavernas em rochas graníticas, até vulcânicas e metaígneas em diversos estados como Santa Catarina, São Paulo, Rio de Janeiro, Espírito Santo, Minas Gerais, Bahia, Paraíba, Alagoas, Ceará entre outros. Contudo, cavernas inseridas em sistemas rochosos menos solúveis tendem a ser mais raras, devido à dificuldade na formação de espaços subterrâneos. Porém, cada vez mais se encontram registros destes tipos de cavidades nos cadastros brasileiros e citações de artigos científicos.

Em Minas Gerais, como no Brasil, há poucas caracterizações ou organizações das informações destes tipos de ocorrências, porém tem destaques menções sobre a gênese aplicando sistemas conhecidos internacionais, e pouca informação sobre as dimensões cadastradas, aspectos geológicos ou de referências sobre os tipos encontrados, litotipos, e outras informações importantes, como a fauna cavernícola nestas cavidades não menos importantes que as demais. Diversos autores estudaram a fauna cavernícola, para fins de comparações quanto à abundância de indivíduos, quanto a distribuição dos individuos, quando comparados a outras litologias e à região da amostra (exemplo Serra do Mar, Serra da Mantiqueira). Diversas cavidades em rochas graníticas, ígneas gnáissicas, ou até basalticas são conhecidas no Cadastro Nacional de Cavernas (CNC - SBE), Cadastro Nacional de Informações Espeleológicas (CANIE, Brasil), citações em artigos, e resultados dos processos de licenciamentos ambientais de empreendimentos como centrais hidrelétricas, minerações de materiais de construções e de

revestimentos, entre outros. São informados neste artigo sobre os quantitativos dos cadastros existentes, para o Estado de Minas Gerais, de modo a ter um retrato do atual conhecimento. No CANIE de um total de mais de 22.620 cavernas cadastradas no Brasil, menos de 2% delas são conhecidas nas rochas graníticas, no CNC da SBE 55 cavidades estão cadastradas nestas litologias em Minas Gerais, sendo a maior até o momento, a Gruta do Pedrão I e II em Heliodora, com 550m de extensão. A média de projeções horizontais apurada em cadastros disponibilizados nos processos de licenciamento em Minas Gerais perfaz para rochas graníticas, granito-gnaisses e gnaisses excetuando-se as duas cavidades de Heliodora, foi de 23,75m. Desta forma, até o presente momento, foi possível verificar que diversas cavidades desta amostra, possuem a gênese por depósito de tálus, depósito de tálus em canais (com erosão pluvial), e junta fechada. Em raras ocorrências podem estar associadas a estruturas do tipo « descascamento » e fraturas associadas, como observado em uma cavidade em granito-gnaisse da Suíte Borrachudos no município de Itabira.

2. Materiais e Métodos

Foram utilizados dados disponibilizados no cadastro do CECAV – CANIE (2022), mais atualizado, consulta ao CNC – SBE (Cadastro Nacional de Cavidades – da SBE, Sociedade Brasileira de Espeleologia – 2023), consultas bibliográficas de artigos disponíveis a respeito do tema de cavidades em rochas graníticas, gnáissicas ou similares (rochas cristalinas) no estado de Minas Gerais, dados disponibilizados de cavidades pela Vale (cadastro Espeleovale), e consultas a alguns processos de licenciamentos de barragens do Governo do Estado de Minas disponibilizados. Através destas bases reunidas se chegou a uma aproximação das cavidades existentes em rochas graníticas, ou gnáissicas dentro de classificações como rochas ígneas e vulcânicas relacionadas nestes cadastros ou citações dentro de artigos, como levantamentos da fauna cavernícola nestes tipos de rochas, tentando-se uma aproximação dos tipos de gêneses associadas e dimensões quando citadas ou mapeadas. A falta de clareza de informações ou de um critério descritivo mais completo destas cavernas (planilhas de cadastros mínimas) nos cadastros ou citações em artigos, foi observada dificultando a construção do estado da arte sobre este tipo de cavidade ou sua distribuição no estado de Minas Gerais, chegando a esta aproximação da informação disponível. Os dados existentes foram planilhados e arranjados conforme os tipos genéticos conhecidos, sendo simplificada a classificação para fins desta primeira aproximação e quantificação.

3. Resultados

Pouco conhecidas no Brasil, porém com diversos registros nas bases consultadas, as cavernas em rochas graníticas, granito- gnáissicas, gnáissicas, e em rochas derivadas de processos vulcânicos, como basálticas são pouco comuns e carecem de estudos mais detalhados. Como já destacado por diversos autores, outras litologias como quartzitos, arenitos, rochas ferríferas e rochas gnáissicas ou graníticas são susceptíveis à formação de cavernas (AULER & PILÓ, 2005 apud Hardt, 2002; Hardt, 2003), podendo serem denominados de “carste não tradicional” conforme proposto por Travassos (2014), e “carste tradicional” aqueles processos sobre rochas carbonáticas, para minimizar os conflitos sobre a definição do termo cárstico. Para rochas graníticas, vulcânicas ou magmáticas, que possuem cavidades associadas, não são atribuídos estes sistemas devido aos tipos genéticos encontrados, embora os processos que atuam nos sistemas descritos para cavidades em “carste não tradicional”, possam ser visualizados neste tipo de sistema parcialmente. Contudo, cavernas inseridas em sistemas rochosos menos solúveis como os granitos, gnaisses e rochas similares tendem a ser mais raras, devido à dificuldade na formação de espaços subterrâneos, e os processos associados sendo estes mais específicos. A gênese das cavidades em rochas granito-gnáissicas, vulcânicas ou magmáticas podem ser associadas a processos de intemperismo, como a esfoliação esferoidal, que se aproveitando das estruturas primárias e secundárias como foliações, juntas e fraturas na rocha encaixante, geram acúmulos de blocos residuais em canais ou pilhas, ou em uma segunda classe formada em juntas abertas ou fechadas como apresentado na classificação de Finlayson (Esch 1991) (Figura 1).

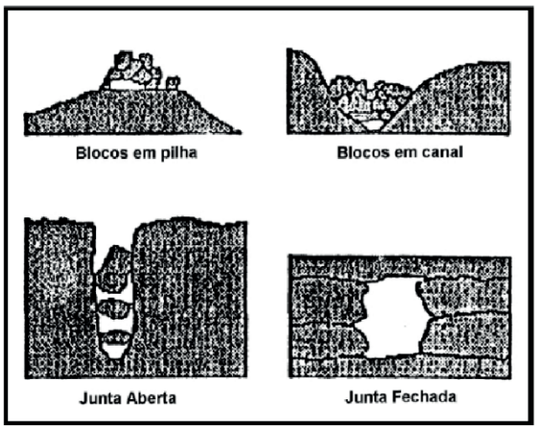


Figura 1: *Esquema da classificação de Finlayson. (ESCH, 1991).*

No Brasil, expedições e pesquisas em cavidades em granitos, granitóides e gnaisses foram realizadas no sul de Minas Gerais (HARDT, 2002; HARDT, 2003), em Bertioga (ZAMPAULO et al., 2007), Itu e Ubatuba (IGUAL et al., 2011) em São Paulo. Na Bahia, cavidades desta litologia foram cadastrados por Auler (2007). Se considerarmos todo o volume da litosfera terrestre, concluímos que quase 80% de sua composição é formada por rochas ígneas ou magmáticas, o que nos leva a refletir que há possibilidade destes tipos de rocha formarem algum tipo de cavidade, revela a importância de conhecermos um pouco mais desse tipo de rocha existente. Diversas cavidades em rochas magmáticas ou plutônicas de derivações mais comuns como granitos e posteriormente metamorfizadas como gnaisses são mencionadas em todo mundo, e no Brasil nos últimos 20 anos vem sendo conhecidas em estados como Rio de Janeiro, São Paulo, Santa Catarina, Paraíba, Ceará e Minas Gerais, entre outros.

Em Minas Gerais poucas cavernas neste tipo de rocha foram mapeadas, sendo destaque menção sobre as Grutas do Pedrão I e II em Heliodora (SENA, 1996), pelos integrantes do Grupo Agster de Pesquisas Espeleológicas (embrião do Guano Speleo). Hardt (2003) cita algumas cavidades na Serra da Mantiqueira, com exemplos de São Paulo e Minas

Gerais e destaca uma cavidade em Monte Sião, apresenta o sistema de classificação de cavidades em rochas graníticas, entre elas a Gruta do Morcego, mapeada pelo Espeleogrupo Monte Sião, desenvolvida por processos. Alguns autores que estudaram cavernas em granito ou gnaisse como no trabalho sobre a ecologia, conservação e a fauna associada a cavernas da Mata Atlântica, SOUZA-SILVA (2008) que amostrou um total de 32 cavidades inseridas em rochas magmáticas, sendo que estas cavidades representam 31% das cavidades amostradas no trabalho, estando distribuídas entre os estados de Minas Gerais e Espírito Santo. Neste trabalho, ele demostra que a riqueza nestas cavidades mostra variações como por exemplo na Gruta da Manga de Pedra (Nacip Raidan – MG). BERNARDI, PELLEGRINI, TAYLOR & FERREIRA (2012) citam a Gruta do Pinhão Assado, formada em depósito de tálus, apresentou um elevado número de espécies quando comparado a grande parte das cavidades de mesma litologia inventariadas por SOUZA-SILVA (2008) e por GNASPINI-NETO e TRAJANO (1994), com 52 morfoespécies. Para rochas graníticas, ou vulcânicas, que possuem cavidades associadas, não são atribuídos estes sistemas citados devido aos tipos genéticos encontrados, embora os processos que atuam nos sistemas como "carste não tradicional" possam ser visualizados neste tipo de sistema parcialmente, como processos erosivos, dissolução parcial, abatimentos, sumidouros e surgências. Um exemplo de dissolução pode ser observado relacionado aos processos de lapiezamento, pode ser observado nos sienitos encontrados no Parque Nacional das Agulhas Negras, na divisa entre os estados de Minas Gerais, Rio de Janeiro e São Paulo. Não raros, sumidouros ativos e surgências entre blocos podem ser observados em regiões com tálus desenvolvidos, ou no interior de rios inseridos nestas rochas. Contudo, cavernas inseridas em sistemas rochosos menos solúveis como os granitos tendem a ser mais raras, devido à dificuldade na formação de espaços subterrâneos, sendo estes mais específicos. Embora raras, já não são comuns pela quantidade de cavidades registradas, e atualmente, no que diz respeito ao potencial espeleológico por litologia (CECAV, 2012), no baixo potencial, se concentram estes tipos de cavidades associadas a rochas dos complexos cristalinos, como granitos, granito-gnaisses, granitóides e outras derivações. Dados do CECAV, a partir do cruzamento de dados da ocorrência de cavidades nas classes de rochas definidas no Mapa das Áreas de Ocorrência de Cavernas do Brasil (ICMBio/CECAV, 2022), é possível observar que o grupo de rochas classificadas como granitóides contempla apenas 2% do total de cavidades registradas que no ano de 2020, o total já ultrapassava 21.500 cavidades (Figura 2). Desse modo, se observa que os estudos em cavidades granito-gnáissicas ainda são bastante incipientes.

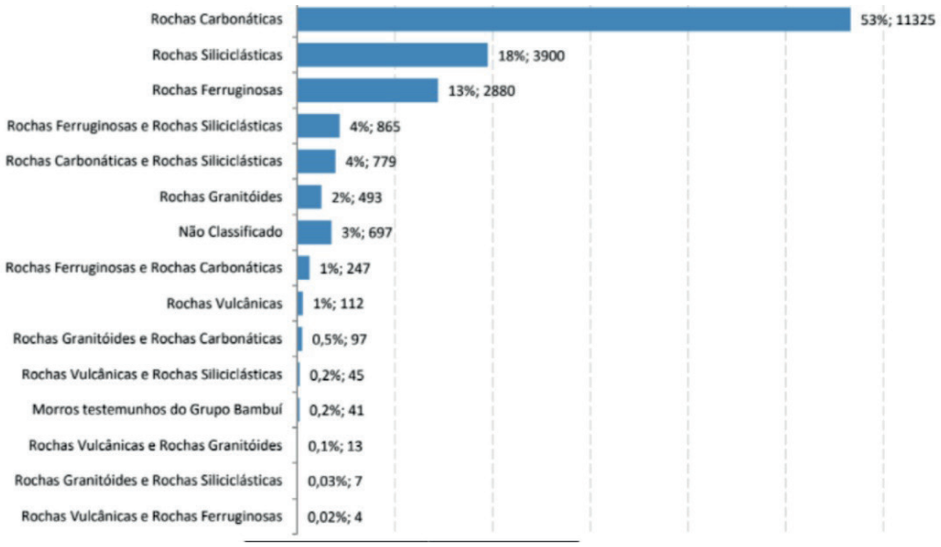


Figura 2: *Distribuição de cavidades segundo a litologia, dados estatísticos gerados a partir do Anuário Estatístico do Patrimônio Espeleológico Brasileiro, realizado pelo ICMBio/ CECAV (2020).*

4. Discussão

Em Minas Gerais, como no Brasil, há poucas caracterizações ou organizações das informações destes tipos de ocorrências, porém tem destaques menções sobre a gênese aplicando sistemas conhecidos internacionais, e pouca informação sobre as dimensões cadastradas, aspectos geológicos ou de referências sobre os tipos encontrados, litotipos, e outras informações importantes, como a fauna cavernícola nestas cavidades não menos importantes que as demais. Diversos autores estudaram a fauna cavernícola, para comparações quanto à riqueza e abundância de indivíduos, SOUZA-SILVA (2008), BERNARDI, PELLEGRINI, TAYLOR & FERREIRA (2012), quanto a distribuição dos indivíduos, quando comparados a outras litologias e à região da amostra (exemplo Serra do Mar, Serra da Mantiqueira). Diversas cavidades em rochas graníticas, ígneas gnáissicas, ou até basalticas são conhecidas no Cadastro Nacional de Cavernas (CNC - SBE), Cadastro Nacional de Informações Espeleológicas (CANIE, Brasil), citações em artigos, e resultados dos processos de licenciamentos ambientais de empreendimentos como centrais hidrelétricas, minerações de materiais de construções e de revestimentos, entre outros. São informados neste artigo sobre os quantitativos dos cadastros existentes, para o Estado de Minas Gerais, de modo a ter um retrato do atual conhecimento. Desta forma, até o presente momento, foi possível verificar que a diversas cavidades desta amostra, possuem a gênese por depósito de tálus, depósito de tálus em canais (com erosão pluvial), e junta fechada. Em raras ocorrências podem estar associadas a estruturas do tipo « descascamento » e fraturas associadas, como observado em uma cavidade em granito-gnaisse da Suíte Borrachudos no município de Itabira (fig.3).



Figura 3: *Esquerda : maciço que abriga na base a Gruta do Pedrão I e II formada em tálus em Heliodora (MG) e na foto da direita, entrada de cavidade na camada do granito-gnaisse da Suíte Borrachudos, associado ao descascamento e foliação com fraturas.*

5. Conclusão

No CANIE de um total de mais de 22.620 cavernas cadastradas no Brasil, menos de 2% delas são conhecidas nas rochas graníticas, no CNC da SBE 55 cavidades estão cadastradas nestas litologias em Minas Gerais, sendo a maior até o momento, a Gruta do Pedrão I e II em Heliodora, com 550m de extensão. Algumas cavernas com destaque no sul de Minas Gerais são formadas em rochas basálticas, porém em depósitos de tálus. A média de projeções horizontais de 23,75m encontrada quando agrupados os dados de tabelas e cadastros disponibilizados nos processos de licenciamento em Minas Gerais perfaz para rochas graníticas, granito-gnaisses e gnaisses excetuando-se as duas cavidades de Heliodora,. Quando associada a esta amostra, as duas cavidades de Heliodora, a Gruta do Pedrão I e II e a Gruta do Cucuruto, a média sobe para 46,86 da amostra de 50 cavidades que possuiam informações de projeções horizontais ou desenvolvimento linear entre outras informações sobre as litologias predominantes como estas derivações de granitos, granitos-gnaisses e gnaisses.

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Desafios da criação e desenvolvimento de um grupo de extensão em espeleologia

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Resumo

As atividades de extensão têm um caráter transformador entre a universidade e comunidades externas. O presente estudo foca-se no grupo de extensão universitária em espeleologia CAVUS, do latim, caverna, criado por dentro do Instituto de Geociências da UNICAMP. O objetivo é apresentar a criação e o desenvolvimento de um grupo universitário de espeleologia com iniciativa puramente discente, visando evidenciar os desafios e a trajetória realizada durante seu primeiro ano de atividades. O procedimento metodológico utilizado é a pesquisa-ação. Como resultados, foram apresentadas as atividades organizadas pelo grupo, bem como o seu percurso formativo. Os principais desafios são na arrecadação de recursos financeiros para poder realizar ações de impacto social, como por exemplo, oficinas com alunos do ensino médio da rede pública, assim como outras iniciativas que permitam difundir os conhecimentos da área. Por um lado, espera-se ver quais serão os resultados da disciplina para que ocorra um ciclo de aprimoramento contínuo, e aplicá-la nos próximos semestres; além de organizar eventos de divulgação científica para toda a comunidade externa.

Abstract

Extension activities play a transformative role in the relationship between the university and external communities. This study focuses on the university extension group in speleology CAVUS—from Latin, “cave”—created within the Geosciences Institute at UNICAMP. The objective is to present the creation and development of a university speleology group, initiated purely by students, highlighting the challenges faced and the progress made during its first year of activities. The methodological approach used is action research. As results, the study presents the activities organized by the group, as well as its formative trajectory. The main challenges involve fundraising to carry out social impact initiatives, such as workshops with public high school students, as well as other efforts aimed at disseminating knowledge in the field. On one hand, the expectation is to assess the outcomes of the course to enable a continuous improvement cycle and apply it in the following semesters; on the other, to organize scientific outreach events for the broader external community.

1. Introdução

As atividades de extensão, segundo o Fórum Nacional de Pró-Reitores de Extensão das Universidades Públicas Brasileiras (FORPROEX, 2007), podem ser divididas em 5 categorias: Programa, Projeto, Curso, Evento e Prestação de Serviço. Sob esse contexto, o CAVUS, um grupo de extensão de espeleologia composto por estudantes de geociências da Universidade Estadual de Campinas (UNICAMP), se enquadra na categoria de Programa por articular diferentes projetos e atividades de extensão de variadas durações.

O surgimento do CAVUS foi derivado do interesse particular dos discentes no tema, somado à ausência de grupos espeleológicos ativos no município de Campinas. O grupo tem como objetivo o desenvolvimento acadêmico dos membros dentro da área de espeleologia, além da difusão dos conhecimentos com a comunidade. Sob esse viés, durante o primeiro ano do grupo, foram realizadas atividades de capacitação dos membros e, principalmente, atividades educativas com público infanto-juvenil externo à comunidade acadêmica, as quais são classificadas como atividades de extensão.

O presente trabalho tem como objetivo apresentar a criação e o desenvolvimento de um grupo universitário de espeleologia com iniciativa puramente discente, visando evidenciar os desafios e a trajetória realizada durante seu primeiro ano de atividades.

A extensão é uma atividade essencial para democratizar o acesso ao conhecimento acadêmico e para pesquisar sobre distintas áreas temáticas, como a espeleologia, de uma forma ativa e prática. Além disso, as atividades de extensão são muito importantes para fortalecer os vínculos entre a universidade e as comunidades. Observa-se, também, que as diferentes áreas estudadas pelos membros do grupo, composto por estudantes de geologia e geografia, contribuem no caráter educativo das atividades, de modo que traz um viés interdisciplinar para os projetos desenvolvidos e para os eventos realizados.

2. Materiais e Métodos

A metodologia abordada é de caráter descritivo, utilizando o conceito de pesquisa-ação como procedimento principal, apoiada em revisão de literatura e descrição de ações no grupo de extensão CAVUS. O uso da pesquisa-ação se dá pois “é um termo que se aplica a projetos em que os práticos buscam efetuar transformações em suas próprias práticas” (BROWN; DOWLING, 2001, p. 152), ou seja, o uso desta terminologia se baseia na simultaneidade de aplicação de métodos teóricos obtidos em pesquisas, e práticos, aplicando ideias discutidas em grupo e inspirações

em outras atividades realizadas por outras entidades.

Isso posto, embora a pesquisa-ação tende a ser pragmática, ela se distingue claramente da prática e, também se distingue da pesquisa científica tradicional, principalmente porque a pesquisa-ação ao mesmo tempo altera o que está sendo pesquisado, e é limitada pelo contexto e pela ética da prática (ELLIOT, 1991). Além disso, embora a pesquisa e a ação atuem de forma concomitante, também atuam uma sobre a outra, desenvolvendo características próprias tanto das práticas do grupo quanto da pesquisa científica.

3. Resultados

O CAVUS surgiu como iniciativa de discentes dos cursos de geologia e geografia, motivados pelo interesse em aprofundar experiências na área, e incentivar à comunidade em geral. Antes da formação do grupo, alguns membros fizeram parte de cursos e encontros da área da espeleologia, o que despertou interesse na área e lhes fez sentir a ausência de um grupo estudantil na área dentro da UNICAMP. Foi assim que em dezembro de 2023 deu-se início ao grupo, atendendo ao desejo de fundar um grupo estudantil com foco na espeleologia; com o apoio do Professor Doutor Alessandro Batezelli que auxiliou com as questões burocráticas dentro do Instituto e na estruturação inicial para a criação do grupo.

É importante indicar o papel crucial do Grupo Pierre Martin de Espeleologia (GPME), pois em razão de atividades prévias realizadas com eles, os discentes identificaram lacunas que motivaram o desejo da eclosão do CAVUS. Em virtude da inexperiência dentro do contexto da espeleologia, GPME auxiliou o CAVUS para impulsionar e melhor consolidar as recentes ideias dos discentes, fornecendo cursos e consultorias que foram determinantes para o surgimento do CAVUS.

A seguir, são elencadas algumas das atividades de formação realizadas por membros do grupo CAVUS:

Curso Básico de Cavernas (2023) - 07 de Outubro a 12 de Novembro de 2023

Entre os dias 07 de Outubro e 12 de Novembro de 2023, os membros fundadores do CAVUS participaram do Curso Básico de Cavernas, ministrado pelo GPME, sendo este o primeiro contato com o GPME. O curso constituiu em uma série de aulas teóricas e práticas, as quais se estenderam ao longo de localidades espeleológicas no Estado de São Paulo.

Durante as aulas teóricas, no primeiro final de semana (07 e 08 de Outubro de 2023), foram abordados temas como a história da espeleologia, as cavernas e sua legislação, geoespeleologia, arqueologia e paleontologia, condições de tempo e clima, biologia subterrânea, prospecção espeleológica, espeleotopografia, entre outros.

Assim, nos dias 21 e 22 de outubro, deu-se início às atividades práticas do curso no Parque Estadual Intervales (PEI), localizado próximo ao município de Ribeirão Grande - SP. Foram realizadas atividades práticas em geoespeleologia, bioespeleologia, topografia e mapeamento de cavernas e, por último, práticas em fotografia em cavidades naturais. As cavernas visitadas foram: Gruta dos Rodrigues,

Grutas Guaecaeiro I e Guaecaeiro II, Gruta dos Paiva, Gruta do Fendão e Gruta Colorida.

Em sequência, durante os dias 28 e 29 de outubro, as aulas práticas tiveram lugar na Estância Turística de Itu (Camping Casarão), estado de São Paulo. Realizou-se uma oficina de técnicas de vertical em cavernas com apresentação dos equipamentos, aprendizagem de confecção de nós em cordas, segurança e equipagem. Em apoio, houve uma atividade prática de vertical no espaço USINARTE, em Sorocaba - SP.

Finalmente, nos dias 11 e 12 de novembro, as aulas práticas ocorreram no Parque Estadual Turístico do Alto Ribeira (PETAR), em Iporanga - SP. Foram realizadas atividades de geoespeleologia, bioespeleologia e fotografia em cavernas na Caverna de Santana (Redes superiores e galeria do rio até Salão Ester), Gruta Morro Preto I Couto e Gruta da Cachoeira do Couto.

I Encontro de Estudos Subterrâneos: os caminhos da conservação - 8 a 10 de Outubro de 2023

Durante os dias 08 e 10 de outubro de 2023, na Universidade Federal de São Carlos (UFSCar), realizou-se o I Encontro de Estudos Subterrâneos: Os Caminhos da Conservação, o qual foi organizado pelo Instituto Brasileiro de Estudos Subterrâneos (IBES) e contou com o apoio do Laboratório de Estudos Subterrâneos da UFSCar, PROEX UFSCar, GPME, Espeleonordeste, Resseg, Gallão Fauna e Ambiente, Mater Natura e Spelayon.

Além dos discentes presentes, no encontro participaram grupos de espeleologia, como o Espeleo Grupo Rio Claro (EGRIC), Grupo Sul Baiano de Espeleologia (GSBE), Espeleonordeste, o Grupo Araras de Espeleologia, o Espeleo Planalto Central, a Sociedade Excursionista e Espeleológica (SEE), Grupo Mundo Subterrâneo de Espeleologia (GMSE) e o Grupo Pierre Martin de Espeleologia (GPME);

Referente à programação, o evento contou com apresentações de trabalhos, palestras, mesas-redondas e rodas de discussão. Além de cursos de curta duração e oficinas. Também, ocorreu uma exposição sobre fauna subterrânea, microrganismos de caverna e fauna do cerrado.

Curso básico de cavernas (2024) - 20 de Abril a 05 de Maio de 2024

Entre os dias 20 de Abril e 05 de Maio de 2024, data em que o CAVUS já se encontrava consolidado como grupo, o grupo participou pela segunda vez, mas com novos membros, do Curso Básico de Cavernas, ministrado pelo GPME. Assim, como no curso do ano anterior, este se constituiu com aulas teóricas e práticas, as quais se estenderam ao longo de localidades espeleológicas no Estado de São Paulo.

O curso realizou-se durante três finais de semana; no primeiro dia, 20 de Abril, houveram uma série de aulas teóricas, contendo temas como a geoespeleologia, a história da espeleologia, as cavernas e sua legislação, condições de tempo e clima, biologia subterrânea, prospecção espeleológica, espeleotopografia - o mapeamento de cavernas - e orientações de segurança para as atividades de campo.

Durante o segundo final de semana, 27 e 28 de Abril de 2024, iniciou-se a parte prática do curso no Parque Estadual de Intervales (PEI), próximo a Ribeirão Grande - SP. Foram realizadas atividades de geoespeleologia, bioespeleologia, topografia e mapeamento de cavernas e, por último, práticas em fotografia em cavidades naturais. As cavernas visitadas foram: Gruta dos Paiva, Gruta do Fendão e Gruta Colorida. As cavernas visitadas inserem-se em contextos carbonáticos, caracterizando-se pela predominância de rochas sedimentares compostas por carbonato de cálcio, cuja dissolução, ao longo do tempo, deu origem às formações subterrâneas visitadas.

Durante o terceiro e último final de semana, 04 e 05 de maio de 2024, o grupo visitou localidades nos municípios de Itú, e Ipeúna - SP, onde realizou visita à Gruta do Fazendão. Nesse final de semana, diferente do anterior, foram visitadas cavernas fora do contexto carbonático; em Itú, a gruta visitada era desenvolvida em maciços graníticos, onde a ação da fratura e erosão modelou a estrutura da caverna, já em Ipeúna visitou-se uma gruta desenvolvida em arenito, rocha sedimentar cuja composição predomina quartzo, feldspato e mica.

23° Encontro Paulista de Espeleologia (23° EPÉLEO) - 8 e 9 de Junho de 2024

O vigésimo terceiro Encontro Paulista de Espeleologia (EPÉLEO) ocorreu nos dias 8 e 9 de Junho de 2024, no bairro Boa Vista, no município de Ribeirão Grande - SP. O evento foi organizado por uma comissão conformada pelo GPME, pela Associação Amigos do Parque Estadual Intervales (APEI), pelo Instituto Brasileiro de Estudos Subterrâneos (IBES)

e pelo Laboratório de Estudos Subterrâneos – Universidade Federal de São Carlos (LES-UFSCar). Contou com apresentações de painéis, estandes, palestras magnas, shows culturais, rodas de conversa e saídas de campo a localidades espeleológicas na região.

O tema do evento foi "Os saberes das comunidades", o qual buscava valorizar aspectos socioculturais locais, apreciar a espeleologia dentro do conceito da Ciência Cidadã e levar à discussão a temática espeleológica para a comunidade do entorno do Parque Estadual de Intervales (PEI), além de reunir a comunidade espeleológica. Nesta edição do EPÉLEO, também se buscou envolver a escola do Bairro Boa Vista, durante o primeiro semestre do ano letivo de 2024, em atividades de educação ambiental conectadas ao evento.

O evento reuniu grupos de espeleologia, tanto universitários quanto externos, como o próprio GPME, Grupo da Geologia de Espeleologia da USP (GGEO), o Laboratório de Estudos Subterrâneos - UFSCar (LES), o CAVUS, a APEI e o IBES. Assim, este encontro foi altamente produtivo e enriquecedor para o CAVUS, pois possibilitou a troca de experiências e conhecimentos com clássicos e antigos grupos de espeleologia do estado de São Paulo.

Oficina e simulado de espeleorresgate - 14 e 15 de Setembro de 2024

A oficina e simulado de espeleorresgate, organizados pelo GPME, tiveram espaço nas instalações do Parque Estadual de Intervales (PEI), localizado próximo ao município de Ribeirão Grande - SP. As atividades se desenvolveram durante os dias 14 e 15 de setembro de 2024. No primeiro dia, realizou-se a oficina. No período da manhã houve aulas teóricas e apresentações, e no período da tarde ocorreram treinamentos em: estabilização da vítima, envelopamento na maca, montagem de ponto quente, porteio da maca, entre outros. Já no segundo dia, levou-se a cabo o Simulado de Espeleorresgate na Gruta dos Paiva. Esta atividade constitui-se essencial para a formação de um espeleólogo, já que o prepara para possíveis situações de risco dentro de uma caverna, buscando o bem-estar e segurança de todos durante a excursão.

A seguir, foram elencadas atividades de extensão organizadas pelos membros do grupo CAVUS:

Participação do CAVUS no 19° UNICAMP de Portas Abertas (UPA) - 17 de Agosto de 2024

A UNICAMP de Portas Abertas é um evento com duração de um dia, que ocorre anualmente e é realizado na Universidade Estadual de Campinas (UNICAMP), no campus de Barão Geraldo. O objetivo é aproximar a comunidade externa ao universo acadêmico, onde a UNICAMP promove uma programação diferenciada que inclui visitas aos institutos e faculdades, palestras, exposições científicas, também abrangentes ao público infanto-juvenil e muito mais, permitindo a interação dos visitantes com a universidade.

No ano de 2024, o grupo espeleológico CAVUS participou da programação de apresentações do Instituto de Geociências, e preparou uma mesa interativa em que os visitantes puderam saber mais sobre o que é a espeleologia, como se formam as cavernas e quais são seus principais elementos, como são formados os espeleotemas e entre outros saberes adicionais que são interessantes aos olhos da comunidade.

A mesa contava com materiais gráficos, livros e revistas, amostras de espeleotemas, e um jogo da memória desenvolvido e materializado pelos membros do grupo; o jogo continha, em uma parcela das cartas, uma série de elementos espeleológicos, como por exemplo, cavernas e a fauna habitante do ecossistema de cavernas, e, em outras cartas estavam as explicações referentes a cada elemento. Assim, a partir das explicações teóricas, da exposição de amostras e do jogo da memória, no evento foi possível transmitir de maneira compreensível uma porção do conhecimento espeleológico para a comunidade e o público presente no evento da UPA.

Participação do CAVUS no 3° Museus da UNICAMP de Portas Abertas (MUPA) - 23 de Novembro de 2024

A terceira edição dos Museus da UNICAMP de Portas Abertas (MUPA) teve espaço em todo o campus de Barão Geraldo da Universidade Estadual de Campinas (UNICAMP) e ocorreu no sábado dia 23 de Novembro de 2024, sob a coordenação conjunta da Pró-reitoria de Extensão, Esporte e Cultura (ProEEC) e o Museu Exploratório de Ciências, com o apoio da UNICAMP. Durante este evento, várias unidades, faculdades e institutos, organizaram apresentações científicas adaptadas para o público infanto-juvenil, já que o evento recebeu mais de 3 mil alunos de escolas públicas vinculadas à Diretoria de Ensino Região de Campinas Oeste (DECOE).

Assim, dentro do Instituto de Geociências, o CAVUS elaborou uma série de atividades, cujo fim era apresentar a espeleologia para a comunidade externa, mas de uma forma didática e acessível para o público alvo. Logo, dentro das atividades organizadas constava uma mesa com um experimento que demonstrava o processo de formação de um espeleotema: a estalactite. Este consistia no princípio fundamental de uma solução saturada em sal (imitando as soluções saturadas em carbonatos de cálcio no ambiente cárstico) separada em dois recipientes e unida por apenas um fio de barbante; após cerca de 72 horas, foi possível enxergar no barbante a deposição de uma "estalactite" derivada da alta concentração de Cloreto de Sódio (NaCl).

Finalmente, a maior atração elaborada pelo CAVUS foi a simulação de uma caverna. Montada a partir da junção de uma barraca e uma tenda, forradas por dentro com tecido preto para formar um ambiente escuro, a caverna do CAVUS estava totalmente preenchida por elementos comumente encontrados dentro de cavernas. Havia aranhas e morcegos de , estalactites de papel pardo pintadas com tinta em spray, um lago elaborado com luzes azuis decorativas, o chão estava coberto por papel pardo para simular uma superfície rochosa, e além disso, havia algumas fotos das nossas excursões expostas nas paredes, com o fim de mostrar como é o interior de uma caverna. Assim, a caverna do CAVUS era adentrada em grupos de três pessoas e lhes foi dado material de proteção e de uso essencial dentro de uma caverna, como capacete e lanterna. Esta atração foi altamente visitada durante todo o evento, satisfazendo os princípios extensionistas do CAVUS, já que possibilitou-se a troca de conhecimentos com o público; isto é, o evento não foi puramente expositivo e sim uma construção de conhecimentos acadêmicos e de saberes empíricos da comunidade.

Disciplina: Tópicos Especiais em Extensão 2 (GE 131) - 11 de Março a 01 de Julho de 2025

Em razão da curricularização da extensão na universidade pública, por iniciativa da professora doutora Carolina Zabini, e com o apoio do professor doutor Bernardo Freitas, ambos os dois do Instituto de Geociências, o CAVUS elaborou o plano de curso para uma disciplina eletiva de extensão na área de espeleologia. A disciplina contará com o apoio do GPME, que reforçará o desenvolvimento de atividades teóricas e práticas na mesma atividade pedagógica. A disciplina será aplicada no primeiro semestre de 2025 dentro do Instituto de Geociências, aberta aos estudantes de graduação da UNICAMP.

A disciplina engloba uma apresentação da espeleologia, incluindo a definição, seus conceitos, sua história, a importância e as legislações, seguido pela teoria atrás da gênese de cavernas (geoespeleologia). Logo em seguida, expõe-se como funciona a extensão universitária na prática, seus conceitos e metodologias, junto com a definição do público-alvo e das estratégias extensionistas a serem adotadas. Assim, destaca-se a importância da comunidade externa na atividade de extensão e inicia-se o planejamento e preparação para execução das atividades de extensão que serão executadas na escola (comunidade) E.E. Bairro Boa Vista Intervales e no Parque Estadual de Intervales, por meio de visitas de campo à comunidade.

O GPME lecionará algumas aulas teóricas e práticas como também uma atividade de campo para os discentes participantes da disciplina, que serão fundamentais para o aprendizado tanto de experiência espeleológica, quanto para o aperfeiçoamento do método de pesquisa-ação para o grupo CAVUS.

4. Discussão

Diante da atuação do grupo descrita ao longo do trabalho, se tornam evidentes três momentos que diferem os tipos de atividades realizadas, sendo o primeiro caracterizado pelo suporte e orientação do GPME, fundamental para que o grupo universitário compreendesse a melhor forma de se estudar e trabalhar com a espeleologia, algo que seria novo no contexto municipal de Campinas. O segundo momento, que ocorre de uma maneira não sequencial, é a participação em eventos espeleológicos, como o EPÉLEO e o I Encontro de Estudos Subterrâneos. O contato com outros grupos universitários é essencial para trocas de experiências e desenvolvimento coletivo, onde se cria uma rede de apoio e contatos com grupos da mesma área de atuação. Por último, é o momento da extensão universitária, representada pelo UPA, MUPA e a disciplina de extensão.

Antes de definir o grupo como de caráter extensionista, foi preciso investigar o que significa a extensão universitária, quais são seus objetivos e a forma que seria implementada no campo da espeleologia. Segundo a resolução nº 7 de 2018 do Ministério da Educação, a extensão é a interação de caráter transformador entre as instituições superiores de educação e as outras esferas sociais. Entretanto, antes desta publicação, a extensão já era mencionada na constituição brasileira, citando que as universidades devem obedecer ao "princípio de indissociabilidade entre pesquisa, ensino e extensão" (Brasil, 1988, Art. 207). Denominada de "terceira missão" das universidades, a extensão já foi e continua sendo tratada de diversas maneiras pelo público atuante.

Para além do assistencialismo, que caracteriza a visão conservadora deste tipo de atividade, a extensão regulamentada pelo governo federal faz parte de um processo dialógico, em que não há uma uma hierarquização de conhecimentos, mas sim uma troca de saberes e experiências. Dessa forma, a curricularização da atividade foi necessária para se entender o que de fato é e como deve ser realizada, sem depender de conceitos vagos.

Sob este propósito, para o primeiro semestre de 2025 foi criada uma disciplina de extensão, orientada a discentes de qualquer curso de graduação da UNICAMP. Para a realização deste projeto foi necessária a atuação do CAVUS, GPME e docentes do IG, que se juntaram para programar uma disciplina que perpassasse por fundamentos teóricos da espeleologia, trabalhos de campo e atividades extensionistas em instituições de ensino básico. A iniciativa surgiu com o intuito de aumentar a rede de atuação extensionista e tornar as atividades mais intensivas, não dependendo de eventos pontuais como o MUPA e UPA, para que haja o diálogo com as comunidades. Entretanto, ambos os eventos foram essenciais para propagar os objetivos e resultados do trabalho que vem sendo feito pelos membros do grupo.

Embora os blocos de atividades descritas ao longo do trabalho se diferenciam quanto ao seu papel e propósito, todos apresentam uma dificuldade, que é o financiamento das iniciativas e projetos. Como foi explicitado, o CAVUS é um grupo gerenciado por discentes, não havendo nenhum tipo de patrocínio ou financiamento externo. Dito isso, toda atividade que necessita de itens como transporte, estadia e compra de materiais, é financiada pelos próprios membros. Isso se torna um empecilho a partir do momento em que o grupo tem o interesse em ampliar seu raio de atuação. O impacto se manifesta desde a compra de equipamentos para a ida a trabalhos de campo, que necessitam o uso de Equipamento de Proteção Individual (EPI), até a produção de materiais pedagógicos para as oficinas infanto-juvenis já realizadas e futuras. Frente a esse problema, a solução de curto prazo é a venda de produtos desenvolvidos pelos membros do grupo, como camisetas, bottons e adesivos, mas que não suprem as necessidades financeiras do grupo, bem como os projetos que estão em fase de planejamento.

5. Conclusão

O propósito do grupo de extensão tem o intuito de ampliar o contato entre o meio interno e externo à academia, tornando o acesso à pesquisa na área do estudo de cavernas, democratizado a todo e qualquer cidadão.

As atividades desenvolvidas pelo CAVUS, demonstram uma diversidade de ações realizadas pelo grupo, mediante encontros espeleológicos, oficinas e eventos integrados à universidade. Sob esse viés, os resultados apresentados manifestam um processo de grupo interessante, junto às parcerias com outros grupos da mesma área temática, que, com a contribuição de discentes, beneficiaram à academia e à comunidade em geral.

Os principais desafios na atuação do grupo, são o incremento de estratégias extensionistas, como o desenvolvimento de oficinas na rede de ensino público da região de Campinas e o planejamento de iniciativas que permitam difundir os conhecimentos obtidos pelo grupo e seus parceiros. Isto posto, implica em indicar que a ausência de recursos financeiros impacta diretamente na execução de atividades que dependem de investimentos, e impedem a implementação de algumas ações e projetos.

Em suma, para ampliar ainda mais a realização de atividades nesse meio, ações que fomentem a melhoria, a introdução de novas oficinas e a aderência a recursos financeiros que possibilitem a confecção de materiais didáticos indicam medidas futuras a serem movidas pela organização do grupo. Paralelo a isso, os resultados da implementação da disciplina desenvolvida será atribuída a atividades posteriores, visando atribuir uma melhoria contínua à matéria.

Agradecimentos

Agradece-se profundamente o Grupo Pierre Martin de Espeleologia (GPME), o qual acolheu o grupo CAVUS desde um início e o impulsionou para que pudesse se desenvolver como grupo sob seus próprios princípios e ideais. Além disso, agradece-se o Programa Tempo Profundo, o qual possibilitou a participação do CAVUS na 3° edição do MUPA. Agradece-se aos professores doutores Carolina Zabini e Bernardo Tavares Freitas por ministrar a disciplina de extensão; e ao professor doutor Alessandro Batezelli, por impulsionar, dentro do Instituto de Geociências da UNICAMP, a criação do CAVUS. Por último, agradece-se aos colegas do GGEO, os quais demonstraram fiel apoio à proposta do CAVUS e contribuíram com seus saberes como veteranos na área.

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Flora Associated with the Volks Club cave, Federal District, Brazil

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Abstract

Caves are unique subterranean ecosystems characterized by the absence of light, thermal stability, and low nutrient availability. These conditions favor the presence of unique microorganisms and a highly adapted flora and fauna, making caves sensitive to environmental impacts and human activities. In the context of the Cerrado biome, in the Federal District, a floristic survey of the Volks Club cave was conducted between 2023 and 2024, during both the rainy and dry seasons. A total of 219 plant species were identified, belonging to 78 families and 156 genera, with 17 species representing new occurrences for the Federal District, according to the Flora e Funga do Brasil database. The collected flora was categorized into vascular and non-vascular plants for analysis. The results highlight the potential of Cerrado caves for botanical and ecological research, emphasizing their relevance for conservation, the understanding of cave ecosystems, and their influence on regional biodiversity.

1. Introduction

The Cerrado, the most biodiverse savanna in the world (BFG, 2021), faces intense anthropogenic pressure, with approximately 50% of its original coverage already converted for human use (Klink & Machado, 2005). This process results in habitat fragmentation and biodiversity loss, affecting not only vegetation but also interconnected subterranean ecosystems such as caves. Caves, in turn, are unique environments characterized by specific microclimatic and ecological conditions, making them biodiversity refuges and areas of great conservation relevance.

Although the Brazilian Constitution and other regulatory frameworks recognize the importance of preserving caves, including their associated fauna and flora, these ecosystems remain threatened by human activities such as urban expansion, intensive agriculture, and mineral exploitation (Watson, 1997). The vegetation present on the surface plays a crucial role in cave dynamics, providing organic matter and nutrients for subterranean organisms. Additionally, plants establish significant ecological connections, such as root penetration into underground chambers, promoting interaction between the cave's external and internal environments (Ferreira; de Oliveira e Silva, 2015), while also helping to prevent soil erosion and excessive water runoff.

The first studies on cave flora date back to the 18th century, with contributions from Alexander von Humboldt and Scopoli (Herrero-Borgoñón, 2024). Despite this, plant diversity in subterranean environments remains poorly documented. It is estimated that between 50,000 and 100,000 plant species are associated with caves worldwide (Culver & Holsinger, 1992), with most records concentrated in Asia, Europe, and North America (Monro et al., 2024). However, little is known about cave-associated flora in Latin America, particularly in Brazil.

The Brazilian Cerrado is understood as a mosaic of vegetation formations, including both forest and savanna physiognomies (Ribeiro & Walter, 1998). In this study, we conducted a floristic survey in the influence area of the Volks Club cave, located in the Cerrado of Brasília, Federal District, Brazil. This cave has two interconnected entrances associated with different vegetation physiognomies. The main entrance is situated in **Cerrado *sensu stricto***, a savanna-like formation with scattered trees and shrubs over a grassy understory, typically found on well-drained, acidic, and nutrient-poor soils. The secondary entrance, in contrast, is located in a **Gallery Forest**, an evergreen forest formation associated with small watercourses, characterized by higher tree density and more humid, generally more fertile soils (Pinto, 1994; Proença, Oliveira & Silva, 2000).

Studies on flora in cave influence areas are essential for understanding the interactions between external and subterranean environments, as well as providing important data for environmental licensing and conservation efforts. This study aimed to inventory the vascular and non-vascular plant species present in the influence area of the Volks Club cave, contributing to the knowledge of cave flora and its ecological connections with the subterranean environment.

2. Materials and methods

2.1. Study Area

The Volks Club cave (DF-007) is located in the Setor de Mansões do Lago Sul, within the São Bartolomeu Environmental Protection Area (APA), in RA XXVII (Jardim Botânico), Brasília (Lat. 15°52'22" S; Long. 47°48'36" W), Federal District, Brazil (Fig. 1).

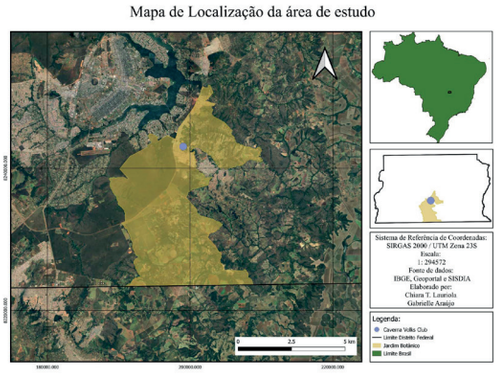


Figure 1: *Location map of the study area.*

Due to its easy accessibility and proximity to residential areas, it is frequently visited and faces challenges such as environmental degradation and improper use (Silva, 2004).

It is a non-carbonate cave formed by siliciclastic rocks of the Paranoá Group, with a linear development, sculpted by an intermittent stream that flows into the Tabocas River (Stump & Ribeiro, 2019). The cave has two entrances: the main entrance is situated in Cerrado *sensu stricto* fragments, while the secondary entrance is located in a gallery forest (Fig. 2).

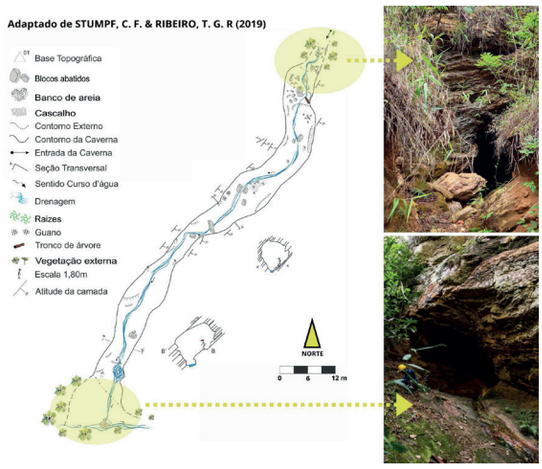


Figure 2: *Adapted from STUMPF & RIBEIRO (2019). Topographic map of the Volks Club cave, highlighting the sampled area at both entrances: main entrance, upper right; secondary entrance, lower right.*

2.2. Floristic Survey

The floristic survey was conducted at both entrances of the cave. The vascular flora (angiosperms, lycophytes, and monilophytes) was investigated only at the main entrance, while the non-vascular flora (bryophytes sensu lato, including mosses and liverworts) was surveyed at both openings. Sampling was carried out in a 20x20 meter (400 m^2) influence area at each entrance. Collections took place between 2023 and 2024, during both dry and rainy seasons, prioritizing fertile plants but also including sterile ones to ensure broader data coverage.

2.3. Sample Processing and Identification

The samples were herborized and deposited in the UB Herbarium, following standard techniques for each plant group. Taxa were identified using botanical dichotomous keys, reference specimens, online platforms (SpeciesLink, Flora e Funga do Brasil), and consultations with specialists. Based on the collected data, species lists were compiled, including the recorded taxa and their associated information. Additionally, a literature review on the dispersal syndromes of the identified vascular species was conducted to assess their relationship with the cave ecosystem. Non-vascular plants were categorized according to the type of collection substrate: **rupicolous** (rock), **terricolous** (soil), **epixylous** (dead wood), and **corticolous** (living trunk). Furthermore, the habitat of non-vascular species on different substrates was analyzed.

3. Results

The floristic survey conducted in the influence area of the Volks Club cave resulted in the identification of a total of 219 plant species, distributed across 78 families and 156 genera, with 17 species representing new occurrences for the Federal District.

Regarding vascular plants, 156 species were identified, distributed among 49 families and 105 genera, of which 10 were new occurrences for the Federal District. The family **Asteraceae** Bercht. & J.Presl stood out with 17 species (10.9%), followed by **Fabaceae** Lindl. (9%), **Malpighiaceae** Juss. (7.7%), and **Melastomataceae** A.Juss. and **Poaceae** Barnhart (5% each), together accounting for 38% of the species, while the remaining 44 families represented 62%.

Concerning the dispersal syndromes of angiosperms, data indicate that **zoochory** (seed dispersal by animals) was the predominant dispersal syndrome, followed by **anemochory** (wind dispersal). **Zoophily** (pollination by animals) was the most frequent pollination syndrome among the identified species (Fig. 3).

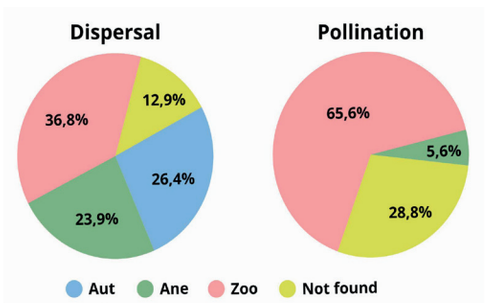


Figure 3: *Distribution of dispersal and pollination syndromes of angiosperm species in the Volks Club cave.*

Regarding non-vascular plants, a total of 70 species were identified, distributed across 28 families and 44 genera, of which 7 were new occurrences for the Federal District. Based on the difference in phytophysiognomy between the two cave entrances, samplings were treated independently. At the **main entrance**, located in **Cerrado *sensu stricto***, 39 species of mosses were recorded, distributed across 18 families and 27 genera. The main families found were **Fissidentaceae** Schimp. and **Sematophyllaceae** Broth. Meanwhile, liverworts presented 14 species, distributed across 8 families and 11 genera. The most diverse families were **Lejeuneaceae** Rostovzev and **Pallaviciniaceae** Mig., while the others had only one representative per family.

At the **secondary entrance**, located in **gallery forest**, 28 moss species were recorded, distributed across 10 families and 15 genera. The main family found was **Fissidentaceae**. Additionally, 10 species of liverworts were recorded, distributed across 6 families and 7 genera. The main families found were **Lejeuneaceae** and **Lophocoleaceae** De Not.

The non-vascular sampling was primarily conducted on **rupicolous** (rock) substrates (47.5%), followed by **terricolous** (soil) (23.3%), **epixylous** (dead wood) (19.4%), and **corticolous** (living trunk) (9.7%). The predominant habitat of the recorded species was exclusively rupicolous, followed by **rupicolous and terricolous**, exclusively **terricolous**, and exclusively **corticolous** (Fig. 4).

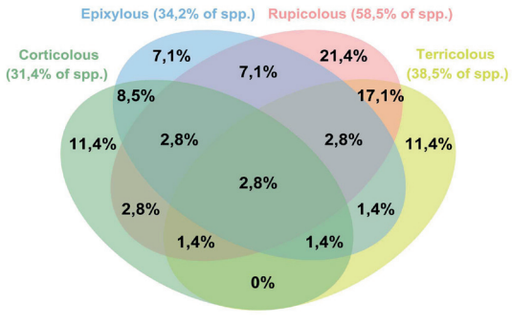


Figure 4: *Habitat of total moss and liverworts species (spp.) found at Gruta Volks Club.*

4. Discussion

Due to the proximity of easily accessible trails and residential condominiums in the Jardim Botânico region, the cave is frequently visited by the local community, resulting in significant impacts on the vegetation and the surrounding environment (Stumpf & Ribeiro, 2019). Among the observed changes, the introduction of exotic and ornamental species stands out, such as *Cyperus alternifolius* L., an aquatic plant native to Africa widely used in landscaping. Additionally, signs of environmental degradation, such as graffiti and excavations, compromise the area's conservation status.

Despite the observed impacts, the area of influence of the Gruta Volks Club exhibited high floristic richness. A total of 156 species of vascular plants were identified in just 400 m², representing 3.3% of the 4,663 species recorded for the Federal District. Regarding bryophytes, 70 species were identified in 800 m², corresponding to 35% of the 200 bryophyte species *sensu lato* recorded in the Federal District (Flora e Funga do Brasil, 2024). However, it is important to emphasize that the diversity of bryophytes found corresponds to surveys conducted in two different phytophysiognomies and a larger area.

The predominance of animal-mediated dispersal and pollination syndromes among the recorded angiosperms suggests a strong interaction between the local fauna and the vegetation of the area. Future studies on fauna behavior are essential to understand its role in the connectivity between subterranean ecosystems and the associated flora. In the case of bryophytes, most species were recorded on rocky substrates and soil, reflecting the direct influence of the karst environment on the cave's floristic composition. The presence of exclusive species on the cave walls reinforces the importance of these microhabitats in maintaining local biodiversity.

The record of 17 new occurrences for the Federal District in the area of influence of the Gruta Volks Club can be explained by different factors related to seed dispersal and anthropogenic influences. A possible hypothesis is the action of frugivorous bats, which may have transported diaspores and facilitated the colonization of new species around the cave. Additionally, increased tourism in the region may have directly impacted the local vegetation, either through the accidental introduction of seeds brought by visitors or through changes in the cave's microenvironmental conditions, such as alterations in humidity, temperature, or soil compaction due to human traffic. These interactions may have favored the germination and growth of species that previously did not occur in the area, contributing to the diversification of the flora recorded in this study.

5. Conclusion

The results of this survey indicate a rich biodiversity in the area of influence of the Volks Club cave, including 17 new occurrences for the Federal District. This finding emphasizes how much remains to be explored in terms of biodiversity in the Cerrado, especially in cave regions, which demonstrate great potential for biological discoveries in studies within the Federal District. These areas are still understudied and offer vast possibilities for future research.

New occurrences are also important because they expand the inventory of known species and provide new biogeographical data on local ecosystems. They also highlight the need for continuous surveys over time to keep the catalog of regional plants updated on accessible platforms, such as virtual herbaria. These data are extremely important for comparative analyses over time and are useful in the development of management and conservation strategies, which are particularly crucial for the Cerrado—one of Brazil's most threatened biomes, whose biodiversity remains largely overlooked.

6. Acknowledgments

We thank the Cave Flora project of the Cryptogams Laboratory (IB/UnB) for the support and opportunity to conduct this study, as well as the financial support from the funding agencies: the Research Support Foundation (FAP-DF), the National Council for Scientific and Technological Development (CNPq), and the University of Brasília Foundation.

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Peruaçu 3D - Uma Experiência Virtual nas Cavernas

Alexandre Lobo (1)

(1) Natureza Subterrrânea, iTeleport

Resumo

O projeto Peruaçu 3D propõe uma experiência virtual e imersiva no **Parque Nacional Cavernas do Peruaçu**, permitindo a visitação remota de cavernas com acesso restrito por motivos de preservação. Além disso, busca ampliar a acessibilidade para pessoas com limitações físicas. A digitalização foi realizada utilizando uma tecnologia 100% brasileira, integrada ao sistema **Matterport**, que combina um scanner a laser e uma câmera 360° de alta resolução. As cavernas foram modeladas em uma maquete digital do Vale do Peruaçu, possibilitando a exploração interativa. Os visitantes podem acessar essa experiência online, de qualquer lugar do mundo, ou presencialmente no centro de visitantes do parque, onde uma tela de 3,2m x 1,8m, gerada por projetor a laser, permite a imersão virtual.

Abstract

The Peruaçu 3D project offers a virtual and immersive experience in the **Peruaçu Caves National Park**, allowing remote visits to caves with restricted access due to preservation concerns. Additionally, it enhances accessibility for individuals with physical limitations. The digitization process was carried out using 100% Brazilian technology integrated with the **Matterport** system, which combines a laser scanner and a high--resolution 360° camera. The caves were modeled in a digital 3D representation of the Peruaçu Valley, enabling interactive exploration. Visitors can access this experience online from anywhere in the world or in person at the park's visitor center, where a 3.2m x 1.8m screen, powered by a laser projector, provides a virtual immersion.

Resumen

El proyecto Peruaçu 3D ofrece una experiencia virtual e inmersiva en el **Parque Nacional Cavernas del Peruaçu**, permitiendo visitas remotas a cuevas con acceso restringido por razones de preservación. Además, busca mejorar la accesibilidad para personas con limitaciones físicas. La digitalización se realizó con una tecnología 100% brasileña, integrada con el sistema **Matterport**, que combina un escáner láser y una cámara 360° de alta resolución. Las cuevas fueron modeladas en una maqueta digital del Valle del Peruaçu, permitiendo una exploración interactiva. Los visitantes pueden acceder a esta experiencia en línea desde cualquier lugar del mundo o presencialmente en el centro de visitantes del parque, donde una pantalla de 3,2m x 1,8m, generada por un proyector láser, permite la inmersión virtual.

1. Introdução

O Parque Nacional Cavernas do Peruaçu é um dos mais importantes sítios espeleológicos do Brasil, abrigando um conjunto de cavernas de grande relevância científica, ambiental e turística. No entanto, algumas dessas cavernas possuem restrições de acesso para preservação de seu patrimônio natural e arqueológico.

Além disso, a visitação convencional pode ser um desafio para pessoas com limitações de mobilidade. O projeto Peruaçu 3D surge como uma solução inovadora para democratizar o acesso a esses ambientes, utilizando tecnologias avançadas de digitalização e realidade virtual para permitir visitas remotas e imersivas.

2. Materiais e Métodos

Para a criação da experiência imersiva, utilizou-se uma combinação de tecnologias avançadas:

Tecnologia 100% brasileira, desenvolvida especificamente para a modelagem digital interativa das cavernas.

Matterport, um sistema híbrido composto por um scanner a laser e uma câmera 360° de alta resolução, responsável pela digitalização dos ambientes subterrâneos.

Drones equipados com câmeras 360°, para captura de imagens aéreas das cavernas e da paisagem ao redor.

Maquete digital interativa, representando o Vale do Peruaçu com suas principais cavernas, permitindo a navegação virtual e o reconhecimento geográfico da região.

Os dados capturados foram processados e integrados em uma plataforma digital que possibilita a visitação online e presencial, criando uma experiência interativa e acessível para diferentes públicos.



Figura 1: *Scanner Matterport em uso na Lapa Bonita.*

3. Resultados

Os principais resultados alcançados pelo projeto incluem:

Repositório digital online, acessível globalmente, reunindo imagens, vídeos e modelos 3D das cavernas do parque.

Experiência imersiva no centro de visitantes do parque, com projeção em tela de 3,2m x 1,8m, permitindo que os turistas explorem as cavernas virtualmente, inclusive áreas de acesso restrito por questões de preservação.

Ampliação da acessibilidade, possibilitando que pessoas com mobilidade reduzida, pesquisadores e o público em geral explorem o interior das cavernas sem impactos físicos ao ambiente.

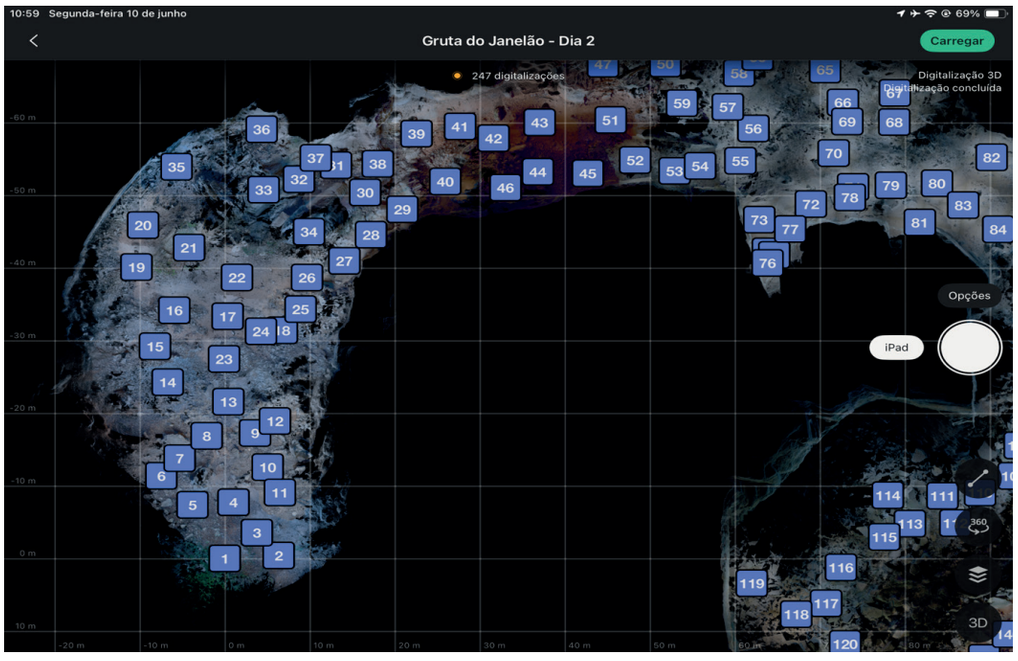


Figura 2: *Print da tela do aplicativode contrôle do scanner Matterport.*

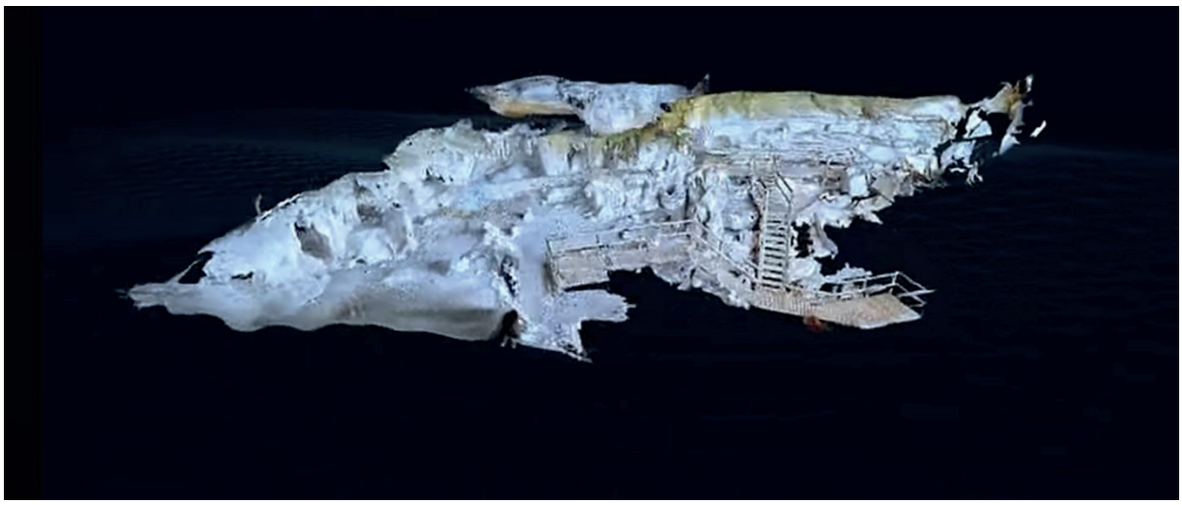


Figura 3: *Modelo 3D da Lapa do ïndio.*

4. Discussão

A implementação de tecnologias imersivas na espeleologia abre novas perspectivas para a conservação e divulgação do patrimônio natural. A digitalização das cavernas do Peruaçu representa um avanço na preservação ambiental, reduzindo a necessidade de visitas presenciais em áreas sensíveis. Além disso, a experiência virtual promove a inclusão social, permitindo que um público mais amplo conheça e valorize o patrimônio espeleológico brasileiro.

5. Conclusão

O projeto Peruaçu 3D demonstra o potencial da tecnologia na preservação e acessibilidade de cavernas. A criação de um ambiente digital interativo contribui para a difusão do conhecimento sobre as cavernas do Peruaçu e amplia as possibilidades de turismo sustentável. Espera-se que essa iniciativa sirva como modelo para outras áreas protegidas no Brasil e no mundo.

Agradecimentos

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Aplicação de Geotecnologias no Monitoramento de Bacia Hidrográfica de Caverna

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Abstract

This study presents the application of geotechnologies in the monitoring of cave watershed contribution areas, focusing on the analysis of Land Use and Land Cover and the identification of anthropogenic sedimentary processes. The adopted methodology combined multispectral orbital images, drone (RPA - Remotely Piloted Aircraft) surveys, and field validation to map and characterize the environmental dynamics of the watersheds. The multiscale approach enabled the detection of seasonal variations and the delineation of critical areas subject to anthropogenic impacts, such as erosion, sedimentation and concentrated water flows. The results demonstrate that the periodicity of monitoring was essential to ensuring the sedimentary stability of the caves and supporting preventive and mitigating measures. Additionally, the integration of different techniques reinforced the reliability of the generated data, contributing to more effective environmental management based on the preservation of these subterranean cavities.

Resumo

Este estudo apresenta a aplicação de geotecnologias no monitoramento de bacias de contribuição hídrica de cavernas, com foco na análise da Cobertura e Uso da Terra e na identificação de processos sedimentares antrópicos. A metodologia adotada combinou imagens orbitais multiespectrais, levantamentos com drones (RPA) e validação em campo para mapear e caracterizar a dinâmica ambiental das bacias hidrográficas. A abordagem multiescalar possibilitou a detecção de variações sazonais e a delimitação de áreas críticas sujeitas a impactos antrópicos, como erosão, assoreamento e fluxos hídricos concentrados. Os resultados demonstram que a periodicidade do monitoramento foi essencial para garantir a estabilidade sedimentar das cavernas e subsidiar medidas preventivas e mitigadoras. Além disso, a integração de diferentes técnicas reforçou a confiabilidade dos dados gerados, contribuindo para uma gestão ambiental mais eficaz e fundamentada na preservação dessas cavidades subterrâneas.

1. Introdução

A bacia de contribuição hídrica desempenha um papel fundamental na gestão ambiental e na conservação dos recursos naturais, sendo também essencial para os estudos espeleológicos. No contexto das cavernas, a bacia hidrográfica influencia diretamente a dinâmica hídrica e sedimentar, afetando a estabilidade e a preservação do ambiente subterrâneo. A avaliação dessas bacias torna-se ainda mais necessária em áreas sujeitas a impactos antrópicos, decorrentes de diferentes usos da terra, como a atividade minerária e a construção de acessos, uma vez que a remoção da cobertura vegetal, a remobilização do solo e as alterações nos canais de drenagem podem comprometer suas funções naturais.

A aplicação de geotecnologias no monitoramento e análise de bacias hidrográficas tem se mostrado essencial para a caracterização ambiental e a identificação de áreas de risco (MACHADO et al., 2017; SILVA et al., 2020). Estudos apontam que o uso de imagens orbitais, dados LiDAR e Modelos Digitais de Elevação (MDE) possibilita análises detalhadas da dinâmica hídrica e sedimentar, contribuindo para o entendimento dos impactos ambientais em diferentes escalas espaciais (MOURA et al., 2018; FERREIRA et al., 2021). Além disso, metodologias baseadas em Sensoriamento Remoto e Sistemas de Informações Geográficas (SIG) vêm sendo amplamente utilizadas para o mapeamento de áreas de vulnerabilidade ambiental e a modelagem hidrológica de bacias hidrográficas (RENNÓ & SOARES, 2001; RENNÓ et al., 2008).

Neste estudo, foi adotada uma abordagem multiescalar baseada em geotecnologias para o monitoramento das bacias de contribuição hídrica de cavernas, com ênfase na análise da Cobertura e Uso da Terra e na identificação de processos sedimentares antrópicos (erosão, transporte e deposição) com potencial impacto sobre as cavidades. Entre os resultados desses processos, destacam-se os movimentos de massa, os fluxos hídricos concentrados, as corridas de lama e o assoreamento. A metodologia adotada envolveu análises de imagens de satélite de alta resolução, a geração de ortomosaicos e modelos digitais de superfície por meio de levantamentos com drone (RPA - Remotely Piloted Aircraft), além de inspeções diretas em campo com pontos de controle. O objetivo principal foi identificar modificações físicas na bacia hidrográfica com potencial de comprometer a estabilidade sedimentar das cavernas, subsidiando a implementação de medidas preventivas e mitigadoras para a sua preservação.

2. Materiais e Métodos

Área de estudo

O método demonstrado neste estudo foi conduzido ao longo de dois anos em 55 cavernas formadas em rochas ferríferas na região de Carajás, no estado do Pará, pertencente à Região Norte do Brasil e inserida na Amazônia Legal (Fig. 1). Dentre essas cavernas, foi selecionada uma área de destaque, considerada didática, para apresentar os resultados obtidos. A região de Carajás se destaca por sua composição geológica predominantemente ferrífera. A Província Mineral de Carajás (PMC) é reconhecida como uma das mais importantes reservas minerais do Brasil, abrigando um dos maiores depósitos de ferro do mundo, além de expressivas ocorrências de cobre, ouro, manganês e outros minerais de grande interesse econômico.

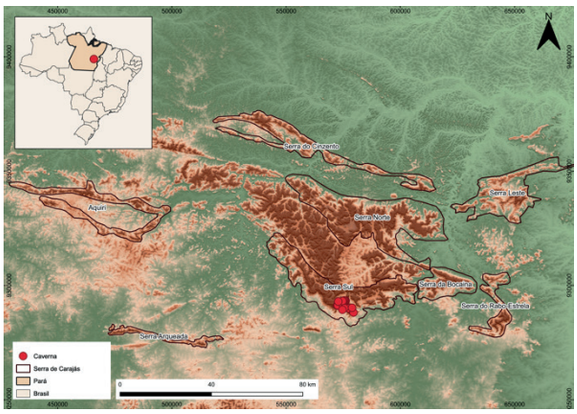


Figura 1: Localização das cavernas estudadas, com destaque para a região de Carajás, no estado do Pará, Brasil.

Metologia

A metodologia adotada foi estruturada em dois componentes principais: Monitoramento por Imagem Orbital Multiespectral e Monitoramento com Drone (RPA - Remotely Piloted Aircraft). A abordagem combinou técnicas de sensoriamento remoto, levantamento aéreos, validação em campo e análise geoespacial para garantir um monitoramento ambiental preciso e eficiente. A finalidade dessa abordagem é aprimorar a detecção de alterações antrópicas por meio do uso de novas tecnologias, proporcionando maior precisão na identificação e caracterização da Cobertura e Uso da Terra e dos fatores que influenciam a vulnerabilidade ambiental.

O Monitoramento por Imagem Orbital Multiespectral foi realizado trimestralmente, garantindo uma análise contínua das variações na cobertura e uso da terra e da dinâmica da paisagem. Esse monitoramento utilizou imagens de satélite de alta resolução da constelação GRUS, operada pela empresa japonesa AXELSPACE, sendo empregadas para a análise da Cobertura e Uso da Terra. Os produtos derivados incluíram composições coloridas das bandas 8 (Infravermelho Próximo), 4 (Vermelho) e 3 (Verde), além do cálculo do Índice de Vegetação por Diferença Normalizada (NDVI). A classificação da cobertura do solo foi feita por máxima verossimilhança, com suporte do algoritmo K-Nearest Neighbor (KNN), e refinada por fotointerpretação manual na escala de 1:7.500. Foram realizadas validações do mapeamento por pontos de controle de campo. As classes de Cobertura e Uso da Terra foram baseadas no Manual Técnico de Uso da Terra – 3ª edição (IBGE, 2013) e adaptadas para este estudo.

Com base nesse mapeamento, foi elaborado o Mapa de Vulnerabilidade à Perda de Solos, seguindo a metodologia proposta por Crepani (2001) e adaptada para este estudo. As variáveis consideradas na modelagem da vulnerabilidade foram Geologia, Solos, Índice Topográfico de Umidade (TWI), Fator Topográfico (LS) e Cobertura e Uso da Terra. A partir dessas análises, foram definidas as áreas prioritárias para monitoramento com Drone (RPA).

O Monitoramento com Drone (RPA) foi realizado anualmente, gerando como produtos Ortofotomosaicos de alta resolução, Modelos Digitais de Superfície (MDS) e modelos interativos 3D para identificar modificações físicas na bacia hídrica com potencial de impactar a dinâmica sedimentar das cavernas.

O levantamento incluiu o registro de Pontos de Apoio Geodésico (GCPs) para o georreferenciamento das imagens. Os voos foram executados com o Mavic Air 2, equipado com sensor CMOS 1/2” de 48 MP e lente FOV 84° (24 mm, f/2.8), com altitude de 80 m e resolução de 5 cm/pixel. Os dados capturados foram processados no WebODM e a fotointerpretação foi realizada no QGIS. Os produtos gerados foram utilizados para o refinamento dos dados de Cobertura e Uso da Terra, além da detecção de feições erosivas e deposicionais, permitindo a identificação de áreas críticas para o monitoramento contínuo. Em locais com restrição de visibilidade para sensores remotos, foram estabelecidos pontos de controle em campo para validação dos dados.

3. Resultados

A bacia da caverna selecionada apresentou, no fechamento dos monitoramentos de 2023 e 2024, predominância de canga, ocupando 82,26% da área em ambos os períodos. A vegetação manteve-se estável, representando 0,81%, enquanto a área destinada à mineração permaneceu em 16,94%. Essa bacia, que contém alterações antrópicas na cabeceira, foi submetida a um monitoramento detalhado por meio de levantamento com drone para avaliar possíveis impactos decorrentes dessas modificações. A porção da bacia com alterações associadas às estruturas da mina (16,94%) está localizada dentro da área licenciada. Ao longo do monitoramento, não foi identificado avanço dessas alterações além da área permitida no licenciamento, nem impactos decorrentes desses fatores. Apesar disso, o monitoramento demonstrou-se essencial para garantir que, caso ocorressem processos desencadeados por essas alterações, como o desenvolvimento de feições erosivas ou deposicionais, estes fossem detectados antes de comprometer a integridade da caverna (Fig. 2).

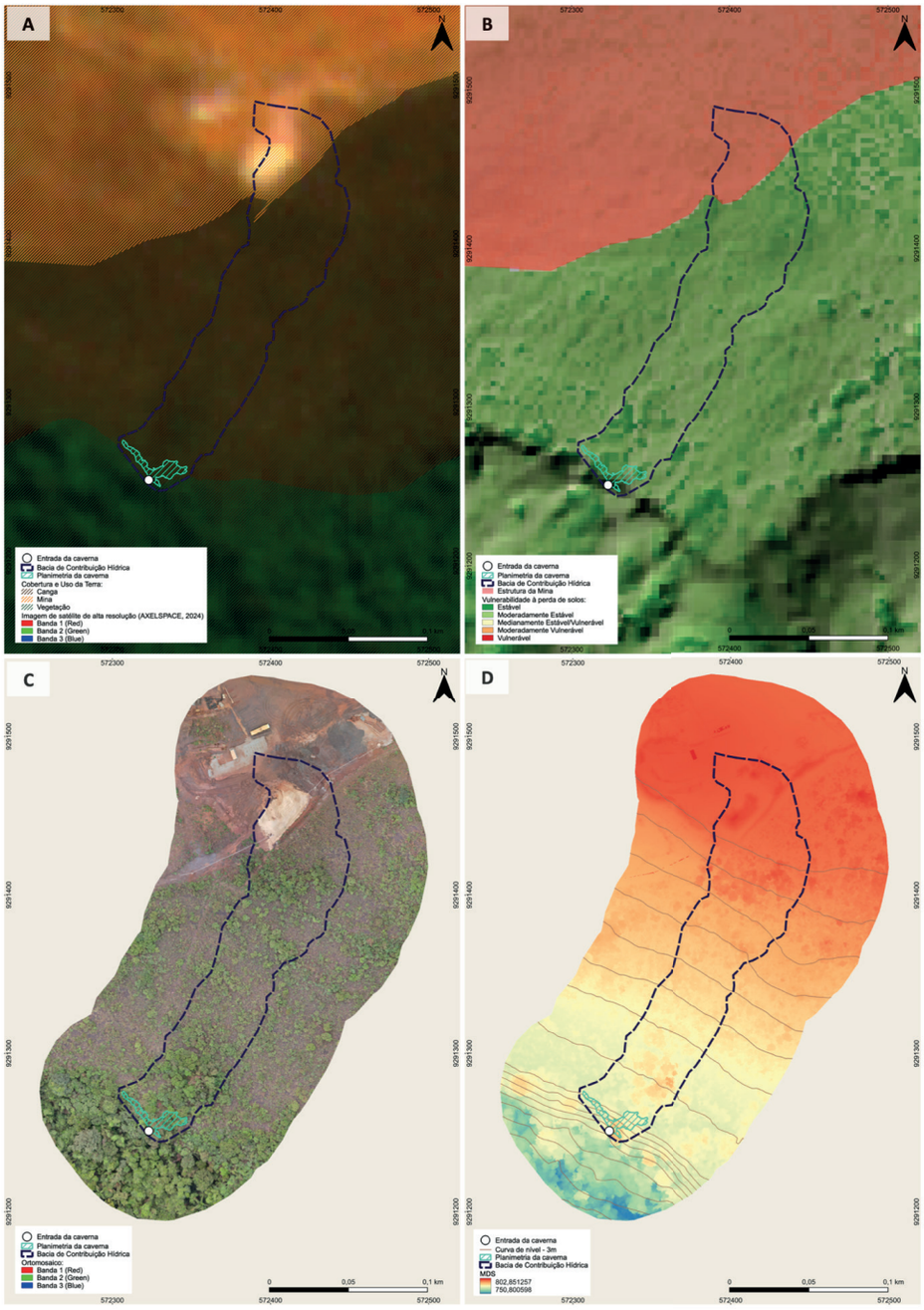


Figura 2: *Dados de 2024 para a bacia de contribuição hídrica da caverna: A. Mapa de Uso e Cobertura da Terra; B. Mapa de Vulnerabilidade à Perda de Solos; C. Ortomosaico gerado pelo levantamento com drone (RPA); D. Modelo Digital de Superfície gerado pelo levantamento com drone (RPA).*

4. Discussão

A aplicação de Geotecnologias no monitoramento mostrou-se fundamental para a gestão ambiental das bacias de contribuição hídrica das cavernas, assegurando um monitoramento contínuo e detalhado. A combinação de sensoriamento remoto, monitoramento aéreo com drones (RPA) e validação em campo possibilitou a identificação de padrões ambientais e a priorização de áreas críticas para acompanhamento. A análise multitemporal da Cobertura e Uso da Terra permitiu detectar variações sazonais que influenciam processos sedimentares, como movimentos de massa, fluxos hídricos concentrados, corridas de lama e assoreamento, auxiliando na caracterização da vulnerabilidade ambiental dessas áreas.

A abordagem adotada demonstrou flexibilidade ao fornecer informações precisas em locais de difícil acesso, como regiões de alta declividade e vegetação densa, onde métodos convencionais apresentam limitações. A utilização de pontos de controle em campo foi essencial para validar as informações obtidas remotamente, garantindo a coerência dos dados, especialmente em áreas de drenagem e zonas sensíveis sujeitas a impactos antrópicos. Além disso, a precisão dos dados reforçou a confiabilidade do Mapa de Uso e Cobertura da Terra, permitindo que as análises espaciais representassem com maior fidelidade as condições observadas em campo.

A periodicidade do monitoramento foi fundamental para acompanhar

as dinâmicas ambientais ao longo do tempo, permitindo a identificação de possíveis alterações, garantindo a estabilidade sedimentar das cavernas e a integridade de suas bacias de contribuição hídrica, além de viabilizar a detecção preventiva de impactos e a implementação de medidas de mitigação eficazes.

Destaca-se que, além das técnicas apresentadas, também é realizado o monitoramento interno de cavernas situadas em zonas sensíveis, como aquelas que recebem contribuição de drenagens conectadas à Área Diretamente Afetada (ADA) ou em áreas de alta vulnerabilidade a impactos iminentes, entre outras. O monitoramento interno reforça a importância dessa abordagem, permitindo a avaliação direta da integridade das cavernas e garantindo maior precisão na identificação de possíveis impactos antrópicos na dinâmica sedimentar.

5. Conclusão

O monitoramento de bacias de contribuição hídrica de cavernas utilizando geotecnologias, permitiu a identificação dos fatores que influenciam a vulnerabilidade ambiental dessas áreas e a delimitação de zonas críticas, onde impactos podem comprometer a estabilidade sedimentar das cavernas.

Os resultados obtidos confirmaram a eficiência da metodologia aplicada na detecção de alterações ambientais e na preservação das cavernas monitoradas. A integração das diferentes técnicas utilizadas possibilitou um modelo de monitoramento confiável, fornecendo subsídios fundamentais para a gestão ambiental. As informações geradas permitem a adoção de medidas preventivas embasadas, garantindo o acompanhamento contínuo das áreas monitoradas e contribuindo para a manutenção de sua integridade ao longo do tempo.

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Observatório das cavernas e da região cárstica do estado do Paraná - OBSCavernas

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Resumo

O estado do Paraná, especialmente a Região Metropolitana de Curitiba, possui mais de 400 cavidades naturais cadastradas que abrigam importantes feições espeleológicas, recursos hídricos, marcadores paleoambientais e formas de vida cavernícolas. Todavia, a mineração de rochas carbonáticas, principal fonte mineral em volume de explotação no território paranaense, coloca em risco as cavidades e os ecossistemas a elas associados. O presente trabalho apresenta a proposta de criação do Observatório das Cavernas e da região cárstica do estado do Paraná – OBSCavernas, ligado à Universidade Federal do Paraná em parceria com o Grupo de Estudos Espeleológicos do Paraná (GEEP-Açungui). O OBSCavernas promoverá a estruturação de um ambiente de monitoramento das condições ambientais e de realização de pesquisas sobre as cavidades naturais e do patrimônio espeleológico paranaense, em especial na região cárstica paranaense. Através de ações de monitoramento, levantamento de dados, suporte a estudos científicos e a promoção da educação ambiental. O observatório buscará conciliar a atividade minerária com a proteção do patrimônio espeleológico. A iniciativa visa, ainda, fortalecer a pesquisa científica, auxiliar na formação de profissionais especializados e sensibilizar a sociedade sobre a importância das cavidades naturais.

Abstract

The State of Paraná, especially the Metropolitan Region of Curitiba, has more than 400 registered natural caves that contain important speleological features, water resources, paleoenvironmental markers and cave life forms. However, the mining of carbonate rocks, the main mineral source in terms of volume of exploitation in the Paraná, poses the caves and their associated ecosystems at risk. This paper presents the proposal for the creation of the Observatory of caves and the karst region of the State of Paraná – OBSCavernas, within the Federal University of Paraná and Paraná Speleological Study Group (GEEP-Açungui). The OBSCavernas aims at structuring a work environment for monitoring environmental conditions and producing studies and research on natural caves and the speleological heritage of Paraná, especially in the karst region of Paraná. Through monitoring actions, data collection, support for scientific studies and the promotion of environmental education, the observatory will seek to reconcile mining activity with the protection of the speleological heritage. The initiative also aims to strengthen scientific research, assist in the training of specialized professionals and raise public awareness about the importance of natural cavities.

1. Introdução

As cavidades naturais, mais conhecidas como cavernas, grutas ou abismos, em especial as desenvolvidas em rochas carbonáticas e areníticas, exibem uma das paisagens naturais mais peculiares e suscetíveis às mudanças ambientais no estado do Paraná. As cavernas, vales cegos, ressurgências, abismos e dolinas são os tipos de cavidades mais comuns e, frequentemente, são objeto de diferentes percepções, muitas vezes ligadas à cultura, à religião e ou à história das sociedades (LOBO, 2013).

De acordo com Travassos (2014) duas ciências se dedicam ao estudo do relevo cárstico: a Carstologia e a Espeleologia, a primeira ocupando-se dos estudos das relações entre os processos superficiais e subterrâneos que formam o relevo cárstico e a segunda preocupando-se unicamente com os processos ocorrentes em ambiente subterrâneo.

Além da paisagem superficial e subsuperficial peculiar, as cavidades naturais podem apresentar ornamentações por espeleotemas, registros arqueológicos, paleontológicos, paleoclimáticos (orgânicos e inorgânicos), também abrigar espécies, frequentemente endêmicas e ameaçadas de extinção, pertencentes ao patrimônio arqueológico, geológico e biológico brasileiro (LOBO, 2013).

A importância da região cárstica, se dá também, pelo seu amplo caráter exploratório das rochas carbonáticas, sendo os litotipos com maior volume de explotação e rentabilidade financeira na Região Metropolitana de Curitiba - RMC. Essas rochas representam a mais importante fonte mineral para a indústria cimentícia, de agregados na construção civil, corretivos agrícolas, minas de rochas ornamentais e fornecimento de insumos para a indústria de transformação, além de abrigar o Aquífero Karst da Região Metropolitana de Curitiba (NASCIMENTO et al. 2024; GUIMARÃES, 2005).

Todavia, a atividade minerária, realizada a céu aberto a partir do

desmonte dos maciços rochosos, geralmente com o uso de explosivos, impacta diretamente a paisagem cárstica e o patrimônio espeleológico regional. Sendo assim, o monitoramento in loco aliado a sistemas de monitoramento com continuidade espacial de imagens aéreas e orbitais, poderá contribuir para capturar a dinâmica do uso e cobertura da terra na região.

Considerando a natureza irreversível dos impactos ambientais resultantes da mineração e a ausência de um monitoramento contínuo regional, a presente proposta culmina na criação do Observatório das Cavernas e da região cárstica do estado do Paraná – OBSCavernas. Portanto, entende-se que o investimento e implementação do OBSCavernas é uma ação estratégica e essencial para a proteção e conservação a longo prazo desses ambientes únicos. O projeto alinhará o estado do Paraná aos objetivos do Programa Nacional de Conservação do Patrimônio Espeleológico (instituído pela Portaria MMA No 358, de 30 de setembro de 2009) - o ICMBio/CECAV.

2. Materiais e Métodos

A abordagem metodológica combinará técnicas de geoprocessamento, análise espacial, trabalho de campo e educação ambiental. A definição das áreas de estudo e monitoramento, muito embora considere a existência de possíveis erros posicionais nas mais de 400 cavidades cadastradas (Figura 1), irá se basear nas localizações definidas nos cadastros oficiais disponíveis (Cadastro Nacional de Informações Espeleológicas - CANIE, Cadastro Nacional de Cavernas - CNC e Cadastro o Cadastro Paranaense de Cavernas - GEEP-Açungui).

2.1. Definição das áreas de ocorrência de cavidades e uso de dados geoespaciais

Levantamento bibliográfico e das bases de dados existentes: A definição da localização das cavidades é de suma importância para a realização do projeto, uma vez que o monitoramento das condições ambientais por dados de sensoriamento remoto (SR) é calcado na componente geoespacial. Todavia, o uso de dados indiretos demandará uma cuidadosa revisão do material bibliográfico existente, tais como relatórios técnicos, bases de dados espaciais (CANIE, CNC e GEEP-Açungui) para identificar, com a máxima acurácia posicional possível, a localização das cavidades naturais cadastradas no Paraná (Figura 2).

Correção e compatibilização de dados geoespaciais: Para a correção, produção, estruturação, e integração de dados geoespaciais (primários ou secundários), de forma interoperável e com capacidade de armazenamento e disponibilização multiplataforma, demandas comuns na atual fase de convergência das geotecnologias (SR, Sistemas de Informações Geográficas – SIG, dados de localização por satélite – GNSS, banco de dados geoespaciais – BDG, softwares...), o projeto utilizará a linguagem de modelagem Unified Modeling Language (UML) e o modelo Object Modeling Technique for Geographic Applications (OMT-G) para a modelagem de dados geoespaciais. Será utilizado o gerenciador de banco de dados PostgreSQL (gratuito e de código fonte aberto) e a extensão PostGIS, que permite a criação de bancos de dados habilitados para armazenar dados geoespaciais.

Monitoramento de uso e cobertura da terra nas regiões de ocorrência de cavidades: Serão utilizadas imagens de satélites e dados de mapeamentos sistemáticos de uso e cobertura da terra em escala nacional. As imagens de satélite Landsat, Sentinel e MODIS, amplamente utilizadas para a classificação de uso e ocupação da terra, oferecem dados com resoluções espaciais e temporais compatíveis com a análise proposta e figuram como as principais opções de imagens para o monitoramento pretendido. Em relação aos produtos de mapeamentos sistemáticos de uso e cobertura da terra em escala nacional, destacam-se o PRODES (ASSIS et al., 2019) e o MapBiomas (SOUZA et al. 2020), pois oferecem mapas de uso e ocupação da terra já processados e classificados, facilitando a análise e comparação de diferentes períodos e regiões com os dados produzidos no OBSCavernas, servindo tanto como dados de validação dos dados produzidos, quanto para a análise temporal de uso e cobertura da terra nas áreas de interesse.

A divulgação de dados será periódica (bimestral ou trimestral - definição com a equipe do OBSCavernas) por meio de um WebSIG e de boletins explicativos. A opção por um WebSIG visa a integração, visualização e análise de dados geoespaciais, especialmente no contexto do monitoramento ambiental e das mudanças no uso e ocupação da terra, ainda devido a possibilidade de usuários sem familiaridade com a manipulação de dados geoespaciais terem acesso aos dados produzidos no OBSCavernas. O MapServer e o Qgis (softwares livres) serão utilizados para a criação e publicação dos dados geoespaciais.

A definição das áreas a serem monitoradas considerará a resolução CONAMA nº 347, que determina a delimitação de 250 m (duzentos e cinquenta metros) ao redor da área ocupada pelas cavidades sem estudos que definam sua área de influência. Quando houver uma avaliação da área de influência da caverna (dimensões subterrâneas mapeadas/estimadas), os dados geoespaciais das projeções horizontais de cada cavidade seguirão esses limites. Assim, haverá dois cenários para a definição das áreas de monitoramento: cenário 1) No caso da inexistência de dados de projeção horizontal, o monitoramento adotará como referência espacial poligonais convexas com 2500 m (dois mil e quinhentos metros) em torno de cada ponto que represente a localização de uma cavidade; cenário 2) No caso da existência de dados de projeção horizontal da cavidade, será monitorada uma poligonal convexa de 500 m (quinhentos metros) no entorno da cavidade representada. A geração de poligonais com áreas superestimadas, em conformidade com a resolução CONAMA nº 347, visa garantir que as áreas de ocorrência de cavidades, sem projeção horizontal sejam monitoradas respeitando sua integridade e que cavidades com a projeção horizontal definida tenham um monitoramento mais direcionado de suas áreas de ocorrência. Considerando que ocorrem mais de 420 cavidades no Paraná, serão monitorados mais de 200 mil hectares.

Preservação do acervo histórico de dados analógicos sobre as cavidades naturais cadastradas no Paraná: Além dos acervos de dados espaciais disponíveis em bases de dados online (CANIE e CNC), existem dados, ainda em formato analógico, de mais de 250 cavidades cadastradas pelo GEEP-Açungui nos últimos 39 anos, os quais se encontram armazenados na garagem da Casa Gomm, edifício que abriga a Coordenação do Patrimônio Cultural (CPC) do estado do Paraná. A base de dados será digitalizada e integrará o acervo de dados do Observatório. A existência de relatórios, croquis, descrições de campo e mapas com grandes formatos, demandará a digitalização do acervo para a integração em meio digital por meio de contratação de uma empresa especializada. Esses dados servirão para refinar a delimitação das poligonais convexas citadas no item anterior. Estima-se que serão digitalizados cerca de 250 mapas (formatos grandes até o formato A0), cerca de 200 croquis e cerca de 2200 páginas de formato A4.

2.2. Educação Ambiental

O observatório visa ainda promover ações de educação ambienta junto à comunidade, sobretudo a escolar. Através de desenvolvimento e publicização de materiais didáticos e de realizações de palestras, oficinas e atividades de campo para observações *in loco* da paisagem e das características ambientais das cavidades e entorno.

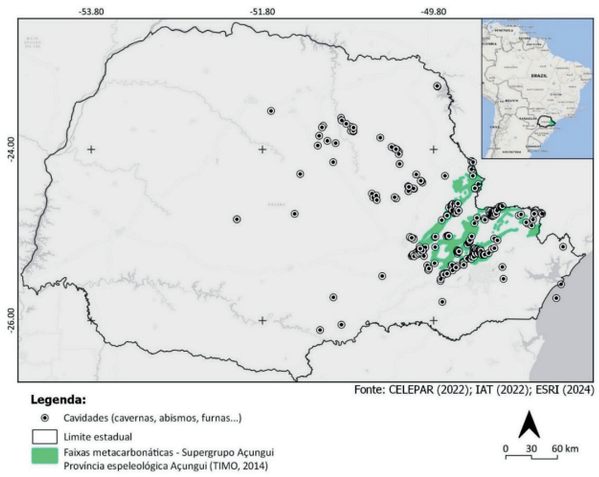


Figura 1: *Localização das cavidades naturais cadastradas no estado do Paraná no CANIE (2022). Obs.: a maior concentração de cavidades coincide com as faixas de ocorrência do Supergrupo Açungui.*



Figura 2: *Gruta Brumado I, município de Rio Branco do Sul - PR. Obs.: Marco geodésico implantado durante o desenvolvimento de projeto financiado pelo Edital Ampliando Rotas - IABS / Edital de Chamada Pública Nº 01/2023 / Item X da Cláusula Segunda do TCCE nº 1/2022/ICMBio / Pesquisa e Conservação do Patrimônio Espeleológico Nacional (Vale do Rio Doce, Centro Nacional de Pesquisa e Conservação de Cavernas - ICMBio/Cecav, Sociedade Brasileira de Espeleologia – SBE).*

3. Resultados

Os resultados esperados com a implementação do observatório são: 1) Criação de um banco de dados geoespacial e de dados não espaciais completo e atualizado, que integre dados de diversas fontes (CANIE, CNC, GEEP-Açungui) em um único sistema, com informações sobre a localização e características das cavidades e seus entornos; 2) Construção e publicação de um webmapa (WebSIG) interativo com ferramenta de visualização e análise de dados geoespaciais e não espaciais que permita o acesso público às informações sobre as cavidades e o monitoramento ambiental de seus entornos, com geração de mapas e relatórios atualizados periodicamente; 3) Promoção de ações de educação ambiental: desenvolvimento de materiais digitais e impressos para a educação ambiental, como palestras, oficinas e trilhas ecológicas com as comunidades, preferencialmente escolares, das áreas que serão selecionadas no decorrer do projeto; 4) Apoio ao setor público: compartilhamento de dados e informações e, quando necessário, participação conjunta em atividades de campo; 5) Comunicação científica: elaboração e publicação de artigos científicos; 6) Divulgação científica: espaço para a divulgação de pesquisas e artigos científicos relacionados ao tema, promovendo a troca de conhecimento entre pesquisadores e o público em geral; 7) Monitoramento dos processos naturais e do uso da terra em ambientes cársticos, através de parâmetros ambientais e sistema de informações geográficas; 8) Tentativa de reduzir os impactos antropogênicos em áreas cársticas frágeis e/ou vulneráveis mediante ações de monitoramento e sensibilização; 9) Fortalecimento da rede de pesquisa e conservação das cavidades naturais do Paraná.

4. Discussão

O Observatório pretende ser um ambiente de estabelecimento de parcerias com instituições públicas e, possivelmente, privadas, para a promoção de estudos sobre as regiões cársticas paranaenses. A capacitação e aprimoramento de recursos humanos, especialmente discentes, em temas relacionados ao patrimônio cárstico e espeleológico pretende auxiliar na gestão, em nível estadual, das cavidades naturais.

A presente proposta, inédita no cenário paranaense, justifica-se devido aos diversos serviços ecossistêmicos, descritos na Lei nº 14.119, de 13 de janeiro de 2021, prestados por cavidades naturais, destacando-se: a) serviços de provisão: Bens ou produtos ambientais utilizados pelo ser humano para consumo (exemplos: cimento, cal, rochas ornamentais, agregados para a construção civil, água mineral, corretivos agrícolas entre outros; b) serviços de suporte: a polinização e a dispersão de sementes por morcegos, o controle de populações de potenciais pragas e de vetores potenciais de doenças humanas e a manutenção da biodiversidade e do patrimônio genético; c) serviços de regulação: sequestro de carbono e manutenção do equilíbrio do ciclo hidrológico; d) serviços culturais: locais de recreação, turismo, de identidade cultural e de experiências espirituais.

Embora a legislação brasileira preveja a proteção de cavidades naturais sua aplicação enfrenta desafios, que derivam desde a falta de dados precisos sobre a localização das cavidades, falta de recursos humanos até pela dificuldade em conciliar as restrições previstas em lei com a importância da atividade de mineração com o desenvolvimento econômico.

5. Conclusão

A busca por soluções de gestão sustentável das áreas cársticas exige a colaboração de diversos atores. A sociedade civil pode contribuir com a criação de modelos de negócios sustentáveis e com a promoção de práticas de consumo consciente. O poder público, por sua vez, deve fomentar a pesquisa e o desenvolvimento de tecnologias limpas e eficientes, além de incentivar a criação de áreas protegidas. A comunidade científica tem um papel fundamental na geração de conhecimento sobre os ecossistemas cársticos e na proposição de soluções inovadoras para a gestão sustentável desses ambientes, como a criação de sistemas de monitoramento e o desenvolvimento de ferramentas de apoio a gestão integrada, a exemplo do OBSCavernas.

As cavidades naturais do estado do Paraná estão expostas à diversas atividades antrópicas, tais como, à extração mineral, à agricultura, à urbanização, à exploração de água, à silvicultura, dentre outras. Estas atividades podem impactar diretamente o funcionamento sistêmico do ambiente cárstico, seja pela destruição dos ecossistemas subterrâneos (terrestres e aquáticos) parcial ou total, e, consequentemente sua biota associada. Além disso estas atividades humanas podem provocar também alterações no nível freático da cavidade pelo consumo humano ou irrigação, bem como promover a poluição química das cavidades por contaminação de fertilizantes e pesticidas, assim como a contaminação orgânica pela descarga de lixo nas aberturas das cavidades. Considerando que o relevo cárstico é vulnerável a vários processos de degradação ambiental, importante destacar a proposta da criação do Observatório das cavernas e da região cárstica do estado do Paraná – OBSCavernas, como ferramenta de estudo, monitoramento, educação e planejamento para a conservação do patrimônio espeleológico e ambiental.

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From vectors to spirals of life: connecting three remarkables sites in the Puerto Rican karst

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Abstract

Building on past work on the social dimensions of cave exploration, science, and mapping, I explore some aspects of cave mapping's creative humanistic potential to highlight typically overlooked aspects of cave and karst research, education, and conservation. These aspects include the significance of domestic spaces and practices as key nodes and processes undergirding a human geography of karst. A more detailed characterization of this geography gives us a more complete picture of not only where the work of karst science and conservation happens, but also discerns a much broader and deeper scope of the values necessary to study, connect with, and protect karst. Indeed, this broader geography shows both the physical and social infrastructure that makes much karst science and conservation possible in the first place. Ethnographic descriptions and reflections of experiences in two specific key locations selected from over five years of fieldwork in Puerto Rico illustrate this contribution's key arguments. An accompanying artistic rendering of their site-specific characteristics as well as their spatial connections and locations with/in the broader landscape helps visualize the potential of a cartographic humanities approach not only in speleology, but in cave and karst research and conservation writ large.

Résumé

En m'appuyant sur des travaux antérieurs sur les dimensions sociales de l'exploration des grottes, de la science et de la cartographie, j'explore certains aspects du potentiel humaniste créatif de la cartographie des grottes pour mettre en évidence des aspects généralement négligés de la recherche et de la conservation des grottes et du karst. Ces aspects incluent l'importance des espaces et des pratiques domestiques en tant que nœuds et processus clés qui sous-tendent une géographie humaine du karst. Une caractérisation plus détaillée de cette géographie nous donne une image plus complète non seulement du lieu où se déroulent les travaux de science et de conservation du karst, mais permet également de discerner une portée beaucoup plus large et plus profonde des valeurs nécessaires pour étudier, se connecter et protéger le karst. En effet, cette géographie plus large montre à la fois l'infrastructure physique et sociale qui rend possible en premier lieu une grande partie de la science et de la conservation du karst. Des descriptions ethnographiques et des réflexions sur des expériences dans trois lieux spécifiques sélectionnés à partir de cinq années de travail sur le terrain à Porto Rico illustrent les principaux arguments de cette contribution. Un rendu artistique d'accompagnement de leurs caractéristiques spécifiques au site ainsi que de leurs connexions spatiales et de leur emplacement avec/dans le paysage plus large aide à visualiser le potentiel d'une approche cartographique des sciences humaines non seulement dans la spéléologie, mais dans la recherche et la conservation des grottes et du karst au sens large.

Resumen

A partir de trabajos anteriores sobre las dimensiones sociales de la exploración, la ciencia y el mapeo de cuevas, exploro algunos aspectos del potencial humanístico creativo del mapeo de cuevas para resaltar aspectos que normalmente se pasan por alto en la investigación, educación y conservación de cuevas y karso. Estos aspectos incluyen la importancia de los espacios y prácticas domésticos como nodos y procesos clave que sustentan una geografía humana del karso. Una caracterización más detallada de esta geografía nos brinda una imagen más completa no sólo de dónde ocurre el trabajo de la ciencia y la conservación del karso, sino que también discierne un alcance mucho más amplio y profundo de los valores necesarios para estudiar, conectarse y proteger el karso. De hecho, esta geografía más amplia muestra la infraestructura física y social que hace posible gran parte de la ciencia y la conservación del karso. Descripciones etnográficas y reflexiones de experiencias en dos específicos lugares importantes seleccionados a partir de más cinco años de trabajo de campo en Puerto Rico ilustran los argumentos clave de esta contribución. Una representación artística adjunta de las características específicas cada sitio, así como de sus conexiones espaciales y ubicaciones con/en el paisaje más amplio, ayuda a visualizar el potencial de un enfoque cartográfico de humanidades no solo en la espeleología, sino también en la investigación y conservación de cuevas y el karso en general.

1. Introduction

Like most contributors to these proceedings, I know well the importance of following the cartographic principles of cave surveying and mapping (DASHER 2011). The international establishment and adoption of such principles and accompanying standards is one of the key achievements of cave science around the world, the cave map becoming a shared language and foundation for other scientific and conservation work. Building on past work on the social dimensions of cave exploration, science, and mapping (PÉREZ 2013), as well as drawing from recent work in the cartographic humanities (ROSETTO and PRESTI 2024), in this contribution I explore some aspects of

cave mappings' creative humanistic potential (COSGROVE 1999) to highlight typically overlooked aspects of cave and karst education, conservation, and research. These aspects include the significance of domestic and other private spaces and practices as key nodes and processes undergirding a human geography of karst.

Historians of science have long focused on the role of homes as sites of scientific activities such as archiving, collecting, and experimenting, as well as performing and communicating knowledge production practices not only to inform and educate, but also, to gain sanction from typically privileged and powerful members of society (SHAPIN 1999 ; LIVINGSTONE 2003). The geographies undergirding science involving fieldwork are even more complex, as scholars investigating the historical, social, and political role of homes and field houses for field science have shown (DRIVER 2000; WITHERS & FINNEGAN 2003; EKERHOLM 2015). Given that in most places around the world it is typically clubs, serious hobbyists, and independent investigators without formal institutional or professional affiliations who carry out cave exploration and research (SHAW 2004), the situation is even more complex and porous between domestic vs. professional spaces. Human geographer Sarah Cant illustrates aspects of this in her detailed analysis of speleology in mid 20th century UK (CANT 2006). While many cavers are likely familiar with some aspect of the complex territorial politics of who has access to which cave systems, many are also likely aware of the challenges that come from determining where collective equipment and field samples will be stored and where they will meet regularly to organize and plan activities. Many involved in the purchase of property are aware of the importance of raising funds for these efforts to ensure conservation of and access to places of scientific and environmental significance.

Given the accelerating devaluing of the humanities in K-12 and higher education by politicians in the United States, it is worth explicitly defining what is at stake : "The humanities explore, interpret, and preserve the diversity of human cultures, ideas, practices and experiences, past and present. They are the languages, religions, laws, philosophies, and customs that make us distinct. They are our history and our cultures, the ideas and movements that have shaped societies throughout time" (NEH 2025). Growing out a long tradition of incorporating the humanities in geographic knowledge, the cartographic humanities "help in enlarging the horizons of map thinking, showing how maps are, and have always been, often simultaneously – rather than in oppositional ways – representations, practices, powerful devices, material objects, cognitive tools, embodied things, works of creativity, emplaced actions, living entities, technological machines, networks of feelings and much more" (ROSETTO and PRESTI 2024, 5). As such, "cartohumanistic" approaches can help better discern a broader scope of the context and values that support and help make educational, conservation, and scientific work possible in the first place. This is premised on the key idea that science is never outside of culture and history. Instead, as a human activitiy, science is always already cultural and ought to be understood and appreciated in its historical context (i.e., PÉREZ 2016 in speleology context). This point helps us better appreciate and support it with the education and institutions necessary to do, maintain, and communicate sound science.

I give examples and further illustrate these points with a significant case from ongoing multi-year research investigating local community efforts advancing karst education, conservation, and science in Puerto Rico. Specifically, I focus on the non-profit organization Ciudadanos del Karso (Citizens of Karst or CDK).

2. Background and Context of Puerto Rican Case Study

Founded in 1994 by a mix of cavers, naturalists, scientists, and other concerned citizens, CDK has become an important organization advocating for conservation, education, and legislative change in Puerto Rico. Among its most significant achievements are legislative ones: the drafting of Law 241 of Puerto Rican Wildlife, approved August 15, 1999, and Law 291 for the Protection and Conservation of Karst Physiography, approved August 21, 1999. Currently, it is engaged in an ambitious project of transforming a historic abandoned school structure in historic downtown Arecibo into the Instituto del Karso de Puerto Rico y el Caribe (Institute of Karst of Puerto Rico and the Caribbean or IKPReC) (Fig. 1).



Figure 1: *The future home of the Instituto del Karso de Puerto Rico y el Caribe, located in downtown historic Arecibo (author's photo, October 2024).*

The multipurpose space will include laboratories and other research spaces, lecture halls, a coffee shop, and a natural history museum for the general public in its ample first floor. Significantly, the building is being designed with sustainability principles and the community in mind. It will have its own energy and water sources in the case of emergencies when government infrastructures fail, a situation happening increasingly often as Puerto Rican face the double crises of climate change and weakening of public investments exacerbated by neoliberal pressures, corruption, and its entrenched condition of coloniality (BONILLA 2020; AYALA 2024).

As is the case of many community-based initiatives—many arising in the aftermath of Hurricane María—, it is Puerto Rican residents who organize and work incessantly and creatively to improve not only their communities but also the entire nation, in some cases drawing from and amplifying regional networks across the Caribbean and beyond (i.e., LLENÍN-FIGUEROA 2019). There is not only hope but growing tangible evidence of a new stance defying the political and economic status quo. For example, in 2019, many Puerto Ricans, indignant and tired of a corrupt and disparaging political leadership, peacefully forced out of office Governor Ricardo Rosselló. New alliances have formed, new leadership has arisen. Puerto Ricans who had long left the "Isla," as many Puerto Ricans refer to the Puerto Rican archipelago, are returning, some eager to invest in diverse new initiatives as the ones described above.

This context is important to better appreciate the breadth and depth of CDK's 30 year work, as well as the challenges that its most recent project faces but is determined to overcome. CDK's leaders, members, and volunteers are not immune to the daily challenges that so many Puerto Rican residents experience. Since I first visited the IKPReC site in 2019, I was inspired by the scope of its ambition but also overwhelmed by the staggering amount of work that lay ahead. How do the members of this organization keep their commitment and hope alive?

This is not the first time that I've asked this question in the context of speleology or even cave and karst conservation in complex and highly challenging economic, political, and environmental contexts (i.e., PÉREZ 2016, 2019). There were and will always be those who leave speleology behind and emigrate, but others endure, sometimes even when having the choice to leave. As part of a family that experienced the very difficult decision and aftermath of leaving our home country, I acknowledge the complex and particular conditions that families face, leading to these consequential decisions. Thus, this contribution must not be read as either an indictment on/of those who leave or a glorification of those who stay. Instead, I aim to illuminate some of the qualities and orientations of the daily lives of key CDK leaders/volunteers to suggest how their domestic

and other personal spaces, not only help sustain natural systems, but are also part of a greater *human* geography of karst. These spaces offer a rarely-commented behind the scenes in which our leaders both affirm their values towards the environments and ecosystems which they strive to defend, as well as connect with and draw inspiration from the very ecosystems they are committed to defending. In these spaces, friends, volunteers, and professional investigators alike advance the key work of research, conservation, and education. Sustaining that work in the short, medium, and long term, also involves tireless administrative, planning, and even political work that goes into nurturing and growing both a physical and social infrastructure that makes cave and karst education, conservation, and research possible in the first place.

3. Experimenting with Cross-Sections of Experience

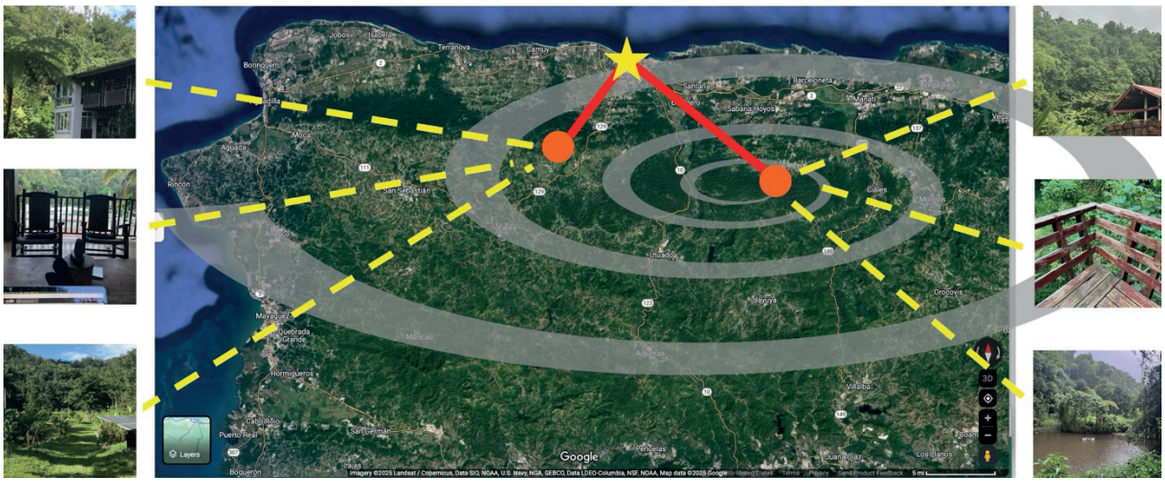


Figure 2: *Cartohumanistic rendering of the connection among three locations in Puerto Ric. From left to right : El Tallonal private nature preserve, the IKPReC (the yellow star), and the House in the Karst, along with visual cross-sections of textures and "experience" at each site (all are author's photos over the Google maps image of the northwestern portion of Puerto Rico's main island).*

Drawing from experiences I have had during preliminary and ongoing fieldwork in Puerto Rico since 2019, I turn to two specific sites related to Ciudadanos del Karso that illustrate this contribution's main arguments. The methods used are drawn primarily from the humanities: auto-ethnography (BUTZ 2009) and key interlocutor life history interviews (YOW 2014). I also reference local newspapers. Although my academic training is in cultural anthropology, part of the main argument and structure of the case study presentation draws from my caver training and experiences over the years with cave surveying and mapping, including numerous intensive field experiences in Puerto Rico collaborating with Michael Lace, Director of the Coastal Cave Survey. During these experiences we have also collaborated with Puerto Rican archaeologists and speleologists, studying and cartographically documenting both coastal and continental karst geomorphology and varied cultural uses of karst. These intense experiences, coupled with recent work in the cartographic humanities (ROSSETTO and PRESTI 2024), undergird the following creative experiment: drafting a geospatial visualization of the relative location of three sites, all located within or near Puerto Rico's northern karst belt, an area that constitutes about 140,000 hectares and is the largest region with exposed limestone in the archipelago's main island (LUGO et al. 2001). The goal is to show the distributed yet interconnected nature of these sites using a top-down "plan-view" perspective. Then, similar to how cave surveyors draw cross-sections of passages to give viewers a better sense of what traversing some of the more peculiar or characteristic parts of the cave are like, I offer three textual cross-sections of "experience" as I attempt to invite the reader to immerse themselves at a particular point (and time) of my exploration in this deeply complex distributed human geography of Caribbean karst. Of course this is a subjective exercise, not unlike the way the sketcher selects cave cross-sections. As in caves, photos cannot capture the totality of the phenomenon. I offer only partial views, focusing primarily on textures of experience, whether symbolic or material. This too is a highly subjective exercise. Creative, maybe? I am not sure if it'll work. Here we go.

El Tallonal. It is 5:30am and the sky's still dark. I leave my room and find Abel, cloaked with his grey Andean poncho, already at his desk. "Buenos días," we say to each other. I go down the wooden staircase, and find Mike sitting at the large wooden dining table, also on his laptop, his brow furrowed, a sign of a working mind trying to make sense of the data gathered in the field the day before. A second round of "Buenos días" exchanged. I am so thankful to find the coffee has already been brewed. I fill my tumbler and make my way to the ample outdoor roofed patio, which also serves as the living room of this relatively simple yet sturdy three-level structure. I sit on my favorite wooden rocking chair, open up my laptop, and get to writing my ethnographic notes on yesterday's karst field experience, notes that will advance my scholarship but also my teachings on human geography and sustainability studies back in West Virginia University, my home institution. Within 30 minutes, the sky lightens; the sun's first rays slowly awaken fellow inhabitants with whom we share this sinkhole. Then, I hear him, the turpial (Icterus icterus), Venezuela's national bird. He loves that palm tree right next to the kitchen. "Your compatriot has arrived," Abel likes to say. "Yes, he has."

This structure, designed with sustainability and durability in mind by a prominent Puerto Rican architect, serves as the headquarter of the management the El Tallonal private reserve, over 100 hectares of a stewardship forest in the middle of the stunning Northern Karst Belt of Puerto Rico. It is also where Abel Vale, president of CDK, spends most of his time. And I get it. It is a stunning and delicate refuge, a forest brimming with life, its main built structure borrowing water from karst aquifers, and running on the generous rays of the sun, the entire place a spiritual homage to living in balance and awe of Earth's natural systems.

You will not find this location on AirBnB. This is no vacation spot. All activities carried out by people who spend time in El Tallonal, including its main caretakers, are dedicated to advancing the mission of CDK, to educate about, investigate, and conserve Puerto Rico's natural systems, in particular its karst (www.cdk-pr.org). This is not an abstract idea; here in El Tallonal there is constant evidence of the considerable labor and significant risk-taking involved in tending to this reserve. It

is a place constantly visited by scientists and even school children and Scout troops, everyone involved in their investigations and learning. Having the privilege of spending a night in this place—in the middle of an extraordinary sinkhole, with no light contamination, with the almost deafening sound of the coquí (*Eleutherodactylus coqui*) and increasingly, also of the endangered sapo concho (*Peltophryne lemur*) being reintroduced to this part of Puerto Rico—is to enter into an unspoken pact: you may stay here to advance your writing and science, you may stay here and drink my water, you may stay and enjoy my peace, but you must respect and defend me in return.

The House in the Karst. This remarkable place, where Nélida Agosto and Jose Colón spend most of their time, is located just shy of 20 hectares in the mountainous and rural area of the Ciales municipality. It is approximately 50 kms by car southwest of El Tallonal, but still within the northern karst belt. It is also the place where CDK was founded in 1994, with both Nélida and Jose becoming founding members (the both remaining active in the CDK Board of Directors). I appreciate Nélida and Jose's expertise as an affirmation of karst's not only geologic and ecological but also cultural dimensions. Nélida, after all, trained as a sociologist of religion at Oxford, doing her thesis work on Haitian voodoo, followed by a significant research on Puerto Rican religions, and then years teaching at the University of Puerto Rico, while Jose is a biologist and internationally recognized bird expert. And not unlike El Tallonal, but perhaps even more so, this place in Ciales is a symbolic and material affirmation of the values of living in, learning from, and conserving the delicate ecosystems increasingly under threat of the destruction of unbridled development, governmental negligence, and coloniality. As a San Juan-based journalist notes in a 1991 newspaper article:

> The architect friend Edwin Quiles and his assistant José Delgado designed the plans for the house, starting from … Nélida's sketch. [The design satisfied] seven goals …: that it could be built by them and their friends in what they call mutual help and self-effort; that both they and those who visited them would feel happy; that wood would be the material used, since it has life; that the orientation would be from north to south to conflict with the magnetic poles of the globe; that they do not incur in monetary debt, so that as they are doing it little by little, little by little they buy the materials, whenever and however they can, always in cash; that it had cross ventilation; that would run on solar energy so that they would depend as little as possible on public services, which are not always optimal. In short, that the house of some committed conservationists would concretize what they believe and preach. (CIDONCHA 1991, 50)

While Nélida and Jose technically own this space, signs at the gate and elsewhere in the property make it clear that the true owners are actually the non-human beings that inhabit it. Moreover, Nélida and Jose, already in their 80s, plan to donate the land and hand-built structures to community conservation and science efforts. Already it has been a space that has and continues to welcome such work, by local and international investigators alike.

But what most captivated me in Nélida and Jose's place was a beautiful spiral (Fig. 3), a small scale earthwork sculpture that Nélida made years ago right under the elevated porch of their home. When I visited on October 18, 2024, it was overgrown with plants, but we were able to clear most of them to capture the sculpture's full dimensions and beauty. Trained as a cultural anthropologist, you'd think I'd ask Nélida what it meant, but I worried that doing so would actually ruin the moment, like trying to analyze an artwork in the moment of encounter and enrapture. She did make a comment on the spiral's cross-cultural significance. Remember her own training as a sociologist… I saw that spiral and its round stone at its center as the beating heart—the symbolic hearth, even—of a simple yet stunning affirmation of connection across space and time.



Figure 3: *Nélida's spiral at the House of Karst (author's photo, October 2024).*

4. From Vector to Spiral

Isn't this what happens? When we stop at our survey station and look up, down, right, and left, when we point the distometer and report the readings? At each station—selected by some complex mix of field experience, both internal (i.e., knee pain ?) and external (i.e., a particular geologic feature in the cave ?) physical constraints, and serendipity—we also sometimes have an opportunity to rest as we wait for the team's sketcher to catch up with us. As a graduate student I was so enthralled with this process that it became the topic of my first peer-reviewed paper (Pérez 2013). I love these moments waiting on station, particularly when they happen in absolute silence and darkness. More often, during my time exploring and surveying the coastal karst of Puerto Rico, they happen in relatively small but also open chambers, with either sunlight, wind, or the sea making their way in (sometimes all at the same time). Not unlike that spot in Nélida and Jose's porch tucked away among the cockpit karst of Ciales, or on that rocking chair early in the morning, in El Tallonal.

In our survey notes, straight lines connect our stations, but we all know there are hardly any natural or cultural processes that proceed in straight, uncomplicated lines (INGOLD 2021). What if, in our effort to become more rigorous cartographers, we followed not only the vectors but also the spirals of life that I keep coming across in Puerto Rico ? Starting from Nélida's stunning spiral, we'd intersect and connect with the lives and dreams of ecologists and spiritualists alike, remarkable people, toiling in, transforming, and defending remarkable spaces in the heart of the Caribbean and beyond. In Puerto Rico, at least, these spaces include spaces of living and rest, which also double as spaces of planning and work. I increasingly regard these spaces as sacred, as well. Including them in our surveys and descriptive accounts of our research are likely to result in broader and much richer geographies of cave and karst science, education, and conservation. At minimum, they are likely to show us the way. At every one of these seemingly ordinary but extraordinary sites, the wind blows. *They go*.

5. Conclusion

In this paper I have advanced a human geography of karst to refer to the both physical and symbolic dimensions of human activities with/in karst, including finding ways of living in it, striving to explore and learn from it, as well as being inspired by and in awe of it. As shown with examples from over five years of fieldwork experience in Puerto Rico, a more detailed characterization of this geography, gives us a more complete picture of not only where the work of karst education, conservation, and science actually happens (unsurprisingly, much of it is done by volunteers and non professional scientists), but also discerns a broader and deeper scope of the values beyond the narrowly scientific. Indeed, this broader geography shows both the physical and social infrastructure that makes much karst education, conservation, and science possible in the first place. Moreover, it aims to encourage creative though no less systematic integrations of cartographic humanities approaches to the ways we document and communicate our research, something that many in our communities (i.e., artist cavers/caver artists especially) have long done. Finally, this paper provides yet another illustration of the importance of humanities research of and for speleology and karst research writ large. It is my hope that more conservancies and other funding agencies from around the world will expand their funding programs to include humanities work by university students and early career university and independent scholars. At least in the US context, refer to the granting program by the Cave Conservancy of the Virginias for an example of this welcome move. May many others follow.

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Exploring suicide pattern in the karst environment of Gunungsewu Indonesia

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Abstract

Suicide is a significant public health concern globally, with certain environmental and socio-economic factors influencing its prevalence. This study explores the spatial patterns of suicide in the karst environment of Gunungsewu, Gunungkidul, Indonesia. Using a combination of quantitative and qualitative approaches, this research analyzes 289 suicide cases reported between 2015 and 2023. Spatial regression analysis, Moran's I, and Local Indicators of Spatial Autocorrelation (LISA) were employed to identify clustering patterns and hotspot areas. The findings reveal that suicide incidents are not randomly distributed but are concentrated in specific regions, particularly in the southern Karst Gunungsewu and parts of the northern Baturagung zone. These hotspots align with factors such as social isolation, economic hardship, and limited healthcare accessibility. The study also highlights cultural beliefs and geographical constraints as contributing factors. Understanding these spatial patterns is crucial for developing targeted intervention strategies and improving suicide prevention efforts in rural and remote areas.

1. Introduction

The environment plays a crucial role in shaping human life patterns, influencing physical conditions, social interactions, and overall health. The characteristics of a region determine how people adapt to theri daily activities, including livelihoods, social engagement, and mental and physical well-being (ESPINOZA, 2023). In certain cases, environmental limitations exacerbated by socio-economic pressures and inadequate healthcare facilities can contribute to increased stress, anxiety, and even decisions to end their life (CHEN et al., 2012). Gunungsewu, a karst region in Gunungkidul, Special region of Yogyakarta, Indonesia, exemplifies how environmental conditions impact the lives of local communities.

The extreme and challenging environmental conditions in Gunungsewu have led many working-age residents to migrate to urban areas in search of better economic opportunities. Meanwhile, older generations often choose to stay in their hometowns, continuing to work as farmers. Despite facing water scarcity, agriculture remains the primary livelyhood in this region, dominating land use (FAIDA & ZAMRONI, 2011; RAHMADI et al., 2018). However, The arid landscape, thin soil layers, and difficulty in accessing water for irrigation pose significant challenges to local farmers, forcing them to rely on dryland farming, which yields low productivity (DARMANINGTYAS 2002 ; REINHART et al., 2022). Historically, JUNGHUHN (1850) described Gunungsewu as a dense forest teeming with diverse species. Today, however, the region widely recognized as a dry and barren karst landscape. The area's hilly terrain, valleys, and numerous caves create a mystical ambiance, reforcing local beliefs in supernatural forces. Traditional beliefs and myths remain deeply embedded in the culture, including the Pulung Gantung phenomenon, which is perceived as a sign that someone may take their own life (SUWENA, 2016).

Suicide has long been a significant concern for the people pf Gunungsewu, Gunungkidul. According to the WHO (2021), suicide is one of the leading causes of death worldwide, with more than 720,000 people losing their lives to it annually. Various contributing factors have been identified, including chronic illness, social and geographical isolation, drought, barren land, and low levels of education. Cultural perspective also play a role, as researchers suggest that suicide decisions in this region are influenced by feelings of shame (wirang), social burden, and strong social ties (NURDIYANTO & JAROAH, 2020). Hanging is the most commonly used suicide method, although some individuals choose to end their live by jumping into vertical caves or wells, depending on the availability of means.

Despite efforts to address the issue of suicide in Gunungsewu, the number of incidents remains persistent, showing no significant downward trend. Given the regional characteristics and the suicide crisis, it is crucial to develop policy strategies tailored to the local context. Studying the spatial patterns of suicide in Gunungkidul is essential, as it can help identify localized contributing factors and inform more effective prevention measures.

2. Materials and methods

This study is conducted in the karst region of Gunungsewu, located in Gunungkidul Regency, Special Region of Yogyakarta, Indonesia, on the island of Java. The study area is illustrated in Figure 1. The research adopts a quantitative approach supported by qualitative data. The secondary data used in this study consists of raw suicide incident reports from 2015 to 2023, totaling 289 cases. These records include information on the district, age, gender, occupation, method, and motive. The data is then categorized based on the region's development zones : the Karst Gunungsewu in the south, the Wonosari Basin in the central area, and the Baturagung zone in the north. The data was obtained drom the Gunungkidul Regency Police Department. The processed data was subsequently analyzed using ArcMap version 10.8.

The spatial analysis methods employed include spatial regression analysis, specifically Moran's I and Local Indicators of Spatial Autocorrelation (LISA). There methods help assess global spatial autocorrelation, identify spatial patterns, and detect suicide hotspots, and coldspots.

However, an in-depth spatial pattern analysis could not be fully conducted due to the data limitations. Additionally, the Standardized Mortality Rasio (SMR) could not be accurately calculated due to potential data biases regarding the total number of deaths. Indonesia still faces challenges in suicide data availability and transparency due to societal stigma (ONIE et al., 2024). The WHO has classified Indonesia's estimated suicide rates with the lowest quality score, reflecting poor data realibility and accuracy. Therefore, qualitative data is used to supplement and reinforce the quantitative findings, providing a broader understanding of potential factors influencing suicide incidents. The qualitative data is gathered through field observations and interviews. Interviews were conducted with local residents, religious leaders, stakeholders, and government officials who knowledge and experience related to this issue.



Figure 1: *Research Area in Karst Region of Gunungsewu, Gunungkidul, Indonesia.*

3. Results

The analysis begins by measuring global spatial autocorrelation using Moran's I on aggregate suicide data from 2015-2023 in Gunungsewu, Gunungkidul Regency. This analysis aims to determine wheter the data exhibits a clustered, random, or dispersed pattern. The results of this analysis are presented in Figure 2.

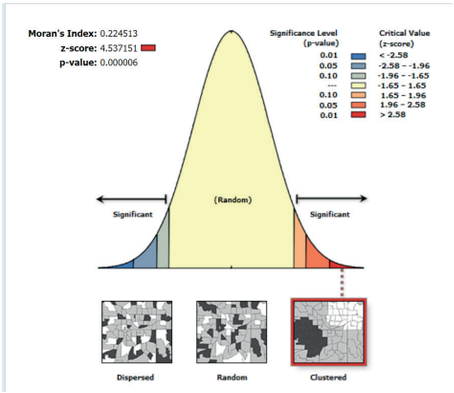


Figure 2: *Results of Moran's I grouping on suicide cases.*

Based on the figure above, the high z-score value of 4.53 (greater than 2.58) indicates that the results are statistically significant. This suggests a strong clustering pattern in suicide incidents within Gunungsewu, Gunungkidul Regency. In other words, suicides cases are not randomly distributed but tend to be concentrated in specific areas.

Following the identification of the clustered global spatial autocorrelation pattern, a more detailed analysis was conducted using the Local Indicator of Spatial Autocorrelation (LISA) on the same dataset. The purpose of this analysis is to break down the global Moran's I statistic into localized contributions from individual areas. The result of the LISA analysis are shown in Figure 3. The resulting map (Figure 3) highlights the distribution of suicide hotspots and coldspots, which appear unevenly across different geographic zones in Gunungkidul Regency. The analysis reveals that suicide hotspots are predominatly found in the southern Karst Gunungsewu region, with a smaller concentration in the nothern Baturagung zone.

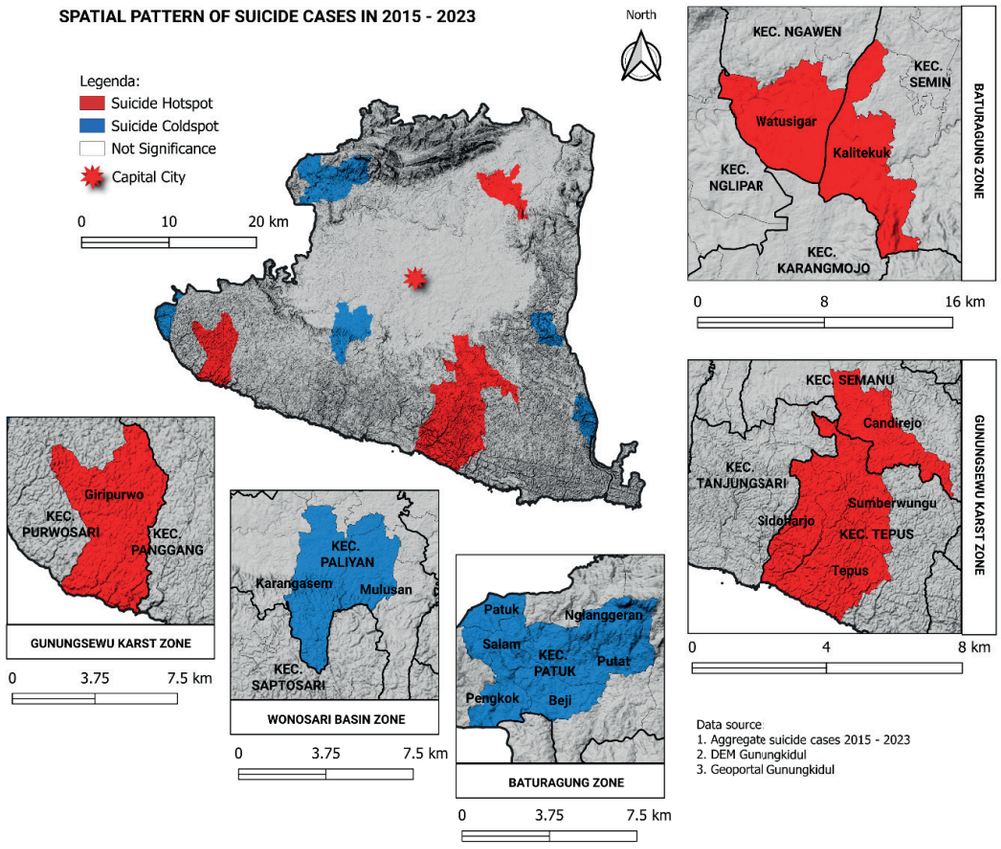


Figure 3: *Spatial pattern of suicide case in Gunungkidul District 2015 - 2023.*

4. Discussion

One of the most striking findings from this research is that suicide cases are not concentrated in the central urban areas, such as Wonosari District and its surrondings, nor in more developed regions. Instead, remote areas, particularly in the Karst Gunungsewu region and parts of the Baturagung zone, tend to exhibit hotspot patterns. This finding aligns with research conducted in several East Asian countries, such as China (PHILLIPS et al., 2002), Japan (YOSHIOKA et al., 2020), and Taiwan (CHANG et al., 2011), where suicide rates tend to be higher in rural and less developed areas. For Example, CHANG (2011) found that suicides in Taiwan were more prevalent in peripheral rural and mountainous regions in the east, while major cities like Taipei did not exhibit significant suicide concentrations in their urban centers.

Data from the Gunungkidul Police Department (2015-2023) indicate that most suicide victims were male (64,71%), elderly Individiuals over 60 years old (36.33%), farmers (67,13%), resident of the Karst Gunungsewu development zone (37,72 %), and people living in rural areas (95,16%). The Primary causes of suicide were chronic illness and depression, followed by family-related issues such as economic difficulties, romantic problems, and mental illness. In the patrialchal society of Gunungsewu, elderly men working as farmers in the karst region are particularly vulnerable. Several factors contribute to this vulnerability, including difficulty expressing emotions (MULYANI & ERIDIANA, 2018; ANDARI, 2017), economic pressure as household heads (ALI & SOESILO, 2021; MULYANI & ERIDIANA, 2018; FAHRUDIN, 2012; ANDARI, 2017), chronic and physical illness (ALI & SOESILO, 2021; MULYANI & ERIDIANA, 2018; FAHRUDIN, 2012; ANDARI, 2017), and loneliness due to their children migrating for works.

The most common suicide methods include hanging, jumping into vertical caves, and jumping into wells. Interviews with village officials in Karst Gunungsewu area reveal that suicide cases in vertical caves are frequently discovered but often go unreported due to stigma surronding suicide, which is considered shameful or taboo in the community. Cave are perceived as mystical spaces, influencing their uses as sites for suicide. At the same time, locals avoid approaching caves carelesslu due to their sacred status. The choice of caves as suicide locations is likely due to the high fatality rate of this method. In comparison, jumping into vertical cave is similar to jumping from a tall building in an urban setting. This suggests that environmental conditions and the availability of certain locations influence the choice of suicide methods (MULYANI & ERIDIANA, 2018). Geographically, Gunungsewu Karst is characterized by steep and rugged hills, resulting in a scattered settlement pattern adapted to the area's morphology. According to ALI & SOESILO (2021), social isolation and loneliness are key factors contributing to suicide, The dispersed settlement pattern leads to reduced social interaction, increasing feeling of isolation. Additionally, poor accesibility limit mobility, further exacerbating the situation. Interviers with residents indicate that many suicide victims suffered from chronic illness but struggled to access adequate healthcare due to the lack of well-equipped facilities in their vicinity. To receive proper medical treatment, they had to travel to urban areas, which was often exhausting and discouraging, particularly for elderly individuals. The Southern Cross Road connects southern regions but does not provide direct access to urban centers or well-equipped healthcare facilities, further complicating access to necessary medical care.

5. Conclusion

This study provides valuable insights into the spatial distribution of suicide cases in the karst region of Gunungsewu, Gunungkidul. The analysis indicates that suicides are significantly clustered in specific rural areas rather than urban centers, highlighting the role of environmental and socio-cultural factors. Key findings suggest that elderly male farmers in socially isolated areas with limited access to healthcare are particularly vulnerable. The most common methods of suicide include hanging and jumping into vertical caves or wells, reflecting both the influence of environmental conditions and the availability of means.

The study emphasizes the need for region-specific suicide prevention strategies, including improving healthcare access, strengthening community support networks, and addressing socio-economic stressors. Additionally, greater efforts are required to overcome the stigma surrounding suicide, which often leads to underreporting of cases. Future research should focus on integrating mental health services with community-based interventions and further exploring the cultural dynamics influencing suicidal behavior in rural karst environments.

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Geoprocessamento aplicado ao contrôle de vibrações em cavidades localizadas no entorno de minerações à céu aberto

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Resumo

Nas atividades minerárias o acompanhamento dos desmonte de rochas com uso de explosivos em regiões de ocorrência de cavidades naturais subterrâneas é de fundamental importância, pois além de atender a legislação ambiental vigente possibilita um melhor planejamento de lavra, sem comprometer a integridade física dessas estruturas. O monitoramento sismográfico aliado às técnicas de geoprocessamento contribui para a sustentabilidade das atividades de mineração e a proteção do patrimônio espeleológico através da análise espacial e tratamento estatísticos de dados provenientes dos desmontes de rocha para a explotação do minério. Com o uso do SIG foi possível gerar mapas e arquivos georreferenciados para serem utilizados pelas equipes de planejamento de mina e desmonte de rochas na execução de lavra em regiões de ocorrência de cavidades. O objetivo desse trabalho é estabelecer faixas de distância georreferenciadas indicando os quantitativos de explosivos a serem utilizados para controlar os valores de vibração de partícula para atendimento à recomendação do Centro Nacional de Pesquisa e Conservação de Cavernas - ICMBIO/CECAV, no que tange aos limites de vibração preliminares para cavidades de máxima relevância.

Abstract

In mining activities, monitoring rock blasting using explosives in regions where natural underground cavities occur is of fundamental importance, since in addition to complying with current environmental legislation, it enables better mining planning without compromising the physical integrity of these structures. Seismographic monitoring combined with geoprocessing techniques contributes to the sustainability of mining activities and the protection of speleological heritage through spatial analysis and statistical processing of data from rock blasting for ore exploitation. Using GIS, it was possible to generate georeferenced maps and files to be used by mine planning and rock blasting teams when executing mining in regions where cavities occur. The objective of this work is to establish georeferenced distance ranges indicating the quantities of explosives to be used to control particle vibration values to meet the recommendation of the National Center for Cave Research and Conservation - ICMBIO/CECAV, regarding preliminary vibration limits for cavities of maximum relevance.

Resumen

En las actividades mineras, el monitoreo de voladuras de roca mediante explosivos en regiones donde se presentan cavidades subterráneas naturales es de fundamental importancia, ya que además de cumplir con la legislación ambiental vigente, permite una mejor planificación minera sin comprometer la integridad física de estas estructuras. El monitoreo sismográfico combinado con técnicas de geoprocesamiento contribuye a la sostenibilidad de las actividades mineras y a la protección del patrimonio espeleológico mediante el análisis espacial y el procesamiento estadístico de datos de voladuras de roca para la explotación de minerales. Mediante el uso de SIG, fue posible generar mapas y archivos georreferenciados para ser utilizados por los equipos de planificación minera y voladuras de roca al ejecutar la minería en regiones donde se presentan cavidades. El objetivo de este trabajo es establecer rangos de distancia georreferenciados que indiquen las cantidades de explosivos a utilizar para controlar los valores de vibración de partículas para cumplir con la recomendación del Centro Nacional de Investigación y Conservación de Cavernas - ICMBIO/CECAV, respecto de límites preliminares de vibración para cavidades de máxima relevancia.

1. Introdução

As atividades para elaboração do presente trabalho foram realizadas no estado do Pará, na cidade de Canaã dos Carajás, especificamente na mina S11D localizada em Serra Sul, uma das serras pertencentes a província mineral de Carajás (Fig. 1).



Figura 1: *Localização da área de estudo.*

A província mineral de Carajás está localizada no sudeste do estado do Pará e possui um padrão de relevo marcado pela presença de serras de topos aplainados com altitudes médias de 650m, denominados Planaltos Residuais do Sul da Amazônia VALENTIM & OLIVITO (2011).

Na mineração, muitas vezes a extração do minério é realizada através do desmonte da rocha com uso de explosivos, e essa técnica tem sido a mais utilizada para a fragmentação de maciços rochosos em níveis compatíveis com as necessidades de uma escala de produção industrial a um baixo custo. A Figura 2 apresenta uma imagem do exato momento da fragmentação de maciços rochosos com uso de explosivos.



Figura 2: *Fragmentação de maciços rochosos com uso de explosivos. Fonte: www.minasjr.com.br.*

Um dos principais problemas do uso dessa técnica é o impacto ambiental causado pela dissipação ou perda de parte da energia gerada pela detonação dos explosivos. Essa energia não utilizada na fragmentação do maciço rochoso se propaga no terreno através de ondas mecânicas denominadas vibrações sísmicas (DALLORA NETO, 2004, p. 21). Dependendo da frequência e magnitude dessas vibrações, as estruturas atingidas podem vir a sofrer danos irreversíveis.

O Decreto Federal 6640/2008, em seu artigo 3º estabelece que a cavidade natural subterrânea com grau de relevância máximo e sua área de influência não podem ser objeto de impactos negativos irreversíveis, sendo que sua utilização deve fazer-se somente dentro de condições que assegurem sua integridade física e a manutenção do seu equilíbrio ecológico (BRASIL, 2008). Nesse caso o acompanhamento dos desmontes de rochas com uso de explosivos em regiões de ocorrência de cavidades é imprescindível e uso de técnicas de geoprocessamento aliadas ao monitoramento sismográfico tornam-se ferramentas fundamentais para o acompanhamento e controle das vibrações.

Considerando todas as questões aqui apresentadas, o presente trabalho tem por objetivo estabelecer faixas de distâncias para as cavidades ao longo das áreas de lavra previstas nas minas, indicando a quantidade de explosivos a serem utilizadas visando o controle do nível de vibração, conforme o limite recomendado pelo Órgão Ambiental para cavidades de máxima relevância.

Vale ressaltar que na literatura são encontrados vários métodos e equações para se prever o nível das vibrações provocados por desmonte de rochas, sendo que a maioria destes métodos procura relacionar a intensidade do movimento oscilatório gerado pelo desmonte, com a distância entre o ponto de monitoramento e o centro geométrico do desmonte, características das rochas, do terreno por onde as vibrações se propagam e massa da carga de explosivos.

É importante avaliar e prever a velocidade de vibração de partícula de pico com precisão. Os modelos para previsão de vibrações causadas por desmonte de rochas podem ser de vários tipos: modelos empíricos, modelos de regressão estatística, rede neural artificial (ANN), algoritmo de máquina de vetores de suporte (SVM), algoritmo genético (GA), entre outros.

A maioria dos modelos empíricos propostos são capazes de prever a velocidade de vibração de pico de partícula (V) com base em dois parâmetros, carga máxima por espera (Q) e distância entre as detonações e os pontos monitorados (D). TORRES, SILVEIRA e LOPES, 2018, apontam que ao longo de anos, vários cientistas e engenheiros propuseram equações que correlacionam estas medidas.

Este trabalho apresenta um estudo de caso, onde uma análise espacial é desenvolvida utilizando métodos quantitativos para definição de cargas de explosivos a serem aplicadas em faixas de distâncias de área de proteção de cavidades no entorno de uma mina de ferro situada no município de Canaã dos Carajás, sudeste do estado do Pará.

2. Materiais e Métodos

Para o desenvolvimento deste trabalho, foram selecionadas de forma estratégica cinco cavidades com o objetivo de cobrir todo o perímetro da mina S11D.

Para tanto, experimento foi desenvolvido em duas etapas, elaboradas em um conjunto de passos, sintetizadas na Figura 3.

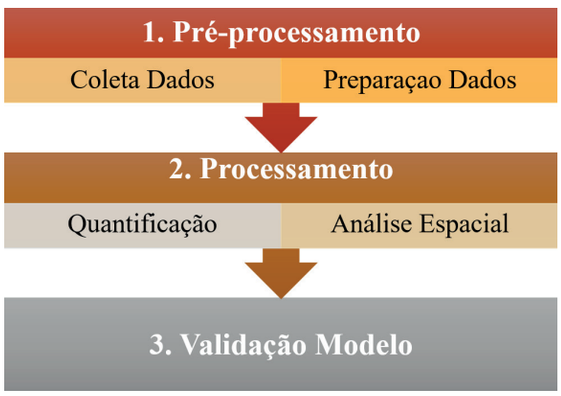


Figura 3: *Fluxograma metodológico.*

As plantas baixas das cavidades alvo do estudo em formato formato *DWG*, devidamente georreferenciadas, foram separadas em pastas e adicionadas no ambiente *GIS* através da ferramenta *Add Data*. O software utilizado foi o ArcMap versão 10.8.1.

Já no ambiente *GIS* o limite externo da cavidade em formato de poligonal foi selecionado utilizando a ferramenta select features e exportado para o formato *shapefile* utilizando o comando *data > export data*. Finalizada essa etapa todos os *shapefiles* gerados foram agrupados em um único arquivo utilizando-se o *ArcToolbox > data Management Tools >General> Merge.*

Para gerar o limite de 250m de cada cavidade foi utilizado novamente o *ArcToolbox* através da ferramenta *Analysis Toos > Proximity > Buffer*. Já com os limites dos raios de proteção gerados, a partir deles foram delimitadas as faixas utilizando a mesma ferramenta do *Arc Toolbox; Analysis Toos > Proximity > Buffer*, onde nessas faixas os desmontes só poderiam acontecer obedecendo as premissas de cargas definidas. Dessa forma foram geradas faixas de 250/300m, 300/400m e 400/500m.

As faixas geradas tiveram a escala de cores definida da mais quente para a mais fria, sendo as cores quentes mais próximas do raio de proteção contendo as cargas mais restritivas e as cores frias mais distantes do raio de proteção e com cargas menos restritivas.

Para a definição das cargas máximas por espera de explosivos a serem atribuídas a cada faixa de distância planejada, foi utilizado o software *Blastware* versão 10.74, onde foi elaborada a equação de atenuação das vibrações pelo terreno, com base em dados sismográficos obtidos em ensaios de desmonte padrão realizados na mina.

Os dados sismográficos foram coletados através do uso de cinco sismógrafos de engenharia da fabricante canadense Instantel, modelo minimate. Estes aparelhos dispõem de um transdutor de vibração triaxial (geofone), capaz de medir a velocidade de vibração de partícula em três direções mutualmente perpendiculares, longitudinal, transversal e vertical (LTV), sendo os valores expressos em milímetros por segundo (mm/s). Os geofones foram fixados no maciço rochoso com o uso de gesso em distâncias pré-definidas. No escritório os dados coletados pelos sismógrafos foram descarregados e tratados utilizando o software *Blastware*. Com o uso do *ArcGis* versão 10.8.1 foi realizado o tratamento dos dados georreferenciados e gerados arquivos vetoriais no formato *shapefile*. Para a cavidade foi atribuída a feição geométrica do tipo polígono e acrescido um raio de 250m em forma de poligonal convexa conforme estabelecido pela resolução 347/2004 do CONAMA.

A partir do raio de 250m das cavidades foram geradas faixas utilizando a ferramenta "*buffer*" com distância de 50 metros para a faixa até 300 metros da cavidade, e faixas com maiores distâncias a partir desta, variando entre 100 e 500 metros. Em seguida, as faixas foram recortadas conforme o limite atual de cava final, para que a delimitação das faixas de cargas se restrinja ao longo das áreas de lavra previstas.

Posteriormente o *shapefile* gerado dessa camada é exportado para outros formatos como *CAD (.dxf)* por exemplo, para ser encaminhado a área de planejamento de lavra, para que possam ser importados em softwares específicos e restringirem as cargas nos planos de lavra previstos. Juntamente com o arquivo *shapefile*, é enviada a premissa de desmonte em formato raster e um documento de texto com as orientações em relação as cargas propostas em forma de tabela.

Para elaboração do mapa final em formato raster, utilizou-se de imagem orbital do satélite *WorldView* do ano de 2020, com resolução espacial de 0,50m e, com exceção do mapa de localização da área de estudo, os produtos foram gerados no sistema de projeção UTM - Universal Transversa de Mercator, e o *Datum* de referência utilizado foi o SAD69, fuso 22S.

3. Resultados

Após realizada a análise espacial da localização das cavidades em relação às frentes de lavra, foram selecionadas cinco cavidades para definição das faixas de distância. Para essas cavidades foram gerados os Buffers de 250m de proteção, e a partir desses foram estabelecidas as faixas no intervalo de 250/300m, 300/400m e 400/500m, onde foram inseridos os *labels* com as informações do quantitativo de explosivos a serem utilizados.

Na etapa de pré-processamento foram coletados um total de 25 registros sismográficos os quais relacionados com a distância escalonada e carga máxima por espera utilizada, permitiram elaborar um modelo matemático de previsibilidade, segundo uma distribuição *log-normal*, no qual a partir da aplicação da linearização dos dados com logaritmo de base 10, são obtidos os coeficientes de atenuação do modelo projecional empírico. Os 25 registros foram inseridos no Blastware para geração dos valores das variáveis que integraram a equação (Fig. 4).

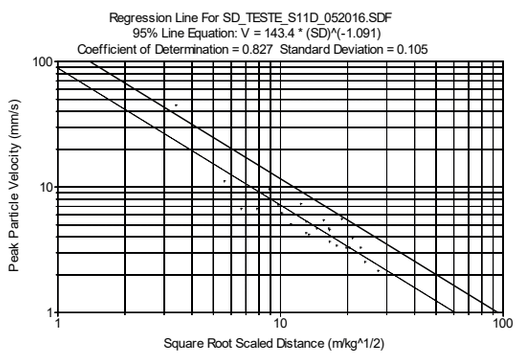


Figura 4: *Equação prognóstica gerada através do software Blastware.*

A partir da equação proposta pela United States Bureau of Mines - USBM, substituindo os valores de k (143,4) e n (-0,105) encontrados na equação prognóstica, é possível definir os valores de carga máxima por espera que deverão ser aplicados a cada faixa de distância proposta conforme figura 4:

$$V = k[\frac{D}{\sqrt{Q}}]^{-n}$$

Faixa de Distância (m)	Carga Máxima por Espera (kg)
250 – 300	247
300 – 400	355
400 - 500	632

Figura 5: *Premissas de CME por faixa de distância.*

Na Figura 6, tem-se uma visão geral da mina S11D, onde podem ser identificadas as cinco cavidades e seus respectivos raios de proteção representados pela cor verde. A linha preta representa o limite da cava licenciada, denominada Área Diretamente Afetada - ADA, já as faixas que compreendem as distâncias de 250/300m, 300/400m e 400/500m foram representadas pelas cores vermelha, laranja e amarela respectivamente. Foi possível estabelecer faixas de distância para cinco cavidades localizadas no entorno da mina, cobrindo todo o perímetro da lavra.

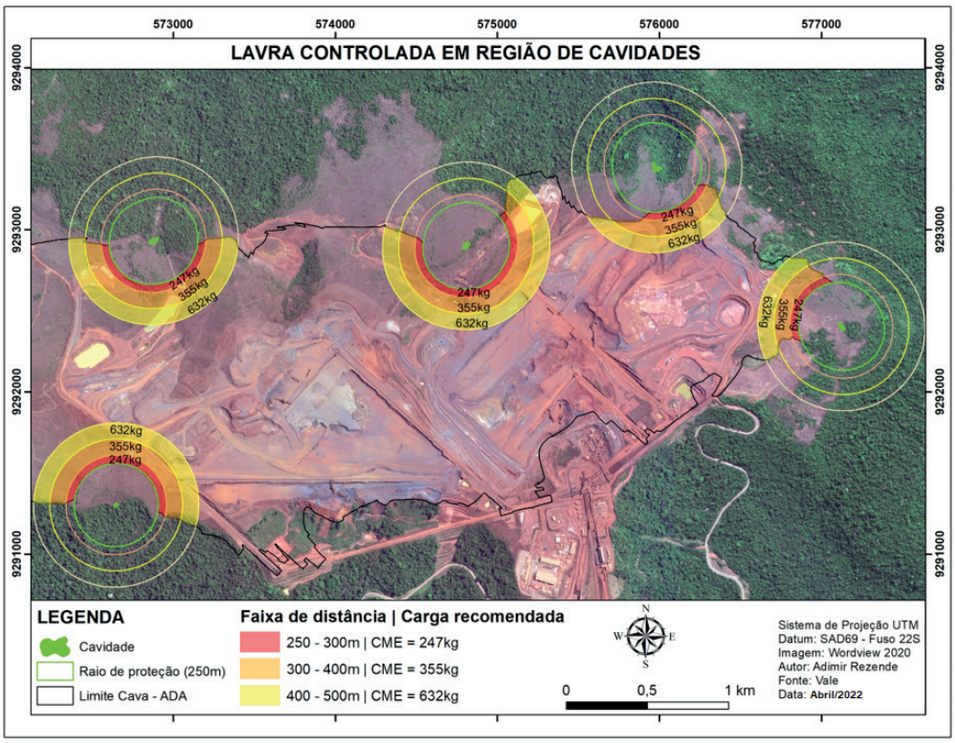


Figura 6: *Mapa de cargas por faixa de avanço obtido por geoprocessamento de dados sismográficos.*

4. Conclusão

Através do uso do geoprocessamento e cartografia digital foi possível a espacialização das informações referentes a localização das cavidades, seus raios de proteção definidos por lei federal e estabelecer faixas de distâncias para execução de desmontes de rocha com uso de explosivos, de forma com que esses fossem praticados dentro das premissas estabelecidas através de métodos quantitativos.

Com o avanço da lavra é necessário que as premissas sejam atualizadas em função da heterogeneidade do meio de propagação das ondas sísmicas. Portanto, os dados obtidos no monitoramento devem retroalimentar o modelo prognóstico, permitindo o ajuste das cargas explosivas, garantindo maior controle do nível de vibração esperado no ponto de interesse.

Como trata-se de ondas mecânicas e sua amplitude e frequência de propagação dependem diretamente das características do meio, sugere-se para os próximos trabalhos que sejam considerados também o modelo de blocos com as informações do perfil geológico dos locais dos desmontes até onde a cavidade está inserida, incluindo a geologia estrutural.

Essa técnica mostrou-se eficiente para o apoio na execução de lavra controlada em região com presença de cavidades naturais subterrâneas, fazendo com que o desafio de conciliar as atividades de extração do minério com a preservação do patrimônio espeleológico sejam alcançados. Entretanto, a aplicação de álgebra de mapas e análise de multicritério pode resultar na maior assertividade na definição das premissas, onde será possível alcançar níveis de vibração seguros de acordo com o grau de resistência e fragilidade das cavidades monitoradas, considerando suas características geomorfológicas, geológicas e geotécnicas. Sendo assim, os valores de vibração estabelecidos para cada cavidade podem ter "limites dinâmicos", com os valores superiores aos limites conservadores recomendados pelo Órgão Ambiental, resultando em uma lavra mais produtiva e de menor custo.

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Potencial Espeleológico Multicritério: estudo da Floresta Nacional de Carajás/PA

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Resumo

A Floresta Nacional (FLONA) de Carajás, localizada no sudeste do Pará, Brasil, é amplamente reconhecida por sua riqueza mineral, importância ambiental e valor espeleológico. Com base na metodologia do ICMBio/CECAV, que classifica áreas pelo potencial espeleológico, com base estrita na litologia, em categorias de "ocorrência improvável, baixo, médio, alto e muito alto". Para o presente artigo fora utilizada a metodologia de análise multicritérios, para tal, foram considerados além da geologia, outros componentes do meio físico, como pedologia, uso do solo, declividade e hidrografia. O cruzamento dessas variáveis resultou no potencial espeleológico multicritério da região, revelando que 76,41% da área da FLONA possui médio potencial espeleológico, enquanto 15,86% hectares foram classificados como de alto potencial. Áreas de baixo potencial representam 7,72% da área, e apenas 0,01% foram classificadas como de ocorrência improvável, não houveram áreas classificadas como muito alto potencial. Os resultados indicaram que os litotipos ferruginosos, os neossolos litólicos, as áreas mais preservadas e os locais próximos aos cursos d'água, associados a relevo com maior declividade, são mais favoráveis à formação de cavernas e outras feições espeleológicas.

Abstract

Multicriteria Speleological Potential: study of Flona Carajás/PA: The Carajás National Forest (FLONA), located in southeastern Pará, Brazil, is renowned for its mineral wealth, environmental significance, and speleological value. Using ICMBio/CECAV's methodology for assessing speleological potential based on geology and categorizing areas as "improbable, low, medium, high, and very high" a multi-criteria analysis was conducted. This approach incorporated geology alongside other physical environmental factors such as soil type, land use, slope, and hydrography. The analysis revealed that 76.41% of the FLONA area has medium speleological potential, 15.86% has high potential, 7.72% has low potential, and only 0.01% is considered improbable for speleological occurrences. The results suggest that ferruginous lithotypes, litholic neosols, well-preserved areas, locations near watercourses, and terrains with higher slopes are more conducive to the formation of caves and other speleological features.

1. Introdução

A região de Carajás, situada no sudeste do Pará, Brasil, é amplamente reconhecida por sua riqueza mineral, sua relevância ambiental e o valor espeleológico. Sua história é marcada pela exploração de recursos naturais e pela busca por equilíbrio com a conservação ambiental.

A descoberta da região ocorreu em 1967, quando a empresa United States Steel identificou ali uma extraordinária reserva de minerais. Em 1974, em parceria com a estatal Companhia Vale do Rio Doce (CVRD), a empresa obteve o direito de explorar o minério de ferro. Naquela década, foi implantado um sistema de beneficiamento e transporte de ferro, seguido pela exploração de outros minerais, como manganês, níquel, estanho, cobre, alumínio e ouro (SANTOS, 1986).

A partir de 1977, a CVRD assumiu o controle exclusivo do empreendimento, com capital 100% nacional (SANTOS, 1986; SANTOS, 2010; MADEIRA et al., 2015). Mais tarde, em 1987, o governo brasileiro concedeu à companhia o direito de uso de 411.948,87 hectares de terras públicas, com a condição de proteger os ecossistemas locais e garantir o amparo às populações indígenas (BRASIL, 1986). Com a privatização da CVRD em 1997, surgiu a necessidade de criar uma unidade de conservação que equilibrasse a exploração mineral com o uso sustentável dos recursos naturais. Assim, foi instituída, em 2 de fevereiro de 1998, a Floresta Nacional de Carajás (FLONA Carajás), por meio do Decreto Federal nº 2.486. Essa área, com 391.008,66 hectares, foi criada com base no conceito de florestas nacionais, conforme definido pelo Decreto nº 1.298 de 1994, priorizando o uso sustentável e a preservação dos ecossistemas.

A Serra dos Carajás, que integra a FLONA, é considerada a maior província espeleológica do mundo em termos de cavidades subterrâneas ferruginosas (WILLIAMS, BARTON, JOHNSON, 2005). Essas formações se desenvolveram em rochas ferríferas bandadas, em coberturas de canga detrítica ou na interface entre essas formações, com potencial para ocorrer também em rochas máficas e ferricretes (PILÓ; AULER, 2009).

As elevações da região, chamadas Serra Norte e Serra Sul, alcançam altitudes médias de 700 metros e abrigam algumas das mais importantes jazidas de minério de ferro de alto teor do mundo. Essas jazidas pertencem à Formação Carajás, composta por itabiritos, jaspelitos e minério

de ferro de qualidade excepcional (IBAMA, 2004; MACAMBIRA, 2003).

A região de Carajás é um exemplo singular de integração entre exploração mineral e conservação ambiental. Reconhecida como a maior província mineral do planeta, também se destaca pela riqueza de seus ecossistemas e cavernas ferruginosas, de importância global. Manter esse equilíbrio entre desenvolvimento e sustentabilidade permanece como um dos principais desafios da gestão dessa área estratégica, sendo a avaliação de seu potencial espeleológico uma ferramenta para auxílio nessa tarefa.

A avaliação do potencial espeleológico tornou-se essencial para o planejamento de estudos e a conservação ambiental. Esse processo identifica as áreas com maior probabilidade de ocorrência de cavernas, utilizando critérios naturais e geológicos para orientar os esforços de pesquisa e preservação.

A classificação do potencial espeleológico, baseada no modelo do ICMBio/CECAV (2009), divide as áreas em cinco categorias: Muito Alto, Alto, Médio, Baixo e Ocorrência Improvável, com base apenas no critério geologia em escala nacional, sendo essa utilizada como Background para as análises multicritérios.

2. Materiais e Métodos

O desenvolvimento de métodos para identificar e definir o potencial espeleológico de uma área é essencial no planejamento de estudos, devido à importância estratégica da conservação espeleológica e às dificuldades de acesso às cavernas impostas pelo ambiente natural. Essa avaliação permite um planejamento estratégico subsidiado pelo diagnóstico das classes propostas por ICMBio/CECAV (2009): Muito Alto, Alto, Médio, Baixo e Improvável.

O ICMBio/CECAV (2009), com base no mapa geológico do CPRM/MME (escala 1:2.500.000), definiu cinco classes de potencialidades litológicas para ocorrência de cavidades, utilizando valores absolutos (geologia). Algumas alterações foram feitas para equilibrar diferenças entre o mapeamento regional e litotipos observados na área. Estudos prévios destacam coberturas recentes, como cangas, que apresentam alto potencial espeleológico, comprovado pelo grande número de cavidades registradas na Serra dos Carajás (ICMBio/CECAV, 2021).

A metodologia para a análise multicriterial baseou-se na álgebra de mapas (Crepani, 1996, 2001) em ambiente de Sistemas de Informação Geográfica - SIG, considerando variáveis "relativas" geológicas, pedológicas, hidrográficas, geomorfológicas (declividade) e de uso e ocupação do solo. O quad. 1 apresenta as bases vetoriais utilizadas na análise.

Cada variável foi atribuída a classes de potencialidade, ponderadas com pesos de 1 a 5, conforme sua contribuição aos processos espeleogenéticos. A equação usada foi:

*(Geologia*3) + (Pedologia*1) + (Uso do Solo*2) + (Declividade*2) + (Hidrografia*2) = Potencial Espeleológico*

É importante destacar que a atribuição dos pesos foi realizada com base na competência técnica da equipe, considerando sua experiência e conhecimento da área de estudo. As variáveis utilizadas e seus respectivos pesos foram: Geologia (3), Pedologia (1), Uso do Solo (2), Declividade (2) e Hidrografia (2).

Os dados foram processados utilizando o software ArcGIS 10.8, por meio do cruzamento dessas variáveis e do cálculo da média ponderada. O banco de dados integrou levantamentos primários realizados com LiDAR, obtidas em trabalhos de campo. Dessa forma, foi possível sintetizar o potencial espeleológico da Floresta Nacional (Flona) de Carajás.

Bases	Informações	Fontes
Mapa Geológico-Geofísico de Arim Carajás	Escala: 1:250.000	CPRM - Companhia de Pesquisa de Recursos Minerais (2016)
Solos Amazônia Legal	Escala: 1:250.000	IBGE - Instituto Brasileiro de Geografia e Estatística (2003)
Uso do Solo	Informações de uso e cobertura do solo	FBDS - Fundação Brasileira de Desenvolvimento Sustentável (2022)
Modelo Digital de Elevação (MDE) ALOS Palsar	Resolução espacial de 30 metros, disponível na forma reamostrada em downsampling para 12,5m	JAXA/METI (2011). JAPAN AEROSPACE EXPLORATION AGENCY - JAXA; MINISTRY OF ECONOMY, TRADE, AND INDUSTRY - METI
Hidrografia	Mapeamento de corpos hídricos	IBGE - Instituto Brasileiro de Geografia e Estatística

Figura 1: *Bases de dados espaciais utilizadas.*

É essencial compreender a interação de fatores naturais e antrópicos para avaliar o potencial espeleológicos de determinadas áreas. O quadro a seguir sintetiza essas interações, apresentando as classes de potencial (de improvável a muito alto) integradas a variáveis geologia, pedologia, uso do solo, declividade e proximidade da hidrografia destacando os elementos que influenciam o potencial para ocorrência de cavidades.

Classe de Potencial	Geologia	Pedologia	Uso do Solo	Declividade (°)	Hidrografia (dist)
Improvável	Silte, Cascalho, Argila, Conglomerado polimítico	Corpo d´água continental	Massas d'água	-	-
Baixo	Metatonalito, Metagranodiorito, Metamáfica, Xistos, Granito, Diorito, Charnockito, Migmatito, Granulito, Granodiorito, Sienogranito, Metamonzogranito, Metapiroxenito, Metaperidotito, Metanorito, Metagabronorito, Metagabro, Metadiorito, Serpentinito, Anfibolito, Metagrauvaca, Rocha metassedimentar clástica, Formação ferrífera bandada, Metavulcânica félsica, Metapiroclástica, Metabasalto, Andesito, Hornblendito, Paragnaisse, Ortoanfibolito, Metavulcânica máfica, Metarriolito, Metadacito, Chert, Metassiltito, Metarenito, Metapelito, Metaconglomerado, Monzogranito, Anfibólio-biotita sienogranito, Anfibólio-biotita monzogranito	Nitossolo Vermelho Distrófico	Área antropizada e/ou edificada	0 – 5 / 5 - 9	>50 m
Médio	Metavulcânica félsica, Metavulcânica máfica, Paragnaisse, Mica xisto, Biotita xisto, Talco xisto, Clorita xisto	Latossolo Vermelho-Amarelo Distrófico	Formação não florestal	9 – 14/14 - 19	30 - 40 m / 40 - 50 m
Alto	Metagrauvaca, Rocha metassedimentar clástica, Formação ferrífera bandada, Metabasalto, Xisto, Biotita xisto, Anfibolito, Protomilonito	-	Floresta Ombrófila	19 – 24/24 - 30	20 - 30 m
Muito Alto	Magnetitito, Laterita	Neossolo Litólico Distrófico	Savana Metalófita	37 – 59 / 59 - 88	0 - 10 m / 10 - 20 m

Figura 2: *Escala de potencialidade atribuída as variáveis consideradas na análise – Flona de Carajás.*

3. Resultados

Para avaliar a assertividade da análise multicritério, foram extraídas as cavidades da base do CANIE/CECAV para a área de estudo e, posteriormente, esses dados foram cruzados com o resultado do potencial espeleológico. Os resultados indicaram que nenhuma cavidade interceptou a classe improvável. Na classe de baixo potencial, houve três cavidades, enquanto na classe de médio potencial foram registradas 277. A classe de alto potencial apresentou 986 cavidades. Desse modo, os resultados obtidos pela avaliação de potencial espeleológico multicritério (Fig. 5) demonstraram que são, de fato, mais fiéis as particularidades ambientais da área de estudo do que o método que trata apenas da variável litológica.

Para a Flona de Carajás, foram obtidas quatro classes de potencial, dentre as cinco classes possíveis, cujos dados quantitativos estão na figura 3.

Em termos quantitativos, destaca-se o médio potencial espeleológico abrange 76 % da Flona de Carajás. De forma secundária, tem-se o alto potencial que contempla um total de 6.0841,30 hectares da área da Flona. Por fim, estão distribuídas as classes com potencial baixo e improvável cujos valores representam 8% e 0,01% da área avaliada, respectivamente (Fig. 4). Não foi possível observar a classe "muito alto" a partir dos resultados da análise multicritério.

Classe de Potencial	Área_ha	Área_km
Improvável	42,07	0,42
Baixo	29619,70	296,20
Médio	293172,00	2931,72
Alto	60841,30	608,41
Total	**383675,07**	**3836,75**

Figura 3: *Quantitativos do Potencial Espeleológico Multicritério para Flona de Carajás.*

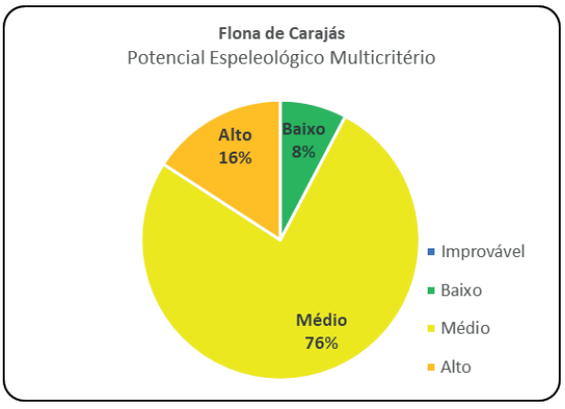


Figura 4: *Distribuição das classes de potencial espeleológico Multicritério para a Flona de Carajás.*

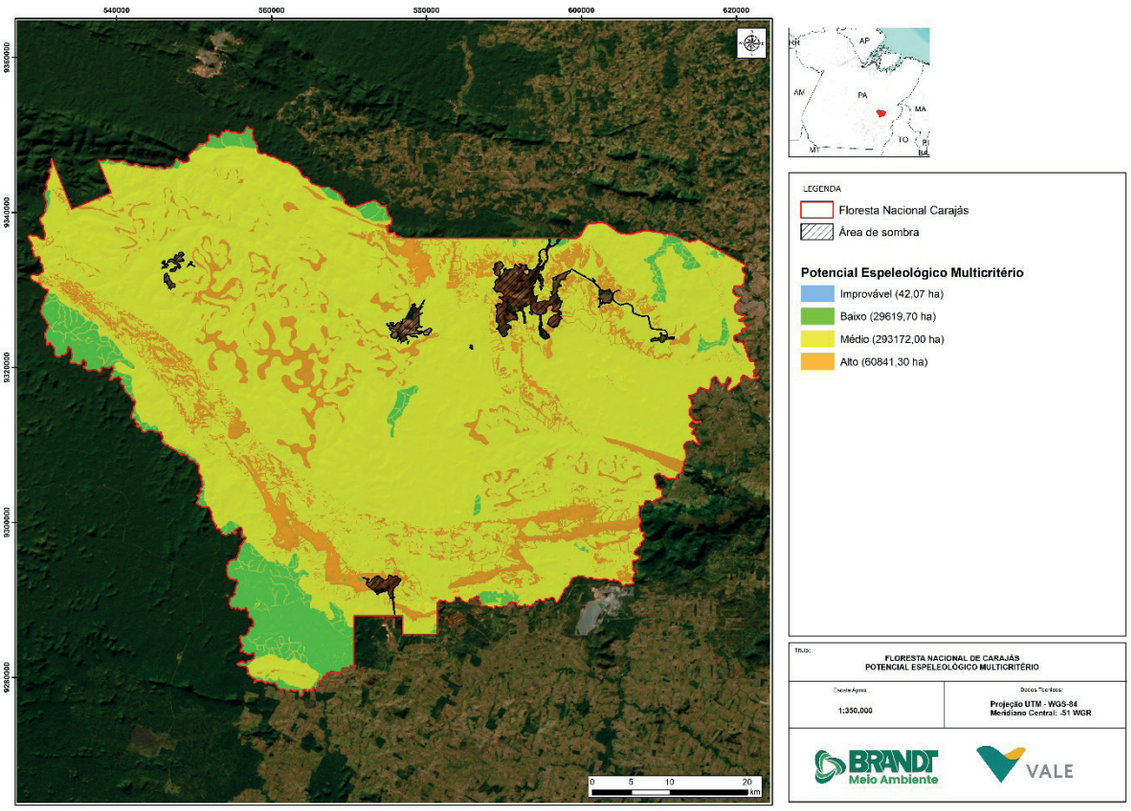


Figura 5: *Resultado do Avaliação do Potencial Espeleológico Multicritério para a FLONA de Carajás.*

4. Discussão

O Potencial Espeleológico Multicritério pretende apresentar o resultado da interação dos atributos físicos que influenciam a espeleogênese. Quanto sistema dinâmico, é insuficiente avaliar a relevância isolada de um atributo ou considerar seu valor absoluto; é necessário compreender a dinâmica de cada um dos atributos e sua relatividade no meio físico.

A litologia é o atributo de maior relevância. De modo geral o potencial espeleológico de cada litotipo é definido com base na classificação do Núcleo de Geoprocessamento do ICMBio/CECAV (2009) que utilizou o mapa geológico do Serviço Geológico do Brasil (CPRM), escala 1:2.500.000; porém as características da área podem conferir ao litotipo um potencial diferente. Porosidade primária e secundária, permeabilidade, resistência mecânica, grau de intemperismo são características que influenciam no potencial espeleológico de um litotipo. Na área da FLONA Carajás ocorre uma variedade de rochas. Dentre eles há litotipos ígneos que possuem baixo potencial devido a sua baixa porosidade primária; litotipos metamórficos cujo potencial pode variar de baixo a médio a depender do seu grau de alteração (xistosidade, deformação, fraturamento, etc); e litotipos sedimentares que tendem a apresentar alto potencial devido a sua porosidade primária. A porção central da FLONA é caracterizada por metassiltitos, lateritas e o batólito Granito Serra dos Carajás. Na porção sudeste também ocorrem coberturas lateríticas e o corredor SE-NW apresenta formações ferríferas de modo subordinado (CPRM, 2016). Os litotipos de maior relevância para a espeleologia são os ferríferos, seja nas formações ferríferas bandadas das Formações Carajás e Igarapé Cigarra ou nas lateritas das coberturas superficiais. A pedologia é outro atributo considerado para o potencial espeleológico uma vez que as características do solo indicam sua resistência mecânica, resistência a erosão, permeabilidade, fatores que influenciam na capacidade deste solo sustentar uma cavidade. Segundo IBGE (2002) a maior parte da FLONA Carajás apresenta solo do tipo neossolo litólico que é caracterizado por ainda preservar estruturas rochosas, o que lhe garante maior resistência mecânica. Ocorrem também os latossolos e argissolos. A hidrografia influencia a formação de cavidades quanto agente erosivo capaz de remover partes da rocha ou do solo, escavando ou expondo os vazios; desta forma quanto mais próximo da drenagem, maior o potencial. O uso do solo, de certa forma, baliza os outros atributos, uma vez que ele se sobrepõe e altera as características naturais do meio. Quanto mais antrópico o uso, menor o potencial espeleológico. Por fim, a declividade é um dos agentes mais importantes para e espeleologia, podendo até definir o peso dos atributos solo e litotipo. Quanto maior a declividade, maior a probabilidade de ocorrer quebras de relevo, menor o tempo de infiltração da água e maior o escoamento superficial; logo áreas em alta declividade associadas a litotipos ferruginosos e/ou neossolos litólicos apresentam alto potencial para o desenvolvimento de cavidades, e este é um cenário recorrente na FLONA Carajás.

5. Conclusão

Em síntese, após a elaboração do potencial multicritérios da FLONA de Carajás, pode-se observar que as classes de probabilidade média e alta para ocorrência de cavidades, despontam como as mais presentes na FLONA, sendo que o médio potencial recobre a maior porção de seus limites, 76% da área. Em seguida o alto potencial para ocorrência de cavernas, que abrange 16% do total da região estudada, sendo

presente de forma mais fragmentada que as demais classes, surgindo majoritariamente nas porções de morrarias e próximo a cursos d'água, corroborando a estrita dinâmica entre os parâmetros mais favoráveis a formação de cavidades juntamente a litologias ferríferas e coberturas recentes de canga.

Em relação aos potenciais baixo (8%) e improvável (0,01%), as áreas mais rebaixadas, principalmente nas proximidades dos limites da FLONA, onde a declividade não possui tanta sinergia com os demais fatores.

A fim de corroborar a eficácia do potencial espeleológico multicritérios, foi realizada ainda a ponderação entre as cavidades extraídas da base de dados do CANIE/CECAV e as classes de potencial obtidas pelo presente estudo, cruzando suas localizações e as quantificando de acordo com cada potencial obtido. Como resultado, observou-se que nenhuma cavidade se encontrava contida em áreas de potencial improvável, três cavidades se localizam em trecho de baixo potencial, além de 277 cavidades registradas em porções de médio potencial. Confirmando as áreas de alto potencial, foram discriminadas 986 cavidades nessas porções, obtendo assim a maior densidade de cavernas dentre as classes presentes na área alvo do estudo.

Em suma, a metodologia utilizada para a definição do potencial espeleológico da FLONA de Carajás obteve êxito, apresentando de forma mais precisa que somente o potencial a nível nacional baseado tão somente em uma variável – litologia -, demonstrando claramente como os diversos fatores físicos naturais agem em sinergia – na configuração de um geossistema - modelando o relevo e suas formas – com maior foco nas cavernas – para a formação de uma área tão singular para a espeleologia, como a Floresta Nacional de Carajás.

Agradecimentos

Agradecemos ao apoio da VALE S.A., a toda equipe de espeleologia da Brandt Meio Ambiente que se mantém comprometida com a entrega e desenvolvimento de produtos com alta qualidade técnica, e a empresa Brandt Meio Ambiente por apoiar o desenvolvimento técnico de seus colaboradores.

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Verão a diversidade: mulheres na espeleologia em um novo tempo

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Resumo

A quarta onda feminista, fortalecida a partir de 2010, impulsionou debates sobre igualdade de gênero, incluindo a espeleologia, onde a representatividade feminina ainda é baixa. Este estudo investiga o impacto da criação do grupo Caverneiras Brasil na visibilidade e inclusão das mulheres no meio subterrâneo, analisando a persistência de estereótipos e a influência de políticas de equidade na ciência. Iniciativas como Quando Chegam as Flores e redes de apoio online fortaleceram a participação feminina, promovendo um novo ciclo de avanços na busca por maior igualdade no campo espeleológico.

Abstract

The fourth feminist wave, strengthened since 2010, has boosted debates on gender equality, including caving, where female representation is still low. This study investigates the impact of the creation of the Caverneiras Brasil group on the visibility and inclusion of women in the underground environment, analyzing the persistence of stereotypes and the influence of equity policies in science. Initiatives such as When Flowers Arrive and online support networks have strengthened female participation, promoting a new cycle of advances in the search for greater equality in the speleological field.

1. Introdução

A quarta onda feminista, fortalecida a partir de 2010, trouxe impactos positivos em diversas áreas, incluindo o meio ambiente. Caracterizada pelo uso de redes sociais para mobilização e conscientização, aborda temas como assédio, representatividade e igualdade de gênero. Também questiona a neutralidade científica, destacando como vieses de gênero e raça influenciam a produção do conhecimento HARAWAY (1988). Além disso, essas discussões influenciam em políticas e programas para promover a equidade de gênero nas ciências. Iniciativas como cotas para mulheres em cargos de liderança, financiamento específico para pesquisadoras e programas de mentoria têm sido implementadas em diversas instituições (European Commission, 2021). Essas políticas visam reduzir as disparidades de gênero e criar oportunidades mais justas Organização das Nações Unidas - ONU (2024)

No contexto atual, a discussão de gênero ganha espaço em diversas esferas. Este estudo busca compreender o cenário das mulheres na espeleologia após a criação do grupo Caverneiras Brasil, conectando-se ao projeto "Quando Chegam as Flores" que visava a realização de ações simultâneas de Caverneiras de todo o Brasil, em seus territórios e Grupos de Espeleologia SOUSA & TOJA (2022) realizado em setembro de 2018 fazendo alusão à Primavera. O Censo Espeleológico de 2018 revelou que apenas 26,8% dos espeleólogos são mulheres, frente a 73% de homens Sociedade Brasileira de Espeleologia - SBE (2018).

Além disso, observou-se a representação estereotipada das mulheres na espeleologia, muitas vezes associadas a papéis tradicionais CRUZ et al. (2019). Contudo, iniciativas como o grupo Caverneiras, surgido no 35º Congresso Brasileiro de Espeleologia (2019), vêm promovendo discussões sobre gênero. Projetos como Quando Chegam as Flores, ações de engajamento nas redes sociais e rodas de conversa virtuais fortaleceram a rede de apoio, ampliando a visibilidade feminina no meio.

Este trabalho busca evidenciar tanto as contribuições históricas das mulheres na espeleologia quanto suas ações contemporâneas de resistência e fortalecimento. A trajetória das Caverneiras mostra a importância de espaços de troca e apoio para garantir maior igualdade de gênero. Se antes o debate florescia na primavera, agora avança para o verão, simbolizando a continuidade da luta por um futuro mais inclusivo.

2. Materiais e Métodos

Após o 35º CBE, durante quase oito meses, o grupo de WhatsApp criado para a interação entre as agora autodenominadas "Caverneiras - Brasil" funcionou principalmente como uma ferramenta de inclusão de novas mulheres no grupo e no movimento, incentivando-as a integrar e a dialogar sobre diversos temas comuns às mulheres na espeleologia. Os debates foram amplos e surgiram questionamentos como: qual o perfil das Caverneiras no Brasil? Existem dificuldades nas atividades sejam profissionais, na pesquisa ou esportiva? Se existem, quais são essas dificuldades? A partir dessas perguntas decidiu-se criar um questionário para entender o perfil das Caverneiras Brasil utilizando-se da técnica de questionário, que segundo GIL (2011) é definido como "técnica de investigação composta por um número mais ou menos elevado de questões apresentadas por escrito às pessoas, tendo por objetivo o conhecimento de opiniões, crenças, sentimentos, interesses, expectativas, situações vivenciadas etc."

O questionário foi criado na plataforma Google Forms em 2018, e em 2024, após seis anos de discussões sobre o tema levantou-se o questionamento: houve mudanças no cenário espeleológico desde a criação do grupo Caverneiras? Com o intuito de responder a pergunta, reaplicamos o questionário de 2018 SOUSA & TOJA (2022), com algumas adaptações e atualizações. A pesquisa ficou disponível de 04 de dezembro de 2024 a 10 de janeiro de 2025, dentro do Projeto Verão a diversidade:

mulheres na espeleologia em um novo tempo, contendo 30 perguntas sendo divididas em quatro secções:

1. Perguntas gerais sobre o perfil: Estado onde reside; Raça, Estado civil, Idade e se tem filhos ou não;
2. Para as mães espeleólogas que responderam "sim", para a pergunta "Tem filhas ou filhos": Quantas Crianças?; Já perdeu alguma oportunidade na espeleologia por ser mãe? Já ficou afastada da espeleologia por ser mãe? Se sim, por quanto tempo?Além da licença maternidade, houve algum outro momento que você precisou se afastar da espeleologia por causa do maternar? Já deixou de ir em algum evento científico ou realizar pesquisa por ser mãe? Atualmente, você leva seu filho para eventos de espeleologia ou para conhecer cavernas?
3. Perguntas relacionadas à atuação profissional: Grau de Escolaridade; Formação Acadêmica, Atuação na espeleologia; Tema de atuação/pesquisa na espeleologia; Quanto tempo de atuação na espeleologia?;
4. Mulheres na Espeleologia, perguntas relacionadas acerca da existência de dificuldades enfrentadas relacionadas ao machismo: Já sofreu algum acidente/lesão atuando na espeleologia? Você já sofreu ou presenciou alguma dessas atitudes durante atuação na espeleologia? (pode marcar mais de uma opção):

- Foi interrompida por um homem, durante sua fala, no momento de discussão/decisão de um determinado assunto;
- Foi recebida ou viu uma colega recebida em um espaço de decisões com elogios à aparência física, ao invés da sua capacidade técnica ou profissional;
- Teve sua fala ou de uma colega, cortada por um homem com o termo "Não é isso" e logo em seguida ele utiliza as suas palavras de outra forma como se ele tivesse falado primeiro;
- Sentiu -se de alguma forma desconfortável por estar em um meio de um grupo de homens pelo fato de ser mulher;
- Já ouvi frases do tipo "Mulher não vai dar conta desse serviço porque é muito pesado, melhor contratar um homem";
- Já foi questionada em alguma vaga se tem filhos, como se isso interferisse nas suas capacidades técnicas;
- Nenhuma das alternativas anteriores. Você considera as atitudes acima machistas?; Em qual situação você já sofreu machismo na espeleologia?; Qual atitude que você considera machista e comumente observa dentro da espeleologia?; Essas atitudes foram: Em grupos de espeleologia; No trabalho; Em meio acadêmico e/ou Outros
- Sente dificuldades em exercer alguma atividade na espeleologia por ser mulher? Qual a maior dificuldade você já enfrentou por ser mulher atuando na espeleologia? Você percebeu mudanças no meio espeleológico após 2018 com as discussões/atuação das Caverneiras? Quais foram essas mudanças? Deixe uma frase ou um comentário para as mulheres que atuam na espeleologia.

É importante informar que toda a pesquisa foi realizada em caráter de anonimato, não foram solicitados nomes nem contatos, garantindo que as mulheres estivessem à vontade para responder. Para as perguntas abertas, caso não quisessem responder a pergunta ficou claro que a opção "Não quero responder" poderia ser utilizada.

Para a análise dos dados relacionados às perguntas abertas fora utilizado um padrão para contabilizar o número de vezes que uma palavra ou situação se repetia de modo a quantificar e não apenas qualificar as respostas. Sendo assim para a pergunta: Em qual situação você já sofreu machismo na espeleologia? Foram analisados termos ou frases que possuíam conotação a respeito de: Nunca sofreram ou não se lembram; Descredibilidade técnica por ser mulher; Em trabalhos de campo; Assédio; Salários menores que os dos homens e outros não especificados; Já para a pergunta: Qual atitude que você considera machista e comumente observa dentro da espeleologia? Foram analisados termos ou frases que possuíam conotação a respeito de: Nunca sofreram ou não se lembram; Descredibilidade técnica por ser mulher; Desvalorização profissional; Assédio; Negação da existência do machismo; Diferença Salarial; Não Especificado.

3. Resultados

De acordo com o Censo da Sociedade Brasileira de Espeleologia (SBE) de 2018, as mulheres representavam 27% da comunidade espeleológica. Uma análise realizada na plataforma LinkedIn, filtrando perfis que mencionam "espeleologia" e classificando-os por gênero, indicou uma participação feminina de 39%, sugerindo um aumento na presença das mulheres na área. Esse crescimento também se reflete na pesquisa do projeto Quando Chegam as Flores, analisada por SOUSA & TOJA (2022), que obteve 56 respostas ao formulário, fornecendo um panorama inicial do perfil das Caverneiras Brasil.

Neste estudo, verificou-se um aumento de 49,5% na participação feminina dentro da espeleologia. O questionário esteve disponível entre 4 de dezembro de 2024 e 10 de janeiro de 2025, com ampla divulgação por meio de redes sociais, grupos de WhatsApp e contatos diretos na mesma plataforma. No total, foram recebidas 113 respostas. Embora esse número não represente a totalidade das mulheres na espeleologia brasileira, ele oferece um panorama significativo para a análise da presença e integração feminina nesse campo de pesquisa.

Entre as 113 participantes, a pergunta sobre o estado de residência indicou a participação de mulheres de 15 estados diferentes. Os estados com maior representatividade foram Minas Gerais, com 46% das respostas, seguido por São Paulo, com 19%, conforme demonstrado na tabela a seguir (Fig 1).

Estado	
Minas Gerais (MG)	52
São Paulo (SP)	22
Distrito Federal (DF)	9
Mato Grosso do Sul (MS)	6
Bahia (BA)	5
Goiás (GO)	4
Pará (PA)	4
Paraná (PR)	3
Rio Grande do Norte (RN)	2
Alagoas (AL)	1
Amazonas (AM)	1
Pernambuco (PE)	1
Piauí (PI)	1
Rio de Janeiro (RJ)	1
Sergipe (SE)	1

Figura 1: *Tabela distribuição das respondentes pelo Brasil.*

Para compreender melhor a dinâmica de mobilidade das participantes, perguntamos sobre sua "Cidade de Origem" e se ainda residiam nela. Os resultados revelaram um padrão interessante: 63 respondentes afirmaram ter se deslocado para outras cidades, enquanto 50 ainda permanecem em sua cidade natal. Esses dados ajudam a mapear a movimentação das mulheres na espeleologia.

Em relação a idade 9% das mulheres estão na faixa dos 20 a 25 anos, 34% na faixa de 26 a 35 anos e a maioria na faixa de 36 a 45 anos sendo 39% das respondentes, 20% possuem idade acima de 45 anos e entre elas, houve algumas respostas dizendo que não sofreram com machismo, mas sim com etarismo. Em relação a pesquisa de 2018, percebemos que mais mulheres entraram para o mundo da espeleologia, mas mais do que isso, outras tantas que antes não conheciam as Carverneiras, aderiram ao grupo e participaram efetivamente da pesquisa.

A presença de mulheres negras na espeleologia ainda é pouco documentada e representada. No Censo Espeleológico de 2018, que apontou que 26,8% dos espeleólogos eram mulheres em comparação a 73% de homens SBE (2018), não houve a inclusão de perguntas sobre autodeclaração racial. Diante dessa lacuna, nossa pesquisa identificou a necessidade e a importância de incorporar essa questão na seção geral, com o objetivo de fomentar discussões sobre o recorte racial dentro da espeleologia. Como resultado, constatou-se que 10% das respondentes se autodeclararam negras. A espeleologia, por si só, é uma área marcada pela baixa diversidade de gênero e raça (Fig. 2) No entanto, observa-se um movimento crescente de inclusão e reconhecimento, ampliando a representatividade e promovendo maior equidade no campo.

Qual raça/cor você se identifica?	
Amarela	2
Branca	66
Indígena	1
Parda	33
Preta	11

Figura 2: *Tabela com os resultados para a pergunta Qual raça/cor você se identifica?*

Para compreender melhor o perfil das mães espeleólogas e suas experiências dentro da comunidade feminina, incluímos no questionário perguntas relacionadas à maternidade. Os resultados revelaram que, entre as 113 participantes, 70% não possuem filhos, enquanto 30% são mães. Esses dados destacam a presença das mães na espeleologia e podem contribuir para reflexões sobre os desafios e adaptações enfrentados por elas na conciliação entre a vida pessoal e a atuação nesse campo (Fig. 3).

Nesse sentido, podemos perceber que apesar de algumas mães terem a necessidade de abdicar-se do seu lado profissional por um tempo para exercer a maternidade, na espeleologia com o passar dos anos conseguimos modificar aos poucos essa realidade.

Na pesquisa realizada, apresentou o mesmo panorama em relação à pesquisa de 2018. Mesmo com resultados similares, é possível perceber grandes mudanças em eventos de espeleologia que tem criado 'Espaços Kids' para as crianças facilitando a participação dos pais nos eventos.

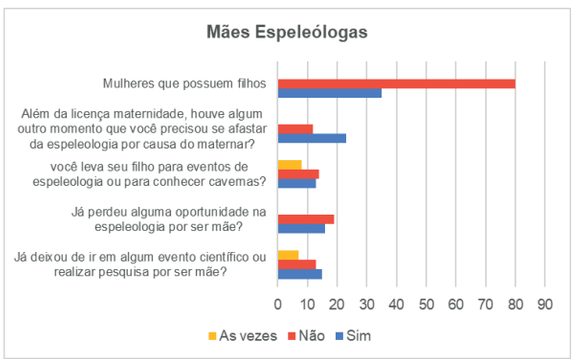


Figura 3: *Resultado para as perguntas relacionadas as mães espeleológicas .*

Em relação seção 4 sobre machismo na espeleologia das afirmações elencadas para a pergunta "*Você já sofreu ou presenciou alguma dessas atitudes durante atuação na espeleologia?*" As que mais se destacaram nas respostas foram os itens 1 e 5 com 56% e 50% de marcações, respectivamente, seguido do item 2, com 47% de marcações; 28 mulheres (24,6% das marcações) responderam que nunca viram ou sofreram alguma das atitudes ilustradas (Fig. 4).

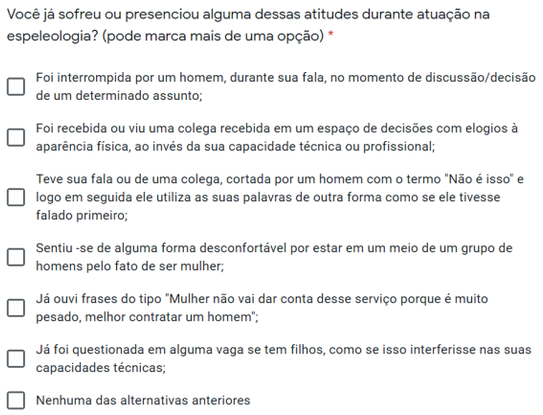


Figura 4: *Questões abordando algumas situações machistas.*

A grande maioria dos respondentes (104) considera que as atitudes mencionadas são machistas, o que indica uma percepção clara do problema. Apenas 2 pessoas não consideram essas atitudes machistas, e 7 têm uma visão parcial. Isso sugere que há um consenso sobre a existência de machismo no meio espeleológico, mas ainda há uma pequena parcela que não reconhece ou minimiza o problema. A maioria das mulheres (59) não sente dificuldade em exercer atividades na espeleologia por serem mulheres, o que é um ponto positivo. No entanto, um número significativo (24) relata sentir dificuldades, e outras 30 têm uma percepção mista ("em parte"). Isso indica que, embora muitas mulheres não enfrentem barreiras explícitas, ainda há desafios relacionados ao gênero que precisam ser abordados (Fig. 5).

A atuação das Caverneiras impactou positivamente, mas ainda há espaço para mais avanços. Enquanto 38 pessoas perceberam mudanças claras, 28 não notaram diferenças, e 47 têm uma visão parcial. Isso sugere que as iniciativas estão surtindo efeito, mas o processo de transformação é gradual e ainda não atingiu todos os espaços ou indivíduos.

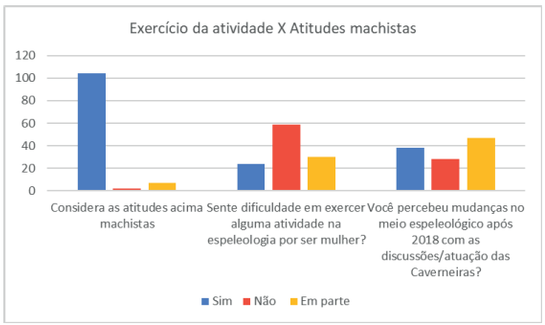


Figura 5: *Gráfico apresentando onde as mulheres atuam na espeleologia e a percepção/ ocorrência de situações machistas.*

A atuação profissional é a área onde as mulheres estão mais presentes (55), e consequentemente é onde ocorre o maior número de situações de machismo (51). Apesar da maior participação feminina no mercado de trabalho, o ambiente profissional ainda é um espaço onde o machismo se manifesta de forma significativa, pois faz parte do processo estrutural de como a sociedade foi construída, e nesse ínterim, esteve relacionado a desigualdades salariais, assédio moral ou sexual, e dificuldades de ascensão a cargos de liderança (Fig. 6).

O que chama a atenção é como nos grupos de espeleologia, em relação a pesquisa de 2018 onde a maioria das situações ocorriam em grupos de espeleologia, com a pesquisa atual percebemos uma mudança significativa, possivelmente, influenciado pelo grupo Caverneiras - Brasil.

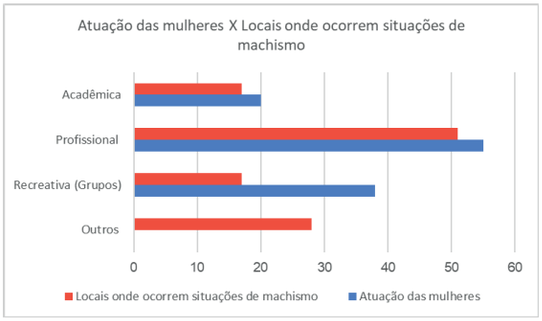


Figura 6: *Gráfico apresentando a atuação das mulheres e os locais onde ocorrem o machismo.*

Foram incluídas no questionário duas questões abertas focadas em situações machistas, seguindo a mesma lógica das perguntas anteriores apresentadas nas figuras 7 e 8.

Desvalorização profissional e descredibilidade técnica são os principais problemas enfrentados por mulheres na espeleologia, indicando que há uma cultura que subestima as capacidades das mulheres nesse campo, principalmente relacionadas ao planejamento, liderança e execução de atividades no escritório. Em relação aos trabalhos de campo são onde o porte físico e a capacidade técnica estão diretamente relacionados tornando o ambiente mais propício para a manifestação de falas e posicionamentos machistas. O assédio sexual é uma questão presente, embora menor relatado em relação à pesquisa de 2018, mas ainda assim preocupante, pois cria um ambiente inseguro para as mulheres.

Em qual situação você já sofreu machismo na espeleologia?	
Nunca sofreram ou não se lembram	33
Descredibilidade Técnica por ser mulher	18
Em trabalhos de campo	27
Assédio	11
Salários menores que os dos homens	0
Outros não especificado	26

Figura 7: *Tabela com resultado de respostas abertas para a pergunta: Em qual situação você já sofreu machismo na espeleologia?*

Qual atitude que você considera machista e comumente observa dentro da espeleologia?	
Nunca sofreram ou não se lembram	**21**
Descredibilidade técnica por ser mulher	**32**
Desvalorização profissional	**48**
Assédio	**1**
Negação do machismo	**1**
Diferença salarial	**1**
Não especificado	**7**

Figura 8: *Tabela com resultado de respostas abertas para a pergunta: Qual atitude você considera machista e comumente observa dentro da espeleologia?*

A diferença salarial não foi citada como um problema, o que pode significar que ela não é percebida ou, de fato, as empresas estão seguindo um dos Objetivos Sustentáveis da ONU de equidade de gênero não há dados suficientes para conclusões. Um número significativo de mulheres afirmou não ter sofrido machismo ou não se lembrar, o que pode indicar que nem todas as mulheres percebem e/ou reconhecem atitudes machistas ou que há parcela que realmente não vivenciou/presenciou essas situações, sendo essa segunda opção o que desejamos como resposta para futuros trabalhos.

4. Discussão

A análise de CRUZ et al. (2019) evidencia como as representações das mulheres na espeleologia ainda carregam um forte caráter estereotipado, refletido, por exemplo, em textos publicados nos boletins informativos da Sociedade Brasileira de Espeleologia. Nessas publicações, as mulheres são frequentemente associadas a papéis tradicionais, como a busca por parceiros, reforçando discursos que as enquadram em um modelo de dependência e subordinação. Essa construção simbólica não é isolada, mas sim parte de um imaginário social cultivado desde a infância, por meio de narrativas que romantizam a submissão feminina. Contos de fadas como Cinderela exemplificam essa dinâmica, ao apresentar uma protagonista cuja jornada é marcada pelo trabalho servil e pela expectativa de ser resgatada por um príncipe, perpetuando a ideia de que a felicidade feminina está vinculada à conquista de um amor idealizado. A mídia, ao longo das décadas, tem reforçado esses padrões ao criar e reproduzir modelos patriarcais, consolidando estereótipos que afetam a percepção das mulheres sobre seu próprio potencial e espaço na sociedade MACIEL (2023).

Essa construção cultural reflete diretamente na experiência das mulheres dentro da espeleologia. SOUSA & TOJA (2022) identificou em sua pesquisa que a maioria das respondentes relatou episódios em que tiveram sua competência questionada ou foram descredibilizadas em alguma atividade simplesmente por serem mulheres. Esse dado reforça a relevância da pauta de gênero dentro da comunidade espeleológica, evidenciando que, apesar dos avanços na representatividade feminina, ainda há barreiras estruturais e culturais a serem superadas. A subestimação das habilidades femininas, muitas vezes expressa de maneira sutil, pode impactar diretamente a permanência e o avanço das mulheres na área, limitando suas oportunidades e reconhecimento profissional. Portanto, discutir a questão de gênero na espeleologia não é apenas uma necessidade acadêmica, mas um passo essencial para a construção de um ambiente mais igualitário e inclusivo.

Esses dados corroboram com a literatura existente, que aponta que mulheres em campos tradicionalmente masculinos, como ciências

naturais e exploração, frequentemente enfrentam questionamentos sobre suas competências e habilidades. Por exemplo, FOX (2006) e LETA (2003), em seu estudo sobre mulheres em ciências e engenharia, destaca que a desvalorização do trabalho feminino é uma forma de manter hierarquias de gênero, limitando o avanço profissional das mulheres. Da mesma forma, SETTLES et al. (2006) e OLIVEIRA & CARVALHO (2018) discutem como estereótipos de gênero podem levar à descredibilidade técnica, especialmente em ambientes onde a competência é associada a características masculinas.

Os trabalhos de campo emergiram como um ambiente propício para a manifestação de machismo, com 27 respostas indicando situações de discriminação nesse contexto. Isso está alinhado com estudos como o de CLANCY et al. (2014), que investigou o assédio sexual em trabalhos de campo científicos e encontrou que mulheres frequentemente enfrentam comportamentos inadequados e assédio nesses ambientes. O assédio foi citado por 11 pessoas na planilha, reforçando a necessidade de políticas específicas para garantir a segurança das mulheres em atividades de campo.

O reconhecimento quase unânime da presença de atitudes machistas no meio espeleológico é um passo importante para combater o problema. Embora a maioria das mulheres não relatam dificuldades explícitas, muitas ainda enfrentam barreiras de gênero, evidenciando a necessidade de políticas e ações para promover a inclusão e a igualdade. A atuação das Caverneiras e outros grupos de mulheres tem impulsionado mudanças positivas, refletidas no aumento do engajamento feminino - de 56 respostas na primeira pesquisa para 113 na segunda. No entanto, ainda há um longo caminho para que essas transformações se tornem mais abrangentes e visíveis para todos.

5. Conclusão

A espeleologia, assim como outras áreas tradicionalmente masculinas, ainda carrega barreiras estruturais e culturais que limitam a participação plena das mulheres. A análise da literatura e os dados coletados evidenciam que estereótipos de gênero, questionamentos sobre a competência feminina e a falta de reconhecimento são desafios recorrentes, muitas vezes naturalizados no ambiente espeleológico. Além disso, relatos de assédio e discriminação em trabalhos de campo reforçam a urgência de medidas concretas para garantir a segurança e o bem-estar das mulheres que atuam nesse meio.

Diante desse cenário, é fundamental que iniciativas como o grupo Caverneiras Brasil não apenas ampliem a representatividade feminina, mas também impulsionem ações que promovam um espaço verdadeiramente seguro e igualitário para todas. Políticas institucionais voltadas à equidade de gênero, a criação de canais de denúncia eficazes e o incentivo ao protagonismo feminino são estratégias essenciais para transformar a espeleologia em um ambiente mais inclusivo. Somente com um compromisso coletivo e contínuo será possível romper com padrões excludentes e garantir que todas as mulheres tenham condições plenas de explorar, pesquisar e contribuir para essa área sem medo ou limitações impostas pelo machismo estrutural. A construção de um espaço onde as mulheres possam se sentir respeitadas, reconhecidas e seguras não é apenas uma questão de justiça social, mas uma necessidade para o avanço e diversificação do próprio campo espeleológico.

Agradecimentos

Agradecemos sinceramente a TODAS as CAVERNEIRAS que responderam a enquete e a TODOS, TODAS e TODES que são parceiro e entendem que tais discussões fazem parte do cenário social da espeleologia e são necessários para que as mulheres se sintam mais seguras tanto para expressar suas opiniões sem invalidações, quanto para exercer a espeleologia sem medo.

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Application of karst disturbance and sensitivity indices and implications for geoconservation on New Providence Island, Bahamas

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Abstract

The geoconservation of karst features in New Providence Island (NP), The Bahamas, is crucial for the preservation of geoarchaeological, historical and cultural heritage that may also provide potential for sustainable development through eco/geo-tourism. The Karst Disturbance Index (KDI, VAN BEYNEN & TOWNSEND 2005), Cave Sensitivity/Disturbance Indices (CSI/CDI, HARLEY et al. 2011 modified from the KDI) and Cave Conservation Index (CCI, DONATO et al. 2014) were applied to publicly accessible caves and blue holes in NP to evaluate environmental impacts and vulnerability. Initial KDI scores are 'minor disturbance' (0.36, Caves Point East/West Caves, CPE/W) and 'moderate disturbance' (0.40, R.M. Bailey Blue Hole; 0.41, Golden Gates Blue Hole). The CSI/CDI and CCI were applied to solutional caves: Bat Cave (BAC), CPE/W, Primeval Forest Caves (PFC), Clifton East Cave (CEC), and Clifton Banana Hole (CBH). Initial CSI scores range from 0.22 'slightly sensitive' (BAC and CPE) to 0.56 'sensitive' (PFC). Initial CDI scores range from 0.18 'pristine' (BAC and PFC) to 0.38 'moderate disturbance' (CPW). Initial CCI scores include 'low priority' (4%, CEC; 13%, CPE), 'moderate priority' (26%, BAC; 31%, CPW), and 'medium' priority sites (43%, PFC; 45%, CBH). The CCI scores for PFC and CBH validate their management in more protected areas.

1. Introduction

Worldwide, karst areas are under threat from the impacts of human activities and New Providence Island (NP) containing the national capital city of Nassau has experienced increasing urbanization over the last several decades (Fig. 1). Cave and blue hole sites in The Bahamas are protected by the Government under the auspices of the Antiquities Monuments & Museums Corporation, and their sustainable usage is regulated by the Department of Environmental Planning and Protection through the 'Biological Resources and Traditional Knowledge Act' (2021). Those sites that occur within the national park system are managed by the Bahamas National Trust (BNT) although typically less management action occurs outside these protected areas. Eco/geo-tourism of caves and blue holes has excellent potential in The Bahamas and can contribute to sustainable development (STEPHENS 2020).

The islands of The Bahamas archipelago are wholly carbonate and the cave karst systems there hold an abundance of geological and archaeological information. The present dry caves in The Bahamas formed during the late Pleistocene, when sea level and freshwater lenses were higher than now and phreatic caves were produced by dissolution; in contrast blue holes represent the cumulative dissolution and collapse that has occurred during many sea-level fluctuations. The main types of caves in NP are pit caves (formed by dissolution from rainfall runoff), flank margin caves (formed in flanks of aeolianite ridges by mixing dissolution at the edge of the freshwater lens), and banana holes (formed at the top of the freshwater lens with roof collapse) (MYLROIE et al. 1991).

2. Materials and methods

A convenience sampling technique was used to assess publicly accessible solutional cave and blue hole sites (n = 8, including those with proximity to sealed roads) for this study (Table 1). Six have previously been described in detail, including maps by MYLROIE et al. (1991, 2008) (from east to west): Bat Cave (BAC), Caves Point East/West Caves



Figure 1: *Map showing the locations of study sites in NP; the capital city Nassau occurs on the eastern side (Google Earth).*

(CPE/W), Primeval Forest Caves (PFC), Clifton East Cave (CEC), and Clifton Banana Hole (CBH). R.M. Bailey Blue Hole (RMB) is ~8/3 m wide/deep and Golden Gates Blue Hole (GGB) is ~21.5/12 m wide/deep. A range of standardised indices were applied to account for the variety of karst cave types with the aim to determine environmental sensitivity/vulnerability and disturbance/impacts, including ranking priority for geoconservation.

Site # - Name	Lat (N) / Lon (W) °
RMB - R.M. Bailey Blue Hole	25.04828 / -77.32811
GGB - Golden Gates Blue Hole	25.01932 / -77.36751
BAC - Bat Cave	25.06467 / -77.43502
CPE - Caves Point East Cave	25.06912 / -77.45016
CPW - Caves Point West Cave	25.06912 / -77.45046
PFC - Primeval Forest Caves	25.01407 / -77.51718
CEC - Clifton East Cave	25.00144 / -77.53567
CBH - Clifton Banana Hole	25.00914 / -77.54628

Table 1: *Location (GPS) of sites used in this study.*

The Karst Disturbance Index (KDI) (VAN BEYNEN & TOWNSEND 2005, refined by NORTH et al. 2009) was used in this study along with the Cave Sensitivity and Cave Disturbance Indices (CSI and CDI; the CDI was modified and adapted from the KDI, HARLEY et al. 2011). For these indices each indicator that is applicable to the site is scored from observations in the field from zero to three based on the level of sensitivity/disturbance observed. Scores for each variable are summed to produce an aggregate number, and the sum is then divided by the total possible score (between 0.00-1.00). The degree of sensitivity uses classifications including 'slightly sensitive' (0.20-0.39), 'moderately sensitive' (0.40-0.50), and 'sensitive' (0.51-0.60); the degree of disturbance includes 'minor' (0.20-0.39) and 'moderate' (0.4-0.5). The KDI has 31 indicators organised into five categories (Table 2, see Results section) and was found to be more applicable to blue holes sites as it has more relevant hydrology impact indicators (water quality/quantity) than the CDI. In the CDI, disturbances by deforestation, agriculture, and urbanisation were evaluated using a 1 km buffer applied around each cave in Google Earth and the area of each relevant outlined polygon summed to calculate a percentage. In the CSI, mineralogy scored zero for all sites and so was removed from Table 3 (see Results section) but remained part of the total possible score. In the CDI there is a lack of data for all sites on biota decline and these variables were removed from Table 4 (see Results section); agriculture, quarry mining, and destruction of cultural artifacts and fossils scored zero for all sites and so were removed from Table 4 (see Results section) but remained part of the total possible score. The KDI and CSI/CDI were applied to Caves Point Caves and exhibited comparable scores; the CSI/CDI were used for the remaining cave sites, along with the Cave Conservation Index (CCI, DONATO et al. 2014; using corrected equations by RABELO et al. 2018).

The CCI (similarly to CSI/CDI) provides two evaluation protocols: rapid assessment protocol of cave vulnerability for prioritization of conservation and/or restoration actions (RAP-cr), and rapid assessment protocol of cave environmental impact (RAP-cei). The RAP-cr is evaluated by summing the scores of sixteen indicators in biotic (B), anthropic (An), and abiotic (Ab) environments (E), both in the hypogean (i, internal) and epigean (e, external) (and varyingly scored from 0-1, 0-2, 0-3, and 0-4). BEi includes occurrence of troglomorphic species, invertebrates and/or vertebrates, invertebrate and bat richness, and fossil presence; BEe is the type of activity found around the cave. AbEi includes speleothem richness and presence of permanent water bodies; AbEe is the karstic environmental heterogeneity. AnEi includes visible mischaracterization, traces of archaeology, scenic beauty, and presence of cultural heritage; AnEe includes the situation of the cave in relation to protected areas, visible anthropogenic alteration (urban domestic or industrial), and presence of buildings or environmental changes (e.g. roads, mining, and agriculture) near the cave area. RAP-cr is calculated thus = (((BEi+BEe)*3)+((AbEi+AbEe)*2)+((AnEi+AnEe)*1))/60*100. The resulting level of vulnerability is classified as 'low' (0-35), 'medium' (36-75), or 'high' (76-100).

In the RAP-cei the main activities causing impact are identified, and a score is assigned for not destroyed (0) or complete destruction (100). Where caves are not destroyed, scoring is given for each type of impact according to the estimated time for effects to be reversed: up to 1 year = 2, 1–10 years = 4, 10–50 years = 6, irreversible = 10. RAP-cei indicators of partial destruction of the cave, changes in water dynamics, and karst changes scored zero for all sites and so were removed from Table 5 (see Results section). The range of impact evaluates spatially the most impactful action: none = 0, local = 5, regional = 10. These are totalled to give a RAP-cei % score with classifications including 'intact' (0-7), 'stable' (8-34), and 'vulnerable' (35-61). The final CCI result is given by subtracting the value obtained in RAP-cei from the value obtained in RAP-cr. The CCI uses classifications including 'low' (0-20), 'moderate' (21-40), and 'medium' (41-60).

3. Results

The main disturbances/impacts for the two blue holes as exhibited in Table 2 include dumping (Fig. 2), vandalism of surrounding fences, proximity to roads and low or no occurrence of plankton algae (chlorine tablets are reportedly used at GGB for swimming). The freshwater lens in GGB is measured to vary ~3-8 m with seasonal/rainfall changes, and tidal influence is observed. The main disturbances/impacts for the caves include graffiti inside CPW and CEC, deforestation in the local areas, trash at CPW/E (popular tourist site) and CEC (Fig. 3), and urbanisation CPW/E (Table 4). In addition, there is sound pollution from nearby busy roads at CPE/W and BAC, and possible oil pollution of groundwater at CBH and CEC from the fuel depot at Clifton (Table 5). The main sensitivities/vulnerabilities for the caves include bats in BAC, CPW, PFC, and CBH; and Lucayan archaeology at CBH (Tables 3 and 6).

CSI scores exhibit: 'slightly sensitive' 0.22-0.25 (BAC, CPE and CEC), 'moderately sensitive' 0.44 (CPW and CBH) and 'sensitive' 0.56 (PFC) (Table 3), with an overall mean of 'slightly sensitive' 0.36. Similarly, RAP-cr scores show: 'low vulnerability' 23% (CEC), and 'medium vulnerability' 38-62% (CPE, BAC, PFC, CPW and CBH) (Table 6). KDI scores exhibit: 'minor disturbance' 0.32 (Caves Point Caves), and for the blue holes sites 'moderate disturbance' 0.42 (GBH) and 0.47 (RMB). CDI scores for cave sites are 'pristine' (0.18, BAC and PFC), and 'minor disturbance' (0.21 CBH, 0.28 CPE, 0.31 CEC, and 0.38 CPW), with an overall mean of 'minor disturbance' 0.26. Similarly, RAP-cei scores for cave sites are 'stable': 9% (PFC), 17% (CBH), 19% (BAC and CEC), 25% (CPE), and 27% (CPW). CCI scores of caves are ranked: 'low priority' (4% CEC and 13% CPE), 'moderate priority' (26% BAC and 31% CPW), and 'medium priority' (43% PFC and 45% CBH) for geoconservation.

Site	GEO	ATM	HYD	BIO	CUL	KDI
RMB	6	NA	6	4	9	0.40
GGB	9	NA	5	4	8	0.41
CPE/W	8	2	0	5	12	0.36

Table 2: *Evaluation of KDI using aggregate scoring for categories: GEO = geomorphology, ATM = atmosphere, HYD = hydrology, BIO = biota, and CUL = cultural. NA = not applicable.*

Site	BIO	HYD	GEO	PAL	CUL	CSI
BAC	2	1	1	0	0	0.22
CPE	1	1	1	0	1	0.22
CPW	3	2	2	0	1	0.44
PFC	3	2	1	1	3	0.56
CEC	2.5	1	1	0	0	0.25
CBH	3	1	1	0	3	0.44

Table 3: *Evaluation of CSI: BIO = biota, HYD = hydrology, GEO = geology, PAL = paleontology, and CUL = cultural/historical.*

Site	TR	SPD	GR	FD	CC	DS	CS	DEF	UR	CDI
BAC	1	0	0	0	1	0	2	2	1	0.18
CPE	1	0	1	1	2	0	1	3	2	0.28
CPW	2	0	3	1	2	0	2	3	2	0.38
PFC	0	0	0	2	0	0	2	2	1	0.18
CEC	2	1	2	1	1	0	1	2	2	0.31
CBH	0	0	0	1	1	1	2	2	1	0.21

Table 4: *Evaluation of CDI: TR = trash, SPD = speleothem damage, GR = graffiti, FD = floor disturbances, CC = condensation corrosion, DS = desiccation, CS = cave sedimentation, DEF = deforestation, and UR = urbanisation.*

Site	ASS	SP	GP	VR	MW	DV	RI	CEI
BAC	0	6	0	6	0	2	5	19
CPE	2	6	0	6	0	6	5	25
CPW	4	6	0	6	0	6	5	27
PFC	0	0	0	0	4	0	5	9
CEC	0	4	4	0	0	6	5	19
CBH	0	6	6	0	0	0	5	17

Table 5: *Evaluation of RAP-cei (%): ASS = alterations of subsurface soil/trampling and compaction; SP = sound pollution; GP = Groundwater pollution; VR = natural vegetation loss; MW = masonry work; DV = disorderly visitation; RI = range of impacts.*

Site	BEi	BEe	AbEi	AbEe	AnEi	AnEe	CR
BAC	6	2	0	1	1	0	45
CPE	3	2	1	1	3	1	38
CPW	7	2	1	1	3	1	58
PFC	6	2	0	1	2	3	52
CEC	2	2	0	1	0	0	23
CBH	7	2	1	1	4	2	62

Table 6: *Evaluation of RAP-cr (%) for the categories: BEi = internal biotic environment, BEe = external biotic environment, AbEi = internal abiotic environment, AbEe = external abiotic environment, AnEi = internal anthropic environment, and AnEe = external anthropic environment.*



Figure 2: *Floating trash on the water surface, and urbanisation in the background, at an otherwise scenic RMB.*



Figure 3: *Occurrence of trash mixed in with natural cave deposits at CEC.*

4. Discussion

The CSI scores are very similar to previous studies in Florida (mean 0.38, HARLEY et al. 2011) and Philippines (mean 0.37, CARANZA & CALDERON 2023) although the CDI scores are lower than in Florida (mean 0.42, HARLEY et al. 2011). The KDI scores are also lower than other more degraded karst areas in Florida due to soil compaction, deforestation,

disturbance of archaeological sites and expanding urban development there (0.69, VAN BEYNEN et al. 2007) but higher than studies in Mexico and Botswana (0.26, KOVARIK & VAN BEYNEN 2015; 0.29, TLHAPISO & STEPHENS 2020, respectively). The lack of natural flushing of the two blue hole sites in NP likely exacerbates the accumulation of trash on the water surface.

The KDI methodology is deemed more suitable for blue hole sites in The Bahamas as it was developed for karst (including sinkholes) in nearby Florida and includes several hydrology indicators (VAN BEYNEN & TOWNSEND 2005). The similarity in scores/classifications for the sites in this study using the indices of HARLEY et al. (2011) and DONATO et al. (2014) show the applicability of both methodologies to dry caves in The Bahamas. The CCI (RAP-cei, DONATO et al. 2014) is particularly useful for those sites with bat populations (BAC, CPW, PFC, and CBH) due to the indicator for sound pollution (Table 5). The RAP-cei also includes pollution of groundwater that, along with sound are less clearly defined in the CDI (HARLEY et al. 2011). Alternatively, the CDI is more precise for evaluating deforestation, agriculture and urbanisation using a 1-km buffer as compared with the RAP-cei which utilises range of impact as 'local' or 'regional'.

The CCI scores show a similar range to impacted karst areas in Brazil (2-56%, DONATO et al. 2014). In addition, the CCI scores show that PFC and CBH have highest priority for geoconservation in NP and validate their management by BNT and Clifton Heritage Authority respectively; CPW has moderate priority, and fencing and marked trails are recommended as occur at the two sites.

5. Conclusion

The geoconservation of karst sites in NP is important for the preservation of natural and cultural heritage with potential for sustainable development through well managed eco/geo-tourism. A range of standardised indices (KDI for blue holes ; CSI/CDI and CCI for caves) were applied to publicly accessible sites in NP to evaluate environmental sensitivity/vulnerability and disturbance/ impacts. The two blue hole sites (GBH and RMB) were found to have 'moderate disturbance' and the six cave sites relatively 'stable' with 'pristine/minor disturbance'. CPW and CBH are 'moderately sensitive' and PFC is 'sensitive' and with 'medium vulnerability' these caves have the highest priority for geoconservation in NP.

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