



MINISTÉRIO DO MEIO AMBIENTE
INSTITUTO CHICO MENDES DE CONSERVAÇÃO DA BIODIVERSIDADE
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RELATÓRIO FINAL DE PROJETO DE PESQUISA CIENTÍFICA

APLICAÇÃO DE TRAÇADORES CORANTES PARA CARACTERIZAÇÃO DA DINÂMICA ATUAL DE FLUXO D'ÁGUA SUBTERRÂNEA NO CARSTE DE SÃO DESIDÉRIO, BAHIA, BRASIL

Belo Horizonte
2025



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Relatório Final apresentado ao Instituto Brasileiro de Desenvolvimento e Sustentabilidade (IABS) para cumprimento dos requisitos da bolsa de estudos de pós-doutorado.

Supervisor: Prof. Dr. Paulo Henrique Ferreira Galvão

Pesquisador: Lucas Padoan de Sá Godinho

Período de realização: 19/09/2022 a 31/07/2025

Belo Horizonte
2025

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1 INTRODUÇÃO

O uso de traçadores corantes fluorescentes como ferramenta de pesquisa hidrogeológica em áreas cársticas tem como principal objetivo confirmar conexões hidráulicas entre pontos de entrada da água no sistema aquífero, como sumidouros e dolinas, e pontos de descarga do sistema, como nascentes cársticas, ou ressurgências (Thraillkill, 1985; Golsheider e Drew, 2007; Benischke, 2021). Além de fornecer informações a respeito da localização aproximada rotas de fluxo em trechos de sistemas de condutos aos quais não há acesso direto, os testes quantitativos com traçadores realizados com auxílio de espectrofluorímetros de monitoramento contínuo *in situ* podem fornecer dados relativos à velocidade de fluxo entre dois pontos distintos do aquífero, o tempo de resposta entre pulsos de recarga e descarga do sistema, a dimensão das áreas de captação, recarga e o grau relativo de carstificação do sistema, a existência ou não de diferentes componentes de fluxo com velocidades de propagação distintas, aspectos da geometria da rede de condutos e a possível origem de fontes contaminantes para a água subterrânea (White, 2002; Ford e Williams, 2007; Goldscheider et al., 2008).

O principal objetivo desta pesquisa de pós-doutorado foi a caracterização da dinâmica atual do sistema de cavernas do rio João Rodrigues, situado na região cárstica de São Desidério, oeste do estado da Bahia, através da descrição e quantificação dos processos de recarga, fluxo e descarga da água subterrânea. Para isto, uma rede de monitoramento hidrológica automatizada com 14 pontos de investigação foi instalada na área de estudo, com operação entre novembro de 2023 a fevereiro de 2024. Foram coletados dados para a elaboração de uma série histórica de dados de alta resolução temporal (1 hora de resolução) para dados hidrológicos, como nível d'água, temperatura e condutividade elétrica em nascentes, rios subterrâneos e lagos do sistema. Foram também realizados o monitoramento da precipitação na área de recarga do sistema, além da coleta de dados hidroquímicos (cátions e ânions maiores e isótopos estáveis de ^{18}O e ^2H), medição de vazão com micromolinete e três testes de injeção com traçadores fluorescentes (Fluoresceína sódica, Rhodamina WT e Tinopal) em diferentes trechos do sistema durante o início do período seco (abril de 2024).

Esta pesquisa, realizada entre 19/09/2022 e 31/07/2025, teve como principais produtos, além da pesquisa principal, os seguintes quantitativos:

- Disciplina Geologia do Carste (carga horária de 60 horas), ministrada duas vezes e no Programa de Pós-graduação em Geologia do IGC-UFMG;
- Disciplina Pesquisa Hidrogeológica (carga horária de 36 horas), ministrada três vezes, em duas turmas, na Pontifícia Universidade Católica de Minas Gerais, IEC - PUC Minas;
- Organização e realização dos eventos técnico-científicos Café Hidrogeológico I e Café Espeleológico I, em 2023, e o Minicurso sobre Hidrogeologia Cárstica e o Simpósio Internacional em Hidrogeologia Cárstica, em 2024;
- Publicação acadêmica de seis resumos de congressos nacionais e internacionais e um artigo científico em revista internacional;
- Apresentação de trabalhos em dois eventos científicos internos do departamento de Geologia do IGC-UFMG;
- Apresentação de três oficinas sobre “Testes com traçadores fluorescentes em aquíferos cársticos: planejamento, execução e interpretação de dados: Segundo Café Hidrogeológico”;
- Participação de sete bancas de defesas de trabalhos acadêmicos nível pós-graduação sobre temas relacionados à hidrogeologia cárstica e espeleologia e duas bancas para seleção de alunos ingressantes em programas de pós-graduação;
- Participação na avaliação de trabalhos concorrentes ao II Prêmio Michel Le Bret de espeleologia: 37° Congresso Brasileiro de Espeleologia, Curitiba, julho/2023.
- Participação na coordenação do comitê científico de geomorfologia cárstica e do seminário em geologia do carste durante o “19th International Congress of Speleology”.

Sendo assim, este projeto, além da pesquisa principal, a partir de vários eventos e atividades, resultou em ampla divulgação e comunicação científica sobre o tema hidrogeologia cárstica e espeleologia tanto no âmbito nacional como internacional, atingindo um público tanto técnico e acadêmico, como um público mais diverso.

2 ATIVIDADES REALIZADAS

2.1 Coleta de dados, experimentos e análises

Durante o projeto de pós-doutorado, foi instalada uma rede de monitoramento hidrológica ao longo do sistema de cavernas do rio João Rodrigues (Figuras 1 e 2) para a coleta de dados em campo e amostras para análise em laboratório. Os dados coletados foram organizados em séries temporais e consistiram principalmente do nível d'água, vazão, temperatura, condutividade elétrica, concentração de isótopos estáveis e principais cátions e ânions de nascentes, lagos e rios subterrâneos. Além do monitoramento hidrológico, foram realizados testes de injeção com traçadores fluorescentes no mesmo sistema de cavernas (Figura 3), a fim de complementar o modelo quantitativo de fluxo d'água subterrânea elaborado para a área de estudo.

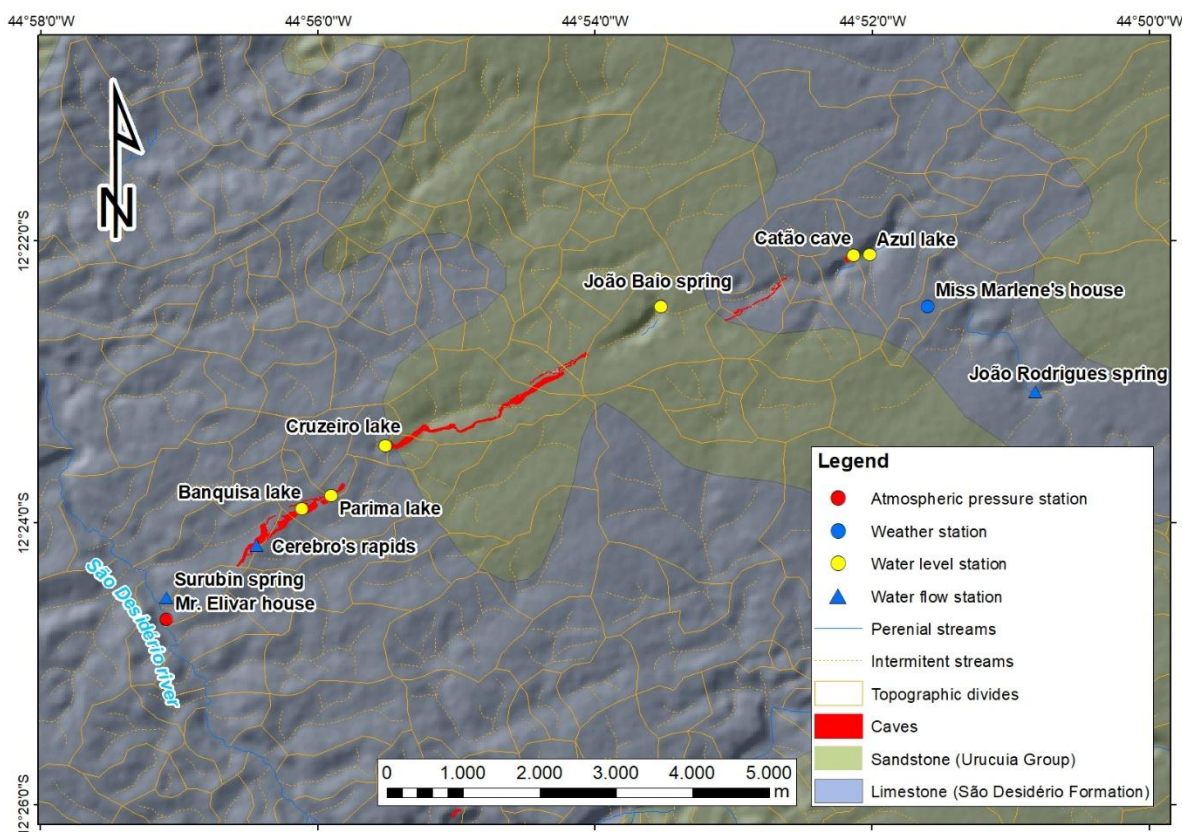


Figura 1: Mapa da rede de monitoramento hidrológica instalada ao longo do sistema de cavernas do rio João Rodrigues, município de São Desidério - Bahia.

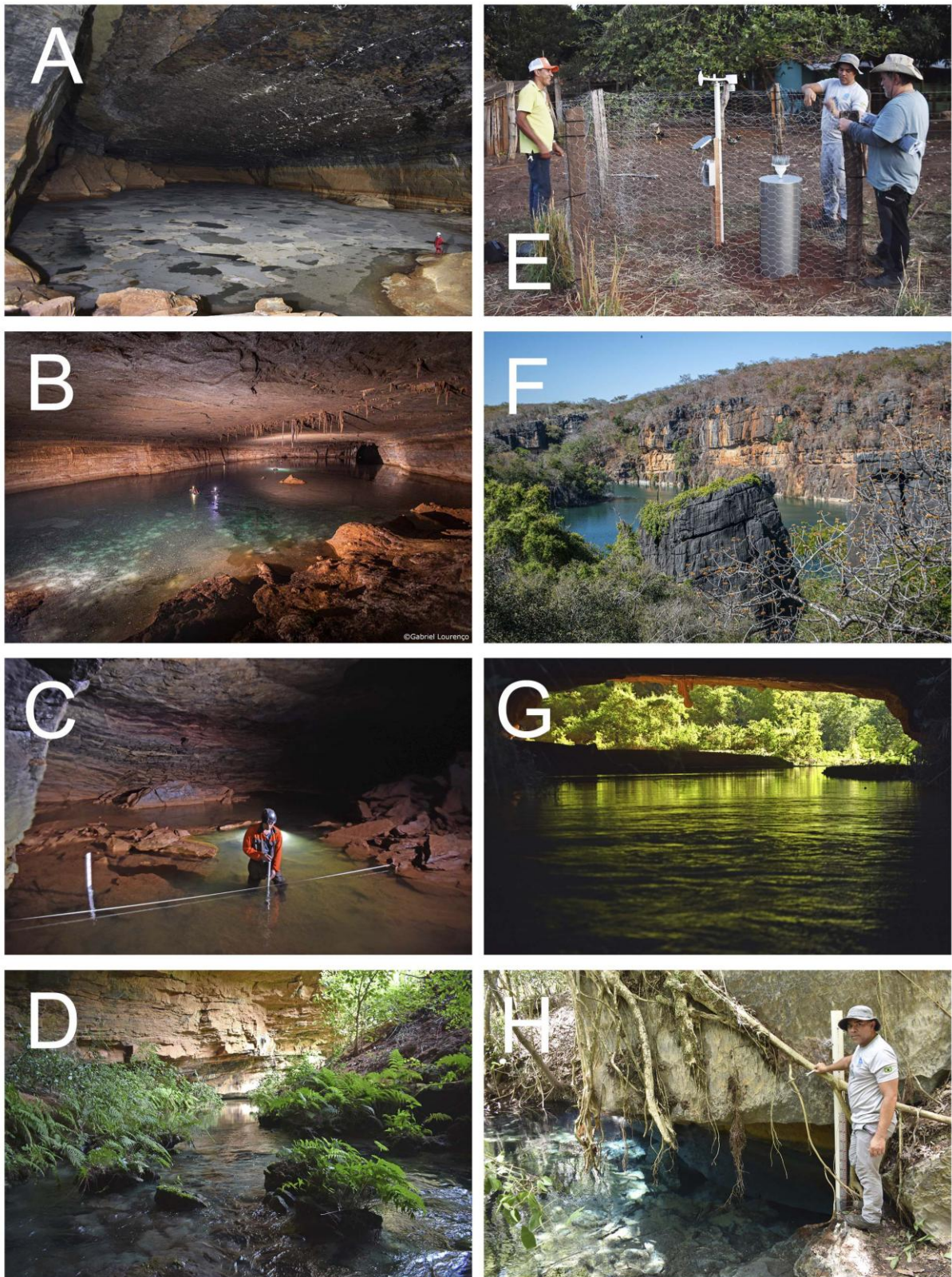


Figura 2: Fotos de pontos da rede de monitoramento hidrológica. A: Lago da Banquisa; B: Lago do Cruzeiro (Foto: Gabriel Lourenço); C: Corredeiras do “Cérebro”; D: Sumidouro do João Baio; E: Estação meteorológica; F: Lago Azul; G: Gruta do Catão; H: Poço do Surubim.

Fotos: Lucas Padoan.



Figura 3: Testes de injeção com traçadores fluorescentes. A: Fluorímetro GGUN instalado no Sumidouro do João Baio; B: Injeção de tinopal no Sumidouro do João Baio; C: Fluorímetro GGUN instalado no Poço do Surubim; D: Injeção de Rodamina WT na caverna Garganta do Bacupari; E: Injeção de fluoresceína no sumidouro a jusante da Gruta do Catão.

2.2 Disciplina(s) ministradas durante a residência pós-doutoral

Na residência pós-doutoral no Programa de Pós-graduação em Geologia do IGC-UFMG, foi ministrada pelo pós-doutorando Lucas Padoan de Sá Godinho a disciplina Geologia do Carste, código GEL919, carga horária de 60 horas (4 créditos),

durante o 2º semestre de 2023, conforme diário de classe em anexo. A mesma disciplina foi oferecida no quadro das disciplinas optativas do 2º semestre de 2024 (realização em fevereiro de 2025), conforme ementa publicada no *website* do IGC, em anexo.

Foram também ministradas pelo mesmo pesquisador 3 ofertas da disciplina Pesquisa Hidrogeológica, para duas turmas, em regime de ensino à distância (online), no Instituto de Educação Continuada da Pontifícia Universidade Católica de Minas Gerais, IEC - PUC Minas, cada qual com carga de 36 horas (vide resultado de avaliação de disciplinas em anexo).

2.3 Organização de eventos acadêmico-científico no Programa de Pós-graduação em Geologia do IGC-UFMG

Como residente de pós-doutorado o pesquisador foi membro da equipe de organização dos simpósios Café Hidrogeológico I e Café Espeleológico I (fotógrafo do evento), durante o 2º semestre de 2023, nas dependências da Escola de Engenharia da UFMG. Esses eventos foram coordenados e organizados pelos professores Dr. Paulo Galvão e Dr. Rodrigo de Paula (Café Hidrogeológico) e pelo então aluno de mestrado Ícaro de Assis (Café Espeleológico), todos integrantes do Laboratório de Estudos Hidrogeológicos (LEHID) do IGC – UFMG.

O pós-doutorando Lucas Godinho também participou como idealizador e organizador principal do Minicurso sobre Hidrogeologia Cárstica, realizado no dia 27 de novembro de 2024, nas dependências do IGC – UFMG, e do Simpósio Internacional em Hidrogeologia Cárstica, realizado nas dependências do prédio do Conservatório da UFMG (Av. Afonso Pena) no dia 28 de novembro de 2024, conforme consta do certificado em anexo. Nesta ocasião participaram renomados professores e pesquisadores(as) nacionais (Instituto do Carste de Belo Horizonte, Instituto de Pesquisas Ambientais de São Paulo, Universidade Federal de Minas Gerais e Vale S.A.) e internacionais (Crawford Hydrology Laboratory da Western Kentucky University).

2.4 Publicação acadêmica relacionada ao projeto desenvolvido (artigos, capítulos, resumos, trabalhos em eventos, entre outros)

Enquanto residente de pós-doutorado pelo Programa de Pós-graduação em Geologia do IGC-UFMG, foram publicados os seguintes resumos de congressos nacionais e internacionais (vide anexos):

- Padoan, L. S. G., Galvão, P., Ferrari, J. A., Assunção, P., Auler, A.S., Karmann, I., Groves, C., Bledsoe, L.A., Singer, A., Tanikawa, W.Y., Lourenço, G., Assis Cruz, I., KARST SPRING MONITORING AND RESPONSE TO EXTREME RAIN EVENTS: THE JOÃO RODRIGUES CAVE SYSTEM IN SÃO DESIDÉRIO, BAHIA, BRAZIL. XXIII Congresso Brasileiro de Águas Subterrâneas, São Paulo, 2024.
- Padoan, LSG; Karmann, I; Granger, D; Laureano, FV; Galvão, PHF; Ferrari, JA; Assunção, PHS; Auler, AS; Groves, C; Bledsoe, L; Singer, A; Morita, T, MILLION YEAR SCALE EVOLUTION OF A KARST AQUIFER IN NE BRAZIL: FROM INTERSTRATAL INITIATION TO MODERN FLOW DYNAMICS. 51° Congresso Brasileiro de Geologia, Belo Horizonte, 2024.
- Padoan, L. S. G.; Karmann, I.; Granger, D. E.; Almeida, R. P.; Laureano, F. V.; Cruz Jr., F. W.; Sawakuchi, A. O.; Fonseca Jr., E. S.; Meza, A. B., UPLIFT MECHANISMS AND EROSION HISTORY OF AN INTRACONTINENTAL PLATEAU IN THE BRAZILIAN STABLE PLATFORM INFORMED BY CAVE SEDIMENT GEOCHRONOLOGY. GSA Connects, Anaheim, 2024.
- Padoan, L. S. G.; Karmann, I.; Granger, D.; Laureano, F. V.; Galvão, P.; Ferrari, J. A.; Auler, A.; Assunção, P.; Groves, C.; Bledsoe, L.; Singer, A.; Lourenço, G. C. O.; Tanikawa, W. Y., Million-year scale evolution and conceptual flow model of a sandstone covered karst aquifer in NE Brazil. GSA Connects, Anaheim, 2024.
- Padoan, I.; Karmann, I.; Granger, D.; Laureano, F. V.; Paes de Almeida, R.; Cruz Jr., F. W.; Sawakuchi, A. O.; Foneca, E. S.; Meza, A. B.; Gallas, J. D. F., Cave sediment chronology and erosion rates in the São Desidério karst reveal a million-year-scale landscap evolution of the Central Brzilian Plateau: *Geomorphology*, v. 483, 2025.
- Padoan, L. S. G.; Karmann, I.; Granger, D.; Laureano, F. V.; Morita, T. D. M.; Duarte, G., Pliocene-Eocene evolution of a cratonic, sandstone covered karst system: NE Brazil, 2025.

2.5 Apresentação de trabalhos relacionados ao projeto em eventos acadêmico-científicos

- Lucas Padoan de Sá Godinho; Paulo Henrique Ferreira Galvão. 2023. Dinâmica hidrológica atual do sistema de cavernas João Rodrigues, São Desidério – BA: XVI Semana da Geologia, Instituto de Geociências, UFMG. Pôster apresentado em novembro de 2023 (vide anexo).
- Lucas Padoan de Sá Godinho; Paulo Henrique Ferreira Galvão. 2023. Dinâmica atual de fluxo d'água subterrânea no carste de São Desidério, BA: Primeiro Café Hidrogeológico. Pôster apresentado em junho de 2023 (vide anexo).

2.6 Palestras, oficinas e cursos relacionados ao projeto desenvolvido

- Pedro Henrique Assunção; Lucas Padoan de Sá Godinho. 2023. Mini-curso: Testes com traçadores fluorescentes em aquíferos cársticos: planejamento, execução e interpretação de dados: Primeiro Café Hidrogeológico, carga 4 horas, ministrado em junho/2023 (vide anexo).
- Pedro Henrique Assunção; Lucas Padoan de Sá Godinho. 2024. Mini-curso: Testes com traçadores fluorescentes em aquíferos cársticos: planejamento, execução e interpretação de dados: Segundo Café Hidrogeológico, carga 4 horas, ministrado em junho/2024 (vide anexo).
- Lucas Padoan de Sá Godinho. 2024. Palestra concedida durante o Seminário Internacional em Hidrogeologia Cárstica, em 28 de outubro de 2024, nas dependências do prédio do Conservatório da UFMG (vide anexo).

2.7 Participações em bancas de defesas de Mestrado e Doutorado no Programa de Pós-graduação em Geologia do IGC-UFMG; em bancas de graduação e especialização

- Participação como avaliador na banca de defesa final de mestrado da discente Gabriela Meira Teixeira, sob orientação do Prof. Dr. Rodrigo Sérgio de Paula, pelo Instituto de Geociências da Universidade Federal de Minas Gerais, com monografia intitulada: "Avaliação e estimativa de recarga dos aquíferos da região da APA Carste de Lagoa Santa, MG". Defesa realizada em agosto/2023.

- Participação como avaliador na banca de qualificação de mestrado da discente Flávia Braga Vieira, sob orientação do Prof. Dr. Paulo Henrique Ferreira Galvão, com monografia intitulada: “Estudos Hidrogeológicos Cársticos Associando Hidrograma de Nascentes, Geofísica, Testes de Bombeamento, Norte de Sete Lagoas/MG”. Defesa realizada em abril/2024.
- Participação como avaliador na banca de qualificação de mestrado do discente Gabriel Lourenço Carvalho de Oliveira, sob orientação do Prof. Dr. Paulo Henrique Ferreira Galvão, com monografia intitulada: Hidrodinâmica da bacia do rio São Miguel: mapeamento da superfície potenciométrica e aplicação de traçadores fluorescentes”. Defesa realizada em agosto/2024.
- Participação como avaliador na banca de qualificação de mestrado do discente Allan Antônio Freitas Matos, sob orientação do Prof. Dr. Paulo Henrique Ferreira Galvão, com monografia intitulada: “Efeito de escala de parâmetros hidráulicos da porção confinada do aquífero cárstico Sete Lagoas – Minas Gerais”. Defesa realizada em agosto/2024.
- Participação como avaliador na banca de defesa final de mestrado do discente Rafael Magno Oliveira, sob orientação do Prof. Dr. Paulo Henrique Ferreira Galvão, com monografia intitulada: “Fatores hidrogeológicos, espeleológicos e estruturais no desenvolvimento de zonas preferenciais de carstificação, nordeste do município de Sete Lagoas, MG. Defesa realizada em setembro/2024.

2.8 Participação em bancas de processos seletivos no Programa de Pós-graduação em Geologia do IGC-UFMG

- Participação como avaliador em Banca de processo seletivo on-line de mestrado, 1º semestre de 2023, regido pelo edital nº 001/2022 do Instituto de Geociências da Universidade Federal de Minas Gerais.
- Participação como avaliador em Banca de processo seletivo on-line de doutorado, 2º semestre de 2023, regido pelo edital nº 001/2022 do Instituto de Geociências da Universidade Federal de Minas Gerais.

2.9 Participação em bancas fora do Programa de Pós-graduação em Geologia do IGC – UFMG

- Participação como avaliador na banca de defesa final de mestrado do discente Tom Dias Motta Morita, sob orientação do Prof. Dr. Ivo Karmann, pelo Instituto de Geociências da Universidade de São Paulo, com monografia intitulada: “Origem biogênica de ácido sulfúrico e sua ação corrosiva na espeleogênese no carste da Bacia de Irecê, Grupo Una”. Defesa realizada em agosto/2023.
- Participação como avaliador na banca de defesa final de mestrado do discente Otávio Barbosa Ferreira, sob orientação da Profa. Dra. Alexandra Vieira Suhogusoff e coorientação da Dra. Tatiana dos Santos Tavares, com monografia intitulada: “Multi-technical approach to evaluate the impacts caused by the Vazante mine (MG) on the Santa Catarina River flow loss through the overexploitation of a fissure-karst aquifer and simulation of mitigating solutions by numerical modeling”. Defesa realizada em abril/2023.

2.10 Demais atividades relacionadas à residência pós-doutoral

- Participação como avaliador de trabalhos concorrentes ao II Prêmio Michel Le Bret de espeleologia: 37º Congresso Brasileiro de Espeleologia, Curitiba, julho/2023.
- Coordenador do comitê de geomorfologia cárstica do 19th International Congress of Speleology, Belo Horizonte, Brazil, julho/2025. Em andamento.
- Coordenador do Simpósio em Geologia do Carste durante o 19th International Congress of Speleology, Belo Horizonte, Brazil, julho/2025.

3 MÉTODOS

Os métodos aplicados nesta pesquisa foram o monitoramento de dados hidrológicos e físico-químicos de nascentes, rios e lagos subterrâneos, a coleta de água para análises hidroquímicas e de isótopos estáveis e a realização de testes de injeção com traçadores corantes fluorescentes, seguindo as recomendações de Field e Pinsky (2000), Worthington e Smart (2003), Goldscheider e Drew (2007), Groves (2007), Goldscheider et al. (2008) e Benishcke (2021).

4 RESULTADOS

Os resultados desta pesquisa são apresentados nos artigos e resumos publicados em congressos e revistas científicas nacionais e internacionais, conforme consta nos anexos deste volume. Parte dos resultados desta pesquisa serão divulgados em publicações futuras (artigos científicos e resumos em eventos acadêmicos), cuja elaboração está em andamento.

5 PRODUTOS

Os produtos citados abaixo serão apresentados nos arquivos do anexo deste volume, bem como arquivos digitais enviados diretamente aos dirigentes do CECAV/IABS:

- Publicação científicas em revistas internacionais e/ou nacionais de impacto reconhecido, bem como a participação e publicidade dos resultados em congressos e simpósios.
- Elaboração de seções verticais representando o modelo hidrológico conceitual da área de estudo;
- Representação cartográfica da bacia subterrânea do sistema de cavernas João Rodrigues;

- Cartilhas ilustradas para divulgação científica ao grande público (link Google Drive para download):

<https://drive.google.com/drive/folders/1Z9DPX9jxVbmXcl2uxlZvsHxYYO5wVD EK?usp=sharing>

- Disponibilização dos *shapesfiles* de mapas temáticos para domínio público (link Google Drive para download):

<https://drive.google.com/drive/folders/1NusFuTG1sUYCDQZjFluKhMSDuCpT HzJW?usp=sharing>

6 EQUIPE PRINCIPAL DE PESQUISA

Nome	Função no projeto	Instituição	E-mail	Link no Currículo Lattes
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7 REFERÊNCIAS BIBLIOGRÁFICAS

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8 ANEXOS

Abaixo são apresentados todos os anexos que comprovam as declarações de atividades realizadas durante o estágio pós-doutoral pelo Programa de Pós-graduação em Geologia no IGC – UFMG.

EXPERIÊNCIA DIDÁTICA



Universidade Federal de Minas Gerais

Diário de Classe Fechamento de Diário de Classe

Emissão
12/12/2023
Página
1 de 2

Período: 2023/2 Ofertante: 041921 IGC - GEOLOGIA/MD
Atividade: DIP GEL919 TOPICOS ESPECIAIS IV
Turma: E Geologia do Carste
Professor(es):

Nº	Matricula	Nome	Presença		Resultado Final		Exame Especial	Result. Após E.E		Situação Final	Observações
			Faltas	S/I	Pontos	Conceito		Pontos	Conceito		
1	2023710507	ALLAN ANTONIO FREITAS MATOS	0	S	70	C		70	C	A	
2	2023663614	CAMILA SANTOS SCHUCH	0	S	90	A		90	A	A	
3	2023722343	Danilo Moacyr Barbosa de Moraes	0	S	80	B		80	B	A	
4	2023722335	EVANDRO LUIZ GARCIA ASSUMPCÃO	0	S	85	B		85	B	A	
5	2023671633	FLÁVIA BRAGA VIEIRA	0	S	70	C		70	C	A	
6	2023710566	GABRIEL LOURENÇO CARVALHO DE OLIVEIRA	0	S	90	A		90	A	A	
7	2022693293	ICARO ASSIS CRUZ	0	S	80	B		80	B	A	
8	2022693080	INGRID FERNANDES	0	S	85	B		85	B	A	
9	2023732993	JULIANA BARBOSA TIMO	0	S	75	C		75	C	A	
10	2023727019	LEDSON ALEXANDRE SILVEIRA SATHLER	0	S	80	B		80	B	A	
11	2023669140	MILLENA NAIME LEMOS GUIMARÃES	0	S	80	B		80	B	A	
12	2023669116	PAULA DANIELE RESENDE SILVA	0	S	75	C		75	C	A	
13	2021708670	PEDRO HENRIQUE DA SILVA ASSUNÇÃO	0	S	90	A		90	A	A	
14	2023663592	SAMUEL AMARAL MOURA SILVA	0	S	85	B		85	B	A	
15	2023708979	WENDY TANIKAWA YOSHIZUMI	0	S	90	A		90	A	A	
16	2023710574	WINICIUS DE JESUS SILVA	0	S	75	C		75	C	A	

Matéria Lecionada

Aula	Data	Dia	Horas Aula	Horário	Tipo	Formato	Assunto
1	16/10/2023	Seg	12	08:00 - 18:00	T	P	Introdução ao carste/ rochas formadoras do carste.
2	17/10/2023	Ter	12	08:00 - 18:00	T	P	Química das águas no carste/ Fluxo d'água subterrânea do carste.
3	18/10/2023	Qua	12	08:00 - 18:00	T	P	Desenvolvimento do relevo cárstico.
4	19/10/2023	Qui	12	08:00 - 18:00	T	P	Espeleogênese/ Minerais e depósitos de caverna.
5	20/10/2023	Sex	12	08:00 - 18:00	T	P	Apresentação dos seminários.

Professor(es) Responsável:

Lucas Rodrigo de Sá Fedorini

Legenda de Observações:

NF - XXXXXXXX => Nota Final alterada fora do Sistema Diário de Classe em: XX/XX/XXXX
 CNG - XXXXXXXX => Conceito alterado fora do Sistema Diário de Classe em: XX/XX/XXXX
 SFR - XXXXXXXX => Situação de Frequência alterada fora do Sistema Diário de Classe em: XX/XX/XXXX
 TTE - X => Aluno em Tratamento Especial com nota anterior igual a X
 Legenda de Situação Final: A - Aprovado, R - Reprovado, 1 - Trancamento Total, 2 - Trancamento sem justificativa,
 3 - Trancamento com Justificativa, 4 - Dispensa, 5 - Cancelamento a Pedido, 6 - Regime Especial,
 7 - Tratamento Especial, 8 - Cancelamento Automático



UNIVERSIDADE FEDERAL DE MINAS GERAIS
INSTITUTO DE GEOCIÊNCIAS
PROGRAMA DE PÓS-GRADUAÇÃO EM GEOLOGIA
MESTRADO, DOUTORADO E PÓS-DOUTORADO

Av. Antônio Carlos, nº 6627, Pampulha, Belo Horizonte,
Minas Gerais - MG, CEP: 31270-901
Telefone: 0055 31 3409-5494
E-mail: posgeol@igc.ufmg.br
Site: sites.igc.ufmg.br/posgeol/
Instagram: @ppgeolufmg

DISCIPLINA OPTATIVA

Ano: 2024 Semestre: 2º

Nome: Geologia do Carste

Docente responsável: Lucas Padoan de Sá Godinho

Área de Concentração: Geologia Regional

Código: GEL919 **Turma:** C **Data:** 03/02 a 08/02/25 **Hora:** 8h às 18h **Carga Horária:** 60h **Créditos:** 04

Trabalho de campo: Parque Estadual do Sumidouro **Datas/horas:** 08/02/2025, 8h às 18h

Pré-requisito: Não possui.

Especificidade: Não possui.

Modalidade: Presencial, conforme Ofício N° 05/2021 do Conselho de Ensino, Pesquisa e Extensão da UFMG, reiterado pelo Ofício N° 01/2022 da PRPG/UFMG.

EMENTA

Nesta disciplina, serão discutidos os principais processos geológicos associados a origem e o desenvolvimento de sistemas cársticos e cavernas. O principal objetivo do curso é abordar a influência dos processos geomorfológicos, hidrológicos, litológicos, climáticos, químicos e biológicos na evolução de terrenos cársticos. As discussões iniciais serão de caráter introdutório, a fim de apresentar aos estudantes conceitos essenciais. Em seguida, tópicos avançados e questões científicas abrangentes serão trabalhadas para interpretação da evolução do relevo e do clima em escala local ou regional com base em registros geológicos no carste. Muito embora o foco da disciplina não seja a aplicação da geologia do carste no mercado de trabalho, as discussões e conceitos abordados poderão auxiliar os estudantes na resolução de problemas práticos da geotecnia, hidrogeologia, geologia de risco e exploração mineral. Ao longo da disciplina, os estudantes irão participar de exercícios e experimentos didáticos e está prevista uma atividade de campo ao carste de Lagoa Santa e gruta da Lapinha (Parque Estadual do Sumidouro), próximo a região metropolitana de Belo Horizonte, Minas Gerais.

PROGRAMA/CRONOGRAMA

- Aula 1 - Introdução ao carste
- Aula 2 - Rochas carstificáveis
- Aula 3 - Águas subterrâneas no carste
- Aula 4 - Química das águas no carste
- Aula 5 - Desenvolvimento do relevo cárstico
- Aula 6 - Espeleogênese: evolução do pensamento
- Aula 7 - Padrões de caverna e estilo de recarga d'água subterrânea
- Aula 8 - Influência da geologia na espeleogênese
- Aula 9 - Minerais e depósitos de caverna
- Aula 10 - Influência do clima na carstificação
- Aula 11 - Clima e intemperismo no interior de cavernas
- Aula 12 - Impactos humanos e aplicações da geologia do carste

METODOLOGIA DE ENSINO

Seminários; trabalhos práticos, provas, participação, etc.

METODOLOGIA DE AVALIAÇÃO

Exercícios e seminário.

BIBLIOGRAFIA

- Ford, D., Williams, P. 2007. Karst Hydrogeology and Geomorphology: John Wiley & Sons, 562 p.
- Palmer, A. N. 2007. Cave Geology: Cave Books, Dayton, 454 p.



Lucas Padoan de Sá Godinho <lucaspsgodinho@gmail.com>

Resultado de Avaliação da Disciplina

1 message

Diretoria de Educação Continuada <secacademicaiec@pucminas.br>

Fri, Jun 23, 2023 at 3:02 AM

Reply-To: secacademicaiec@pucminas.br

To: lucaspsgodinho@gmail.com

Prezado(a) Lucas Padoan de Sá Godinho

Segue abaixo consolidação das avaliações dos alunos da disciplina Pesquisa Hidrogeológica - CH: 36.

Curso M. ENG. em Engenharia Hidrogeológica, Oferta 2, Turma 1, Online

Coordenadores: Elizângela Augusta dos Santos , Josias Eduardo Rossi Ladeira , Rafael Colombo Pimenta

Datas de Início e Fim da Disciplina: 01/02/2023 a 23/05/2023

Número de Alunos da Turma:	33
Número de Questionários Respondidos:	14
Porcentagem de Alunos	42,42%

AVALIAÇÃO DO(A) PROFESSOR(A) - Lucas Padoan de Sá Godinho - CH: 36	Média	Moda	Mediana	Desvio Padrão
Apresentou o plano de ensino no início da disciplina.	4,93	5,00	5,00	0,26
As aulas foram executadas com clareza e profundidade adequadas.	4,86	5,00	5,00	0,35
Promoveu a articulação dos conteúdos teóricos à prática profissional.	4,71	5,00	5,00	0,59
Foi pontual, assíduo, e cumpriu a totalidade da carga horária de cada aula.	4,93	5,00	5,00	0,26
O conteúdo programático foi abordado com a devida profundidade.	4,79	5,00	5,00	0,41
O material didático utilizado está atualizado e organizado.	4,86	5,00	5,00	0,35
Desperta o interesse pelo conteúdo da disciplina.	4,86	5,00	5,00	0,52
Está preparado para as aulas online.	4,93	5,00	5,00	0,26
Média das Avaliações	4,86	5,00	5,00	0,38

AVALIAÇÃO DA DISCIPLINA	Média	Moda	Mediana	Desvio Padrão
Importância da disciplina para formação profissional do aluno.	4,86	5,00	5,00	0,35
A posição da disciplina na grade curricular está adequada.	4,50	5,00	5,00	0,73
A carga horária da disciplina está apropriada ao seu plano de ensino.	4,71	5,00	5,00	0,59
O nível de profundidade dos conteúdos da disciplina está consonante com o previsto no plano de ensino.	4,57	5,00	5,00	0,62
Média das Avaliações	4,66	5,00	5,00	0,57

COORDENAÇÃO DO CURSO	Média	Moda	Mediana	Desvio Padrão
Responde em tempo hábil às questões de interesse dos acadêmicos.	4,29	4,00	4,00	0,70
A coordenação é participativa.	4,14	5,00	4,00	0,83
Disponibilidade para contato.	4,21	4,00	4,00	0,86
Média das Avaliações	4,21	4,33	4,00	0,80

CONDIÇÕES INSTITUCIONAIS	Média	Moda	Mediana	Desvio Padrão
Avalie a facilidade de contato com os canais do IEC PUC Minas.	4,29	4,00	4,00	0,70
Avalie a qualidade de atendimento do Apoio Acadêmico.	4,14	5,00	4,00	0,91
Avalie a qualidade de atendimento do Setor Financeiro.	4,21	4,00	4,00	0,86
Avalie a qualidade de atendimento do Suporte Técnico.	4,36	5,00	4,50	0,72
Média das Avaliações	4,25	4,50	4,13	0,80

SISTEMA CANVAS	Média	Moda	Mediana	Desvio Padrão
Facilidade de uso.	4,57	5,00	5,00	0,62
Instruções sobre as funcionalidades do sistema.	4,36	5,00	5,00	0,90
Resolução de problemas técnicos.	4,43	5,00	5,00	0,73
Atendimento do setor de suporte técnico.	4,36	5,00	5,00	0,81
Média das Avaliações	4,43	5,00	5,00	0,77

SISTEMA MICROSOFT TEAMS	Média	Moda	Mediana	Desvio Padrão
Facilidade de uso.	4,71	5,00	5,00	0,45
Instruções sobre as funcionalidades do sistema.	4,64	5,00	5,00	0,48
Resolução de problemas técnicos.	4,64	5,00	5,00	0,48
Atendimento do setor de suporte técnico.	4,57	5,00	5,00	0,62
Qualidade da gravação das aulas ao vivo.	4,50	5,00	5,00	0,82
Média das Avaliações	4,61	5,00	5,00	0,57

A escala de avaliação utilizada pelos alunos varia entre 1 (grau mínimo) e 5 (grau máximo)

Legenda:

Média = representa a média aritmética das notas obtidas.

Mediana = representa o número central do conjunto de notas.

Moda = é o valor da nota que mais se repete, o que ocorre com maior frequência.

Desvio padrão = é uma medida que expressa o grau de dispersão do conjunto de notas obtido. Quanto mais próximo de zero (0) for o desvio padrão, mais homogêneo são os dados.

Quais comentários adicionais, sugestões, pontos fortes ou fracos que gostaria de destacar. Utilize esse espaço para dar sua opinião.

Como sugestão, o professor poderia utilizar o sistema Canvas de forma sistemática para facilitar o controle de entregas (demandas, prazos etc).

Não há

O professor demonstrou domínio do conteúdo e facilidade de relacioná-lo à prática profissional dos alunos. A disciplina abordou conceitos que ainda serão vistos em outras disciplinas posteriores na grade, devendo ser avaliada uma mudança na ordem das disciplinas.

Atenciosamente,

Secretaria Acadêmica

IEC PUC Minas

NÃO RESPONDA A ESSE E-MAIL. ELE FOI GERADO AUTOMATICAMENTE.



Ata de Notas

Localização: Online
Curso: M, ENG, em Engenharia Hidrogeológica (5233)
Oferta: 3 **Início:** 03/04/2023 **Término:** 30/10/2024 **Turma:** 1 **Módulo:** 1
Disciplina: Pesquisa Hidrogeológica
Professor: Lucas Padoan de Sá Godinho **Cod. Prof./Pessoa:** 335329 / 1423040
 Pedro Henrique da Silva Assunção 336357 / 1502261

Aluno	Código	A1	Total	Faltas
Alan Mendes Feitosa	179736	90,00	90,00	0
Ana Carolina Batista Gomes	177669	90,00	90,00	0
Ananda Laignier Pascoal Romano	179252	75,00	75,00	0
André Gustavo da Cunha Ramalho	179103	95,00	95,00	0
Angelica Pedro Santana	178277	95,00	95,00	0
Anna Luiza Lopes Matos	177725	80,00	80,00	0
Átila Almeida Rios de Assunção	179154	80,00	80,00	0
Bruno Erickson Matos Facundo	178718	70,00	70,00	0
Carlos Eduardo Furtado Gabarron *	180424	0,00	0,00	0
Cleide Aparecida Campos dos Santos Moraes	184540	70,00	70,00	0
Daiane Rodrigues Brandão *	176812	0,00	0,00	0
Daniela Carla dos Santos	179994	70,00	70,00	0
Eduardo Moussalle Grissolia	181309	80,00	80,00	0
Elizângela Gabriela Nunes *	180850	0,00	0,00	0
Fabiana Vasconcelos Caldas *	177095	0,00	0,00	0
Fabio de Jesus Moreira Júnior	185373	80,00	80,00	0
Fernando Carolino da Silva	180772	70,00	70,00	0
Gene Clebson Apolinario Santos	183904	70,00	70,00	0
Guilherme Cristian Andrade de Freitas	178570	100,00	100,00	0
Guilherme Madrid Pereira	177016	95,00	95,00	0
Gustavo Pimenta Sant'Ana	179364	70,00	70,00	0
Gwenhwyfar de Laia Menezes *	183908	0,00	0,00	0
Harrison Ruiz da Cruz e Souza *	178674	0,00	0,00	0
Igor Cavalcante Viana *	185787	0,00	0,00	0
Isabela Santhiago Soares de Oliveira	180948	80,00	80,00	0
Jéssica Lopes Tintori	183670	70,00	70,00	0
José Guilherme Teixeira de Oliveira *	184448	0,00	0,00	0
Karina Cunha dos Santos	178989	100,00	100,00	0
Keyla de Oliveira Neves Batista	179629	100,00	100,00	0
Luand Roberto Aparecido Piassa	178542	95,00	95,00	0
Lucas César Vaz dos Santos	180994	100,00	100,00	0
Lucas Quaiatti Vieira	180559	90,00	90,00	0
Luciano Marques Alcantara	179404	80,00	80,00	0
Lúcio César de Souza Mesquita	184312	70,00	70,00	0
Maira Hilgemberg Alves	185760	100,00	100,00	0
Márcio Luiz Geremias	179269	85,00	85,00	0
Maria Cristina Franceschini Chade	180445	75,00	75,00	0
Maria Luiza Menezes Cordeiro	178540	70,00	70,00	0
Marjorie Brandão Justino *	183666	0,00	0,00	0
Natália Gonçalves Mendes	181308	85,00	85,00	0
Neuber Tadeu Ferreira Elizário	185386	85,00	85,00	0
Pablo Augusto da Silva Gomes Ribeiro	181290	75,00	75,00	0
Paula Marina Ferreira Borges *	179965	0,00	0,00	0
Paulo Aruanã Cezar	183328	75,00	75,00	0
Paulo Vinicius de Andrade Saporì	179598	70,00	70,00	0
Pedro Henrique Cruz Lopes	178802	95,00	95,00	0
Pedro Retamal Weinem *	176670	0,00	0,00	0
Rafael Marcarini Barbosa *	180993	0,00	0,00	0
Renata Santos Moreira da Silva *	178836	0,00	0,00	0

* Reprovado

** Reprovado com direito a Exame Especial

(!) Inativo



Ata de Notas

Localização: Online
Curso: M, ENG, em Engenharia Hidrogeológica (5233)
Oferta: 3 **Início:** 03/04/2023 **Término:** 30/10/2024 **Turma:** 1 **Módulo:** 1
Disciplina: Pesquisa Hidrogeológica
Professor: Lucas Padoan de Sá Godinho **Cod. Prof./Pessoa:** 335329 / 1423040
Pedro Henrique da Silva Assunção 336357 / 1502261

Aluno	Código	A1	Total	Faltas
San Carlos de Oliveira	183660	100,00	100,00	0
Sérgio Fernandes Pinto	179422	85,00	85,00	0
Tamara Souza e Santos	179868	80,00	80,00	0
Thalita Ribeiro da Silva	178667	70,00	70,00	0
Thiago Anastacio Madeira *	180572	0,00	0,00	0
Thiago Tapajós Pereira Brito	177984	85,00	85,00	0
Thomaz Yanca Zulpo Pereira	184568	75,00	75,00	0
Vanderlucio Henrique Menezes Souza	181124	70,00	70,00	0

Matrículas por tipo:		Matrículas por situação:	
Disciplina Isolada	0	Válida	45
Normal	57		
Recadastramento Parcial	0	Trancada	7
Recadastramento Total	0	Cancelada	5
Total:	57		

Assinatura do professor: _____

* Reprovado

** Reprovado com direito a Exame Especial

(I) Inativo



Lucas Padoan de Sá Godinho <lucaspsgodinho@gmail.com>

Resultado de Avaliação da Disciplina

1 message

Diretoria de Educação Continuada <secacademicaiec@pucminas.br>

Sat, May 18, 2024 at 3:01 AM

Reply-To: secacademicaiec@pucminas.br

To: lucaspsgodinho@gmail.com

Prezado(a) Lucas Padoan de Sá Godinho

Segue abaixo consolidação das avaliações dos alunos da disciplina Pesquisa Hidrogeológica - CH: 36.

Curso M, ENG, em Engenharia Hidrogeológica, Oferta 4, Turma 1, Online

Coordenadores: Elizângela Augusta dos Santos , Josias Eduardo Rossi Ladeira , Rafael Colombo Pimenta

Datas de Início e Fim da Disciplina: 13/12/2023 a 17/04/2024

Número de Alunos da Turma:	21
Número de Questionários Respondidos:	10
Porcentagem de Alunos	47,62%

AVALIAÇÃO DO(A) PROFESSOR(A) - Lucas Padoan de Sá Godinho - CH: 36	Média	Moda	Mediana	Desvio Padrão
Apresentou o plano de ensino no início da disciplina.	4,80	5,00	5,00	0,60
As aulas foram executadas com clareza e profundidade adequadas.	4,70	5,00	5,00	0,90
Promoveu a articulação dos conteúdos teóricos à prática profissional.	4,80	5,00	5,00	0,60
Foi pontual, assíduo, e cumpriu a totalidade da carga horária de cada aula.	4,50	5,00	5,00	0,92
O conteúdo programático foi abordado com a devida profundidade.	4,70	5,00	5,00	0,90
O material didático utilizado está atualizado e organizado.	4,80	5,00	5,00	0,60
Desperta o interesse pelo conteúdo da disciplina.	4,60	5,00	5,00	0,92
Está preparado para as aulas online.	4,70	5,00	5,00	0,64
Média das Avaliações	4,70	5,00	5,00	0,76

AVALIAÇÃO DA DISCIPLINA	Média	Moda	Mediana	Desvio Padrão
Importância da disciplina para formação profissional do aluno.	4,60	5,00	5,00	0,66
A posição da disciplina na grade curricular está adequada.	4,60	5,00	5,00	0,92
A carga horária da disciplina está apropriada ao seu plano de ensino.	4,70	5,00	5,00	0,64
O nível de profundidade dos conteúdos da disciplina está consonante com o previsto no plano de ensino.	4,60	5,00	5,00	0,92
Média das Avaliações	4,63	5,00	5,00	0,79

COORDENAÇÃO DO CURSO	Média	Moda	Mediana	Desvio Padrão
Responde em tempo hábil às questões de interesse dos acadêmicos.	4,80	5,00	5,00	0,60
A coordenação é participativa.	4,70	5,00	5,00	0,64
Disponibilidade para contato.	4,80	5,00	5,00	0,40
Média das Avaliações	4,77	5,00	5,00	0,55

CONDIÇÕES INSTITUCIONAIS	Média	Moda	Mediana	Desvio Padrão
Avalie a facilidade de contato com os canais do IEC PUC Minas.	4,80	5,00	5,00	0,60
Avalie a qualidade de atendimento do Apoio Acadêmico.	4,80	5,00	5,00	0,60
Avalie a qualidade de atendimento do Setor Financeiro.	4,80	5,00	5,00	0,60
Avalie a qualidade de atendimento do Suporte Técnico.	4,80	5,00	5,00	0,60
Média das Avaliações	4,80	5,00	5,00	0,60

SISTEMA CANVAS	Média	Moda	Mediana	Desvio Padrão
Facilidade de uso.	4,60	5,00	5,00	0,80
Instruções sobre as funcionalidades do sistema.	4,50	5,00	5,00	0,81
Resolução de problemas técnicos.	4,50	5,00	5,00	0,81
Atendimento do setor de suporte técnico.	4,60	5,00	5,00	0,80
Média das Avaliações	4,55	5,00	5,00	0,81

SISTEMA MICROSOFT TEAMS	Média	Moda	Mediana	Desvio Padrão
Facilidade de uso.	4,90	5,00	5,00	0,30
Instruções sobre as funcionalidades do sistema.	4,80	5,00	5,00	0,40
Resolução de problemas técnicos.	4,70	5,00	5,00	0,64
Atendimento do setor de suporte técnico.	4,80	5,00	5,00	0,60
Qualidade da gravação das aulas ao vivo.	4,80	5,00	5,00	0,60
Média das Avaliações	4,80	5,00	5,00	0,51

A escala de avaliação utilizada pelos alunos varia entre 1 (grau mínimo) e 5 (grau máximo)

Legenda:

Média = representa a média aritmética das notas obtidas.

Mediana = representa o número central do conjunto de notas.

Moda = é o valor da nota que mais se repete, o que ocorre com maior frequência.

Desvio padrão = é uma medida que expressa o grau de dispersão do conjunto de notas obtido. Quanto mais próximo de zero (0) for o desvio padrão, mais homogêneo são os dados.

Quais comentários adicionais, sugestões, pontos fortes ou fracos que gostaria de destacar. Utilize esse espaço para dar sua opinião.

A disciplina deveria ter uma carga horária maior.

Acredito não ser viável tirar essa disciplina do curso. Por mais que ela seja conceitual ela é fundamental para o hidrogeólogo no dia a dia, pois ela fundamenta boa parte das nossas ações aplicadas.

Foi todo ótimo o curso gostei muito.

Atenciosamente,

Secretaria Acadêmica

IEC PUC Minas

NÃO RESPONDA A ESSE E-MAIL, ELE FOI GERADO AUTOMATICAMENTE.

CERTIFICADOS

CERTIFICADO


O PROGRAMA DE PÓS-GRADUAÇÃO EM GEOLOGIA (PPGEOL) E O LABORATÓRIO DE ESTUDOS HIDROGEOLÓGICOS (LEHID) DO INSTITUTO DE GEOCIÊNCIAS DA UFMG E A ASSOCIAÇÃO BRASILEIRA DE ÁGUAS SUBTERRÂNEAS (ABAS) CERTIFICAM QUE

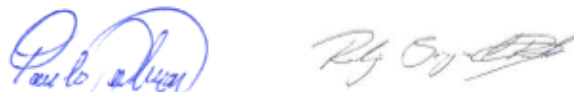
LUCAS P. S. GODINHO

ATUOU COMO COORDENADOR DO MINICURSO SOBRE HIDROGEOLOGIA CÂRSTICA, MINISTRADO PELOS PESQUISADORES DA CRAWFORD HYDROLOGY LABORATORY DR. CHRIS GROVES, MSC. LEE ANNE BLADSOE E MSC. AUTUMM SINGER, EM 27 DE OUTUBRO DE 2024, E DO SEMINÁRIO INTERNACIONAL EM HIDROGEOLOGIA CÂRSTICA, EM 28 DE OUTUBRO DE 2024, NA UFMG.

BELO
HORIZONTE

OUTUBRO
2024


MAURÍCIO BERTACHINI
PRESIDENTE ABAS NÚCLEO MINAS GERAIS


PAULO GALVÃO/RODRIGO DE PAULA
COORDENADORES PPGEOL/LEHID


ABAS - MG


PROGRAMA DE
PÓS-GRADUAÇÃO
EM GEOLOGIA - UFMG
LEHID
Laboratório de Estudos Hidrogeológicos

CERTIFICADO

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LUCAS P. S. GODINHO

PARTICIPOU COMO PALESTRANTE DO SEMINÁRIO INTERNACIONAL EM HIDROGEOLOGIA CÁRSTICA, NO DIA 28 DE OUTUBRO DE 2024, NAS DEPENDÊNCIAS DO PRÉDIO DO CONSERVATÓRIO DA UFMG, COM PALESTRA INTITULADA "GIANT UNDERGROUND LAKES AND RITHMIC KARST SPRINGS: UNUSUAL EFFECTS OVER KARST WATER FLOW DYNAMICS".

BELO
HORIZONTE

OUTUBRO
2024



MAURÍCIO BERTACHINI
PRESIDENTE ABAS NÚCLEO MINAS GERAIS



ABAS - MG



PAULO GALVÃO/RODRIGO DE PAULA
COORDENADORES PPGEOL/LEHID



PROGRAMA DE
PÓS-GRADUAÇÃO
EM GEOLOGIA - UFMG
LEHID
Laboratório de Estudos Hidrogeológicos



Certificamos que o trabalho

KARST SPRING MONITORING AND RESPONSE TO EXTREME RAIN EVENTS: THE JOÃO RODRIGUES CAVE SYSTEM IN SÃO DESIDÉRIO, BAHIA, BRAZIL

Foi apresentado no formato ORAL durante o XXIII Congresso Brasileiro de Águas Subterrâneas, XXIV Encontro Nacional de Perfuradores de Poços e FENÁGUA 2024, promovidos pela ABAS – Associação Brasileira de Águas Subterrâneas e realizados de forma presencial de 12 a 15 de agosto de 2024, na cidade de São Paulo, SP. Autores: Lucas Padoan de Sá Godinho, Paulo Henrique Ferreira Galvão, José Antonio Ferrari, Pedro Henrique da Silva Assunção, Augusto Sarreiro Auler, Ivo Karmann, Christopher Groves, Lee Anne Bledsoe, Autumn Singer, Wendy Tanikawa Yoshizumi, Gabriel Lourenço e Icaro Assis Cruz

São Paulo, 15 de agosto de 2024


José Paulo G. M. Netto
Presidente da Associação Brasileira de Águas Subterrâneas


Ricardo Hirata
Presidente da Comissão Organizadora do XXIII Congresso Brasileiro de Águas


Paulo Galvão
Presidente da Comissão Científica do XXIII Congresso Brasileiro de Águas

PROMOÇÃO



ASSOCIADOS PATROCINADORES





51º CONGRESSO BRASILEIRO DE
GEOLOGIA

13 A 17 DE OUTUBRO DE 2024
BELO HORIZONTE - MG
Centerminas Expo

CERTIFICADO

Certificamos que o

TRABALHO CIENTÍFICO intitulado **MILLION YEAR SCALE EVOLUTION OF A KARST AQUIFER IN NE BRAZIL: FROM INTERSTRATAL INITIATION TO MODERN FLOW DYNAMICS** dos autores Lucas Sá Godinho Padoan, Ivo Karmann, Darryl Granger, Fernando Verassani Laureano, Paulo Henrique Ferreira Galvão, Jose Antonio Ferrari, Pedro Henrique Silva Assunção, Augusto Sarreiro Auler, Christopher Groves, Lee Anne Bledsoe, Autumn Singer, Tom Dias Motta Morita foi apresentado no 51º Congresso Brasileiro de Geologia, realizado de 13 a 17 de outubro de 2024 no Centerminas Expo em Belo Horizonte/MG, na forma de apresentação: Oral.

Belo Horizonte, 17 de outubro de 2024

Joana Reis Magalhães
Presidente SBG - Núcleo Minas Gerais

Tiago Amâncio Novo
Presidente 51º CBG

CERTIFICADO

A ASSOCIAÇÃO BRASILEIRA DE ÁGUAS SUBTERRÂNEAS - ABAS NÚCLEO MINAS GERAIS E
O PROGRAMA DE PÓS-GRADUAÇÃO EM GEOLOGIA - IGC/UFMG CERTIFICAM QUE

*Pedro Henrique Assunção e
Lucas Padoan de Sá Godinho*

MINISTRARAM O CURSO "TESTES COM TRAÇADORES FLUORESCENTES EM AQUIFEROS CÁRSTICOS: PLANEJAMENTO,
EXECUÇÃO E INTERPRETAÇÃO DE DADOS", DE 4 HORAS DE CARGA HORÁRIA, DO PRIMEIRO CAFÉ HIDROGEOLÓGICO,
REALIZADO NO DIA 13 DE JUNHO DE 2023, DE 8 ÀS 12H, NO INSTITUTO DE GEOCIÊNCIAS DA UFMG.



MAURÍCIO BÉRTACHINI
PRESIDENTE - ABAS MG



PAULO GALVÃO
COORDENADOR DO PPG IGC/UFMG



ABAS - MG



PROGRAMA DE
PÓS-GRADUAÇÃO
EM GEOLOGIA - UFMG

JUNHO
2023


CERTIFICADO



A ASSOCIAÇÃO BRASILEIRA DE ÁGUAS SUBTERRÂNEAS - ABAS NÚCLEO MINAS GERAIS E O PROGRAMA DE PÓS-GRADUAÇÃO EM GEOLOGIA (PPGEOL) - IGC (UFMG) CERTIFICAM QUE

*Pedro Henrique Assunção e
Lucas Padoan de Sá Godinho*

MINISTRARAM O CURSO "TESTES COM TRAÇADORES FLUORESCENTES EM AQUÍFEROS CÁRSTICOS: PLANEJAMENTO, EXECUÇÃO E INTERPRETAÇÃO DE DADOS, DE 4 HORAS DE CARGA HORÁRIA, DO SEGUNDO CAFÉ HIDROGEOLÓGICO, REALIZADO NO DIA 18 DE JUNHO DE 2024, DE 8 ÀS 12H, NO INSTITUTO DE GEOCIÊNCIAS DA UFMG.

BELO
HORIZONTE
OUTUBRO
2024


MAURÍCIO BERTACHINI
PRESIDENTE ABAS NÚCLEO MINAS GERAIS

 
PAULO GALVÃO/RODRIGO DE PAULA
COORDENADORES PPGEOL/LEHID


ABAS - MG

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PÓS-GRADUAÇÃO
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LUCAS P. S. GODINHO

PARTICIPOU COMO PALESTRANTE DO SEMINÁRIO INTERNACIONAL EM HIDROGEOLOGIA CÁRSTICA, NO DIA 28 DE OUTUBRO DE 2024, NAS DEPENDÊNCIAS DO PRÉDIO DO CONSERVATÓRIO DA UFMG, COM PALESTRA INTITULADA "GIANT UNDERGROUND LAKES AND RITHMIC KARST SPRINGS: UNUSUAL EFFECTS OVER KARST WATER FLOW DYNAMICS".

BELO
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OUTUBRO
2024



MAURÍCIO BERTACHINI
PRESIDENTE ABAS NÚCLEO MINAS GERAIS



ABAS - MG



PAULO GALVÃO/RODRIGO DE PAULA
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LEHID
Laboratório de Estudos Hidrogeológicos

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LUCAS P. S. GODINHO



ATUOU COMO COORDENADOR DA EQUIPE ORGANIZADORA DO MINICURSO SOBRE HIDROGEOLOGIA CÁRSTICA, MINISTRADO PELOS PESQUISADORES DA CRAWFORD HYDROLOGY LABORATORY DR. CHRIS GROVES, MSC. LEE ANNE BLEDSOE E MSC. AUTUMN SINGER, EM 27 DE OUTUBRO DE 2024, E DO SEMINÁRIO INTERNACIONAL EM HIDROGEOLOGIA CÁRSTICA, EM 28 DE OUTUBRO DE 2024, NA UFMG.

BELO
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OUTUBRO
2024


MAURÍCIO BERTACHINI
PRESIDENTE ABAS NÚCLEO MINAS GERAIS



 
PAULO GALVÃO/RODRIGO DE PAULA
COORDENADORES PPGEOL/LEHID





UNIVERSIDADE FEDERAL DE MINAS GERAIS - UFMG
INSTITUTO DE GEOCIÊNCIAS - IGC
PROGRAMA DE PÓS-GRADUAÇÃO EM GEOLOGIA - PPGeol
MESTRADO, DOUTORADO E PÓS-DOUTORADO

Av. Presidente Antônio Carlos, N° 6627, Pampulha,
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E-mail: posged@igc.ufmg.br
Site: sis.igc.ufmg.br/ppgeol/
Instagram: [@ppgeolufmg](https://www.instagram.com/ppgeolufmg)

DECLARAÇÃO

DECLARO, para os devidos fins, que os(as) Profs(as). Drs(as). **Rodrigo Sérgio de Paula (Orientador(a) - UFMG)**, **Paulo Henrique Ferreira Galvão (UFMG)**, **Lucas Padoan de Sá Godinho (UFMG)** e **Luana Alves de Lima (UFVJM)** participaram, como titulares, no dia 25 de agosto de 2023, às 9h, a distância, via Plataforma Conferência Web, da banca de defesa de Dissertação de Mestrado intitulada “*AVALIAÇÃO E ESTIMATIVA DE RECARGA DOS AQUÍFEROS DA REGIÃO DA APA CARSTE DE LAGOA SANTA, MG*”, apresentada pelo(a) discente Gabriela Meira Teixeira, nº de registro acadêmico 2020726542, do Programa de Pós-Graduação em Geologia (PPGeol), do Instituto de Geociências (IGC), da Universidade Federal de Minas Gerais (UFMG).

WILLIAM CAMPOS VIEGAS
Servidor Assistente em Administração
Lotado na Secretaria do Colegiado do Programa de
Pós-graduação em Geologia - PPGeol
IGC/UFMG





UNIVERSIDADE FEDERAL DE MINAS GERAIS - UFMG
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Instagram: [@ppgeolufmg](https://www.instagram.com/ppgeolufmg)

CERTIFICADO

CERTIFICO, para os devidos fins, que o(a) Dr(a). **LUCAS PADOAN DE SÁ GODINHO**, designado(a) pela Portaria Nº 003/2023/PPGeol/UFMG, de 06 de janeiro de 2023, integrou, como TITULAR, a Comissão Examinadora do Processo Seletivo de Mestrado - 2023/1º, do Programa de Pós-graduação em Geologia (PPGeol), do Instituto de Geociências (IGC), da Universidade Federal de Minas Gerais (UFMG).

PAULO HENRIQUE FERREIRA GALVÃO
Coordenador do Colegiado do Programa de
Pós-graduação em Geologia - PPGeol
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Instagram: [@ppgeolufmg](https://www.instagram.com/ppgeolufmg)

CERTIFICADO

CERTIFICO, para os devidos fins, que o(a) Dr(a). **LUCAS PADOAN DE SÁ GODINHO**, designado(a) pela Portaria Nº 016/2023/PPGeol/UFMG, de 23 de junho de 2023, integrou, como TITULAR, a Comissão Examinadora do Processo Seletivo de Doutorado - 2023/2º, do Programa de Pós-graduação em Geologia (PPGeol), do Instituto de Geociências (IGC), da Universidade Federal de Minas Gerais (UFMG).

PAULO HENRIQUE FERREIRA GALVÃO
Coordenador do Colegiado do Programa de
Pós-graduação em Geologia - PPGeol
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UNIVERSIDADE FEDERAL DE MINAS GERAIS - UFMG
INSTITUTO DE GEOCIÊNCIAS - IGC
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Instagram: [@ppgeolufmg](https://www.instagram.com/ppgeolufmg)

DECLARAÇÃO

DECLARO, para os devidos fins, que o(a) Prof(a). Dr(a). **LUCAS PADOAN DE SÁ GODINHO** participou, como titular, no dia 11 de setembro de 2024, às 13h, presencialmente, na sala 2024, do Instituto de Geociências (IGC), da Universidade Federal de Minas Gerais (UFMG), da banca de defesa de Dissertação de Mestrado do(a) discente Rafael Magno Oliveira, nº de registro acadêmico 2021708998, do Programa de Pós-Graduação em Geologia (PPGeol) do IGC/UFMG, que apresentou a pesquisa "*Fatores Hidrogeológicos, Espeleológicos e Estruturais no Desenvolvimento de Zonas Preferenciais de Carstificação, Nordeste do Município de Sete Lagoas, MG*". A Comissão Examinadora foi composta também pelos Profs. Drs.: Paulo Henrique Ferreira Galvão (UFMG), Humberto Luis Siqueira Reis (UFOP) e Rodrigo Sérgio de Paula (UFMG).

PAULO HENRIQUE FERREIRA GALVÃO
Coordenador do Colegiado do Programa de
Pós-graduação em Geologia - PPGeol
IGC/UFMG





UNIVERSIDADE FEDERAL DE MINAS GERAIS - UFMG
INSTITUTO DE GEOCIÊNCIAS - IGC
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Av. Presidente Antônio Carlos, N° 6627, Pampulha,
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Instagram: [@ppgeolufmg](https://www.instagram.com/ppgeolufmg/)

DECLARAÇÃO

DECLARO, para os devidos fins, que os(as) Profs(as). Drs(as). **Rodrigo Sérgio de Paula e Lucas Padoan de Sá Godinho (UFMG)** participaram, como titulares, no dia 28 de agosto de 2024, às 10h30, presencialmente, na sala 2024 do IGC/UFMG, da banca de defesa de Seminário de Dissertação de Mestrado do(a) discente Gabriel Lourenço Carvalho de Oliveira, número de registro acadêmico 2023710566, do Programa de Pós-Graduação em Geologia (PPGeol), do Instituto de Geociências (IGC), da Universidade Federal de Minas Gerais (UFMG). O(A) estudante apresentou a pesquisa intitulada "*HIDRODINÂMICA DA BACIA DO RIO SÃO MIGUEL: MAPEAMENTO DA SUPERFÍCIE POTENCIOMÉTRICA E APLICAÇÃO DE TRAÇADORES FLUORESCENTES*", orientada pelo(a) Prof(a). Dr(a). Paulo Henrique Ferreira Galvão.

WILLIAM CAMPOS VIEGAS
Servidor Assistente em Administração
Lotado na Secretaria do Colegiado do Programa de
Pós-graduação em Geologia - PPGeol
IGC/UFMG





UNIVERSIDADE FEDERAL DE MINAS GERAIS - UFMG
INSTITUTO DE GEOCIÊNCIAS - IGC
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Instagram: [@ppgeolufmg](https://www.instagram.com/ppgeolufmg)

DECLARAÇÃO

DECLARO, para os devidos fins, que os(as) Profs(as). Drs(as). **Rodrigo Sérgio de Paula e Lucas Padoan de Sá Godinho (UFMG)** participaram, como titulares, no dia 28 de agosto de 2024, às 8h30, presencialmente, na sala 2024 do IGC/UFMG, da banca de defesa de Seminário de Dissertação de Mestrado do(a) discente Allan Antônio Freitas Matos, número de registro acadêmico 2023710507, do Programa de Pós-Graduação em Geologia (PPGeol), do Instituto de Geociências (IGC), da Universidade Federal de Minas Gerais (UFMG). O(A) estudante apresentou a pesquisa intitulada *"EFEITO DE ESCALA DE PARÂMETROS HIDRÁULICOS DA PORÇÃO CONFINADA DO AQUIFERO CÁRSTICO SETE LAGOAS - MINAS GERAIS"*, orientada pelo(a) Prof(a). Dr(a). Paulo Henrique Ferreira Galvão.

WILLIAM CAMPOS VIEGAS
Servidor Assistente em Administração
Lotado na Secretaria do Colegiado do Programa de
Pós-graduação em Geologia - PPGeol
IGC/UFMG





Universidade de São Paulo

DECLARAÇÃO

O(A) Prof(a). Dr(a) Lucas Padoan de Sá Godinho participou, na qualidade de membro, da Comissão Julgadora da Defesa da Dissertação de Mestrado do(a) pós-graduando(a) Tom Dias Motta Morita, apresentada para a obtenção do título de Mestre em Ciências - Área: Geoquímica dos Processos Exógenos, realizada em 02 de Agosto de 2023, ocorrida no(a) Instituto de Geociências, intitulada:

"Origem biogênica de ácido sulfúrico e sua ação corrosiva na espeleogênese no carste da Bacia de Irecê, Grupo Una"

A Comissão Julgadora foi constituída pelos seguintes membros:

Prof(a). Dr(a). Ivo Karmann (Presidente)

Prof(a). Dr(a). Vivian Helena Pellizari

Prof(a). Dr(a). Lucas Padoan de Sá Godinho

São Paulo, 02 de Dezembro de 2024.



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Juliana de Moraes Leme Basso

Nº USP: 3501515

Data: 02/12/2024 14:35

Perfil assinante:: Presidente da Comissão de Pós-Graduação



Janus

Universidade de São Paulo

DECLARAÇÃO

O(A) Prof(a). Dr(a) Lucas Padoan de Sá Godinho participou, na qualidade de membro, da Comissão Julgadora da Defesa da Dissertação de Mestrado do(a) pós-graduando(a) Otavio Barbosa Ferreira, apresentada para a obtenção do título de Mestre em Ciências - Área: Hidrogeologia e Meio Ambiente, realizada em 04 de Outubro de 2023, ocorrida no(a) Instituto de Geociências, intitulada:

"ABORDAGEM MULTITÉCNICA PARA AVALIAR OS IMPACTOS DA MINA DE VAZANTE (MG) SOBRE A PERDA DE VAZÃO DO RIO SANTA CATARINA PELA DA SUPEREXPLOTAÇÃO DE UM AQUÍFERO FISSURO-CÁRSTICO E SIMULAÇÃO DE SOLUÇÕES DE MITIGAÇÃO POR MODELAGEM NUMÉRICA"

A Comissão Julgadora foi constituída pelos seguintes membros:

Prof(a). Dr(a). Alexandra Vieira Suhogusoff (Presidente)

Prof(a). Dr(a). Paulo Henrique Ferreira Galvão

Prof(a). Dr(a). Lucas Padoan de Sá Godinho

São Paulo, 02 de Dezembro de 2024.



USPAssina - Autenticação digital de documentos da USP

Registro de assinatura(s) eletrônica(s)

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Juliana de Moraes Leme Basso

Nº USP: 3501515

Data: 02/12/2024 14:36

Perfil assinante:: Presidente da Comissão de Pós-Graduação

ARTIGOS COMPLETOS E RESUMOS DE CONGRESSO



Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.journals.elsevier.com/geomorphology

Cave sediment chronology and erosion rates in the São Desidério karst reveal a million-year-scale landscape evolution of the Central Brazilian Plateau

L. Padoan^{a,*}, I. Karmann^a, D. Granger^b, F.V. Laureano^a, R. Paes de Almeida^a, F.W. Cruz Jr.^a, A.O. Sawakuchi^a, E.S. Fonseca Jr.^c, A.B. Meza^c, J.D.F. Gallas^{a,1}

^a Institute of Geosciences, Rua do Lago 562, São Paulo University, São Paulo, Brazil

^b Department of Earth and Atmospheric Sciences, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN, USA

^c Transport Engineering Department, Polytechnic School, Avenida Prof. Luciano Gualberto, Travessa do Politécnico 390, São Paulo University, São Paulo, Brazil

ARTICLE INFO

Keywords:

Cave geology
Burial dating
Erosion rates
São Desidério karst
Central Brazilian Plateau

ABSTRACT

In central Brazil, regional-scale plateaus and ridges have developed during the Cenozoic in cratonic terrains, after the continental breakup of Pangea. The timing and mechanisms associated with the uplift of such landscape features are poorly understood due to the scarcity of data concerning crustal dynamics and erosion rates. This study used limestone caves containing a rich sedimentary record to obtain new erosion and fluvial incision rate data from the last 3 Ma in the Central Brazilian Plateau. The combination of different geochronological methods (cosmogenic ²⁶Al and ¹⁰Be, OSL, and U–Th series), cave passage leveling, and geophysical soundings allowed for the reconstruction of the valley incision history of the São Desidério River since the Late Pliocene. Knickpoint migration rates in the limestone towards the sandstone contact varied from 3782 ± 984 and 1122 ± 198 m/Ma in the São Desidério River and a major tributary. An expressive base level drop of 30–50 m has occurred between 1 and 2 Ma from present and is evidenced by distinct cave levels and the entrenchment of vadose canyons. The average fluvial incision rate in the limestone was determined as 52.5 ± 13.0 m/Ma. The average fluvial incision rate associated with the removal of sediment infill from the conduits was determined as 657.0 ± 31.0 m/Ma. The average erosion rate in the plateau's sandstone-covered catchment areas was 17.1 ± 1.4 m/Ma. Knickpoint retreat and valley incision rates suggest that the onset of the limestone exposure and prominent karst landscape development occurred during the Late Pliocene.

1. Introduction

While major karst rivers at the surface undergo an erosional trend, tributary underground rivers along conduit systems entrench their own channel beds, seeking equilibrium with an external base level (Ford, 1971). Groundwater and base level stability periods can lead to the enlargement of low-gradient wide passages (i.e., true cave levels), so cave river terraces will match the elevation of an external base level river terrace (Palmer, 1987). Significant surface river aggradation will cause cave passages to be entirely or partially filled with clastic sediments until a shift to a new phase of erosion may partially wash out the cave deposits (Farrant and Smart, 2011). The succession of events of this

nature will imprint erosive and depositional features inside caves, building the bulk of evidence to reconstruct the geological evolution history of a cave. Careful study and organization of all evolutionary phases of a cave system, together with precise anchoring in time, can help understand the climate and landscape evolution history of a region (Ford and Williams, 1989; Palmer, 2007).

Thanks to the development of several geochronological methods during the last few decades, such as in situ cosmogenic nuclides and optically stimulated luminescence (OSL) burial dating (Granger, 2006; Rhodes, 2011), paleomagnetism (Sasowsky et al., 1995), and U–Th–Pb decay series (Shen et al., 2002; Stock et al., 2005), fluvial terraces preserved inside caves became important records in Earth Sciences. The

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¹ In memoriam.

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applications of cave chronology include the timing of surface river valley erosion and deposition events, determining valley incision and knickpoint retreat rates, dating fluvial piracy events, interpreting climate change influence on landscape evolution, among many others (Granger et al., 2001; Anthony and Granger, 2004; Häuselmann et al., 2007; Polyak et al., 2008; Auler et al., 2009; Laureano et al., 2016; Nehme et al., 2020).

Recent studies have given significant contributions to quantitatively describe the landscape evolution in Brazil through apatite fission track thermochronology (Harman et al., 1998; Turner et al., 2008; Japsen et al., 2012; Jelinek et al., 2014; Fonte-Boa et al., 2022), cosmogenic nuclides dating (Pupim et al., 2015; Witmann et al., 2015; Gonzalez et al., 2016; Laureano et al., 2016; Vasconcelos and Carmo, 2018; Souza et al., 2019), and numerical modeling of surface and lithosphere processes (Kamer and Driscoll, 1999; Rodríguez Tribaldos et al., 2017; Sacke et al., 2019; Baiadori et al., 2024). Nevertheless, study efforts and

data are primarily concentrated in the southeastern and eastern regions of the South American Platform, where passive margin escarpments occur, and a significant knowledge gap remains for other expressive plateaus and ridges in tectonically stable terrains that have developed after the continental breakup of Pangea in the Mesozoic (Almeida et al., 2000).

This study aimed to analyze cave deposits and obtain the first quantitative erosion and incision rate data in the Central Brazilian Plateau, a regional intracratonic highland and expressive continental-scale watershed divide, whose landscape evolution is poorly understood. Fluvial terraces preserved only inside the caves allowed the calculation of incision rates and knickpoint migration rates in the São Desidério River valley, where the retreat of the plateau escarpment and its sandstone cover exposes the underlying limestone unit and controls karst evolution in a plateau margin context.

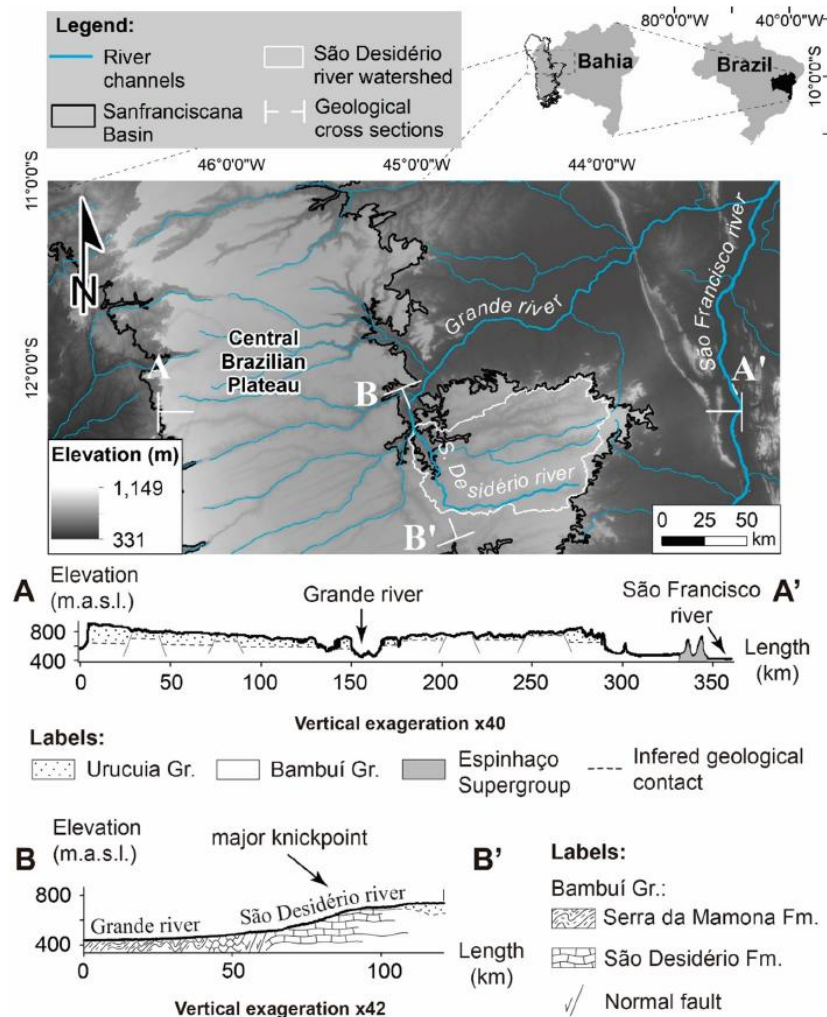


Fig. 1. Digital elevation model showing the location and geomorphology of the Central Brazilian Plateau. Cross-section A-A' outlines the limestone exposure by river incision in the middle section of the plateau and the irregular erosive unconformity that separates the sandstones from the Urucuia Group and the limestones from the Bambuú Group. Cross-section B-B' represents the Grande River and the São Desidério River equilibrium profiles, and the location of a major knickpoint is highlighted. Satellite image source: SRTM, one arc-second, USGS – United States Geological Service (2019).

2. The São Desidério karst area

2.1. Geology and geomorphology

The Central Brazilian Plateau is an extensive intracratonic ridge with maximum elevations of 1000 m.a.s.l. that occupies an area of 125,000 km² in northeastern Brazil (Fig. 1). The eastern and western borders of the plateau are defined by steep escarpments that expose Cretaceous sandstones of the Urucuia Group (Campos and Dardenne, 1997a) at the top of the stratigraphy, separated at the base by an erosive unconformity with Neoproterozoic limestone and mudstone rocks of the Bambuí Group (Babinski et al., 2007; Zalán and Romeiro Silva, 2012). At some locations near the base of the escarpments, it is possible to find outcrops of the Archean to Paleoproterozoic granite-greenstone belt terrains that constitute the basement rocks (Alkmim and Martins-Neto, 2001; Hasui, 2012). The study site, located in the São Desidério river watershed, lies in the western limit of the São Francisco Craton, in a transition zone with the Rio Preto Orogenic Belt, so deformation and metamorphism progressively decrease southwards, in the direction of the interior of the craton (Egydio da Silva et al., 1989; Uhlein et al., 2011).

The geological contacts represented in Fig. 1 were obtained from geological plan view maps (Egydio da Silva et al., 1989; Souza et al., 2004). Contacts at depth, as the graben structure pattern and the thickness of the sandstone cover under the plateau surface, were inferred from geophysical vertical cross-sections (Lima, 2007; Lima and Santos, 2011) and borehole drill data (ANA, n.d.; SIAGAS, 2018).

Differential erosion affects landscape development in the São Desidério River watershed. This river has a wide catchment area over

the sandstones in the middle to eastern regions of the plateau, so escarpment and knickpoint retreat caused by fluvial processes are responsible for the partial removal of the sandstone cover and exposure of the underlying limestone and mudstone units. The major knickpoint is located at the contact between the sandstone and the limestone units, so lithological contrast divides areas of lower and higher surface gradients. Besides the mineralogical and textural differences between sandstone and limestone that affect how these rocks are altered and eroded, remnants of a very resistant iron-rich lateritic layer cover the sandstone. Hard lateritic crusts are a widespread feature in Brazilian plateaus and ridges, and they are responsible for significantly lowering the pace of denudation, thus preserving landscape heights for long periods (Vasconcelos et al., 2019; Sacek et al., 2019).

The drainage pattern in this watershed is guided by major Proterozoic faults in the basement, with ENE-WSW and NNW-SSE directions, later reactivated to affect upper stratigraphic units (Campos and Dardenne, 1997b; Lima, 2007; Reis and Suss, 2016). There is no clear or unequivocal evidence of neotectonic (Cenozoic) fault movements that could have influenced the development of the fluvial landscape.

Average temperature in this region is 24 °C, while minimum and maximum temperatures can reach 11 and 40 °C. The mean annual precipitation equals 1200 mm/year (ANA, n.d.). Vegetation changes according to elevation, varying from cerrado (Brazilian savannah) to dry deciduous or evergreen humid forests at the bottoms of perennial river valleys (Mauro et al., 1982).

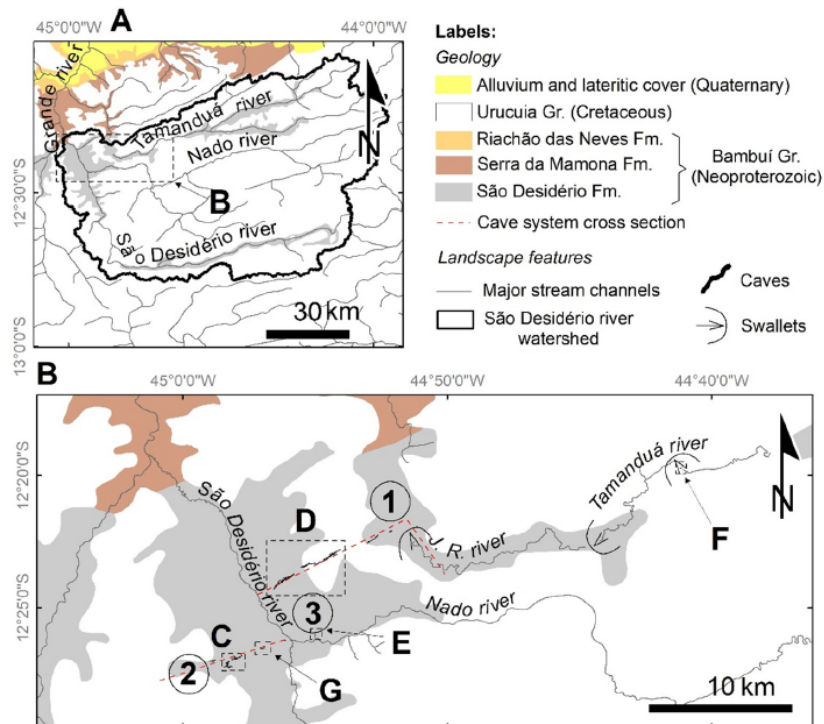


Fig. 2. Geological map showing the limestone exposures in the São Desidério River watershed and the plan view projection of the three studied cave systems, namely João Rodrigues (indicated as number 1 in the map), Manoel Lopes (2), and Beleza (3). Insets indicated in the map as letters C to G are detailed in Fig. 3. Abbreviations: J.R. River: (João Rodrigues River). All cave maps are a courtesy of the “Grupo Bambuí de Pesquisas Espeleológicas” caving club (GBPE), except the Beleza cave map, provided by “Grupo da Geo” caving club (GCEO).

2.2. Cave systems

Three important and representative cave systems in the São Desidério karst area were selected for this study: João Rodrigues, Manoel Lopes, and Beleza (Fig. 2). They all consist of epigenic caves, developed through meteoric recharge, relatively shallow groundwater flow and discharge into local rivers, enlarging the limestone secondary porosity (fractures and bedding planes) by dissolution into karst conduits (sensu Ford, 2004). Most prominent caves develop from sinking streams at the limestone-sandstone contact and follow as underground rivers into passages in a sub-parallel orientation to the directions of fault planes. Cave development in the study area is interpreted to be intimately associated with the retreat of the plateau escarpment and removal of the sandstone cover, allowing undersaturated and aggressive rivers from the sandstone to enter and dissolve the limestone rock after it is exposed to the surface.

Passages in all cave systems have dendritic to rectilinear plan view morphology (Fig. 3 C, D, and E), indicating that cave evolution was guided by punctual recharge through sinkholes and sinking streams (sensu Ewers, 1978; Palmer, 1991). The predominant dendritic pattern is sometimes overlapped by network or anastomosing mazes and extensive breakdown chambers (Fig. 3 C, F, and G). Successive cave river flooding is the most likely process to explain those secondary cave patterns, in agreement with speleogenetic discussions by White and White (1969) and Palmer (1991). Extended longitudinal profiles summarize recharge, flow, and discharge systems in Fig. 4. The sum of passage lengths in all studied cave systems reaches about 22.5 km.

Different generations of deposits in all studied cave systems indicate successive hydraulic abandonment and reactivation of the conduits (Fig. 5 D and E), probably caused by base level fluctuations in the major surface river (sensu Farrant and Smart, 2011). Passage abandonment and downward canyon incision features include subaerially exposed lacustrine mud plains, remnants of ancient fluvial deposits in passage walls and ceiling, and deeply entrenched vadose canyons (Fig. 5 A, B, and C), as the singenesis process explained by Ford (1971) and Palmer (1991). Evidences of aggradation and upward passage enlargement are ceiling channels, wall pendants, and sediment infill up to the passage ceiling (Fig. 5 B and C), following the fluvial reworking process described by Palmer (1987).

The process of upward erosion and solution of cave passages under pressure in the phreatic zone, and induced by sediment deposition and

shielding of the cave floor, is widely referred to in the karst literature as paragensis (e.g. Pasini, 2009; Farrant and Smart, 2011). This term was originally created to describe upward solution in the phreatic zone, under a low groundwater flow regime that results in aggradation and the deposition of mud and silt deposits (Renault, 1968). From now on, we will refer to the process of aggradation and upward erosion and solution in cave passages of the São Desidério karst as fluvial reworking (sensu Palmer, 1987), since it differs from the original concept of paragensis by occurring in the vadose zone and high flow regime, resulting in the deposition of sand and gravel deposits.

Several distinct depositional events are commonly recognized in most cave passages. In Fig. 5, number 1 is a very well-cemented and lithified middle to fine-grained sandstone terrace, 2 is an unconsolidated medium sand fluvial bar covered by flowstone, 3 is a muddy sand paleo-terrace remnant preserved at the ceiling of the passage, and 4 is a well-lithified cobble conglomerate river bar. The erosive contacts separating different sedimentary facies, and the contrasting cementation and cohesion characteristics of the deposits, are useful field evidences to discriminate between distinct depositional events.

In the Manoel Lopes cave system, where original passage morphology is better preserved from later collapse, two distinct cave levels in different elevations are recognized at 555 and 525 m.a.s.l. They are characterized by low gradient, large passages, oriented parallel to the limestone strike, and are vertically connected by narrow vadose canyons with high passage gradient following the dip of the strata (Fig. 4 and Fig. 5), matching the characteristics of true cave levels (sensu Palmer, 1987; Palmer, 2007).

3. Methods

3.1. Cave level recognition

In this research, the description of cave geology features and the study of cave genesis aimed to recognize evidence of base level change events in order to reconstruct part of the São Desidério River valley incision history and the Central Brazilian Plateau escarpment retreat. One of the most important features in a cave that can provide information on base level change are cave levels. Here we adopt the concept of cave level from Palmer (1987), who defines a true cave level as a large horizontal phreatic passage, formed in equilibrium with the elevation of a base level on the surface, like a river, lake, or the sea. So, the elevation

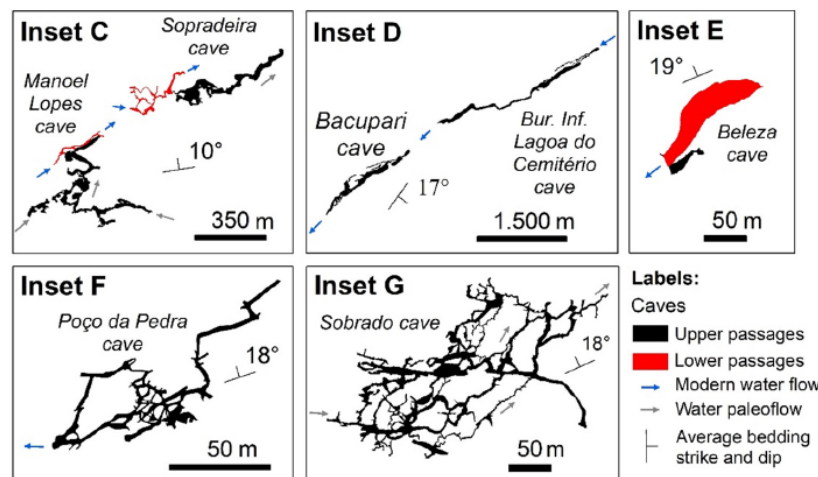


Fig. 3. Passage morphology plan views of some representative caves in the study area. The modern flow and paleo flow directions taken from scallops in cave passage walls always converge to the major rivers on surface.

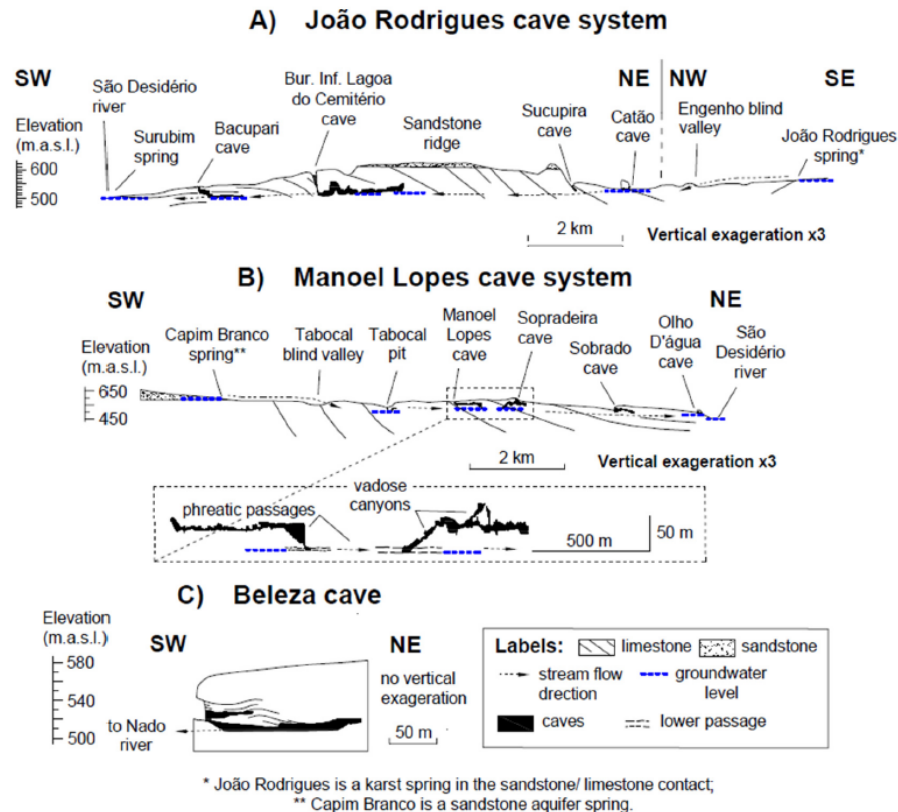


Fig. 4. Profiles of the studied cave systems and the corresponding topographic and geologic profiles. Note the gradual increase in passage elevation to the upstream direction, following the hydraulic gradient. Vertical exaggeration may cause a false and steep representation of limestone low to medium strata dip angles.

of a cave level can be associated with the position of previous base level control features.

According to Palmer (1987, 1991, 2007) and other authors (Ford, 1971; Ford and Ewers, 1978; Worthington, 2001, 2005; Audra and Palmer, 2015; Klimchouk, 2000, 2009; Calvet et al., 2024) horizontal cave passages can form in several ways and are not necessarily related to base level control. Examples include cave passages perched by insoluble or less soluble strata, deep phreatic loops developed well below the water table in unconfined aquifers (10^1 – 10^2 m scale in depth), and hypogenic dissolution along the horizontal strata in confined aquifers with ascending groundwater flow.

A true cave level (i.e. formed in equilibrium with an external base level) must attend to unequivocal morphological features, as the transition from vadose canyons developed parallel to the dip of the strata to phreatic passages parallel to the strike of the strata, known as the piezometric point (Palmer, 1987; Palmer, 2007). This condition is more prone to occur in low dip strata or densely fractured limestone contexts, which favor groundwater flow along shallow phreatic routes (Ford and Ewers, 1978; Calvet et al., 2024). Finally, cave level passages do not have their elevation guided by lithological control, such as mineral composition and fractures, but generally cut across less soluble layers or discordant structures instead (Palmer, 1991).

3.2. Cave passage leveling

For this study, 6.8 km of cave passages were surveyed. Every topographic station was tied to pertinent geological and morphological

features, like fluvial terraces, strike and dip of the strata, phreatic and vadose passage cross sections, and paleo-water-level indicators, allowing a precise representation of their lateral and vertical distribution. The laser distance meter Leica DistoX310 was used for the cave survey, with an upgrade adaptation for azimuth measurements (DistoX2). The average error in elevation for surveyed stations was 1 m.

GNSS (Global Navigation Satellite System) receivers were used to connect underground survey stations to a precise position at the surface. Two JAVAD/Topcon Legacy GD receivers were used to obtain GNSS system observable signals during fieldwork. Planimetric and altimetric positioning at the surface was defined through the satellite positioning technique, where a base station is used as a reference for GPS rover processing, according to the static relative positioning method described by Monico (2007).

GNSS data processing was performed with the GAMIT/GLOBK (GG) software, aiming to estimate station coordinates and velocities, post-seismic deformations, atmospheric delays, satellite orbits, and Earth orientation parameters (Herring et al., 2018). For base GNSS processing, the following stations were incorporated into the data analysis: BRFT (Fortaleza - CE), SAVO (Salvador -BA), SALU (São Luís - MA), BABB (Barreiras - BA), and BRAZ (Brasília - DF) from the Brazilian Continuous Monitoring Network (RBMC). Later, the resulting base coordinates were used to process rover coordinates. This procedure gives better reliability to the altimetric results and guarantees an average elevation error on surface stations close to 6 cm (see the GNSS positioning data in the supplementary materials, available in the online version of this article).

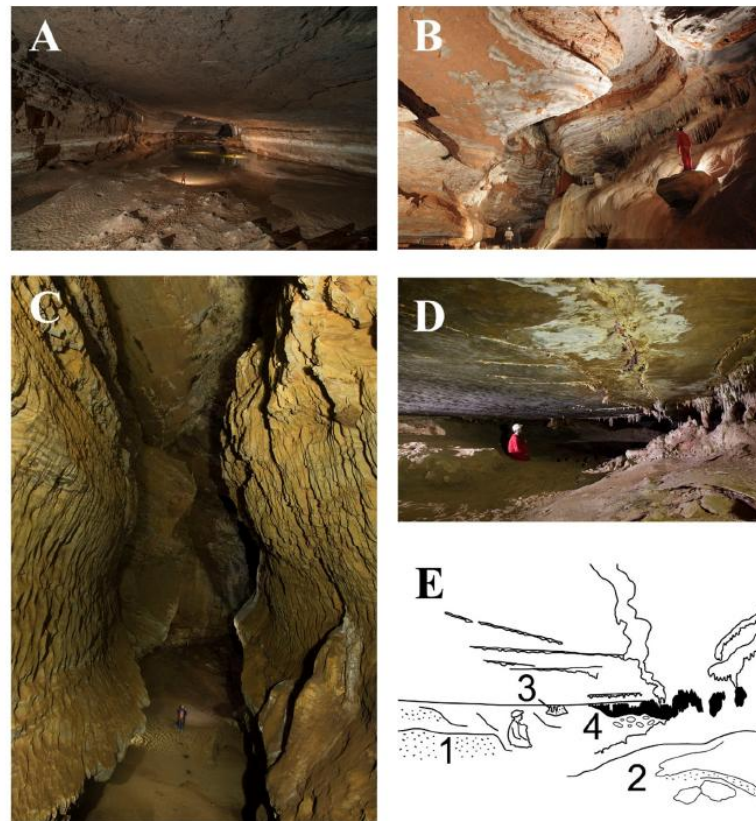


Fig. 5. Erosional and depositional features in cave passages. A) Main passage at Buraco do Inferno da Lagoa do Cemitério cave, largely affected by breakdown (photo: Kevin Downey); B) Fluvial aggradation reworking features in Sopradeira cave, as the ceiling channel and the remnants of sediment deposits with reddish color in the passage walls and ceiling; C) 30 m deep vadose canyon, connecting the upper and lower cave levels at the Manoel Lopes cave (photo: Tom Morita); D) and E) Sediment infill at the upper passage level of the Manoel Lopes cave.

3.3. Vertical electrical sounding (VES)

A geophysical survey was carried out to determine the alluvial sediment thickness and the limestone surface depth below the São Desidério River. The electrical resistivity technique by vertical electrical sounding (VES) was chosen because it is ideal for identifying geological contacts with low dip angles over a wide range of depths (Telford et al., 1976). An ABEM Terrameter resistivity meter (model SAS300C) was used for the acquisition of the resistivity data. Following the Schlumberger arrangement, the current transmission and potential measurement electrodes were arranged parallel to the river direction, with a maximum distance of up to 50 m from the resistivity meter. The data were interpreted in diagrams of resistivity (Ωm) vs. depth (m) on a logarithmic scale using IPI2win software (Kurniawan, 2009).

3.4. Geochronology

In this study, three geochronological methods were used. Burial ages of cave fluvial deposits were determined by the pair of cosmogenic ^{26}Al and ^{10}Be isotopes and the optically stimulated luminescence (OSL) techniques in quartz-rich sediments. For dating calcite and aragonite speleothem precipitation over cave fluvial terraces, the ^{230}U – ^{230}Th series method was used. Sediment sampling for geochronology considered the following criteria: (i) to represent the diversity of depositional

events at the same passage elevation and between different cave levels, ranging from potentially older to younger deposits; (ii) to anchor in time the most important speleogenetic events associated with base level fluctuations, such as fluvial terrace abandonment, vadose canyon entrenchment, and sedimentary aggradation.

3.4.1. Cosmogenic ^{26}Al and ^{10}Be

The cosmogenic ^{26}Al and ^{10}Be analysis followed the method described by Granger et al. (1997) and Granger (2006). Besides calculating burial ages, pre-burial erosion rates at the sediment source area were determined according to the method described by Granger and Muzikar (2001). This method allows burial dating (shielding from cosmic rays) for an ideal age interval between 200 ka and 5 Ma, with an analytical error of approximately 100 to 200 ka (Dunai, 2010).

Twenty samples of quartz-rich clastic sediments were used. Most samples were taken from the caves, but a few samples from the surface had to be used for the zero-age hypothesis test. For unconsolidated sands and gravels, samples had approximately 0.5 kg, while for lithified sedimentary rocks, such as cave conglomerates, fragments of at least 50 different quartz pebbles were collected for statistical representation. The mathematical solution given by the simple burial case was considered, where shielding from cosmic rays is complete after burial (i.e., from the moment sediments enter the cave). This is because limestone rock thickness above the roof of the caves varies between about 20 to 80 m,

which is usually enough to completely shield cave deposits from significant post-depositional cosmogenic production by muons (Granger and Muzikar, 2001).

Sample preparation was performed at the PRIME Lab (Purdue Rare Isotope Measurement Laboratory) at Purdue University, Indiana, U.S.A., according to the following steps: quartz separation and purification, Al and Be chemical separation through cation and anion columns, and final sample analysis with an accelerator mass spectrometer (AMS) based on a tandem electrostatic accelerator.

3.4.2. Optically stimulated luminescence

The optically stimulated luminescence (OSL) burial dating followed the method described by Rhodes (2011) and Wintle and Murray (2006). The ideal dating range for this method typically rests between 1 year and 200 ka for using the mineral quartz (Rhodes, 2011).

Eight quartz-rich unconsolidated cave sediment samples were collected and carefully stored in opaque PVC tubes to prevent sunlight bleaching. The samples had approximately 0.3 to 0.4 kg each. They were prepared and analyzed in dark rooms at the Gamma and Luminescence Spectrometry Laboratory (LEGal) at the Geosciences Institute of the São Paulo University (IGc-USP). The measurement of the luminescent signal was performed using a Risø TL/OSL DA-20 reader, with the following characteristics: beta irradiation source ($^{90}\text{Sr}/^{90}\text{Y}$), dose rate of 0.119 Gy/s, reader's blue LEDs with peak emission at 470 nm, and infrared LEDs with peak emission at 870 nm. The GG-420 filter (high-pass filter) was used to select light stimulation. The Hoya U-340 filter, used for light detection, transmits wavelengths between approximately 200 to 400 nm and peaks around 340 nm (ultraviolet). The dose recovery tests allowed determining the preheating temperatures at 240, 200, and 160 °C. The single aliquot regenerative dose protocol (SAR) was followed to measure the luminescent signal of the samples, as proposed by Murray and Wintle (2000).

The sample's natural radiation dose rates were obtained by high-resolution gamma spectrometry using a high-purity germanium detector (HPGe) with ultralow background shielding, energy resolution of 2 keV, and relative efficiency of 60 %. The radionuclide concentrations were converted to dose rates following Guérin et al. (2011). The dose rates produced by cosmic radiation were calculated using the model developed by Prescott and Stephan (1982).

3.4.3. U—Th series

The $^{238}\text{U}/^{230}\text{Th}$ decay series method was used to date calcite and aragonite speleothems, following the procedures described by Shen et al. (2002) and Richards and Dorale (2003). The age determination limits for this method vary between 1 year to 500 ka. This analysis aimed to determine the minimum depositional age of fluvial terraces inside the caves since cap speleothem deposition marks the end of clastic deposition after subaerial exposure of alluvial bars or lacustrine layers (Farrant and Smart, 2011).

Twelve speleothem samples were collected from the top of subaerially exposed fluvial terraces and lake deposits. Powdered aliquots of 0.1 to 0.2 g were collected for each sample at the Karst Systems Laboratory of IGc-USP. Chemical preparation and sample dating were carried out at the Isotope Laboratory of the Institute of Global Environmental Change, Xi'an Jiaotong University, China, where carbonate samples were dissolved, and the U and Th elements were separated in cation and anion columns. Final solutions were sent for isotopic U and Th ratio measurement in an inductively coupled plasma mass spectrometer (ICP-MS), Finnigan Neptune model.

3.5. Calculating river incision and knickpoint migration

As cave passages evolve in response to the changes in the fluvial landscape on the surface, underground streams tend to preserve deposits that mark the positioning and timing of base level changes and knickpoint migration (Granger et al., 1997; Anthony and Granger, 2004). Two

or more distinctive fluvial terraces at different elevations in a cave can be used to determine the average incision rate of the cave stream (I_r) and, therefore, the incision rate of a river at the surface since cave passages tend to reach an elevation equilibrium with its external base level. This can be done either through linear regression analysis of multiple burial ages vs. elevation data of the cave deposits (Granger et al., 1997) or by applying the average velocity equation to calculate the incision rate (I_r) as the ratio between the vertical erosion amplitude (ΔElv) and the burial age difference between two distinct fluvial terraces (t_b), from the relation: $I_r = \Delta Elv \cdot t_b^{-1}$. Examples of this approach to reconstruct valley deepening are demonstrated by Karmann (1994) and White (2007).

Major cave systems in the São Desidério River karst area are expected to become gradually younger to the upstream direction along the surface river as new limestone surfaces are exposed to punctual recharge by knickpoint migration, in a similar way to the plateau margin cave evolution model proposed by Crawford (1984) in the Cumberland Plateau, USA. This study considers the minimum age of cave development as the timing for knickpoint migration along the surface river. This is because limestone exposure occurs in response to the knickpoint migration, allowing punctual recharge directly through the limestone, accelerating the enlargement of conduits to form well-established flow routes in an underground tributary cave river system (Palmer, 1991; White, 2007).

Average knickpoint migration rates (K_m) can then be calculated by the ratio between the lateral distance of two cave systems along an external base level river ($\Delta Dist$) and the respective minimum ages of cave development (t_c), following the expression: $K_r = \Delta Dist \cdot t_c^{-1}$. We emphasize this is not a stream power modeling approach to calculate knickpoint migration (e.g. Whipple and Tucker, 1999). Instead, we consider that caves developing in a plateau margin context can provide knickpoint positioning through time, and so, are prone to be directly used as a proxy for calculating knickpoint migration by the ratio between distance and time.

During the calculations of river incision and knickpoint migration rates, the error of each parameter must be properly propagated.

Uncertainties for calculating river incision and knickpoint migration rates, as described above, are primarily associated with errors in fluvial terrace burial age and minimum cave development determination. When sediments enter a cave (burial), they can be later reworked along underground streams before deposition (Bosch and White, 2004). So, burial ages represent only the maximum ages for a cave fluvial terrace. Also, when fluvial deposits start to infill a cave under vadose flow conditions, groundwater flow routes had already begun to dissolve and enlarge passages in a previous phreatic flow stage (Ford, 1971; Palmer, 1991), so cave deposits mark only a minimum age for the development of cave systems.

Despite these uncertainties, the association between cave river fluvial terraces, minimum age of cave development, and base level fluctuations is a well-established and valid concept that has been widely applied over the last three decades (Granger et al., 1997; Granger et al., 2001; Anthony and Granger, 2004, 2007; Häuselmann et al., 2007; Polyak et al., 2008; Laureano et al., 2016; Nehme et al., 2020; Calvet et al., 2024), showing a consistent and coherent correspondence to landscape evolution, taken that careful study of cave geology features and speleogenesis is carried out and indicates this elevation correspondence to land surface features.

4. Results

4.1. Cave sediment chronology

All three studied cave systems preserve an extensive sedimentary record. Deposits with allochthonous origin (sediments transported into the cave from the river catchment on the surface) consist primarily of fluvial and lacustrine successions. In contrast, autochthonous sediments (produced inside the cave) consist of chemical deposits (speleothems)

and massive collapse block piles from the walls and ceiling in large chambers. The maximum observed thickness for sedimentary deposits is about 30 m, which is also the average difference in elevation from the upper and lower cave levels in the Manoel Lopes cave system.

Fig. 6 shows the sediment distribution along the studied caves and the location of the samples taken for geochronologic analyses. Most samples were taken from the upper passages since more evidence of different depositional episodes could be easily recognized. Despite being fewer in occurrence and sampling, deposits from the vadose canyons and the lower passage level were essential to characterize the timing of the base level drop and canyon incision.

Geochronological results for the burial ages are presented for cosmogenic nuclides (Table 1) and OSL analysis (Table 2). The end of fluvial or lake depositional trends in cave passages is marked by flowstone and carbonate mineral deposition that cover previous allocthonous successions, as indicated by U–Th series dating (Table 3).

4.2. Base level investigation

The São Desidério River represents the lower limit for tributary cave systems' entrenchment since underground rivers tend to adjust their long profiles according to the base level elevation on the surface. Therefore, knowing the maximum depth to which the São Desidério River has eroded its own channel bed is crucial for discussing base level fluctuations and calculating erosion rates to reconstruct the landscape evolution history.

A geophysical electrical resistivity investigation was performed to determine the thickness of alluvium deposits under the São Desidério River and, consequently, the at-a-valley depth of the limestone rock erosive surface. Five vertical electrical soundings (VES) were carried out to build a geophysical cross section perpendicular to the river's long axis (Fig. 7), showing that the São Desidério River entrenchment reached its maximum depth at the elevation of 439 m. The alluvium thickness below each VES station varies between 4.5 and 7 m, while the water level depth varies between 1.3 and 3.5 m. The maximum sediment thickness is approximately 13 m, as indicated by the difference in elevation between the top of the river terrace and the base of the deposits below the river channel.

The numerical results of this geophysical investigation are shown in Table 4 and Fig. 8, including the thickness and depth of all geoelectric layers recognized for each VES station. Layers 1 to 3 show a gradual

decrease in apparent resistivity values (ρ) along the first meters from the surface and are interpreted as residual soil and unconsolidated sediments in the vadose and phreatic zones. From 4.5 to 7 m depths, the abrupt increase in ρ values is interpreted as the transition between alluvial sediments and the carbonate rock (layer 4). The gradual increase in ρ values continues to the maximum investigated depth of 50 m. The abrupt reductions in ρ values, typically at a depth of 20 m, are explained by the spacing rearrangement of M and N electrodes that measure the electric potential difference.

4.3. Knickpoint migration rates

The geochronological analysis showed that the oldest deposits from every studied cave system in the São Desidério River karst area get progressively younger in the upstream direction (Fig. 9). This data agrees with the conceptual model adopted here for landscape and cave evolution (e.g. Crawford, 1984; Anthony and Granger, 2004), according to which the escarpment retreat and the exposure of new limestone outcrops to the upstream direction are associated with the development of successively younger cave systems. Although caves can start to form under the sandstone cover by infiltrating meteoric water, cave passage enlargement and fluvial deposition is more expressive after limestone exposure and punctual recharge directly into the soluble rock. Since knickpoint migration controls the retreat of the sandstone-limestone contact and the development of new cave systems controlled by punctual recharge, minimum ages of cave development can be used to calculate knickpoint migration rates.

In Bacupari cave, the oldest deposit for the João Rodrigues cave system was found as remnants of a very well-cemented conglomerate bar (sample BAC-11C, Table 1, ^{26}Al and ^{10}Be age: 2.64 ± 0.19 Ma) and sedimentary breccia that fills in phreatic proto-conduits near the ceiling (sample BAC-03, Table 3, ^{26}Al and ^{10}Be age: 3.03 ± 0.19 Ma). In Sopradeira cave, the oldest deposit for the Manoel Lopes cave system was sampled from conglomerates covered by calcite flowstone (sample SOP-13 A, Table 1, ^{26}Al and ^{10}Be age: 2.15 ± 0.18 Ma) at the transition between the upper cave level and the vadose canyon (Fig. 6). In Beleza cave, the oldest deposits occur in the upper cave passage, where very well-lithified conglomerates cover wall and ceiling pendants (sample BEL-01, Table 1, ^{26}Al and ^{10}Be age: 0.82 ± 0.30 Ma).

Knickpoint migration rates were thus calculated for two different stretches of the exposed limestone rock. The João Rodrigues and the

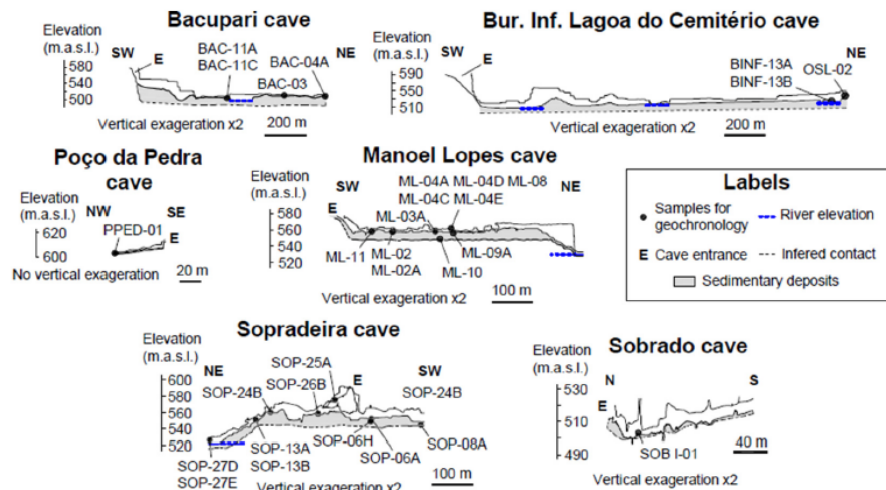


Fig. 6. Profiles of the caves and the location of the samples collected for geochronological analysis. The minimum thickness for the sedimentary deposits is indicated by a dashed line based on direct observations of natural erosional vertical exposures. The sediments comprise river, lake, and breakdown deposits.

Table 1
Cosmogenic ^{26}Al and ^{10}Be concentration results and the calculated burial ages and erosion rates from cave quartz-rich sediments.

Sample	Cave ^a	[^{10}Be] (10^6 at/g)	[^{26}Al] (10^6 at/g)	[$^{26}\text{Al}/^{10}\text{Be}$]	Burial age (Ma)	Erosion rate (m/Ma)	Elevation (m.a.s.l)
Água Branca	Surface	0.413 ± 0.010	2.170 ± 0.075	5.26 ± 0.23	0.31 ± 0.08	5.90 ± 0.28	670 ± 20
BAC-03	Bacupari	0.178 ± 0.006	0.246 ± 0.023	1.39 ± 0.14	3.03 ± 0.19	3.40 ± 0.39	512 ± 0.5
BAC-11A	Bacupari	0.415 ± 0.011	1.729 ± 0.098	4.17 ± 0.26	0.77 ± 0.12	4.60 ± 0.32	505 ± 0.5
BAC-11C	Bacupari	0.174 ± 0.007	0.295 ± 0.026	1.69 ± 0.17	2.64 ± 0.19	4.27 ± 0.47	505 ± 0.5
BEL-01	Beleza	0.099 ± 0.008	0.423 ± 0.058	4.25 ± 0.67	0.82 ± 0.30	19.70 ± 3.31	527 ± 0.5
BEL-02B	Beleza	0.258 ± 0.009	1.224 ± 0.044	4.75 ± 0.23	0.55 ± 0.10	8.52 ± 0.45	511 ± 0.5
CT-122	Surface	0.138 ± 0.005	0.982 ± 0.042	7.13 ± 0.39	-0.25 ± 0.11	24.36 ± 1.40	650 ± 20
ML-04A	Manoel Lopes	0.105 ± 0.003	0.415 ± 0.018	3.97 ± 0.20	0.96 ± 0.10	17.43 ± 0.94	559 ± 0.5
ML-04C	Manoel Lopes	0.091 ± 0.004	0.614 ± 0.027	6.78 ± 0.45	-0.14 ± 0.13	35.14 ± 2.43	560 ± 0.5
ML-08	Manoel Lopes	0.065 ± 0.003	0.336 ± 0.018	5.18 ± 0.34	0.42 ± 0.13	37.14 ± 2.58	559 ± 0.5
ML-09A	Manoel Lopes	0.106 ± 0.004	0.614 ± 0.030	5.80 ± 0.38	0.18 ± 0.13	25.55 ± 1.74	552 ± 0.5
ML-10	Manoel Lopes	0.065 ± 0.002	0.236 ± 0.020	3.63 ± 0.34	1.16 ± 0.18	25.59 ± 2.51	545 ± 0.5
PPED-01	Poço de Pedra	0.247 ± 0.010	0.812 ± 0.058	3.29 ± 0.27	1.29 ± 0.16	6.05 ± 0.54	600 ± 0.5
SOB I-01	Sobrado I	0.180 ± 0.006	0.907 ± 0.033	5.05 ± 0.24	0.45 ± 0.10	13.00 ± 0.67	503 ± 0.5
SOB II-01	Sobrado II	0.073 ± 0.004	0.429 ± 0.039	5.87 ± 0.64	0.16 ± 0.21	37.51 ± 4.27	511 ± 0.5
SOP-06A	Sopradeira	0.244 ± 0.007	1.388 ± 0.061	5.69 ± 0.28	0.19 ± 0.10	10.85 ± 0.57	552 ± 0.5
SOP-06H	Sopradeira	0.187 ± 0.007	1.159 ± 0.042	6.21 ± 0.31	0.02 ± 0.10	15.52 ± 0.83	548 ± 0.5
SOP-13A	Sopradeira	0.119 ± 0.007	0.262 ± 0.020	2.20 ± 0.21	2.15 ± 0.18	8.26 ± 0.85	550 ± 0.5
SOP-25A	Sopradeira	0.123 ± 0.008	0.554 ± 0.033	4.51 ± 0.40	0.69 ± 0.17	16.94 ± 1.59	575 ± 0.5
SOP-26B	Sopradeira	0.110 ± 0.004	0.565 ± 0.031	5.12 ± 0.30	0.44 ± 0.12	21.48 ± 1.33	558 ± 0.5

UTM coordinates for surface samples: Água Branca E 540438/ N 8638264; CT-122 E 499111/ N 8622524; Zone 23; τ_{Al} and τ_{Be} mean lives considered for age calculation where respectively 1.021 ± 0.025 and 2.001 ± 0.017 Ma (Nishiizumi, 2004; Chmeleff et al., 2010; Korschinek et al., 2010). The Initial ratio "Rher" used was 6.8 (Nishiizumi et al., 2007). ^{26}Al and ^{10}Be production rates calculated were respectively 31.41 and 4.91 at $\text{g}^{-1} \text{yr}^{-1}$, following the method proposed by Lal (1991). The erosion rates were calculated using the method presented by Granger and Muzikar (2001), with a free path length for neutrons of 160 g/cm^2 and a rock density (shielding over the cave roof) of 2.6 g/cm^3 , resulting in 61 cm of penetration length (Granger, 2014).

^a Samples collected outside of the caves for the zero-age determination are indicated as "surface".

Manoel Lopes cave systems are located along the São Desidério River (Fig. 2), so the minimum ages of cave development can be used to calculate the knickpoint migration rate in the same river. On the other hand, the Beleza and Manoel Lopes cave systems are located between the Nado River and its junction with the São Desidério River (Fig. 2), and they give information about the knickpoint migration rate in the Nado River. The calculation parameters and results for knickpoint migration rates are presented in Table 5.

The knickpoint retreat rate calculated in the São Desidério River (3782 ± 984 m/Ma) is higher than in the Nado River (1122 ± 198 m/Ma). This is coherent because the major river in the watershed will usually have a higher flow and erosive potential than its tributaries. From these results, it is also possible to infer that the São Desidério River, as the major stream in the watershed, maintained a proportionally higher Q (stream flow) to S (gradient) ratio in relation to the Nado River from the late Pliocene to the present, that is, the main watershed structure defined by the two rivers was probably the same during this period.

4.4. Erosion rates in the catchment area

Erosion rates presented in Table 1 are derived from cosmogenic ^{26}Al and ^{10}Be isotope data and represent pre-burial erosion conditions in the catchment areas of the cave systems, where the Uruçua Group sandstone is the dominant rock type. From the exposure vs. erosion diagram (burial dating plot) in Fig. 10 it is possible to recognize significantly lower paleo erosion rates for the João Rodrigues cave system (min.: 4.3 ± 0.5 ; max.: 6.1 ± 0.5 m/Ma; arithmetic mean: 4.8 ± 0.4 m/Ma) in comparison to the Manoel Lopes and Beleza cave systems (min.: 8.3 ± 0.8 ; max.: 37.5 ± 4.3 m/Ma; arithmetic mean: 21.1 ± 1.7 m/Ma). Although all cave systems belong to a similar geological context, their distinct recharge to discharge groundwater flow paths and surface catchment area morphology may explain those differences in erosion rates.

The average slope of a given surface drainage basin tends to be directly proportional to runoff rates. So, landscape gradient is one of the morphological parameters with the most significant influence over erosion (Vente et al., 2007; Portenga and Bierman, 2011). The João

Rodrigues cave system catchment basin has an average landscape gradient of 0.0068 (0.68 %), lower than the Manoel Lopes cave system, with 0.0095 (0.95 %). This suggests that the catchment area of the João Rodrigues cave system should have lower erosion rates in comparison to the Manoel Lopes and Beleza cave systems, in agreement with erosion rates calculated from cosmogenic isotopic data.

The burial dating plot in Fig. 10 also shows differences in erosion rate dispersion for the studied cave systems. While the João Rodrigues cave system has low dispersion and a reasonably good alignment with the radioactive decay lines, data from the Manoel Lopes and Beleza cave systems show a much higher dispersion. When individual caves are grouped in the Manoel Lopes cave system, a much better alignment to the radioactive decay lines is achieved (dashed clusters).

This data scatter pattern is probably a result of each cave system's differences in cave passage morphology and recharge mechanisms. The João Rodrigues cave system has one major sinking stream that forms very rectilinear cave passages (Fig. 3), so only one catchment is associated with this system. On the other hand, the Manoel Lopes cave system has many different sinking streams that form a dendritic passage morphology (Fig. 3), so sediment is transported to the caves by different catchment areas. The availability of different transport routes and clastic sediment provenance to a cave system may favor higher cosmogenic erosion rate data dispersion since hill slope and fluvial processes may vary from one catchment area to another.

Erosion rate data also show significant variations over time (Fig. 11). Despite a general trend for a gradual erosion rate increase with time, linear regression analysis shows a low correlation between the data parameters in all cave systems ($R^2 < 0.6-0.1$). This scatter indicates that erosion rate variation was not linear over time.

4.5. Incision rates in the limestone

Fluvial deposits that cover limestone surfaces at different elevations in the caves, like flat horizontal rock terraces and wall notches, were used to calculate the incision rate of the underground river when downcutting through the limestone. The data for this calculation came from the Manoel Lopes cave system because two distinctive cave levels were recognized (Fig. 4), allowing us to associate a base level drop event

Table 2
OSL burial ages and luminescent and radiation production results for quartz rich cave sediments.

Sample	Cave	ED* (Gy)	Approved aliquots	K (%)	Th (ppm)	U (ppm)	Gamma (Gy/ka)	Beta (Gy/ka)	Cosmic dose rate (Gy/ka)	Total dose rate (Gy/ka)	OD** (%)	Age - MAM (ka)	Age - CAM (ka)	Elevation (m. a.s.l.)
ML-02	Manoel Lopes	41.2 ± 1.3	21	0.149	1889	0.485	0.18	0.219	0.0278 ± 0.0094	0.4264 ± 0.0362	13	83.0 ± 7.1	96.6 ± 8.7	554 ± 0.5
BAC-04A	Bacupari	3.7 ± 0.2	23	0.016	0.869	0.305	0.079	0.071	0.0053 ± 0.0003	0.1530 ± 0.0135	23.4	19.0 ± 1.8	24.2 ± 2.5	508 ± 0.5
BNF-01	Bur. Inf. Lagoa do Cemitério	11.4 ± 0.7	22	0.148	3.363	0.689	0.253	0.256	0.0021 ± 0.0002	0.5117 ± 0.0415	30.2	13.5 ± 1.2	22.3 ± 2.3	538 ± 0.5
BNF-13A	Bur. Inf. Lagoa do Cemitério	2.45 ± 0.1	19	0.067	3.484	1.261	0.318	0.289	0.001 ± 0.0001	0.6081 ± 0.525	54.3	4.0 ± 0.4	14.8 ± 1.3	524 ± 0.5
BNF-13B	Bur. Inf. Lagoa do Cemitério	2.07 ± 0.16	23	0.025	3.232	1.130	0.287	0.238	0.001 ± 0.0001	0.5260 ± 0.0466	62.6	3.9 ± 0.5	12.0 ± 1.1	524 ± 0.5
SOP-27D	Sopradreira	1.78 ± 0.06	19	0.29	5.972	2.197	0.506	0.533	0.001 ± 0.0001	1.0400 ± 0.0767	28.7	1.7 ± 0.1	3.1 ± 0.2	526 ± 0.5
SOP-27E	Sopradreira	1.27 ± 0.07	22	0.36	10.446	2.418	0.732	0.697	0.001 ± 0.0001	1.4293 ± 0.1054	44.4	0.9 ± 0.1	1.8 ± 0.1	526 ± 0.5
DAG-01	Olho D'água	0.88 ± 0.03	21	0.046	1.055	0.375	0.104	0.108	0.0832 ± 0.0083	0.2947 ± 0.0221	89.8	3.0 ± 0.2	11.2 ± 0.8	486 ± 0.5

MAM: minimum age model; CAM: central age model. SAR-OSL protocol used for equivalent dose analysis in quartz grain aliquots (Murray and Wintle, 2000); Steps: 1 - Initial dose; 2 - Pre-heat at 240 °C for 10s; 3 - OSL at 125 °C for 40s; 4 - Test doses; 5 - Pre-heat at 160 °C; 6 - OSL at 125 °C for 40s; 7 - Blue bleach at 280 °C for 40s; 8 - Return to step 1.

* ED: Equivalent dose.
** OD%: Overdispersion.

Table 3
U-Th series geochronological results for carbonate speleothems.

Sample	Cave	²³⁸ U (ppb)	²³² Th (ppt)	²³⁰ Th / ²³² Th (at x10 ⁻⁶)	d ²³⁴ U* (measured)	²³⁰ Th / ²³⁸ U (activity)	d ²³⁴ U _{initial} ** (corrected)	²³⁰ Th Age (yr BP)*** (corrected)	Elevation (m.a.s.l.)
ML-03-A	Manoel Lopes	108.5 ± 0.2	33.393 ± 0.2	670 ± 3	165.5 ± 22.1	0.6830 ± 0.0077	211 ± 29	85,840 ± 6241	554 ± 0.5
ML-04D-4 mm	Manoel Lopes	554.2 ± 2.1	168 ± 3	65.129 ± 1359	291.0 ± 3.6	1.1950 ± 0.0051	551 ± 9	226,256 ± 3669	560 ± 0.5
ML-04D-47 mm	Manoel Lopes	291.0 ± 0.9	907 ± 18	6.428 ± 131	306.2 ± 3.6	1.2154 ± 0.0047	583 ± 9	228,243 ± 3512	560 ± 0.5
ML-04E-17 mm	Manoel Lopes	1110.4 ± 6.9	26.943 ± 554	924 ± 19	317.4 ± 5.5	1.3601 ± 0.0094	824 ± 39	337,875 ± 15,558	560 ± 0.5
ML-06-65 mm	Manoel Lopes	48.2 ± 0.6	3.614 ± 73	223 ± 5	929.5 ± 25.0	1.012 ± 0.0142	1.147 ± 32	74,523 ± 2099	565 ± 0.5
ML-06-850 mm	Manoel Lopes	42.1 ± 0.5	312 ± 7	2.594 ± 65	-250.3 ± 25.9	0.7423 ± 0.0086	-1.052 ± 160	508,756 ± 40,354	554 ± 0.5
ML-11C	Manoel Lopes	28.0 ± 0.1	4.630 ± 92	74 ± 2	78.4 ± 5.9	0.7423 ± 0.0086	110 ± 8	119,946 ± 4245	554 ± 0.5
CAT-02-1	Catão	3200.6 ± 5.7	13.043 ± 261	209 ± 4	488.2 ± 1.8	0.0516 ± 0.0002	493 ± 2	3698 ± 58	555 ± 0.5
CAT-02-3	Catão	1657.4 ± 11.5	23.236 ± 492	44 ± 1	578.0 ± 5.7	0.0373 ± 0.0003	582 ± 6	2281 ± 184	555 ± 0.5
CAT-02-5	Catão	1860.3 ± 3.6	35.844 ± 720	32 ± 1	496.8 ± 2.4	0.0375 ± 0.0003	601 ± 3	2175 ± 248	555 ± 0.5
CAT-02-8	Catão	3499.3 ± 24.0	9.258 ± 194	374 ± 8	494.7 ± 5.1	0.0600 ± 0.0005	501 ± 5	4343 ± 52	555 ± 0.5
CAT-02-9	Catão	2455.5 ± 13.2	17.278 ± 358	123 ± 3	461.8 ± 4.5	0.0526 ± 0.0004	467 ± 5	3779 ± 103	555 ± 0.5

U decay constants: $\lambda_{238} = 1.55125 \times 10^{-10}$ (Jaffey et al., 1971) and $\lambda_{234} = 2.82206 \times 10^{-6}$ (Cheng et al., 2013). The decay constant: $\lambda_{230} = 9.1705 \times 10^{-6}$ (Cheng et al., 2013). Corrected ²³⁰Th ages assume the initial ²³⁰Th/²³²Th atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$. Those are the values of a material at secular equilibrium, with the bulk earth ²³²Th/²³⁸U value of 3.8. The errors are arbitrarily assumed to be 50 %.

* $d^{234}U = ((^{234}U / ^{238}U)_{activity} - 1) \times 1000$.

** $\delta^{234}U_{initial}$ was calculated based on ²³⁰Th age (T), i.e., $\delta^{234}U_{initial} = \delta^{234}U_{measured} \times e^{\lambda_{234}T}$.

*** B.P. stands for "Before Present" where the "Present" is defined as 1950 A.D.



Fig. 7. Geological interpretation of the São Desidério River geophysical cross-section. The erosive contact between the alluvium deposits and the limestone rock is represented. The locations of the vertical electrical soundings are indicated as “VES”. Note the maximum sediment thickness of 13 m from the top of the river terraces to the lowest limestone erosive surface elevation. A reference station at the profile was tied to GNSS positioning data for a more precise elevation representation.

Table 4

Interpretation of the AB/2 electrode distance (equivalent to the depth in meters) versus ρ curves, establishing the limits for each geoelectric layer. Different layers are interpreted from curve inflection points in Fig. 7, and they correspond to distinct geological environments. VES: vertical electrical sounding station; n: geoelectric layer; ρ : apparent resistivity; h: depth variation; d: depth; alt.: depth with 0 m reference to the surface; RMS: root mean square (error).

	n	ρ (m Ω)	h (m)	d (m)	alt. (m)	RMS (%)
VES-2	1	20.4	1.2	1.2	-1.2	12.9
	2	5.9	1.7	2.9	-2.9	
	3	150	0.6	3.5	-3.5	
	4	40	3.5	7.0	-7.0	
	5	7202	-	-	-	
VES-3	1	56.7	2.8	2.8	-2.8	12.2
	2	46.4	0.7	3.5	-3.5	
	3	11.8	3.5	7	-7	
	4	17,393	-	-	-	
VES-4	1	70.6	1.2	1.2	-1.2	5.34
	2	20	0.1	1.3	-1.3	
	3	10.6	4.2	5.5	-5.5	
	4	5150	-	-	-	
VES-5	1	85.1	0.75	0.75	-0.75	6.59
	2	20	1.75	2.5	-2.5	
	3	10	2	4.5	-4.5	
	4	135	-	-	-	
VES-6	1	101	0.579	0.579	-0.579	2.07
	2	32.3	1.52	2.099	-2.099	
	3	6.27	2.9	4.999	-4.999	
	4	1895	-	-	-	

with the fluvial deposits from different cave passage elevations.

The oldest river terrace encountered in the Manoel Lopes cave system occurs in the upper passage level of the Sopradeira cave (sample SOP-13A, Table 1, ²⁶Al and ¹⁰Be age: 2.15 ± 0.2 Ma), and this probably represents a condition prior to the hydraulic abandonment of the upper cave level. In the Manoel Lopes cave, the oldest vadose canyon infill deposit is represented by well-lithified conglomerates (sample ML-10, Table 1, ²⁶Al and ¹⁰Be age: 1.16 ± 0.2 Ma) at the base of the canyon. As this is older than any other deposits preserved in the lower cave passage level, it may represent the base of the canyon stratigraphy, marking the maximum age for the lower passage level development (Fig. 12).

It should be kept in mind that the transition between vadose cave passages oriented parallel to the dip of the strata and phreatic passages parallel to the strike (piezometric point) was observed in the Manoel Lopes cave system. Following the cave level concept as discussed by Palmer (1987, 2007) and Calvet et al. (2024), this is unequivocal evidence that the lower passage level was developed in the epiphreatic zone, in equilibrium with an external base level. Therefore, the lower passage level cannot be older than the vadose canyon above it, so the minimum age for the canyon entrenchment is also the maximum age for the lower passage level development.

The elevation of the upper cave level fluvial terrace (sample SOP-13A) is known and precisely determined at 550 ± 0.5 m.a.s.l. by cave

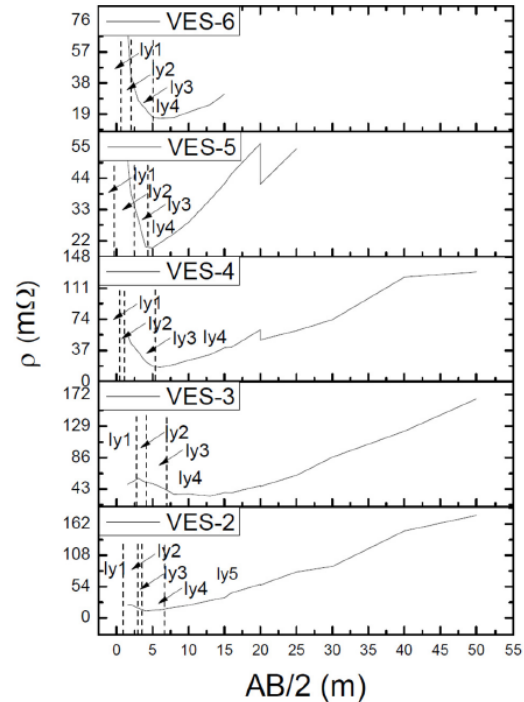


Fig. 8. Results from each electrical sounding station (VES), represented as AB/2 distance (investigated depth) vs. average apparent resistivity (ρ) graphs.

survey and GNSS data analysis methods (Table 1), as well as the average elevation of the flat limestone surface underneath those deposits (558 ± 1 m.a.s.l.). On the other hand, the elevation of the rock floor at the lower passage level is unknown since modern river deposits entirely cover it. This is a problem when calculating river incision rates because the vertical amplitude of the canyon entrenchment must be known.

Two different approaches were adopted to estimate the elevation of the limestone floor at the lower cave level. The first assumed that the maximum depositional thickness in the cave passage is equivalent to the maximum thickness of alluvial deposits at the São Desidério River, which is equal to 13 m (Fig. 7), resulting in an elevation of 509 m.a.s.l. to the buried limestone floor. The second consisted of extrapolating the elevation of the rocky channel bed at the São Desidério River to the lateral position of the cave fluvial terraces that were dated, using for this the overall passage gradient of the Manoel Lopes cave system, resulting in an elevation of 503 m.a.s.l. The cave passage gradient was determined as 0.017 (1.7 %) by measuring the difference in elevation between the São Desidério River bed and the active underground river bed further upstream at the Manoel Lopes cave system. In Table 6, the calculation of the fluvial entrenchment rates is demonstrated using two elevation scenarios of the rock floor in the lower passage level. The average entrenchment rate using both scenarios is 52.5 ± 13.0 m/Ma.

4.6. Incision rates in the unconsolidated sediment

To calculate erosion rates that correspond to the removal of the unconsolidated sedimentary infill of a cave passage, deposits belonging to the moments of aggradation and sediment removal events must be correlated. The youngest fluvial terraces that occur in the upper level of the Manoel Lopes cave system correspond to a fine to medium sand fluvial bar (sample ML-02, Table 2, OSL age: 96.6 ± 8.7 ka), where a

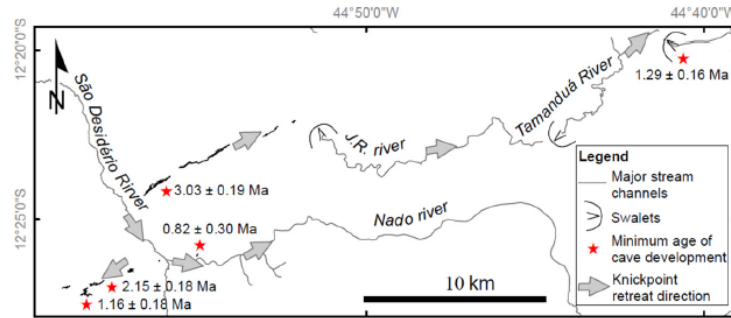


Fig. 9. Schematic representation of knickpoint and escarpment retreat. The minimum age of the caves gets progressively younger in the upstream direction, confirming the adopted plateau margin cave evolution model (sensu Crawford, 1984). All ages shown are derived from cosmogenic ²⁶Al and ¹⁰Be data (Table 1).

Table 5
Knickpoint retreat rates for the São Desidério and Nado rivers, calculated through ²⁶Al and ¹⁰Be burial ages. Error propagation was properly calculated until the final erosion rate results. Abbreviations: "JR": João Rodrigues; "ML": Manoel Lopes; "BEL": Beleza.

Knickpoint retreat rate - São Desidério river					
Minimum age JR system (Ma)	Sample	Minimum age ML system (Ma)	Sample	Lateral distance (m)	Upstream retreat rate (m/Ma)
3.03 ± 0.19	BAC-03	2.15 ± 0.18	SOP-13A	3781.5 ± 30	3782 ± 964
Knickpoint retreat rate - Nado river					
Minimum age ML system (Ma)	Sample	Minimum age BEL system (Ma)	Sample	Lateral distance (m)	Upstream retreat rate (m/Ma)
2.15 ± 0.18	SOP-13A	0.82 ± 0.30	BEL-01	2244.2 ± 30	1122 ± 198

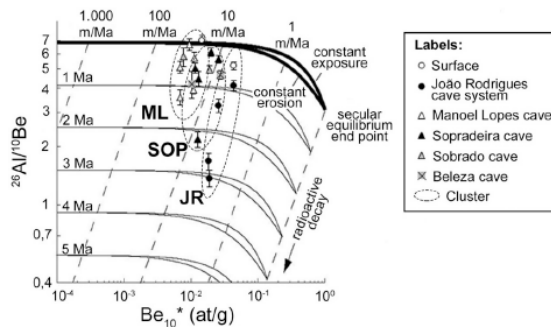


Fig. 10. Exposure vs. burial diagram, comparing the ²⁶Al/¹⁰Be ratio with ¹⁰Be* concentration normalized to the reference production rate. Reference curves for burial ages and erosion rates are indicated. Data corresponding to the same cave system or individual caves are grouped, as indicated by the dashed ellipses and their respective labels (JR: João Rodrigues, SOP: Sopradeira, ML: Manoel Lopes). Note how each cave cluster has a different position in relation to the radioactive decay curves, indicating significant differences in erosion rates for each cave system's catchment areas.

carbonate flowstone covers the top of this unconsolidated deposit (sample ML-03A, Table 3, U–Th age: 85.8 ± 6.2 ka). This fluvial bar probably represents the last time the upper passage level was active,

before a new sediment removal event brought the riverbed to the lower cave level again.

The early stage of deposition after this last base level drop event is probably represented by the oldest unconsolidated sediments in the lower passage level. In the Olho D'água cave, the base of a fissure-like passage, approximately 15 m high and 2 m wide, filled almost entirely with coarse to medium quartz sand, is the oldest sediment deposit encountered in the lower passage level (sample DAG-01, Table 2, OSL age: 11.2 ± 0.8 ka). This sample was taken from only 2 m above the active river elevation, suggesting that this is a close position to the base of the stratigraphy in the lower passage level. Also, in Sopradeira cave, a 1.5 m deep trench was carved in a muddy sand fluvial bar aside the modern river channel (samples SOP-27D and E, Table 2, OSL ages: 3.1 ± 0.2 ka and 1.8 ± 0.1 ka), so this probably represents the sediment transport, deposition and reworking much after the last base level drop event.

In Table 7, the calculation of the underground river incision rates is shown, and results vary from 576.5 ± 59.9 to 743.2 ± 63.5 m/Ma. The minimum and maximum depositional ages of the fluvial bar at the upper passage level were calculated using a combination of different dating methods. The OSL data represents the maximum age of deposition since the fluvial bar cannot be older than the sediment entry into the cave. The U–Th data gives a minimum deposition age since calcite flowstone crystallization must postdate the fluvial deposition. There is a 10 ka difference between ML-02 (maximum) and ML-03A (minimum) ages, corresponding to the fluvial deposition age determination error. Maximum and minimum incision rates calculated for each channel bed elevation scenario show differences of 85.7 to 96.1 m/Ma, representing a deviation of 9 to 10 % around absolute values.

Erosion rates shown in Table 7 have an arithmetic average of 657.0 ± 31.0 m/Ma, 10 to 15 times greater than the average incision rate in the limestone rock (Table 6). These results are consistent with the physical properties of the different materials that undergo erosion, as cohesive limestone rock will be much more resistant to erosion than the unconsolidated river deposits.

5. Discussion

5.1. Age relationships in the karst landscape evolution

Knickpoint migration along the São Desidério River controls the retreat of the sandstone cover, so its migration rate can be used to estimate when the limestone surface was exposed and a typical karst landscape started to form in this watershed. Similarly, incision rates in underground rivers can be used to reconstruct part of the valley entrenchment history. Fluvial erosion rates vary according to climate changes and other geomorphological and lithological parameters, so applying the same rates over time is essentially a rough approximation,

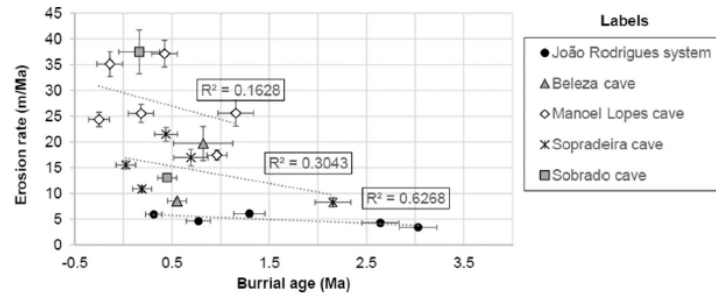


Fig. 11. Catchment area erosion rates variation in time for the São Desidério karst area over the last 3 Ma. The data is derived from cosmogenic ²⁶Al and ¹⁰Be dating (Table 1).

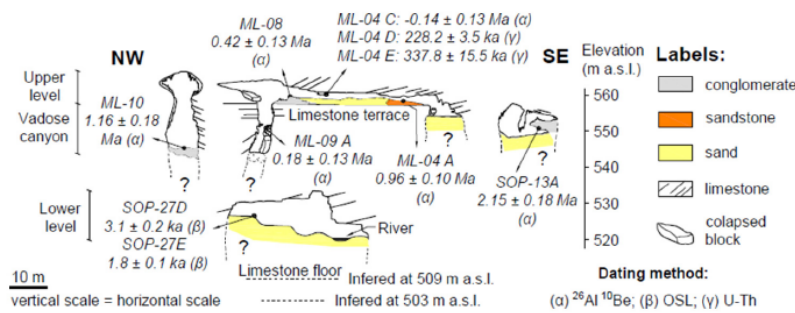


Fig. 12. Passage cross sections and respective elevation references in the Manoel Lopes and Sopradeira caves.

Table 6
Fluvial entrenchment rates over the rocky channel bed at the Manoel Lopes cave system.

Vertical entrenchment - Manoel Lopes cave/ Sopradeira cave							
Channel bed type	Min. age - upper level (Ma) (²⁶ Al- ¹⁰ Be)	Sample	Max. age - lower level (Ma) (²⁶ Al- ¹⁰ Be)	Sample	Upper level elev. (m) ^a	Lower level elev. (m) ^{b,c}	Incision rate (m/Ma)
Rocky α	2.15 ± 0.18	SOP-13A	1.16 ± 0.18	ML-10	558 ± 0.5	509 ± 0.5	49.5 ± 12.3
Rocky β	2.15 ± 0.18	SOP-13A	1.16 ± 0.18	ML-10	558 ± 0.5	503 ± 0.5	55.6 ± 13.8

α: estimate of the lower level rocky channel bed using 13 m of maximum sediment thickness; β: estimate of the lower level rocky channel bed by extrapolating the rocky channel bed at the surface river by the passage gradient.
^a Rocky channel bed at the upper level directly observed.
^b Rocky channel bed elevation estimated through geophysical cross section data at the São Desidério river.

Table 7
Fluvial entrenchment rates over the unconsolidated sedimentary channel bed in the Manoel Lopes cave system.

Vertical entrenchment - Manoel Lopes cave/ Sopradeira cave							
Channel bed type	Upper terrace age (ka) (OSL and U-Th)	Sample	Lower terrace age (ka) (OSL)	Sample	Upper level elev. (m) ^a	Lower level elev. (m) ^{b,c}	Incision rate (m/Ma)
Sedimentary 1 α	96.6 ± 8.7	ML-02	11.2 ± 0.8	DAG-01	558 ± 0.5	509 ± 0.5	576.5 ± 59.9
Sedimentary 1 β	96.6 ± 8.7	ML-02	11.2 ± 0.8	DAG-01	558 ± 0.5	503 ± 0.5	647.1 ± 67.1
Sedimentary 2 α	85.8 ± 6.2	ML-03A	11.2 ± 0.8	DAG-01	558 ± 0.5	509 ± 0.5	662.2 ± 56.7
Sedimentary 2 β	85.8 ± 6.2	ML-03A	11.2 ± 0.8	DAG-01	558 ± 0.5	503 ± 0.5	743.2 ± 63.5

1: maximum age of deposition for the fluvial bar, given by the sediment burial age (OSL CAM); 2: minimum age of deposition for the fluvial bar, given by the calcite crystallization age (U-Th); α: estimate of the lower level rocky channel bed using 13 m of maximum sediment thickness; β: estimate of the lower level rocky channel bed by extrapolating the rocky channel bed at the surface river by the passage gradient.
^a Rocky channel bed at the upper level directly observed.
^b Rocky channel bed elevation estimated through geophysical cross section data at the São Desidério river.

depending on the dataset representability, as pointed out by White (2007).

Using the São Desidério river knickpoint migration rate (3782 ± 984 m/Ma, Table 6) and the lateral migration distance measured in a topographic map along the river thalweg from the downstream end of the João Rodrigues cave system to the geological contact between the limestone unit and the underlying metapelitic unit (Fig. 2), equivalent to 11 km, a retreat interval of 2.9 ± 0.8 Ma is achieved. Similarly, raising the São Desidério River valley thalweg using the entrenched limestone vertical extent of 140 m (Figs. 1 and 2) at an average rate of 52.5 ± 13.0 m/Ma (Table 6), the erosion surface was at the top of the limestone unit at 2.7 ± 1.3 Ma.

Both estimates are coherent with the minimum age of the João Rodrigues cave system (sample BAC-03, Table 3, ^{26}Al and ^{10}Be age: 3.03 ± 0.19 Ma), when punctual recharge directly through the limestone rock started, increasing the enlargement rate of cave passages after the sandstone cover was partially removed. Therefore, this represents the timing for the onset of limestone exposure and prominent surface karst landscape development. Since this time projection does not extrapolate the burial ages from this study, river incision and knickpoint migration rates may be representative of the period under analysis.

Valadao (1998, 2009) places the uplift of the Central Brazilian Plateau between the Cretaceous and the Miocene, using morphological and geological relationships between the extensive erosion surface that cut the cap sandstones of the Urucuia Group (Sanfranciscana Basin) and the shales and limestones of the Sabiá Formation (Recôncavo Basin). The uplift of the plateau escarpments and the newly established hydraulic gradient would then promote a diffuse recharge from the sandstone cap rock to the underlying limestone unit. Limestone dissolution taking place at depth, below an older and insoluble cap rock, is termed interstratal karstification (sensu Ford and Williams, 1989). This process was probably responsible for the initiation and enlargement of conduit aquifer systems in the São Desidério karst before the limestone was exposed to the surface by erosion.

5.2. Trigger mechanisms for base level fluctuation

The oldest cave deposit records in the São Desidério karst (that also represents the oldest records in Brazilian caves up to date), and the diversity of underground fluvial terraces with different ages in the upper and lower cave levels, shows that, since the late Pliocene, the São Desidério River faced periods of base level stability, interchanged with pulses of base level lowering (river incision) and rise (river aggradation).

The causes associated with those base level fluctuations are difficult to discuss due to the lack of tectonic and paleoclimatic records. Tectonic uplift data based on apatite fission-track thermochronology in the São Francisco Craton are always older than 50 Ma, do not cover the area of the Central Brazilian Plateau, and have no resolution to allow the reconstruction of crustal cooling during the Neogene and Quaternary periods (Harman et al., 1998; Japsen et al., 2012; Jelinek et al., 2014). Paleoclimate records in Brazil are based on a wide variety of different proxies, like speleothem, lake, ocean, plant, charcoal, and pollen records, but are mostly restricted to the last 20–100 ka from present (Ledru et al., 2001; Cruz Jr. et al., 2005; Pessenda et al., 2010; Novello et al., 2012; Stríkis et al., 2015; Utida et al., 2020; Reis et al., 2022), and rarely reach a million-year scale (Kern et al., 2023). Therefore, there is no possibility of a direct comparison of the data from this study with paleoclimatic records.

The base level lowering event that caused the abandonment of the upper cave level and the entrenchment of vadose canyons down to the new established lower cave level could be associated with the migration of knickpoints along the São Desidério River. Since the minimum ages of the cave systems get progressively younger in the upstream direction in this watershed, the migration of knickpoints could be the cause for major base level lowering events. This is a hypothesis to explain high amplitude (30–50 m) and long river incision trends (1–2 Ma) that

require further investigation.

Climate change is a potential cause for cave passage aggradation (fluvial reworking) and sediment removal events on a scale of 10^4 – 10^5 years in the São Desidério karst. Humidity and vegetation respond to the stability of the hillslope and the sediment production in the catchment areas, as the processes discussed by Langbein and Schumm (1958) and Acosta et al. (2015). Since very low or high precipitation will disfavor erosion, respectively, due to the lack of transport capacity and to favoring hillslope stability by vegetation growth, an intermediate stage between rainfall and vegetation development is expected to cause a peak in hill slope denudation rates and sediment production.

Auler et al. (2009) interpreted cyclic sedimentation events in caves associated with humidity variation for the last 250 ka in central and eastern Brazil, based on U–Th dating of speleothems that cover fluvial bars in caves and $\delta^{18}\text{O}$ isotopic records from stalagmites. This approach would still have to be attempted in the context of the Central Brazilian Plateau to test the hypothesis of climate control over base level fluctuation events.

5.3. Erosion rates in a cratonic environment

The erosion rates from this study in the Central Brazilian Plateau, western São Francisco Craton, vary from 3.4 ± 0.4 to 37.5 ± 4.3 m/Ma during the last 3 Ma (Table 1). This variation may be explained by lithological and geomorphological aspects. The Urucuia Group sandstone is predominantly composed of fluvial and aeolian sedimentary facies (Campos and Dardenne, 1997b), but local occurrences of iron-rich lateritic crusts, known as canga, may locally induce lower erosion rates. Also, different catchment areas with higher or lower landscape gradients tend to show a positive correlation with the erosion rates in the São Desidério karst (Fig. 10).

In the central São Francisco Craton, Laureano et al. (2016) obtained erosion rates in the Chapada Diamantina Plateau from cosmogenic ^{26}Al and ^{10}Be burial dating of cave sediments. The erosion rates reported by these authors range from 1.33 ± 0.09 to 2.56 ± 0.14 m/Ma during the last 2 Ma from present. An important characteristic of the cave system catchment area in Chapada Diamantina is the extremely high resistance to erosion of the provenance rocks, characterized by Proterozoic quartzites.

Other cratonic areas around the world with ancient landscape features (e.g. bedrock inselbergs and high plateau surfaces) have erosion rates typically ranging from 0.5 to 5 m/Ma, as demonstrated by geochronological studies in the Canadian shield, southern and central Australia, South Africa, the central Namib desert and southern India (Bierman and Turner, 1995; van der Wateren and Dunai, 2001; Flowers et al., 2006; Gunnell et al., 2007; Burke and Gunnell, 2008). Nevertheless, higher erosion rates in cratonic environments (10 to 25 m/Ma) have also been reported as a consequence of differential erosion (Gunnell et al., 2007) or shorter distances from tectonic boundaries (Hecht and Oguchi, 2017). Therefore, the erosion rate data in the São Francisco Craton based on cave records from Laureano et al. (2016) and this study are coherent with other cratonic areas in the world.

6. Conclusion

The association between cave sediment geochronological analysis and careful study of cave erosion and depositional features showed that knickpoint migration controls the evolution of progressively younger caves in the upstream direction in the São Desidério River watershed. Knickpoint migration rates in the limestone through sandstone contact during the last 3 Ma were determined as 3782 ± 984 m/Ma in the São Desidério River and 1122 ± 198 m/Ma in its major tributary, the Nado River.

Between approximately 1 and 2 Ma from present, an expressive base level drop event was marked by vadose canyon entrenchment cutting through the limestone rock pavement in the caves, with an average

incision rate of 52.5 ± 13.0 m/Ma. After successive fluvial aggradation and reworking of the conduits, the incision rate of the last erosion trend to wash out the sediments down to the modern river passage level was determined as 657.0 ± 31.0 m/Ma. The age determination error for the deposition of fluvial bars in the studied caves is approximately 10 ka, based on the age difference between burial (cosmogenic ^{26}Al and ^{10}Be) and calcite precipitation (U–Th series). Erosion rates in the catchment areas of the sandstone-covered plateau since the Late Pliocene ranged from 3.40 ± 0.39 to 37.51 ± 4.27 m/Ma, and this variation was demonstrated to correspond to local watershed gradient conditions.

The erosion rates presented here were obtained from geochronological analysis of cave deposits, and they are, to the best of our knowledge, the first quantitative data reported in the Central Brazilian Plateau. This dataset may help understand the pace of the landscape evolution in stable terrains from South America during the Cenozoic and the origin of regional-scale, high-elevation plateaus. Future studies can use erosion rates to calibrate numerical models for knickpoint migration and crustal evolution to depict the long-term erosion history of intra-continental escarpments.

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CRedit authorship contribution statement

L. Padoan: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. I. Karmann: Supervision, Project administration, Investigation, Funding acquisition, Conceptualization. D. Granger: Writing – review & editing, Supervision, Methodology, Investigation. F.V. Laureano: Methodology, Investigation. R. Paes de Almeida: Methodology, Investigation. F.W. Cruz: Methodology, Investigation. A.O. Sawakuchi: Methodology, Investigation. E.S. Fonseca: Methodology, Investigation. A.B. Meza: Methodology, Investigation. J.D.F. Gallas: Methodology, Investigation.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Grammarly software in order to improve language and readability only. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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

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Abstract

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

1. Introduction

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

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

In the São Desidério karst area (Figure 1), northeastern Brazil, large limestone cave systems develop at the margins

of a sandstone covered plateau and preserve sedimentary records that indicate successive base level fluctuations. The causes associated with those changes in base level are not well understood, so careful study of cave geology, karst geomorphology and hydrogeology may help to connect local and regional aspects of the karst system evolution.

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



Figure 1: Collapse sinkholes with limestone cliffs, aligned in

the ENE-WSW direction, parallel to a major cave system. The low gradient landscape that surrounds the sinkholes is covered by sandstone. The major axis of the sinkhole in the

foreground is 180 m, and its depth is 90 m. Photo: Gabriel Lourenço.

2. Materials and methods

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

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

where used to characterize the lithostratigraphy, typify karst recharge styles and recognize paleokarst features.

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

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

3. Results

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

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

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

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



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

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

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

Hydrochemical analysis of karst waters showed that Ca²⁺ and HCO₃⁻ represents 60-80% of the ionic species in solution, while SO₄²⁻ usually constitutes <20% of dissolved species.

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

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

Calcite flowstone speleothems that cover fluvial river bars in the upper passage level shows a wide range of crystallization ages (337.9 ± 15.6 ky, 228.2 ± 3.5 ky, 85.8 ± 6.2 ky, U-Th age). Subaquatic speleothems with stromatolitic lamination (speleomicrobialites) locally form thick crusts (≈ 10 -30 cm) on the sinkhole cliffs and all-around collapsed cave passage walls and ceiling (Figure 3). The subaquatic speleothems

occur up to 40 m above the modern cave river level and they consist of interchanged vadose (soda straw) and phreatic (stromatolitic lamination) facies. Ages of deposition vary from 4.3 ± 0.052 ky to 2.2 ± 0.248 ky.



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

4. Discussion

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

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

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

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

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

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

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

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

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

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

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

5. Conclusion

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

Neogene transition. The most prominent phase of cave systems development started in the Pliocene, after the modern exposure of the limestone rocks to the surface.

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

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KARST SPRING MONITORING AND RESPONSE TO EXTREME RAIN EVENTS: THE JOÃO RODRIGUES CAVE SYSTEM IN SÃO DESIDÉRIO, BAHIA, BRAZIL

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INTRODUCTION

One of the major challenges concerning the study of karst aquifers reside in their heterogeneity and anisotropy. To characterize flow dynamics and the catchment area of a karst groundwater basin, conventional hydrogeology investigation methods alone are sometimes insufficient, and specific techniques more suitable to karst research must be applied, like dye tracing tests, spring hydrographs, cave survey, among others. Karst springs are typically the most important monitoring points in a karst aquifer system because they can provide information of all processes influencing surface or subsurface flow dynamics and signal transformations from recharge to discharge points (Larocque et al., 1998; White, 2002; Groves, 2007; Ford and Williams, 2007).

In Brazil, many karst springs are important water supplies to small communities and big cities, but few of them have ever been studied and none present long-term monitoring hydrographs. This scenario reveals a problem for groundwater management, especially considering population growth in a climate changing world. This study concerns the groundwater monitoring of the João Rodrigues cave system (Figure 1) at the São Desidério municipality (state of Bahia), where expressive groundwater lakes exert a major control in groundwater flow patterns. Besides this rare hydrologic scenario, an environmental conservancy area is being implemented at São Desidério to protect some of the largest caves in Brazil that face potential threats due to land use (agriculture and highway building).



Figure 1. A: Surubim karst spring, the major discharge point for the João Rodrigues cave system. Average flow rate is 0.95 m³/s (Hidrovia, 2012). B: Banquisa underground lake in the Bacupari cave. The yellow ellipse indicates a speleologist for scale. Thin calcite rafts cover the surface of the lake.

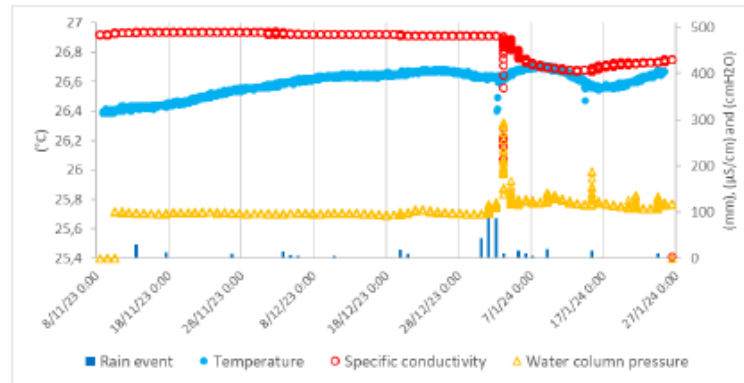


Figure 2. Hydrograph for the Surubim karst spring, from 2023, November 8 to 2024, January 25.

For data acquisition, water level, specific conductivity, temperature, and precipitation were monitored in the study area, starting from November 2023, by using auto level loggers and a weather station. The Surubim spring hydrograph and the precipitation curve for the catchment area (Figure 2) show two extreme rain events of 99,3 mm in 2023, December 31 and 87,3 mm in 2024, January 01. The response to this intense recharge pulse at the spring was a 1.8 m rise in water level 7 hours after the rain event. The linear distance between the sinking stream and the spring is approximately 9.8 km. Water level rise is inversely proportional to specific conductivity and temperature. While the storm water level rapidly decreases, temperature and specific conductivity tend to follow a slower recovery trend. This suggests that the cave system is composed of two major flow zones: the fast zone, represented by the underground river with quick response to input signals, and the slow zone, probably represented by lateral ponding of the river system in the form of underground lakes. The slow zone would be responsible for an important component of water storage in the system and the delayed recovery of monitored parameters at the spring.

CONCLUSION

These are preliminary results of hydrograph monitoring that will continue until January 2025. The time response at the spring to two extreme rain events were measured and a delay effect from underground lakes was identified. Besides the Surubim spring, 13 other points along the João Rodrigues cave system are currently being monitored for water level, water flow rate, temperature, hydrochemistry, and stable isotopes.

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ID do trabalho: 1164

Área Técnica do trabalho: TEMA 02 - Recursos Hídricos e Geociências Ambientais

Título do Trabalho: MILLION YEAR SCALE EVOLUTION OF A KARST AQUIFER IN NE BRAZIL: FROM INTERSTRATAL INITIATION TO MODERN FLOW DYNAMICS

Forma de apresentação: Oral

Autores: Padoan, L S G¹; Karmann, J²; Granger, D³; Laureano, F V⁴; Galvão, P H F¹; Ferrari, J A⁵; Assunção, P H S¹; Auler, A S⁶; Groves, C⁷; Bledsoe, L A⁷; Singer, A⁸; Morita, T D M²;

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Resumo do trabalho:

Most of the central and eastern Brazilian karst areas are formed within Neoproterozoic limestone deposits that were impacted by western Gondwana accretion metamorphism with intensity grades from the margins to the core of cratonic domains. Until the Cenozoic, important neotectonic reactivations of Proterozoic faults resulted in a complex structural arrangement that would later guide dissolution and the development of phreatic karst conduit systems. The onset of modern karstification in this context can be traced back to the arrangement of continental scale watersheds during the Cenozoic, but studies concerning detailed geochronological and geomorphological data to anchor the stages of karst aquifer development in time are scarce in the literature. Here we present an example of a multi-method approach to date cave sediments (cosmogenic ²⁶Al and ¹⁰Be, OSL and U-Th-Pb series) from the São Desidério karst area in the São Francisco Craton, where the Neoproterozoic Bambuí Group limestones are overlain by the Cretaceous Urucua Group sandstones. An average fluvial incision rate of $52,5 \pm 13,0$ m/My over the limestone rock was estimated by dating fluvial cave terraces at different elevations, while an average $17,1 \pm 1,4$ m/My erosion rate over the sandstone landscape was determined from ¹⁰Be concentrations representative of the cave sediment source area. The period of exposure of the limestone rock to the surface and the beginning of the most prominent karst aquifer development phase was estimated from maximum cave deposit ages and downcutting river rates as approximately $2,7 \pm 1,3$ to $3,03 \pm 0,19$ My. Prior to this limestone exposure, infiltration through the sandstone cover probably initiated interstratal karst development along the contact with the limestone rock. The minimum age for this initial stage of the covered karst aquifer evolution was estimated by extrapolating fluvial incision rates to the time necessary to consume a measured thickness of sandstone cover and limestone rock, resulting in a $23,3 \pm 5,3$ My minimum age for the São Desidério river valley. The novelty in this approach was to bring precise geochronological data to estimate the establishment of the Brazilian Chapadão Central plateau landscape, a regional topographic divide between the São Francisco and Tocantins river watersheds, and to provide a reference for the beginning of the modern karstification process. Paleovalley surfaces are present along the limestone-sandstone contact, and so, paleokarst features may also be preserved, representing an ancient phase of karstification prior to the burial of the Bambuí Group during the Paleozoic. Quantitative groundwater flow studies are still ongoing in the attempt to characterize modern flow patterns, connect enclosed depressions in the assumed recharge area to the major discharge karst springs and estimate maximum depth of flow in the phreatic zone.

Palavras-Chave do trabalho: conceptual groundwater flow model; fluvial erosion rates; geochronology; Karst aquifer evolution; São Desidério;

GSA Connects 2024 Meeting in Anaheim, California

Paper No. 163-6

Presentation Time: 9:50 AM

UPLIFT MECHANISMS AND EROSION HISTORY OF AN INTRACONTINENTAL PLATEAU IN THE BRAZILIAN STABLE PLATFORM INFORMED BY CAVE SEDIMENT GEOCHRONOLOGY

PADOAN, Lucas¹, KARMANN, Ivo², GRANGER, Darryl E.³, ALMEIDA, Renato Paes de², LAUREANO, Fernando Verassani⁴, CRUZ Jr., Francisco W.⁵, SAWAKUCHI, André O.⁶, FONSECA Jr., Edvaldo Simões da⁷ and MEZA, Alex Boava⁷, (1)Instituto de Geociências, Universidade Federal de Minas Gerais, Av. Antônio Carlos, 6.627, Pampulha, Belo Horizonte, Minas Gerais 31270-901, Brazil, (2)Instituto de Geociências, Universidade de São Paulo, Rua do Lago, 562, São Paulo, 05508-080, Brazil, (3)Earth Atmospheric and Planetary Sciences, Purdue University, 550 Stadium Mall Dr., West Lafayette, IN 47907, (4)Reparation Directory, Vale S.A., Av. Dr. Marco Paulo Simon Jardim, 3580, Nova Lima, Minas Gerais 34006-270, Brazil, (5)Institute of Geosciences, University of São Paulo, São Paulo, 05508-080, Brazil, (6)Institute of Geosciences, University of São Paulo, São Paulo, Brazil, (7)Escola Politécnica, Universidade de São Paulo, Travessa do Biênio, 83, São Paulo, São Paulo 05508-070, Brazil

The origin and evolution of intracontinental plateaus in stable terrains is a controversial subject. In the South American Platform, most of the extensive plateaus ranging from 600 to 1,000 m.a.s.l. in elevation occur in Brazil, and their structural context varies from cratonic nuclei to Neoproterozoic accretionary terranes. They were formed in the Cenozoic, after rifting and break-up of Pangea in the Mesozoic. Since the 1950's, different models based on topographic and stratigraphic relationships, apatite fission-track thermochronology, ⁴⁰Ar-³⁹Ar weathering chronology, marine platform sedimentary production, and lithosphere thermomechanical numerical modeling have argued for distinct and sometimes mutually exclusive landscape evolution hypotheses. These models explain the modern topography by underplate magmatism, edge-driven mantle convection, isostatic flexure rebound due to convergent intraplate stress accumulation or fluvial erosion, and resistant iron-rich regolith covers, but there is no consensus about the dominant uplift processes and erosive stages. In this study, new fluvial erosion rate data are presented for the Central Brazilian Plateau, an extensive ridge (125,000 km²) in the São Francisco Craton. The erosive retreat of the plateau escarpment controls the evolution of large cave systems in a Neoproterozoic limestone covered by Cretaceous sandstone. Cave sedimentary terraces at different elevations were dated through cosmogenic ²⁶Al-¹⁰Be, OSL and U-Th series geochronology, revealing an average fluvial incision rate of 52.5 ± 13.0 m/Ma for the São Desidério River, the local base level for all tributary caves. The average knickpoint migration rate at the limestone/ sandstone contact was determined as 3,782 ± 984 m/Ma. According to the cosmogenic data, the average erosion rate in the sandstone catchment area is 17.1 ± 1.4 m/Ma with a gradual increase from 3.4 ± 0.4 m/Ma over the last 3 Ma. Extrapolating these rates into the past suggests that the time span for major river valley entrenchment was 23.8 ± 6.2 Ma. This agrees with previous models suggesting establishment of the Central Brazilian Plateau near the Oligocene-Miocene transition. It is suggested as a preliminary hypothesis that regional scale river erosion surrounding the resistant Central Brazilian Plateau has caused flexural uplift of the plateau margins due to isostatic rebound.

[Recorded Presentation](#)

Session No. 163

[T101. Karst Sedimentary, Paleoclimate, and Historical Records](#)

Tuesday, 24 September 2024: 8:00 AM-11:05 AM

212B (Anaheim Convention Center)

Geological Society of America *Abstracts with Programs*. Vol. 56, No. 5
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GSA Connects 2024 Meeting in Anaheim, California

Paper No. 134-3

Presentation Time: 2:10 PM

MILLION-YEAR SCALE EVOLUTION AND CONCEPTUAL FLOW MODEL OF A SANDSTONE COVERED KARST AQUIFER IN NE BRAZIL

PADOAN, Lucas¹, KARMANN, Ivo², GRANGER, Darryl E.³, LAUREANO, Fernando Verassani⁴, GALVÃO, Paulo¹, FERRARI, José Antonio⁵, AULER, Augusto⁶, ASSUNÇÃO, Pedro Henrique da Silva¹, GROVES, Chris⁷, BLEDSOE, Lee⁸, SINGER, Autumn⁸, LOURENÇO, Gabriel¹ and TANIKAWA, Wendy¹, (1)Instituto de Geociências, Universidade Federal de Minas Gerais, Av. Antônio Carlos, 6.627, Pampulha, Belo Horizonte, Minas Gerais 31270-901, Brazil, (2)Instituto de Geociências, Universidade de São Paulo, Rua do Lago, 562, São Paulo, 05508-080, Brazil, (3)Earth Atmospheric and Planetary Sciences, Purdue University, 550 Stadium Mall Dr., West Lafayette, IN 47907, (4)Reparation Directory, Vale S.A., Av. Dr. Marco Paulo Simon Jardim, 3580, Nova Lima, Minas Gerais 34006-270, Brazil, (5)Núcleo de Geociências, Instituto de Pesquisas Ambientais, Rua Joaquim Távora, 822, São Paulo, São Paulo 04015-011, Brazil, (6)Instituto do Carste, Carste Ciência Ambiental S.A., Alameda do Ipê Amarelo, 830, Belo Horizonte, Minas Gerais 31275-090, Brazil, (7)Western Kentucky University, (8)Crawford Hydrology Laboratory, Department Earth, Environmental, and Atmospheric Sciences, Western Kentucky University, Bowling Green, KY 42101

Karst areas in Central Brazil are typically developed within Neoproterozoic limestone covered by Cretaceous sandstone. The groundwater flow interaction between these two rock units is poorly understood and quantified, making it difficult to assess precise groundwater budgets and support environmental management decisions in an area where aquifers are highly affected by deforestation and extensive agriculture in one of the world's largest soy plantations. In this context, a multi-method approach to groundwater conceptual flow modeling was adopted to investigate the São Desidério karst area, where solution conduits in the limestone started to develop in an interstratal (sandstone buried) stage, and are now receiving both diffuse recharge from the sandstone and punctual recharge from sinkholes and blind-valleys in the partially exposed limestone. Spring inventory, hydrochemical and geochemical analysis, cave passage morphology, karst landscape features and geochronological data from cave deposits (cosmogenic ²⁶Al and ¹⁰Be, OSL, and U-Th series) are discussed. The major karst spring catchment area receives a perennial and proximal recharge from the sandstone, while intermittent pulses triggered by extreme rain events may connect the system to an upstream watershed, forming a potentially > 80 km long and > 300 m deep groundwater flow route. Where the limestone is exposed to the surface, convergent (dendritic) conduit systems connect allogenic and autogenic streams to alluviated and non-alluviated karst springs close to the base level rivers. Local processes include a rare perennial rhythmic karst spring and sulfuric acid dissolution in the vadose zone by the oxidation of pyrite. The major phases of karst aquifer evolution are: (1) interstratal dissolution at the limestone-sandstone contact since modern regional scale plateau landscape was well established in the Oligocene-Miocene transition (≈ 23 Ma); (2) sandstone cover erosive retreat and limestone exposure, leading to the major cave development stage in the Pliocene; (3) base level fluctuations driven by changes in sediment supply, vegetation cover and climate over the last 3 Ma, and consequent burial and alluviation of karst springs; (4) groundwater level fluctuations with > 40 m vertical amplitude and the development of giant groundwater lakes (≈ 12,000 m²) and subaquatic speleothems over the last 6,000 yr.

[Recorded Presentation](#)

Session No, 134

[T97. New Frontiers in Cave and Karst Science](#)
Monday, 23 September 2024: 1:30 PM-5:30 PM

212B (Anaheim Convention Center)

Geological Society of America *Abstracts with Programs*. Vol. 56, No. 5
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Dinâmica hidrológica atual do sistema de cavernas João Rodrigues, São Desidério – BA

Pós-doutorando: Dr. Lucas Padoan de Sá Godinho
Supervisor: Prof. Dr. Paulo Henrique Ferreira Galvão

O sistema de cavernas do rio João Rodrigues se desenvolve no contexto dos calcários Neoproterozoicos do Grupo Bambuí, sendo então o mais importante tributário subterrâneo da bacia do rio São Desidério. O rio subterrâneo, com escoamento de base da ordem de $1 \text{ m}^3/\text{s}$, corre ao longo de volumosos sistemas de cavernas por cerca de 10 km desde sua nascente principal até sua ressurgência. Ali, se encontram os maiores lagos subterrâneos do Brasil (como o Lago da Banquisa na caverna Garganta do Bacupari, exemplificado na fotografia abaixo), além de uma rara nascente rítmica perene (a única da América do Sul e uma das poucas conhecidas no mundo). Este projeto, ainda em fase inicial de desenvolvimento, visa aplicar técnicas modernas para a caracterização da dinâmica atual de fluxo deste sistema cárstico, tais como testes quantitativos com traçadores fluorescentes, monitoramento pluviométrico, de nível d'água, condutividade elétrica e vazão, análises hidroquímicas dos elementos maiores, parâmetros físico-químicos e isótopos estáveis (^2H , ^{18}O , ^{13}C) das águas.



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Dinâmica atual de fluxo d'água subterrânea no carste de São Desidério, BA



Lucas Padoan de Sá Godinho

Perguntas científicas:

- Quais as velocidades de fluxo no sistema de cavernas João Rodrigues?
- Qual a influência dos grandes lagos subterrâneos na dinâmica de fluxo?
- Quais os prováveis limites da bacia de águas subterrâneas deste sistema?



Lago do Cruzeiro (esq.) e Lago Parima (dir.), os dois maiores lagos subterrâneos do Brasil.



Teste de injeção com fluoresceína no Parque da Lagoa Azul.

Instalação do fluorímetro de campo na ressurgência do Poço do Surubim, com auxílio de técnicas verticais.

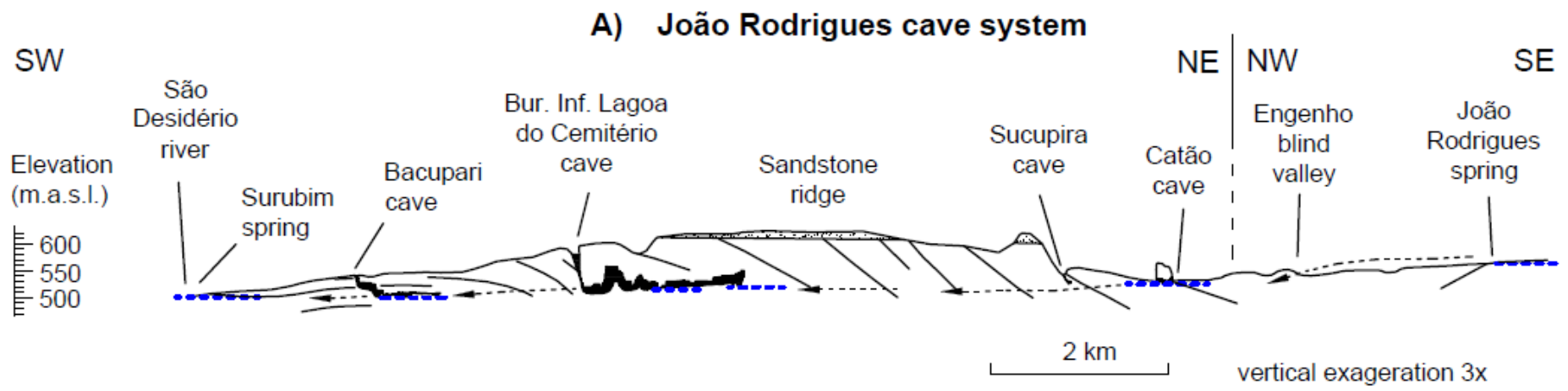
Métodos aplicados:

- Testes de injeção quantitativos com traçadores fluorescentes.
- Monitoramento pluviométrico, fluviométrico e piezométrico.
- Análise de cátions e ânions maiores, ^{18}O , ^2H , ^3H , ^{14}C .

Financiamento:

CECAV/Ministério do Meio Ambiente

**SEÇÕES VERTICAIS REPRESENTANDO O MODELO
HIDROGEOLÓGICO DA ÁREA DE ESTUDO**



**REPRESENTAÇÃO CARTOGRÁFICA DA BACIA
SUBTERRÂNEA DO SISTEMA DE CAVERNAS JOÃO
RODRIGUES**

