33rd INTERNATIONAL KARSTOLOGICAL SCHOOL
"CLASSICAL KARST"

33. MEDNARODNA KRASOSLOVNA ŠOLA "KLASIČNI KRAS"

CARBON PATHWAYS IN KARST

POTI OGLJIKA V KRASU

ABSTRACTS & GUIDE BOOK

POVZETKI & VODNIK

Postojna
2026

Editors / Uredniki:
Franci Gabrovšek, Vanessa E. Johnston, Mitja Prelovšek

Issued by / Izdal:
Scientific Research Centre of the Slovenian Academy of Sciences and Arts (ZRC SAZU), Karst Research Institute, Titov trg 2, 6230 Postojna, Slovenia

Published by / Založila:
Založba ZRC

Represented by / Zanju:
Oto Luthar, Nataša Ravbar

Printrun / Naklada:
160 copies / 160 izvodov

Organizing committee / Organizacijski odbor:
Matej Blatnik, Jasmina Čeligoj Biščak, Vanessa E. Johnston, Franci Gabrovšek, Matej Jelovčan, Žan Kafol, Blaž Kogovšek, Darja Kolar, Peter Kozel, Martin Knez, Cyril Mayaud, Tinkara Mazej, Janez Mulec, Magdalena Năpăruş Aljančič, Uroš Novak, Bojan Otoničar, Metka Petrič, Tanja Pipan, Mitja Prelovšek, Nataša Ravbar, Sara Skok, Tadej Slabe, Sonja Stamenković, Filip Šarc, Stanka Šebela, Astrid Švara, Slavuljka Šušak, Nadja Zupan Hajna.

Supported by / Izid knjige so podprli:
Scientific Research Centre of the Slovenian Academy of Sciences and Arts
Slovenian National Commission for UNESCO
Slovenian Research Agency
Municipality of Postojna / Zavod Znanje

Cover photo / Naslovna fotografija:
Planinska Jama, photo: Franci Gabrovšek
Printed by / Tisk:
CICERO, Begunje, d.o.o.

First edition, first printrun. / Prva izdaja, prvi natis.

Postojna 2026

CIP - Kataložni zapis o publikaciji
Narodna in univerzitetna knjižnica, Ljubljana

551.44(082)

MEDNARODNA krasoslovna šola Klasični kras (33 ; 2026 ; Postojna)
Carbon pathways in Karst = Poti ogljika v Krasu : 33rd International Karstological School "Classical Karst" = 33. mednarodna krasoslovna šola "Klasični kras" : abstracts & guide book = povzetki & vodnik : Postojna, 2026 / [editors Franci Gabrovšek, Vanessa E. Johnston, Mitja Prelovšek]. - 1st ed., 1st printrun = 1. izd., 1. natis. - Ljubljana : Založba ZRC, 2026

ISBN 978-961-05-1147-2
COBISS.SI-ID 278854403

CONTENTS

VSEBINA

PROGRAM AND GENERAL INFORMATION

PROGRAM IN SPLOŠNE INFORMACIJE

PROGRAM

Monday, June 15th, 2026 **Ponedeljek, 15. junij 2026**		
08:00–13:00	**REGISTRATION** / **PRIJAVA UDELEŽENCEV**	Cultural Centre Postojna Kulturni dom Postojna
09:00–09:30	**OPENING CEREMONY** / **OTVORITVENA SLOVESNOST**	
	SESSION 1 **SKLOP 1**	
09:30–10:00	*Keynote lecture* / *Plenarno predavanje* **Zaihua Liu *et al.***: Carbonate weathering turns karst waters into carbon sinks via a biological carbon pump	
10:00–10:15	**Jaime Fernández-Ortega *et al.***: Early Warning Systems as dynamic karst groundwater protection tools: the case of Sierra de Ubrique aquifer (S Spain)	
10:15–10:30	**Liangxing Shi**: Both enhanced carbonate and silicate weathering strategies improve soil carbon sequestration via different pathways	
10:30–10:45	**Martin Sauter *et al.***: The karst vadose zone – infiltration dynamics and storage	
10:45–11:15	*Coffee break* / *Odmor za kavo*	
	SESSION 2 **SKLOP 2**	
11:15–11:45	*Keynote lecture* / *Plenarno predavanje* **Nenad Buzjak**: Beyond the "dogma" of mean annual cave air temperature: rethinking cave microclimate monitoring	
11:45–12:00	**Dalibor Paar**: Surface climatic processes as a key to interpreting carbon pathways in karst and caves: the example of Northern Velebit, Croatia	
12:00–12:15	**Philipp Häuselmann *et al.***: CO_2 around Milandre Cave (Jura, Switzerland)	
12:15–12:30	**Neven Bočić & Slaven Vuković**: Long-term monitoring of CO_2 concentration in cave air using the CM-0018 1% CO_2 Data Logger (CO_2 Meter) instrument (Upper Barać Cave, Croatia)	
12:30–14:00	*Lunch break* / *Odmor za kosilo*	
	SESSION 3 **SKLOP 3**	
14:00–14:30	*Keynote lecture* / *Plenarno predavanje* **Sibo Zeng *et al.***: A greening Earth has increased the trend of karst-related carbon sink under a warming climate	
14:30–14:45	**Dénes Szieberth *et al.***: Challenges and methods for sampling gas-rich thermal springs discharging into water bodies - case studies from Slovenia and Hungary	
14:45–15:00	**Lukas Plan *et al.***: Speleogens formed by locally produced sulphuric and carbonic acid in large epigene caves of the NCA (Austria)	
15:00–15:15	**Mingyu Shao & Zaihua Liu**: Carbon Footprint of the Loess–Karst Aquatic Continuum: Organic Matter Sources, Transformation, and Carbon Sink Effects	
15:15–15:45	*Coffee break* / *Odmor za kavo*	
	SESSION 4 **SKLOP 4**	
15:45–16:00	**Attila Kovács**: Karst conduit network generation conditioned by geology, geomorphology, and hydrodynamic behaviour	
16:00–16:15	**Raffaele Bruschi *et al.***: Microplastics in pristine caves of the Timavo karst system: contamination patterns and spatial heterogeneity	
16:15–16:30	**Samah Moustafa Abozeid**: Coastal karst geomorphology and submerged archaeological features at Ras Alam El-Rum, northwest coast of Egypt	
16:30–16:45	**Paul Griffiths & Carolyn Ramsey**: Karst and Wind Energy Development in British Columbia, Canada: Implications of a Regulatory Transition	

16:45–17:15	*Break to move* / *Odmor za premik*	KRI IZRK
	POSTER SESSION **POSTERJI**	
17:15–18:30 18:30–21:00	Quick poster presentations / Hitra predstavitev posterjev Poster display / Ogled posterjev	
19:00–21:00	**ICE BREAKER** **UVODNO DRUŽENJE**	

Tuesday, June 16th, 2026 **Torek, 16. junij 2026**		
08:30–11:00	**REGISTRATION / PRIJAVA UDELEŽENCEV**	Cultural Centre Postojna Kulturni dom Postojna
	SESSION 5 **SKLOP 5**	
09:00–09:30	*Keynote lecture / Plenarno predavanje* **Marek Lang**: Impact of "parasitic phenomena" on the microclimate of the show caves: A case study from the Balcarka Cave (Moravian Karst, Czech Republic)	
09:30–09:45	**David Domínguez-Villar *et al.***: Understanding ventilation dynamics and CO_2 concentration variability of the permanent outflowing cave of Los Pilones (Spain)	
09:45–10:00	**Shengxin Peng & Wen Liu *et al.***: Dynamic patterns and resilience of cave air CO_2 under tourism interferences in the Lushan National Geopark, north China	
10:00–10:15	**Kristina Krklec et al.**: Cave air ventilation dynamics in Eagle Cave (Spain): Unraveling the controls and sources of cave air CO_2	
10:15–10:30	**Laura Sanna**: Near-surface CO_2 dynamics in a karst vadose zone: insights from a tectonically stable setting	
10:30–11:00	*Coffee break / Odmor za kavo*	
11:00–11:30	*Keynote lecture / Plenarno predavanje* **François Bourges**: Insights into karst from monitoring heritage caves	
11:30–11:45	**Marjan Temovski *et al.***: Cave monitoring at Drenska Peštera (N. Macedonia): Insight from carbon isotopes	
11:45–12:00	**Petra Bajo *et al.***: CO_2 and radon variability in a karst cave: Insights from Nova Grgosova Cave, Croatia	
12:00–12:15	**Łukasz Lewkowicz**: How to Professionally "Sell" a Cave? Speleological Marketing of the Demänová Caves Association (1924–1954)	
12:15–14:00	*Lunch break / Odmor za kosilo*	
14:00–19:30	**Afternoon field trip (A) / Popoldansko terensko delo (A)** "Composition and dynamics of air in the Škocjan Caves" *Bus drive and walk (several km).* »Sestava in dinamika zraka v Škocjanskih jamah« *Vožnja z avtobusom ter hoja (nekaj km).*	

Wednesday, June 17th, 2026 **Sreda, 17. junij 2026**		
08:30–09:30	**REGISTRATION / PRIJAVA UDELEŽENCEV**	Cultural Centre Postojna Kulturni dom Postojna
	SESSION 6 **SKLOP 6**	
09:00–09:30	*Keynote lecture / Plenarno predavanje* **James Bendle *et al.***: Unlocking karst archives: Lipid biomarkers as underutilized paleoclimate proxies in speleothems and cave sediments	

09:30–09:45	**Ivona Ivkić Filipović *et al.***: Holocene variability of internal carbon cycling in a karst Lake Velo Blato (Pag Island, Croatia) inferred from stable isotopes in lake sediments	Cultural Centre Postojna Kulturni dom Postojna
09:45–10:00	**Bogusz Kulus**: Forms of calcium carbonate precipitation in Pleistocene glacial sediments of Poland	
10:00–10:15	**Astrid Švara & Nadja Zupan Hajna**: Reconstructing hydrological changes in contact karst using tectonic uplift phases (Postojna Contact Karst, W Slovenia)	
10:15–10:30	**Hélène Cassagne *et al.***: Geochemical and mineralogical modifications in speleothems associated with past bat occupations (Demoiselles and Roquette caves, Gard, France)	
10:30–11:00	*Coffee break / Odmor za kavo*	
11:00–11:15	**Matija Perne *et al.***: Modelling and observation of CO_2 and temperature in an intermittently-visited showcave	
11:15–11:30	**Stanka Šebela**: Spatial variation in carbon dioxide concentrations between the entrance and deeper parts of Postojna Cave, Slovenia	
11:30–11:45	**Franci Gabrovšek**: Diurnal CO_2 variability in air exhaled from a deep vadose borehole in Planina Cave	
11:45–12:00	**Nadja Zupan Hajna**: From UNESCO proclamation to global implementation: The International Day of Caves and Karst	
12:00–12:30	**Closing debate: The role of karst as a global carbon sink**	
12:00–14:00	*Lunch break / Odmor za kosilo*	
14:00–19:30	**Afternoon field trip (B) / Popoldansko terensko delo (B)** "Cave air–water–rock interactions in a mature, well-ventilated stream cave; case study of the Križna Cave" *Bus drive and walk (several km).* »Interakcije med jamskim zrakom, vodo in kamnino v dobro prezračeni vodni jami: primer Križne jame« *Vožnja z avtobusom ter hoja (nekaj km).*	

Thursday, June 18th, 2026 **Četrtek, 18. junij 2026**		
08:30–18:00	**Whole-day field trip (C) / Celodnevno terensko delo (C)** "Carbon fluxes and related research from the Postojna–Planina caves system" *Bus drive and walk (several km).* »Tokovi ogljika in druge sorodne raziskave v Postojnsko planinskem jamskem sistemu« *Vožnja z avtobusom ter hoja (nekaj km).*	
18:00–19:30	*Break / Odmor*	
19:30	**Reception at the Karst Research Institute** **Sprejem na Inštitutu za raziskovanje krasa**	KRI IZRK

Friday, June 19th, 2026 **Petek, 19. junij 2026**		
08:30–16:00	**Whole-day field trip (D) / Celodnevno terensko delo (D)** "Karst of the Ljubljanica Recharge Area" *Bus drive and walk (several km).* »Kraško zaledje izvirov Ljubljanice« *Vožnja z avtobusom ter hoja (nekaj km).*	

LIST OF POSTER PRESENTATIONS

The following list presents the order of the 2-min long flash presentations. Authors are kindly invited to prepare 1–2 slides to attract attention to the content of the poster. Flash presentation and poster showing will both take place at Karst Research Institute ZRC SAZU.

Na spodnjem seznamu je abecedni red dve-minutnih kratkih predstavitev. Avtorje vljudno vabimo, da pripravijo 1–2 prosojnici, da pritegnejo pozornost na vsebino plakata. Kratke predstavitve in predstavitev plakatov bodo potekali na Inštitutu za raziskovanje krasa ZRC SAZU.

	1st AUTHOR	TITLE
1	Asaye Yohannes	Karst Distribution in Ethiopia: An Overview
2	Audra Philippe	Modeling of aerological, energy, and condensation volume balance. Chameau Cave, Zegzel, Morocco
3	Balázs Viktória Bernadett	In situ determination of the CO_2 content of cave air with community science methods
4	Ciesielczuk Justyna	Origin of organic matter present in the karst system in the Rovte area, Central Slovenia
5	Cinus Daniela	Resilience of Nettuno tourist cave (Alghero, Italy) to CO_2 pressure: multi-year monitoring of tourist flow and meteomarine disturbance
6	Engelhardt Irina	Hydrogeological drought assessment under semi-arid climate for the highly karstified Western Mountain Aquifer
7	Funk Barbara	Determining the water storage capacity of different types of limestone and dolomite using ERT
8	Gaber Ahmed	Landslide Hazard Zonation in a cut slopes along Sohag–Safaga highway based on slope properties and rock mass classification
9	Gebus-Czupyt Beata	New preliminary oxygen stable isotope results of carnivore coprolites from Biśnik Cave (southern Poland)
10	Grošanić Klara	Morphology and speleogenesis of the Vrlovka Cave (Kamanje, Croatia)
11	Huang Jenny	A field-inspired, systematic investigation of conduit network impacts on flow and transport in karst aquifers
12	Jelovčan Matej	GIS-Based Analysis of Dinaric Karst Poljes: An Integrated Approach and Preliminary Results
13	Johnston Vanessa	Rock–water–air carbon exchange along the Postojna–Planina caves system
14	Kepic Tinkara	Use of ^{13}C to trace the origin of dissolved inorganic carbon in water and organic carbon in sediments: a case study of the permanent subsurface flow of the karstic Reka River
15	Kurečić Tomislav	Towards a systematic stratigraphy of Croatian cave sediments: the QUEECAD project
16	Lončarić Robert	MOKRO project - Environmental changes of the littoral karst during the late Quaternary
17	Mammadov Ali	Carbon and oxygen stable isotope composition of speleothems from Čulejca Cave (N. Macedonia): preliminary insight on Holocene paleoclimate changes
18	Martín Pérez Andrea	Identification of organic compounds in moonmilk-forming waters by Liquid Chromatography High-Resolution Mass Spectrometry (LC-HRMS)

19	Mayaud Cyril	Using FloodWatch on the field: a first assessment
20	Năpăruş-Aljančič Magdalena	ZRC SAZU and EPOS ERIC: Data provision and seismic monitoring in the Slovenian karst
21	Nunes Alvarado Diego Alfonso	Modeling CO_2 concentration of a karstic soil from Dalmatia (Croatia) and implications for endokarst CO_2 dynamics
22	Persoiu Aurel	Climate signals and historical ice exploitation in a high-altitude mountain karst: Crna ledenica Ice Cave (Croatia)
23	Roche Prune	Physics based modeling of speleogenesis in openKarst - preliminary results
24	Ruttyn Lilas	Towards a calibration of the infiltrability potential of the geological substratum on the Aix-Marseille Provence Metropole (SE France)
25	Rzadkowski Kewin	Denudation processes in isolated karst: a case study of the Rovte region in Central Slovenia
26	Slabe Tadej	Stone forests, developed from subsoil karren
27	Soto Limaris	Who needs to know about karst? From awareness to policy and protection
28	Surić Maša	QUEECAD - Quaternary Environmental Evolution archived in Croatian Cave Deposits
29	Šarc Filip	Coupled ventilation and hydrogeological controls on seasonal radon dynamics in Vrelo Cave (Croatia)
30	Trinajstić Nina	Karst bauxites as archives of Paleogene volcanism: Evidence from the Dinarides
31	Tyc Andrzej	MIS 6 climate variability in Central Europe recorded in a speleothem from Prekova jama cave (Central Slovenia)
32	Vivien Langhans	Long-Term Monitoring in the Vadose Zone of a Karst System: Investigating Environmental Drivers of CO_2 Transport Dynamics Using Machine Learning

CLOSING DEBATE: THE ROLE OF KARST AS A GLOBAL CARBON SINK

Recent studies suggest that the terrestrial carbon sink may have been significantly overestimated, while major uncertainties also remain regarding the magnitude and dynamics of the oceanic carbon sink. In this context, the contribution of karst systems to global carbon sequestration remains particularly poorly constrained, with current estimates ranging widely from approximately 0.3 to 0.9 PgC yr^{-1}.

To evaluate the current state of knowledge, identify the key challenges in constraining these estimates, and discuss approaches for improving future assessments, we will host a closing debate on the global importance of karst as a carbon sink. The session will take the form of a moderated panel discussion featuring invited experts from different disciplines relevant to karst science and the global carbon cycle.

Panelists will begin with short introductory remarks before moving into an open discussion addressing current evidence, methodological challenges, and future research priorities. The session will conclude with approximately 10 minutes for questions and comments from the audience.

We warmly invite all conference participants to join this discussion and contribute their perspectives to what promises to be an engaging and thought-provoking conclusion to the conference.

GENERAL INFORMATION

Registration

- Registration is possible on Monday (8:00–13:00), Tuesday (8:30–11:00), and Wednesday (8:30–09:30) in the Cultural Centre Postojna (Gregorčičev drevored 2a, Postojna).
- **Registration is obligatory for all participants.**

Oral presentations

- Lectures will take place in the Cultural Centre Postojna (Gregorčičev drevored 2a, Postojna).
- PowerPoint presentations **should be given to the organizers** during the break before the Session with the presentation.
- Maximum duration of the lecture is 15 min (12 min for talk and 3 min for discussion). Invited lecturers (keynote speakers) have 30 min for the lecture. Due to a tight schedule, we ask you to please be punctual!

Posters

- Poster size: mandatory max. format is A0 – 841 x 1189 mm (portrait layout).
- Poster presentation and display will be held at the Karst Research Institute in the hall and the stairway.
- A flash presentation session will be organized at the beginning of the poster session. For this, each author(s) is asked to prepare a 2-minute-long flash presentation with 1–2 slides to attract attention to the content of the poster. After the flash session, the posters will be displayed and the authors will be able to answer the questions and discuss their research in detail.
- Leave the posters and short poster presentations (.ppt, .pdf; please name file with your surname) at the registration desk on Monday, June 15th, before the lunch break.
- Stand by your poster during the poster display.

Meals

- Lunches are not organized during the session days and afternoon field trips (Tuesday and Wednesday).
- During whole-day field trips (Thursday and Friday) simple lunches will be provided. Due to the length of the Thursday`s and Friday's excursions (Excursion C and D) we suggest you take with you some additional snacks.
- Lunch breaks are timetabled into the schedule during the session days (Monday, Tuesday and Wednesday). You can go for lunch at several restaurants, including Štorja pod stopnicami, Bar Bor, Pri kaminu, Čuk, Pizzaria Minutka, and Bistro Perspektiva.
- On Thursday a reception dinner will be provided.

Field trips

- All fieldtrips will be combined with a bus drive and walk (several km per day).
- Registration for each field trip will be possible only on Monday, 15th June 2026 at the registration desk.
- Bus departure for the field trips is from the Postojna bus station (marked as No. 3 on the map of Postojna).
- Because of visits of caves, walking shoes, field clothes and headlamps are obligatory. At most excursions, a lot of walk is expected. Please, be ready for possible hot weather or/and rain.
- Insect repellents are recommended as we will be walking in areas populated with ticks (Ixodes ricinus) that transfer mainly lyme desease and tick-borne meningitis. Check yourself in the evening after each field trip.
- Participation on the excursions is voluntary and at your own risk. The organizers do not accept any liability for any loss, damage, injury or death arising from or connected with the excursions. Participants are advised to arrange an appropriate insurance policy. The participants are obliged to comply with the instructions of the organizers.

OSNOVNE INFORMACIJE

Prijava

- Registracija je mogoča v ponedeljek (08:00 – 13:00), torek (08:30 – 11:00) in sredo (8:30 – 09:30) v Kulturnem domu v Postojni (Gregorčičev drevored 2a, Postojna).
- **Registracija je obvezna za vse udeležence.**

Predavanja

- Večina predavanj poteka v Kulturnem domu v Postojni (Gregorčičev drevored 2a, Postojna).
- Prosimo, da PowerPoint predstavitve **oddate organizatorjem** v odmoru pred začetkom tematskega sklopa, v katerem imate predstavitev.
- Dolžina predavanja je omejena na 15 minut (12 minut za govor in 3 minute za razpravo). Vabljena predavanja so omejena na 30 minut. Prosimo vas, da se strogo držite predpisanega časa!

Posterji

- Velikost posterjev: obvezen največji format je A0 – 841 x 1189 mm (pokončna lega).
- V začetku predstavitve posterjev bo potekala hitra predstavitev s pomočjo prosojnic. Pri tem vse avtorje vabimo k pripravi dve minuti dolge predstavitve - napovednika (ena do dve prosojnici), v kateri pritegnete pozornost na vsebino posterja. Hitri predstavitvi bo sledil klasičen ogled posterjev, kjer bodo avtorji lahko odgovarjali na morebitna vprašanja udeležencev.
- Posterje in kratke prestavitve (.ppt, .pdf) pustite pri mizi za prijavo udeležencev, in sicer v ponedeljek, 15. junija, do odmora za kosilo.
- Med ogledom posterjev stojte poleg svojega posterja.

Obroki

- Kosilo med predavanji in popoldanskim terenskim delom (torek in sreda) ni organizirano.
- Med celodnevnim terenskim delom (četrtek in petek) organiziramo enostavne obroke. Zaradi dolžine četrtkove in petkove ekskurzije (Ekskurzija C in D) priporočamo, da si s sabo vzamete še kakšen dodaten prigrizek.
- Odmori za kosilo so v času predavanj (ponedeljek, torek in sreda) vključeni v program. Jeste lahko v Štorji pod stopnicami, Bar Boru, Pri kaminu, v Čuku, Bistro Perspektiva, itd.
- V četrtek je v večernem delu programa planirana pogostitev.

Strokovne ekskurzije

- Vse ekskurzije bodo kombinirane z avtobusno vožnjo ter hojo (nekaj km/dan).
- Prijave za strokovne ekskurzije bodo mogoče le še v ponedeljek, 15. 6. 2026 pri mizi za prijavo udeležencev.
- Odhod avtobusov je z glavne avtobusne postaje Postojna (označeno s št. 3 na karti Postojne).
- Zaradi predvidenih obiskov jam je obvezna primerna oprema (pohodni čevlji, terenska oblačila, svetilke). Na vseh ekskurzijah pričakujemo precej hoje. Pripravite se tudi na možno vročino ali/in dež. Na ekskurzijah bomo veliko hodili – bodite pripravljeni.
- Priporočamo uporabo repelentov proti insektom. Hodili bomo po območjih, kjer se nahajajo populacije klopov (*Ixodes ricinus*), ki so lahko prenašalci povzročiteljev lymske borelioze ali meningitisa.
- Udeležba na terenskem delu je prostovoljna in na lastno odgovornost. Organizator ne prevzema odgovornosti za morebitne izgube, škodo, poškodbe ali smrtne primere, ki bi nastali v povezavi s terenskim delom. Udeležencem svetujemo, da si pred odhodom na terensko delo uredijo ustrezno zavarovanje. Udeleženci so tekom terenskega dela dolžni upoštevati navodila organizatorja.

MAP OF POSTOJNA

ZEMLJEVID POSTOJNE

1 - Karst Research Institute ZRC SAZU / Inštitut za raziskovanje krasa ZRC SAZU
2 - Cultural Center of Postojna / Kulturni dom Postojna
3 - Postojna bus station / Avtobusna postaja postojna
4 - Entrance to Postojna cave / Vhod v Postojnsko jamo

A - Pizzeria and restaurant Minutka / picerija in restavracija Minutka
B - Bistro Štorija / Bistro Štorija
C - Restaurant Proteus / Restavracija proteus
D - Bistro Bar Bor / Bistro Bar Bor
E - Pizzeria and restaurant Čuk / Picerija in restavracija Čuk

Post office / pošta
ATM / bankomat
Market / trgovina
Bakery / pekarna
Fast food / hitra prehrana

FIELD TRIPS

TERENSKO DELO

Afternoon field trip (A):

COMPOSITION AND DYNAMICS OF AIR IN THE ŠKOCJAN CAVES

Tuesday, 16th June 2026, 14:00–19:30

Stops:

1 – Škocjan Caves

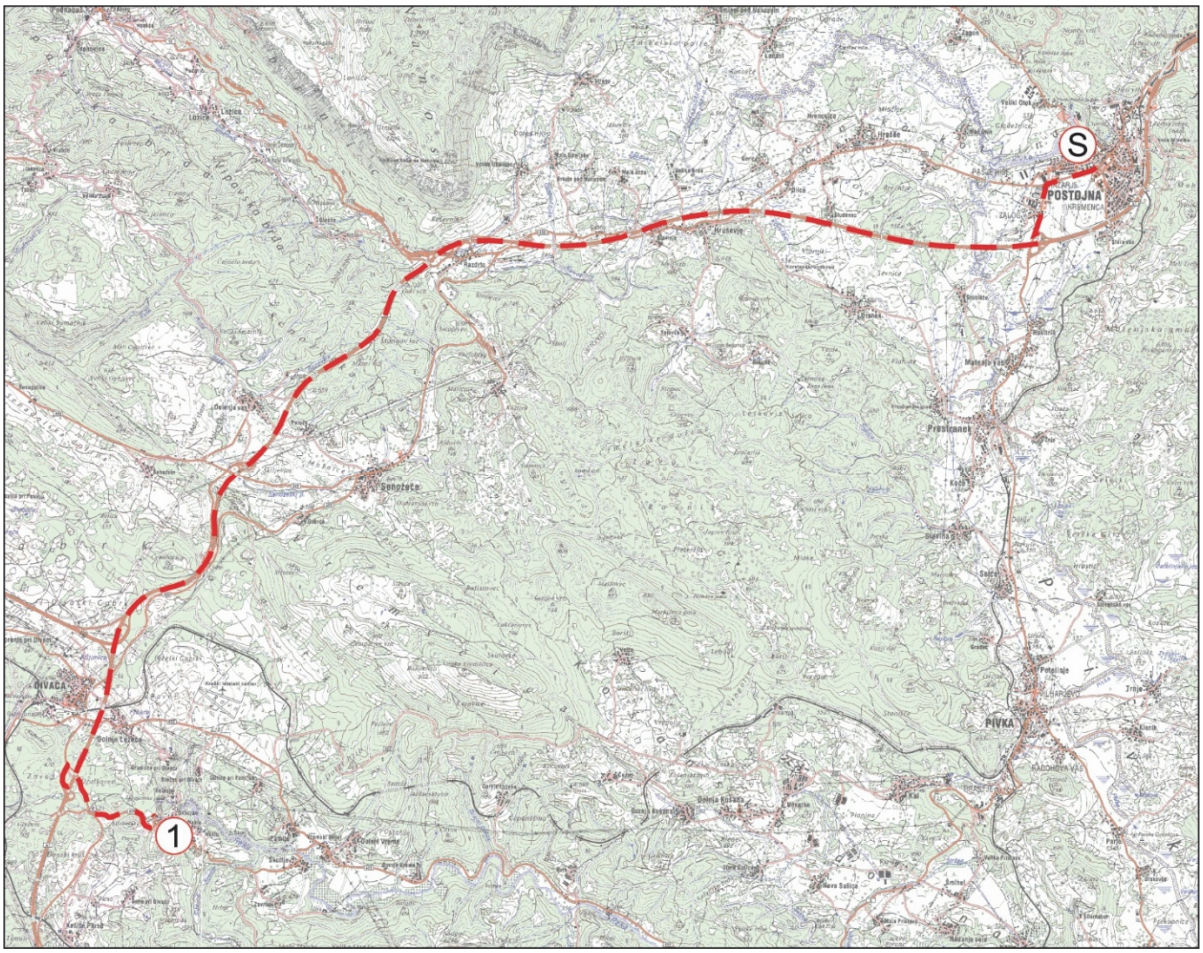


Fig. 1.1: Location of the Škocjan Caves.

Škocjan Caves and Kras Region

The Škocjanske Jame (Škocjan Caves) are an over 6 km-long system of caves and collapse dolines in the Divača Karst in the southwestern part of Slovenia and a world-famous natural site. Since 1986 they have been on the UNESCO World Heritage List because of their extraordinary underground canyon—one of the largest in the world.

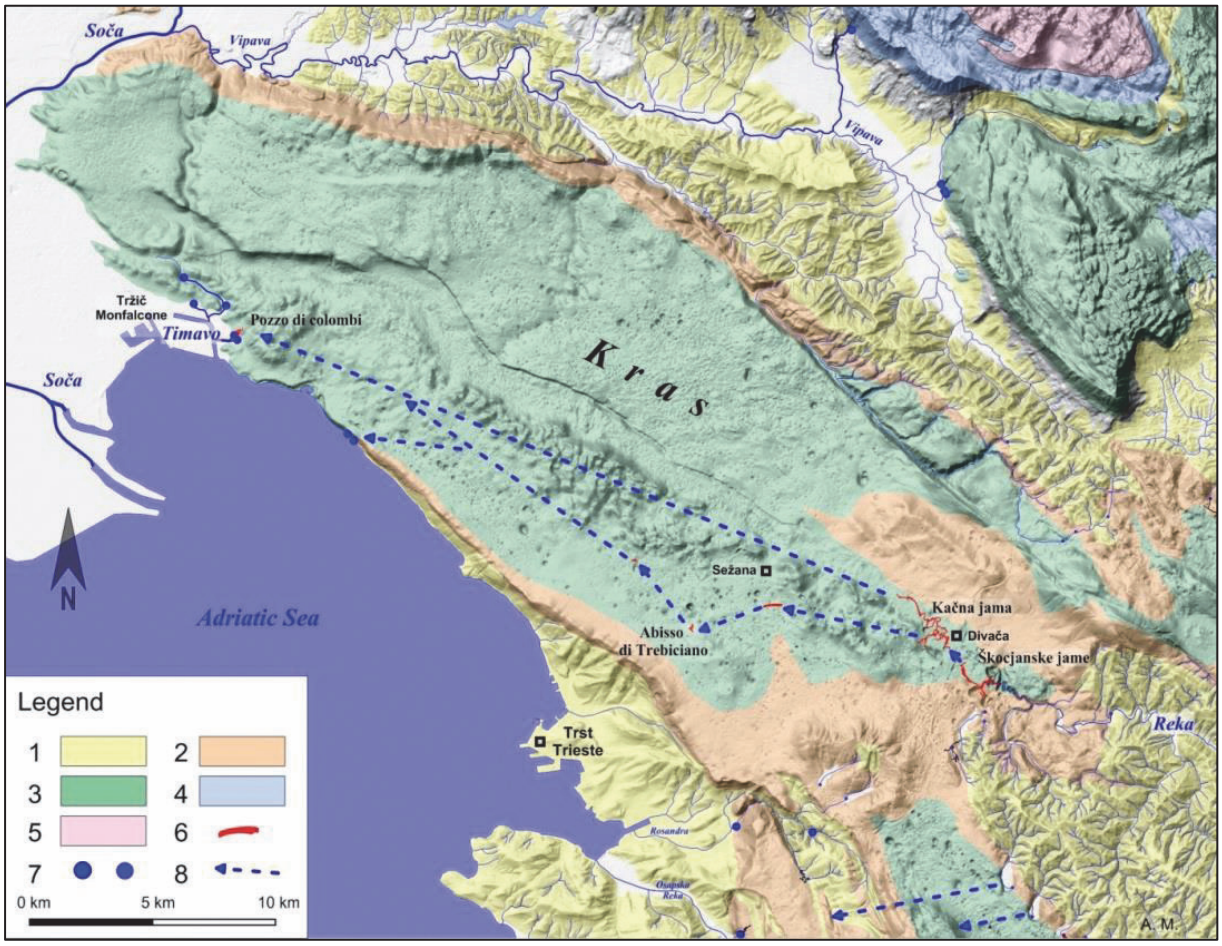


Fig. 1.2: Lithology, hydrology and morphology of the Kras Plateau. Legend: 1. Eocene flysch; 2. Paleocene limestone; 3. Cretaceous limestone and dolomitic limestone; 4. Jurassic limestone and dolomite; 5. Triassic dolomite; 6. important cave; 7. springs; 8. General groundwater flow direction. Source of data: Geodetski oddelek ARSO.

The Škocjanske Jame are located at the SE edge of the Kras (Karst Plateau; Figs. 1.1 and 1.2) and present an initial part of over 35 km-long underground flow of Reka/Timavo (Fig. 1.3), which surfaces back near the Adriatic coast, NW of Trieste, along with autogenic recharge from the Kras plateau, and transaquifer flow from the Soča/Isonzo alluvial aquifer. The position of the cave is predetermined by the proximity of the contact between Cretaceous and Paleocene carbonates and impermeable flysch of Eocene age (Fig. 1.2). Škocjanske Jame present the ponor of the Reka River. The caves consist of extensive cave passages and large collapse chambers in several inclined levels. The passages of the Škocjanske Jame system are developed within components of a 300 m-thick

sequence of Cretaceous and Paleocene limestones (Šebela 2009). The underground Reka in Šumeča Jama and Hankejev Kanal flows mostly within a 130 m-thick segment of the Lipica Formation (K_2^{4-5}) and follows the direction of the bedding-plane dip.

The catchment area of the Reka covers more than 365 km^2, with about 60% of the surface runoff on flysch (Peric & Hribar 2010) (Q_{min}= 0.25 m^3/s, Q_{mean}= 7.89 m^3/s, Q_{max} > 320 m^3/s, ARSO 2023). The groundwater flows towards the spring belt between the Nabrežina/Aurisina and the Timava/Timavo springs in the Gulf of Trieste (Fig. 1.2).

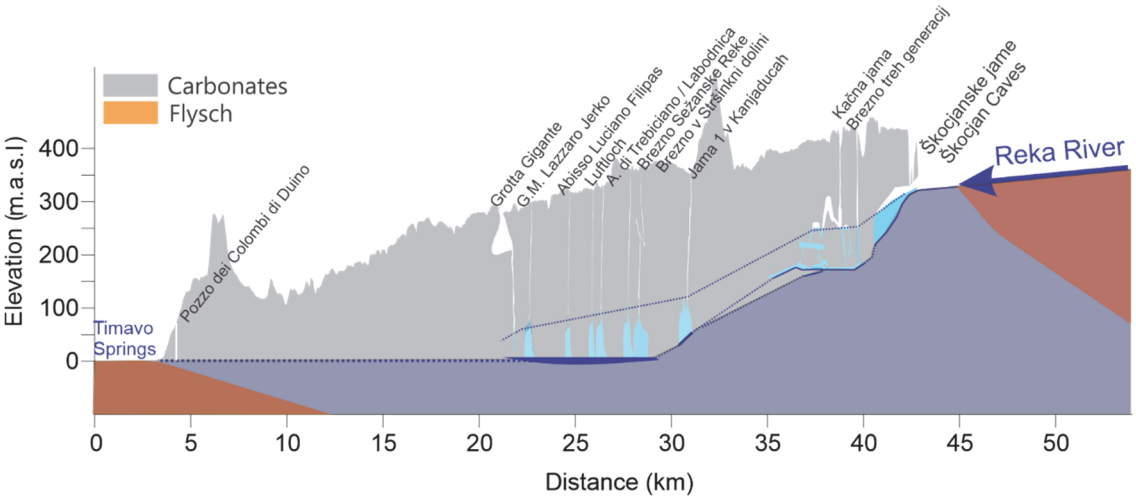


Fig: 1.3 Schematic Cross-section of Kras Plateau with caves reaching groundwater baseflow level.

Kras/Carso is a carbonate plateau, about 40 km-long and 13 km-wide, stretching between the Bay of Trieste, the Vipava Valley and the Soča River in the direction of NW–SE (i.e., in the ''Dinaric'' direction) (Fig. 1.2). The plateau generally dips from SE to NW where it sinks under the alluvium of the Soća/Isonzo River (see also Fig. 1.3). It consists of Cretaceous and Paleogene limestones and dolomites and is encircled by flysch sediments of Eocene age (e.g., Gospodarič 1983; Jurkovšek et al. 1996, 2013). From a tectonic point of view, the Kras belongs to the Komen nappe of the NW part of the External Dinarides (Placer et al. 2010). There are about 3,500 known caves on the plateau; they span the entire vadose zone, with 10 (so far) known caves reaching the base flow level and few more the upper epiphreatic part.

The climate of the Kras is sub-Mediterranean with warm, dry summers and most precipitation in autumn and spring. Cold winters, with NE wind "burja" (bora = Borealis), show a strong influence on the continent. The average annual precipitation varies between 1,200 and 1,650 mm.

Groundwater dynamics

The Reka River enters the Kras aquifer at Škocjanske Jame. Its flow can currently be accessed in 10 other caves between Škocjanske Jame (Fig. 1.3) and a series of springs between Aurisina and Duino on the northwestern coast of the Gulf of Trieste, with the Timavo Springs being the most abundant. High recharge variability and complex geometry, characterized by large variations in cross-sectional area and multiple cave levels, give rise to extreme hydrological dynamics. During extreme floods, water levels can rise by up to 150 m, with rates exceeding 10 m/h (Gabrovšek et al., 2018).

Figures 1.4 and 1.5 present an example of the February 2019 flood event in Škocjanske Jame and Kačna Jama (see Fig. 1.3). Combined modelling and continuous monitoring of water level, temperature, and conductivity have shown that major floods in Kačna Jama and Škocjanske Jame are caused by downstream flow restrictions below Kačna Jama (Gabrovšek et al., 2018).

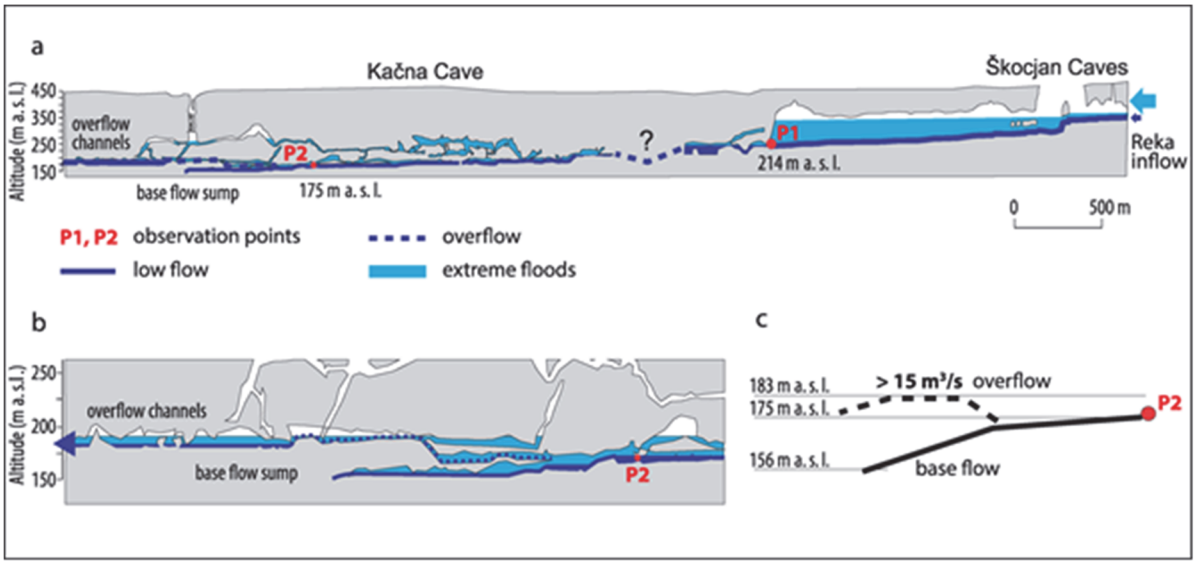


Fig. 1.4: a) Cross-section through Škocjanske Jame and Kačna Jama with the position of observation points. Dark blue lines/regions indicate low flow water positions, and the pale blue shows the floodwater situation. b) Detailed view of the region of P2 in Kačna Cave. c) Flow routing at low flow (solid line) and high flow (dotted line) behind P2 (from Blatnik et al. 2020).

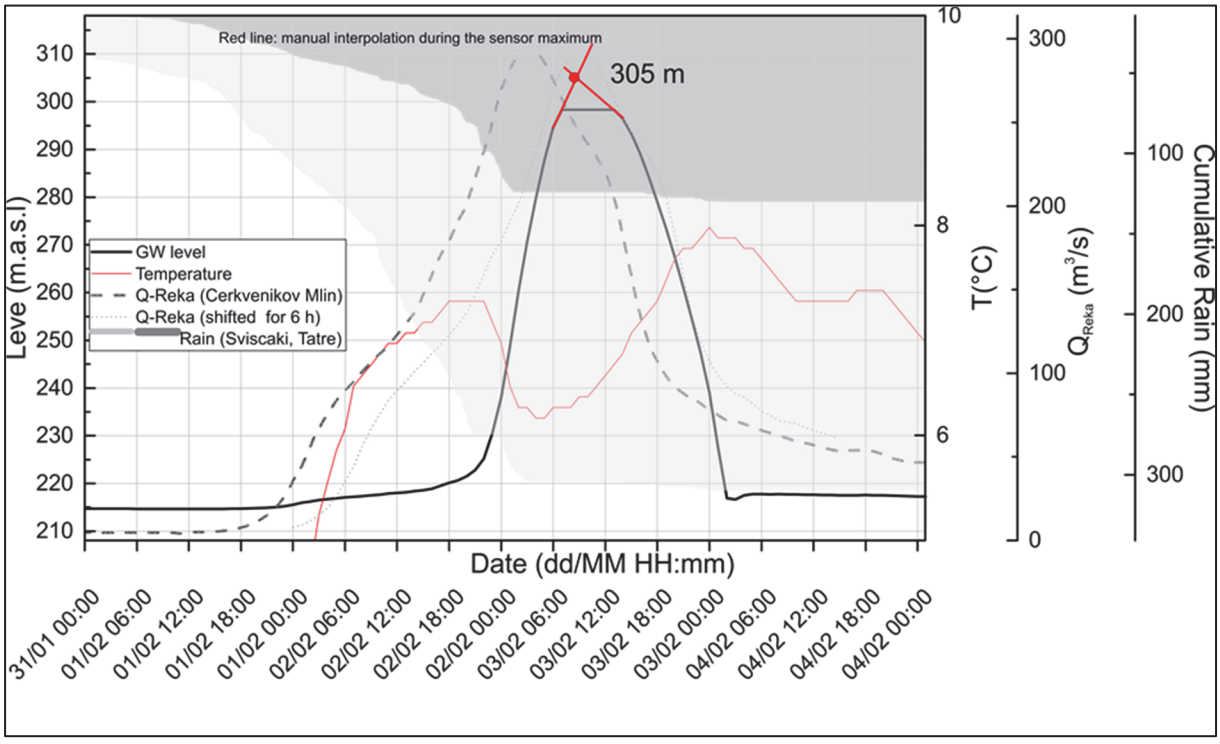


Fig. 1.5: The flood event of 2019: Cumulative rain at two stations, discharge of the Reka River and level and temperature in Martel's Chamber (from Blatnik et al. 2020). Dotted grey line shows discharge shifted for six hours, an estimated travel time from gaging station to Martel's Chamber.

During the event the discharge of the Reka River at the Cerkvenikov Mlin gaging station peaked at 300 m^3/s. The water in Škocjan Caves rose at rates up to 10 m/h and reached a level of 305 m a.s.l. in Martel's Chamber (Figs. 1.4 and 1.5) and about 307.5 m a.s.l. in Šumeča Jama. The flood was the largest in the last 50 years. High water caused severe damage to infrastructure and deposited a considerable amount of mud and immense amount of organic matter; at some places the thickness of fresh deposits was above 50 cm (Fig. 1.6).

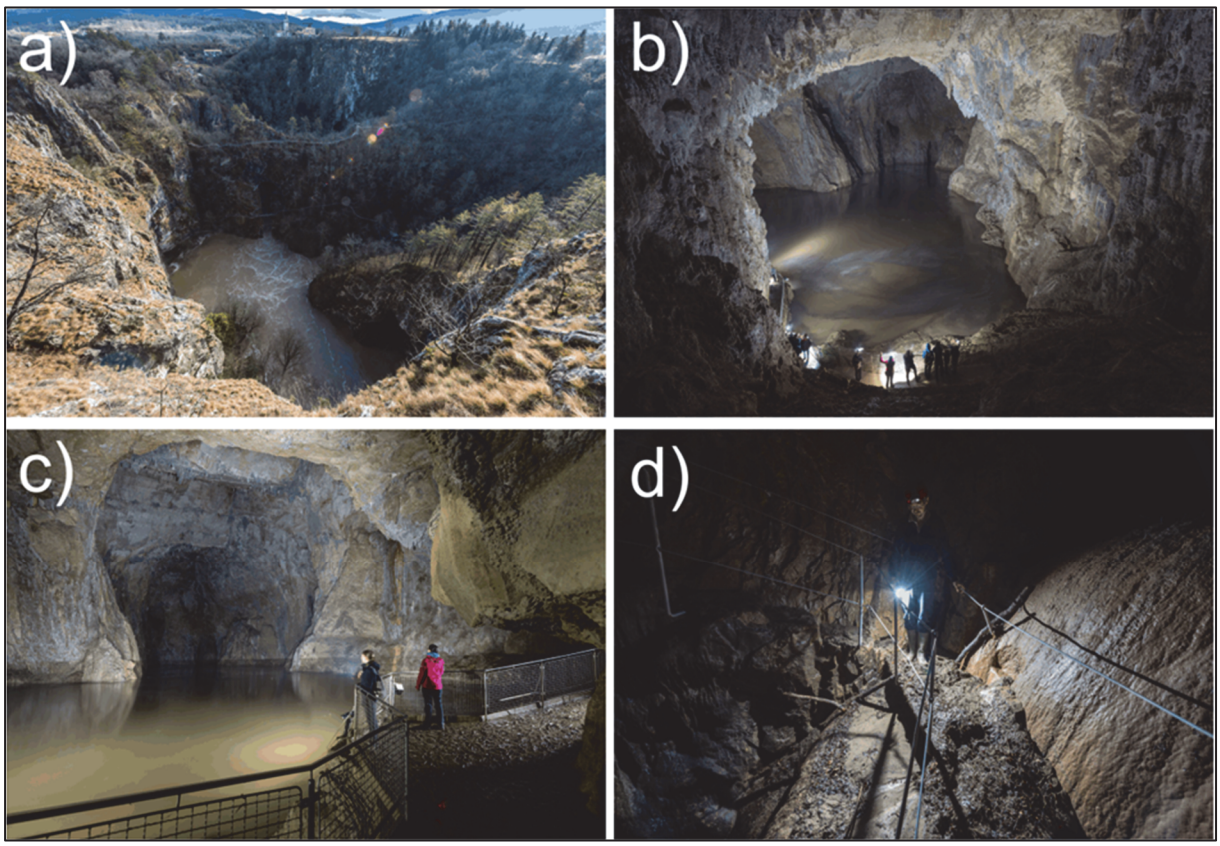


Fig. 1.6: Photos of the 2019 flood. a) Velika Dolina. b,c) Sumeča Jama (Rumouring Cave) d) Flood deposits on the footpath in Hanke's Channel (photos B. Lozej (a, b, c), F. Gabrovšek (d)).

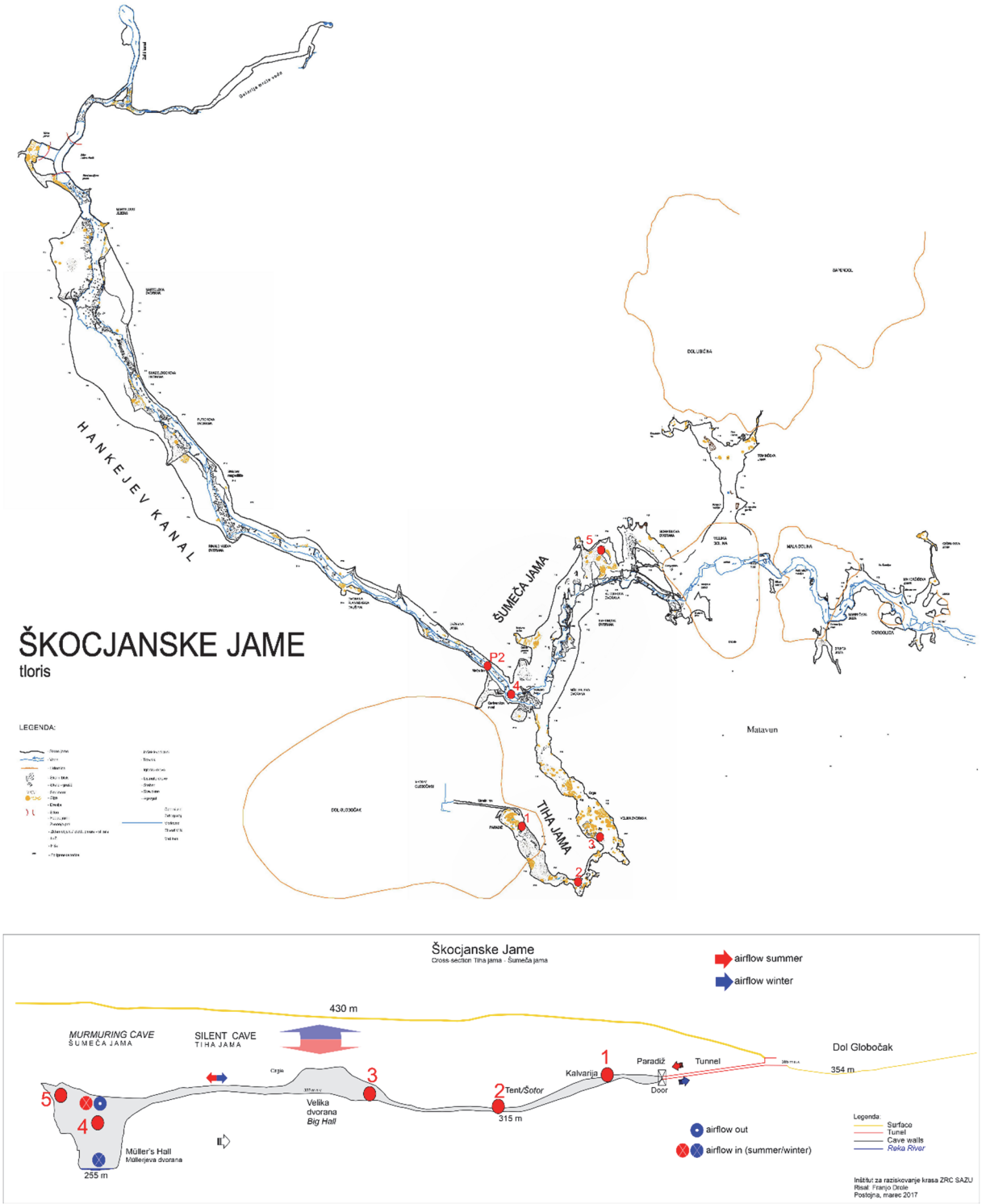


Fig. 1.7: ***Top:*** *Map of Škocjanske Jame, with locations of observation stations referred to in this section (IZRK ZRC SAZU).* ***Bottom:*** *Profile from the dolina Globočak through Tiha Jama to Reka Canyon (Murmuring Cave/Šumeča jama). Point 5 is not properly located (see map), but is placed for the elevation reference of Ponvice station. Arrows indicate direction of airflow (red: summer, blue: winter).*

Air in the Škocjan Caves

Škocjan Caves exhibit at least two very distinct meteorological patterns. In the Reka Canyon, the airflow dynamics are driven by intrusion of cold air and formation of the counterflow (see Fig. 1.8) in the winter. In extremely cold periods, temperatures along the streambed drop below freezing point all the way to the Martel Chamber. On the other hand, temperatures under the ceiling of the canyon are above 5°C, even in the coldest period. Figure 1.9 shows airflow and temperatures in a cold period in February 2018; measurements were taken just above the streambed and below the ceiling, and compared with outdoor temperatures from the end of February to the beginning of March 2018. The temperature below the ceiling (P2, Fig. 1.8) is constantly in the range of 5°C, and the temperature at the bottom (P1, Fig. 1.8) follows the outdoor temperature. The airflow speed increases at both points with external cooling and reaches 1.5 m/s at both points, when the outdoor temperature drops below −10°C.

Fig. 1.8: Observations and concept of the convection cell in the Reka Canyon in Škocjan Caves (F. Gabrovšek). Left: Picture of Šumeča Jama (Murmoring Cave) and Hanke Channel with position of anemometers (P1–6th Waterfall, P2–Novak Bridge) and the line of temperature loggers below P2. Right: Profile of Reka Canyon with (so far) estimated convection cell. Arrows indicate temperature (blue to red = cold to warm) and direction of airflow.

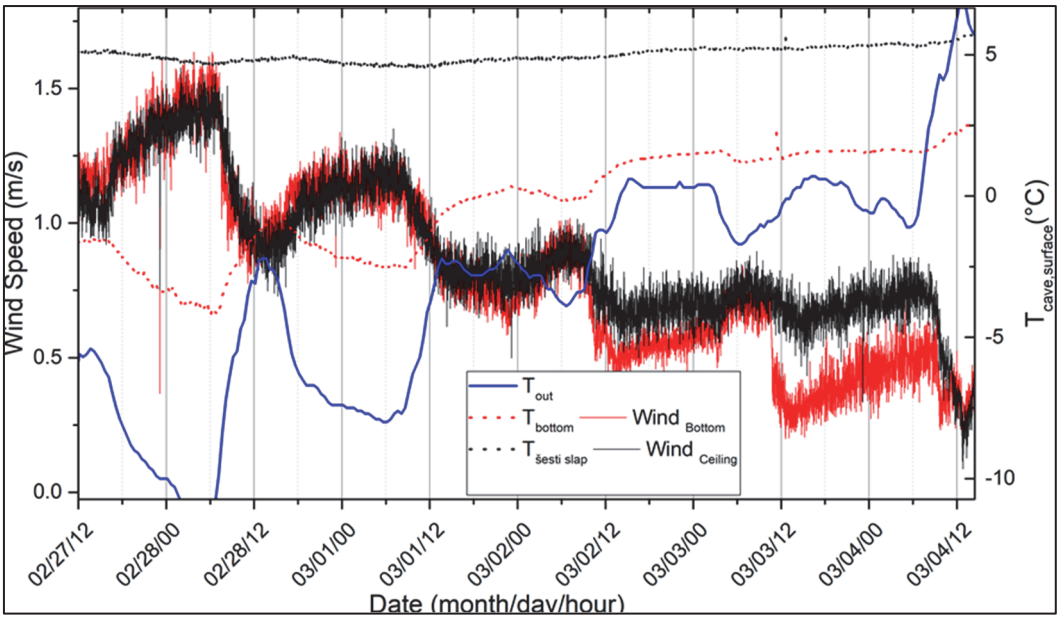


Fig. 1.9: Airflow velocity and temperature at the river bed (P1, red curves) and below the ceiling of the canyon (P2, black curves) in winter 2018 (F. Gabrovšek). Blue curve shows the outside temperature.

The things become even more interesting and complicated, when diurnal values of external temperatures rise and fall above/below 12°C. Such a case is presented on Figure 1.10, which shows airflow, external temperature and cave temperature at the Ponvice Station (#5 in Fig. 1.7). The airflow is directed outwards for T_{out} < 12°C and turns direction for T_{out} > 12°C. During cold periods, the station is within the flow domain of air returning from the interior of the canyon. During warm period, there is an intrusion of warm air recorded at this point, as can be seen from the temperature record. However, the spatial airflow pattern has still not been revealed for the warm period and requires further and more detailed monitoring in the entrance part. But the inward flow during warm periods was also recorded at Novak Bridge. One has to have in mind that the air in the canyon is also influenced by the presence of Reka River.

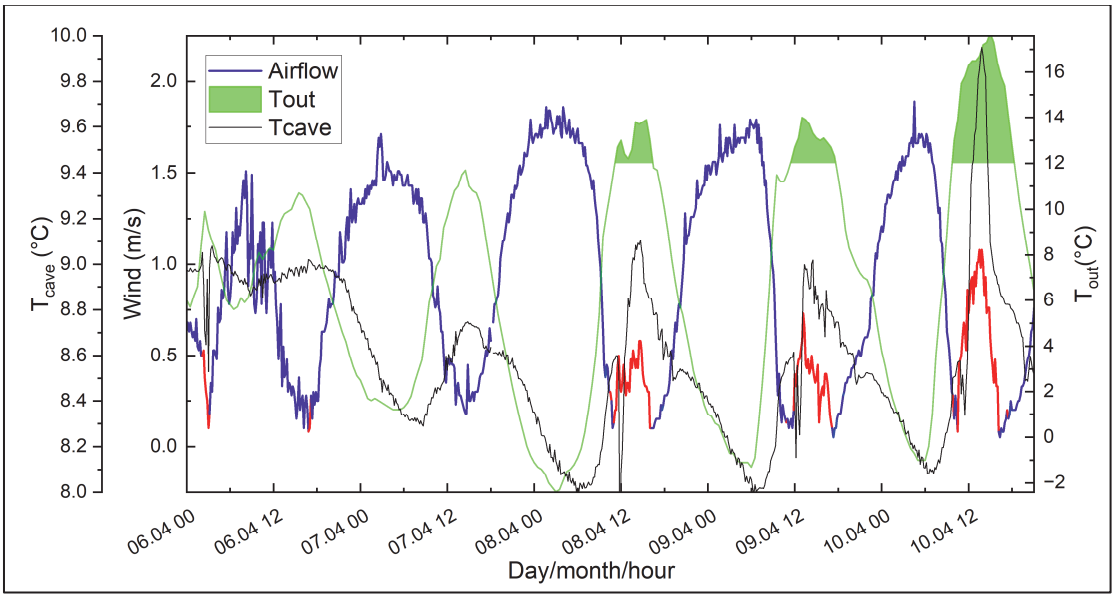


Figure 1.10: Airflow and temperature at the Ponvice station (#5 in Fig. 1.7), and external temperature during transitional period in April 2025.

Figure 1.11 shows the airflow velocity at the ceiling (P2, Fig. 1.7) as a function of external temperature. During the cold period, when the convection cell is active, the velocity shows a (apparently?) linear relation with the difference between the temperature of the massif (about 12°C) and the temperature of the outside air. During the warm period, when the air flows into the cave, the velocity of the air flow and the differences between the outside temperature and the temperature of the massif show a square root relation.

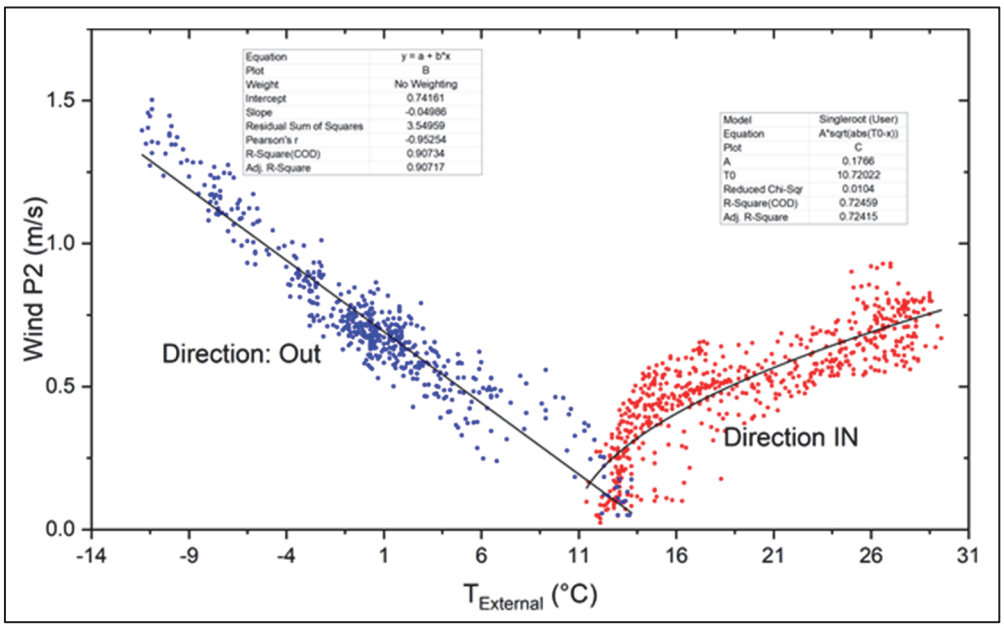


Fig. 1.11: Airflow velocity at Novak Bridge (P2 in Fig. 1.7) versus external temperature.

The Tiha Jama (Silent Cave) is a meteorologically conservative part of the cave system. The only open entrance to Tiha Jama is Šumeča Jama (Reka Canyon/Murmuring Cave). The second "entrance" is an artificial tunnel from the collapse doline Globočak, which is open only during the passage of tourists (see Fig. 1.7). In a sense, a silent cave can be considered a "blind passage", with no large passage connecting it to the surface.

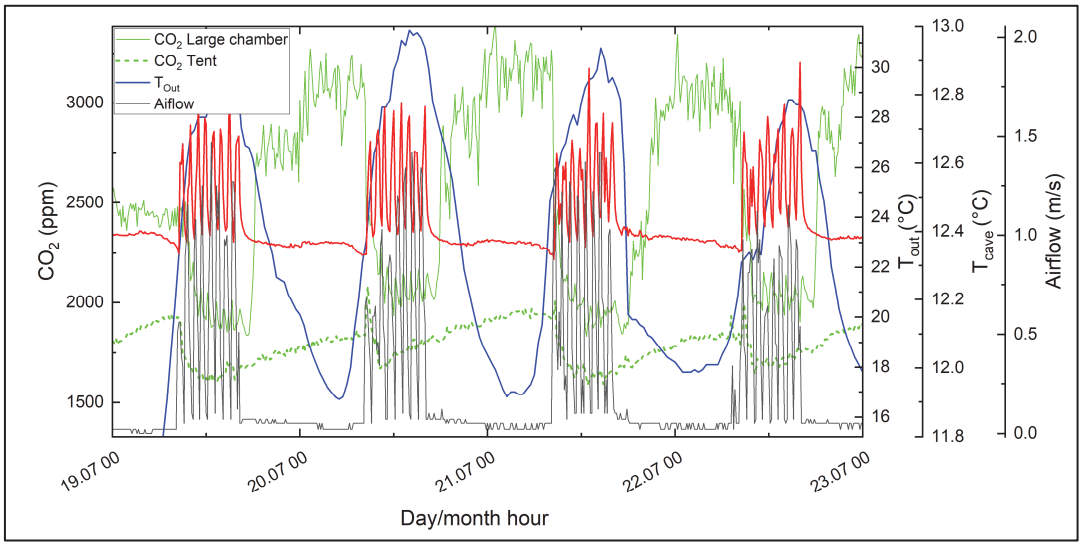


Fig. 1.11: Air parameters in the Large Chamber (Velika Dvorana) in the warm season of July 2025.

The temperature in the Velika Dvorana (Large Chamber, point 3 on Fig. 1.7) varies between 12.2°C and 12.6°C; the annual maximum is in late August and the minimum in March. Figure 1.11 shows airflow, CO_2, temperature and external temperature typical for high season. The airflow is minimal, but activated during gate opening as the tourist groups enter. The CO_2 accumulates during the night and is diluted by ventilation during the day, when the doors to the tunnel are opened for tourists. Note that in this example, the night external temperature is always above 12°C, which probably causes minimal, yet important, advective flow of air from the vadose zone, causing CO_2 accumulation. The CO_2 variations are much smaller at the Šotor/Tent site (point 2 in Fig. 1.7).

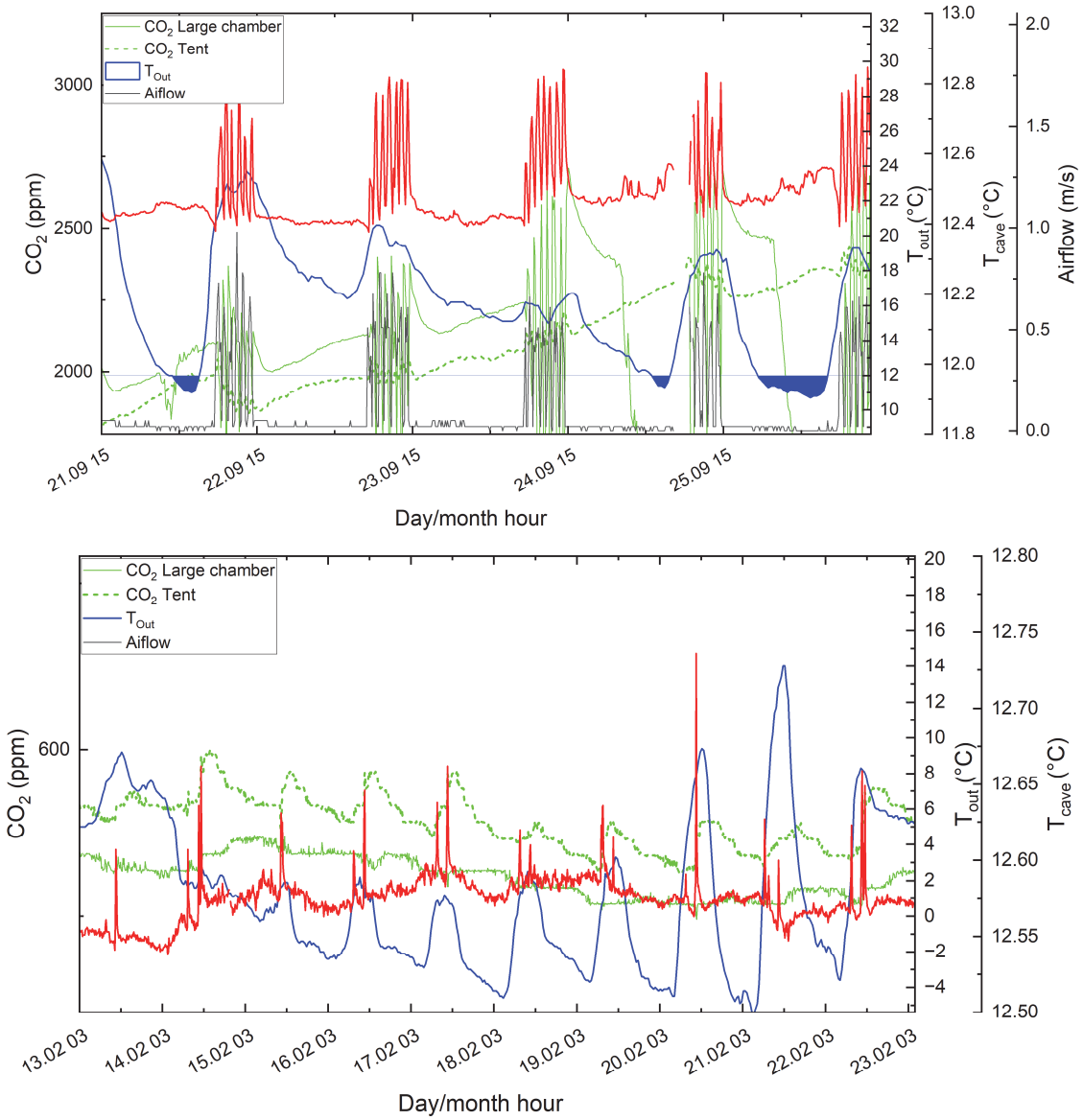


Fig. 1.12: Top: Air parameters in Large Chamber during a transitional period in September 2025. Bottom: Records of temperature and CO_2 during a cold season.

During transitional periods (Fig. 1.12 top), when the diurnal external temperature fluctuates above and below 12°C, nocturnal accumulation is reduced, and CO_2 concentrations in the Large Chamber show rapid declines when the temperature falls below 12°C. This causes a reversal of airflow, with air entering the chamber from the Murmuring Cave. During the cold season (Fig. 1.12 bottom), CO_2 concentrations drop below 600 ppm, and ventilation is directed from the Murmuring

Cave. Interestingly, higher CO_2 values and greater variability are recorded at the Šotor/Tent site (point 2 in Fig. 1.7).

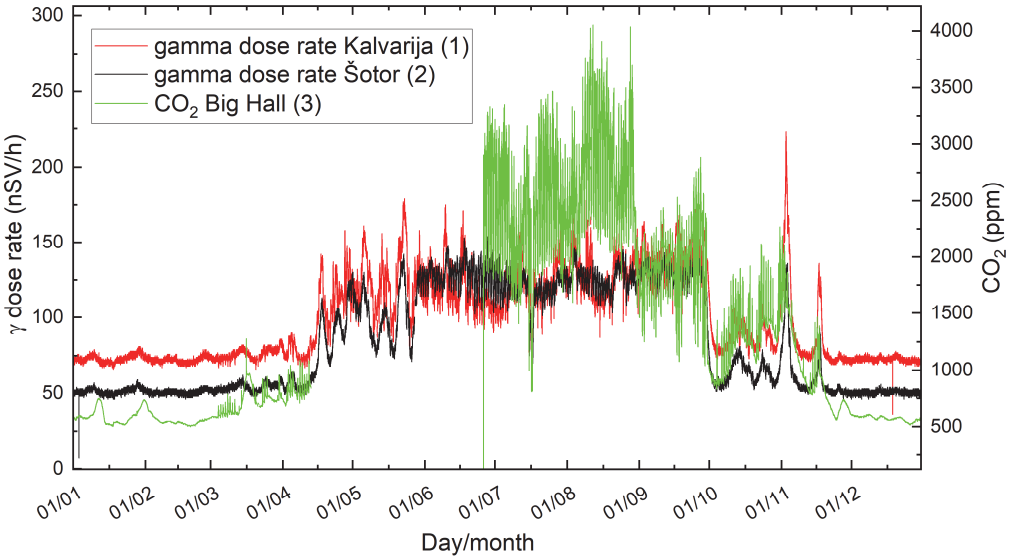


Fig. 1.13: Gamma dose rate at Calvary and CO_2 concentration in Large Chamber throughout 2025.

In addition to radon monitoring for occupational safety, gamma dose rate is continuously measured in Tiha jama, as it can serve as a proxy for radon presence. These data, together with CO_2 concentrations in the Large Chamber, are presented in Figure 1.13. The measurements indicate higher dose rates during summer and lower values during winter and transitional periods. Although further analysis is required, the results suggest that both CO_2 and radon concentrations are strongly controlled by the cave ventilation regime. During warm periods, CO_2- and radon-enriched air is advectively transported from the vadose zone, whereas during cold periods, airflow originating from the Murmuring Cave is characterized by low CO_2 and radon concentrations.

References

- ARSO 2023: Slovenian Environment Agency, Archive hydrological data. [Online] Available from: http://vode.arso.gov.si/hidarhiv/pov_arhiv_tab.php [Accessed 25th April 2023].
- Gabrovšek, F., Peric B., Kaufmann, G., 2018: 'Hydraulics of Epiphreatic Flow of a Karst Aquifer'. Journal of Hydrology 560 (May): 56–74. https://doi.org/10.1016/j.jhydrol.2018.03.019.
- Gospodarič, R., 1983: About geology and speleogenesis of Škocjanske Jame. Geološki zbornik, 4, 163–172.
- Jurkovšek, B., Toman, M., Ogorelec, B., Šribar, L., Drobne, K., Poljak, M., Šribar, L., 1996: Geological map of the southern part of the Trieste-Komen plateau, Cretaceous and Paleogene carbonate rocks 1:50 000. Inštitut za geologijo, geotehniko in geofiziko, 143 pp.
- Peric, B., Hribar, M., 2010: Reka. DEDI - digitalna enciklopedija naravne in kulturne dediščine na Slovenskem, http://www.dedi.si/dediscina/143-reka.
- Placer, L., Vrabec, M., Celarc, B., 2010: The bases for understanding of the NW Dinarides and Istria Peninsula tectonics. Geologija, 53/1, 55–86.
- Šebela, S., 2009: Structural geology of the Škocjan Caves. Acta carsologica, 38/2–3, 165–177.

Afternoon field trip (B):

CAVE AIR–WATER–ROCK INTERACTIONS IN A MATURE, WELL-VENTILATED STREAM CAVE; CASE STUDY OF THE KRIŽNA CAVE

Wednesday, 17th June 2026, 14:00–19:30

Stops:

1 –Križna Cave

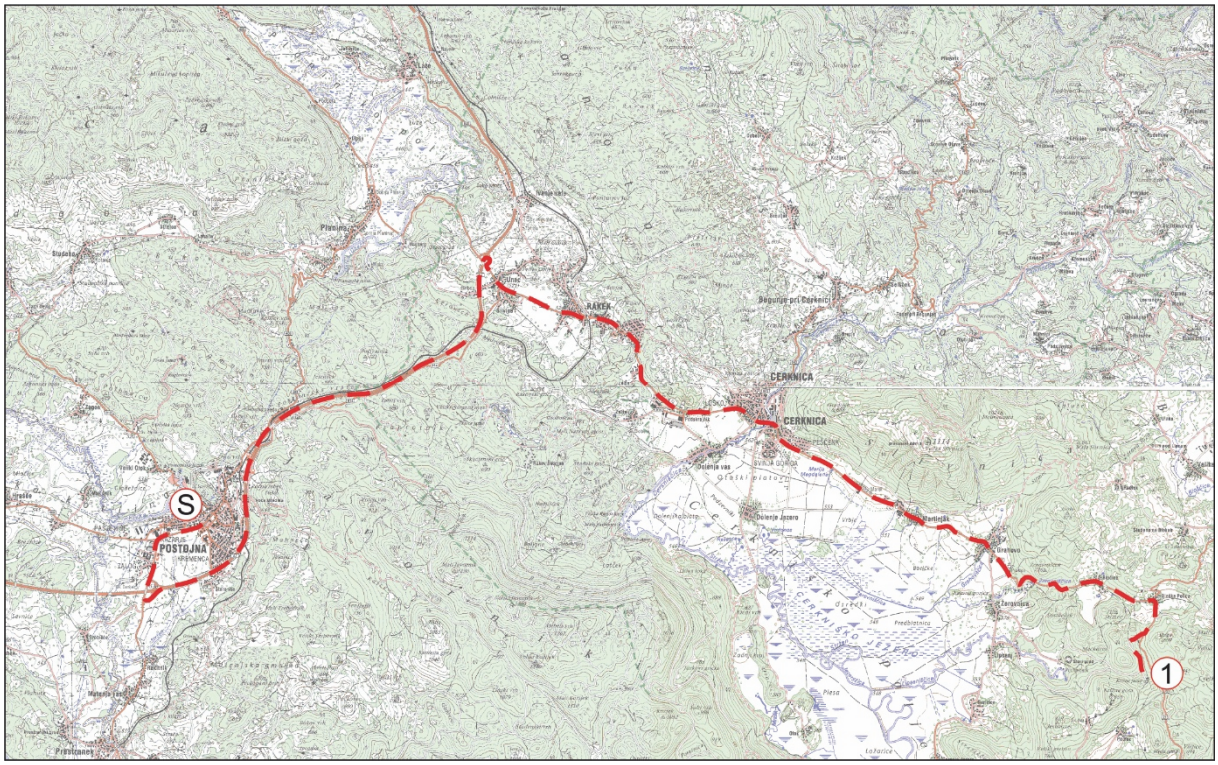


Fig. 2.1: Location of the Križna Cave

The Križna Cave (KC; length of 8.3 km; Slovenian "križ" = English "cross", therefore "Cave under the Holly Cross mountain") is located at 620 m a.s.l. between in the centre of the Classical Karst between Bloke Plateau (~720 m a.s.l.) and Cerknica Polje (~550 m a.s.l.). The downstream continuation is recognized as the New Križna Cave or Križna jama 2 (NKC; length of 1.4 km; closed for the purpose of nature conservation; Fig. 2.2). Both caves are separated by a sump, at least 124 m-deep, related to a collapse doline between them. While the entrance parts of the caves are located close to the surface (at the entrances, some dolines are already part of the unroofed part of the cave system), the rest of the underground passages are up to 220 m under the surface. Two main upstream passages of KC (Blata passage and Pisani passage) are explored up to an unpassable breakdown, the downstream continuation in the 70 m-deep sump was not yet found. In NKC, the upstream and downstream explored trunk passage ends in sumps. Both caves together form the Križna Cave System. While the highest measured discharge in the KC was 5.3 m^3/s (+82 cm at the water gauge in the 1st lake of the KC), the underground channel with lakes usually dries up during summer droughts. Typical discharge through KC is approximately 0.2 m^3/s. Discharge in NKC is up to 1.2 m^3/s higher when compared to KC due to inflow of partly allogenic water in the deep sump between both caves. Allogenic inflow between the two caves is evident by higher seasonal temperature variation (about +0.2 °C in summer and

−0.2 °C in winter) and earlier detection of tracer in NKC injected at Bloke Plateau than in upstream-located KC. Based on disciplines related to the IKS main topic, the KC can be categorized as:

- geomophology (mature cave, epiphreatic cave, water-table cave, branchwork/dendritic cave);
- hydrology (epigene/hypergene/meteoric cave, stream cave, autogenic recharge cave with occasional allogenic inputs);
- meteorology/cave climate (highly-ventilated cave, flow-through cave, chimney/stack-effect cave).

NKC is similar from a geomorphic and hydrogeological perspective but different from the perspective of cave climate.

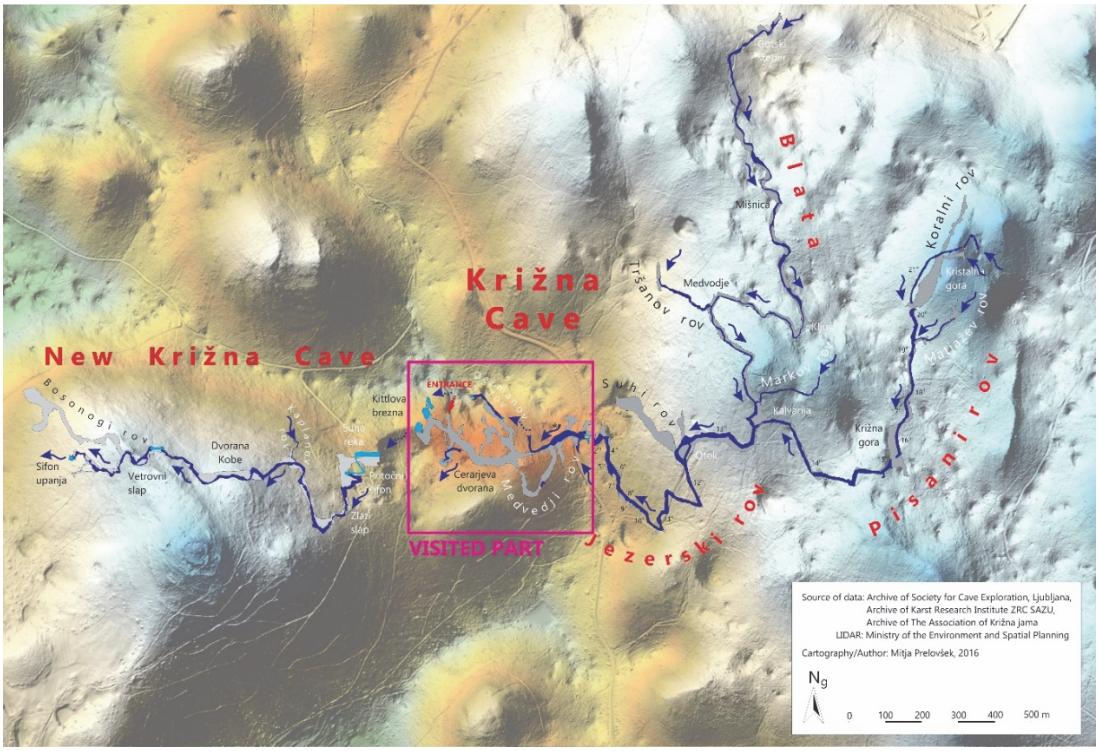


Fig. 2.2. Plan of the Križna Cave System.

Hydrology

During periods of low water levels, KC drains percolated water from the nearby hilly karst area (primary infiltration of percolation water). Only when the water level is very high, KC also drains allogenic sinking water from the Bloke Plateau. This was proved by tracer test in 2007 when only 1.3 % of the tracer injected at Bloke Plateau appeared in KC despite the cave's location between the main sink and the main spring (Kogovšek et al., 2008). During such floods, water temperature surpasses maximal seasonal water temperature variation (0.1 °C) by several degrees Celsius. The hydrological network of the Križna Cave System with many tributaries and no water loss indicates the cave system as a collector type of the cave. Owing to the mainly autogenic recharge, percolation water is relatively rich in CO_2 ($CO_{2(eq)\ AVG}$ = 11,300 ppm), dissolved calcite and dolomite (SEC_{AVG} = 462 µS/cm), and saturated in carbonate minerals when it emerges in the KC. The water percolates through Upper Triassic and Lower Jurassic dolomite and Lower–Middle Jurassic limestone (Ca/Mg_{AVG} = 2.1). More detailed and comprehensive information on hydrology of the Križna Cave System is available in the paper by Prelovšek (2014).

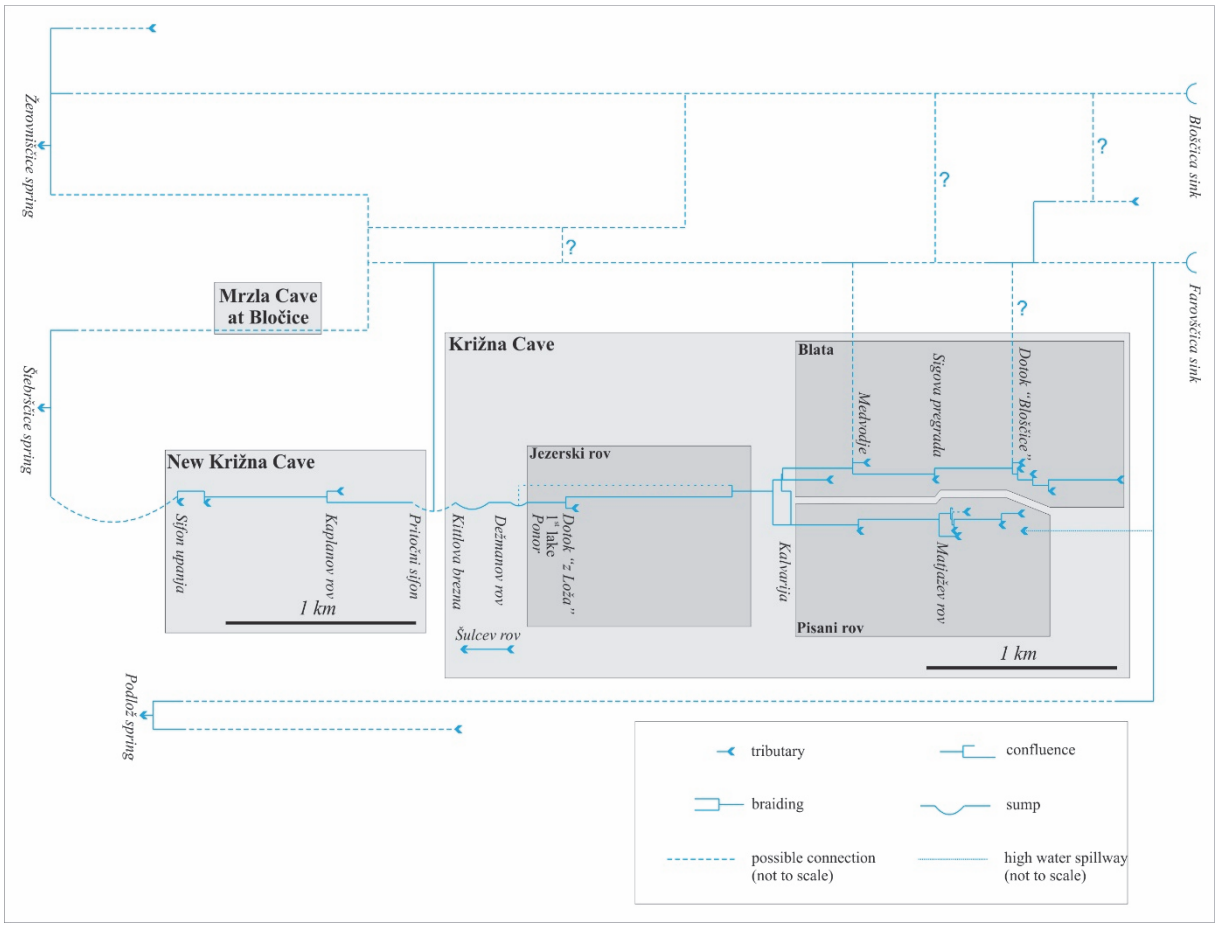


Fig. 2.3: Hydrological network of the Križna Cave System between the Bloke Plateau (Bloščica and Farovščica sinks) and Cerknica polje (Žerovniščica and Štebrščica springs) or Lož polje (Podlož Spring).

Cave Climate

Despite being karstified, the rock mass surrounding the cave can be considered to have restricted ventilation, and therefore, carbonate equilibrium is often reached. On the other hand, the trunk passages of KC are intensively ventilated. The lowest entrance is the main entrance that has a wide opening even before artificial modification. Both trunk passages (the Blata passage and the Pisani passage) are explored up to the unpassable breakdown, but due to ventilation patterns, there must be airflow connections reaching the surface at a higher elevation than the main entrance. The chimney effect results in updraft of atmospheric low-CO_2-concentration air through the main entrance in cold seasons and downdraft during periods with higher temperatures outside than inside the cave. As a result, cave CO_2 concentrations are almost at atmospheric levels during winter time and up to about 1,500 ppm in summer time when ventilation is strongest (Fig. 2.4). Weak ventilation results in a rise of CO_2 concentration in the cave air up to 3,500 ppm. The origin of cave air CO_2 is associated with water CO_2 outgassing and drag from the vadose zone. Due to extensive natural ventilation, a visitor-exhaled CO_2 source is considered as negligible. The ventilation situation is different in the NKC. Air flow pulsation at the NKC entrance indicates only one entrance of bigger (passable) dimensions. However, weak unidirectional air flow that occurs only during very low or very high outside temperatures indicates that the only passable entrance of NKC as upper entrance while the lower ones should be much smaller. Therefore, the CO_2 concentrations in NKC are higher than those in KC, where the highest

occasional handheld-measured CO_2 concentration in NKC was detected during winter (3,700 ppm) and the lowest in summer (900 ppm).

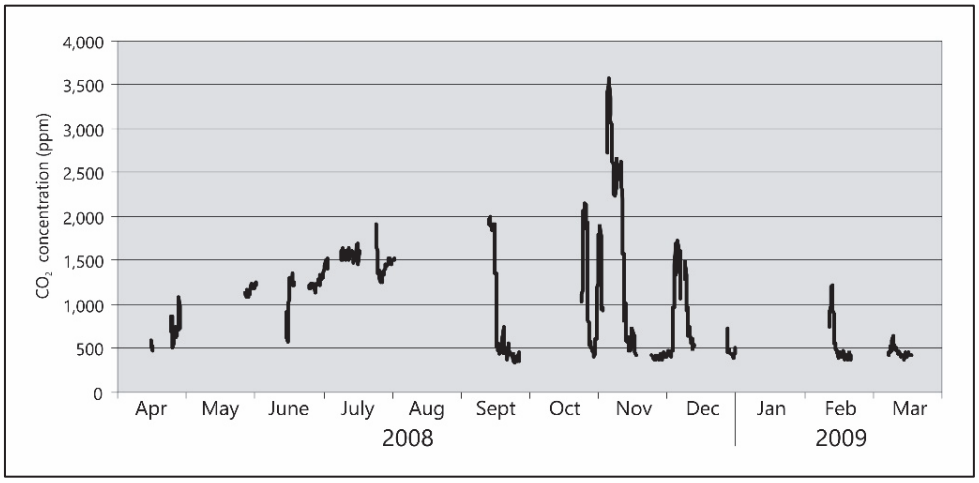


Fig. 2.4: Occasional measurement of CO_2 close to the 1st lake in the Križna Cave.

Processes at the rock-water-air interface

Since cave air CO_2 concentration is always well below that in the water, the logical consequence is CO_2 outgassing, especially in KC. This is the most evident as a downstream rise in pH under springs or confluences in both caves indicating H^+ consumption in the water to produce H_2CO_3 from H^+CO_3 (Fig. 2.5). Due to higher discharge (typically 0.2 m^3/s), the process is much more intense compared to dripstone formation. Water CO_2 outgassing results in calcite oversaturation with calcite precipitation (Fig. 2.6); while typical calcite precipitation rates are 0.5 µm per measurement period (15 days), rates up to 15 µm per measurement period are detected during very cold winter days (Prelovšek, 2009b). While the real reason for this is still unexplained, it should be conceptually associated with higher calcite oversaturation due to extensive ventilation (Prelovšek, 2009a). Despite water oversaturation, such high calcite precipitation rates were never observed in the NKC since it is much less ventilated.

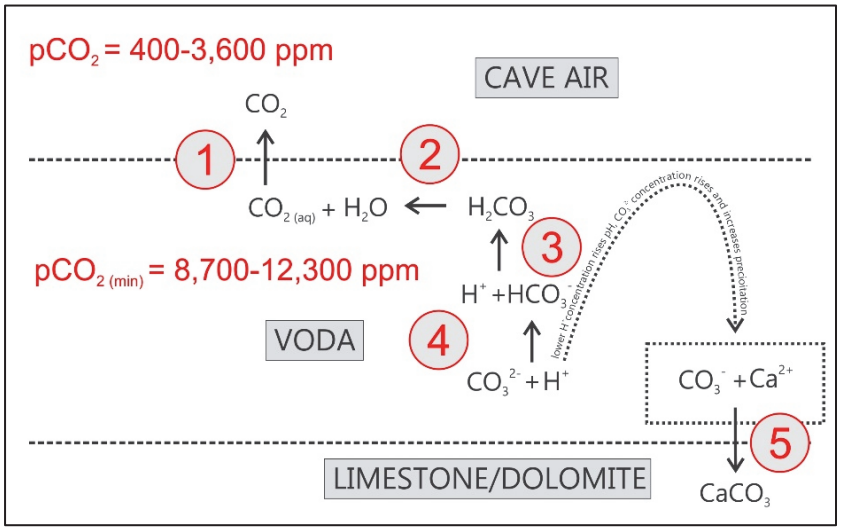


Figure 2.5. Series of reactions (1–5) due to water CO_2 outgassing (1) ends with calcite precipitation (5). Values are typical for the Križna Cave.

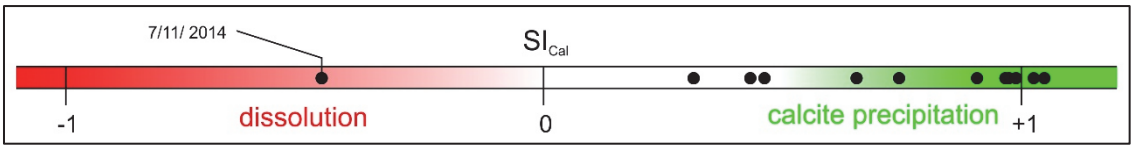


Figure 2.6: Calcite saturation index of sampled water in the 1st lake of the Križna Cave. The only undersaturated water is associated with a very high discharge event with a recurrence period of several decades.

The mature state of the karst aquifer affected by ventilation shows a dynamic exchange of carbon between rock, water and cave air. Since processes connecting all three spheres are in a dynamic equilibrium, change of one parameter results in the tendency to reach new equilibrium with bidirectional carbon fluxes. From an empirical and conceptual point of view, the mature state of stream caves with ventilation in temperate climates that drain water rich in carbonates (i.e., Pivka River in the Postojna–Planina Caves System, Reka River in the Škocjan Caves) shows a reverse carbon flux than expected from general limestone dissolution in karst area; instead of carbon transfer from the atmosphere and rock to the water that occurs due to carbonate dissolution, carbon flux back into the atmosphere (due to CO_2 outgassing) at the cave air–water interface is more common in such caves. In one cave studied in details (Covington et al., 2013) CO_2 outgassing decreases dissolution rates; very similar situation has been studies along the Logsdon River in the Mammoth Caves where CO_2 outgassing into the cave atmosphere appears to be the major process controlling the evolution of the groundwater forcing the water from under saturated state into (over)saturated (Anthony et al., 2003). Beside spatial heterogeneity, temporal variability due to climate change is also evident; the actual thickness of precipitated calcite that corresponds with calculated calcite thickness based on measured rates during the Holocene period in the Križna Cave or the Škocjan Caves indicates only Holocene-related calcite precipitation. Much lower precipitation rates (if any) and lower carbon fluxes into the atmosphere from the underground water is expected for Pleistocene colder periods.

References

- Anthony, D.M., Groves, C., Meiman, J., 2003: Preliminary investigations of seasonal changes in the geochemical evolution of the Logdson River, Mammoth Cave, Kentucky. Speleogenesis and Evolution of Karst Aquifers 1 (4), 6 pp.
- Covington, M.D., Prelovšek, M., Gabrovšek, F., 2013: Influence of CO_2 dynamics on the longitudinal variation of incision rates in soluble bedrock channels: Feedback mechanisms. Geomorphology 186, 85-95.
- Kogovšek, J., Prelovšek, M., Petrič, M., 2008: Underground water flow between Bloška planota and Cerkniško polje and hydrologic function of Križna jama, Slovenia. Acta Carsologica 37/2-3, 213-225.
- Prelovšek, M., 2009a: Influence of meteorology on speleothem deposition: example from Križna jama, Slovenia. Proceedings of the International congress of speleology (Kerrville, USA), 1643-1649.
- Prelovšek, M., 2009b: Present-day speleogenetic processes, factors and features in the epiphreatic zone (PhD dissertation). University of Nova Gorica, Nova Gorica, 297 pp.
- Prelovšek, M., 2014: The Hydrogeological Setting of Križna jama. — Mitt. Komm. Quartärforsch. Österr. Akad. Wiss., Wien, 21-27.

Whole-day field trip (C):

CARBON FLUXES AND RELATED RESEARCH FROM THE POSTOJNA–PLANINA CAVES SYSTEM

Thursday, 18th June, 2026, 8:30–18:00

Stops:

1 – Postojna Cave

2 – Pivka & Črna Cave

3 – Malni Spring

4 – Planina Cave

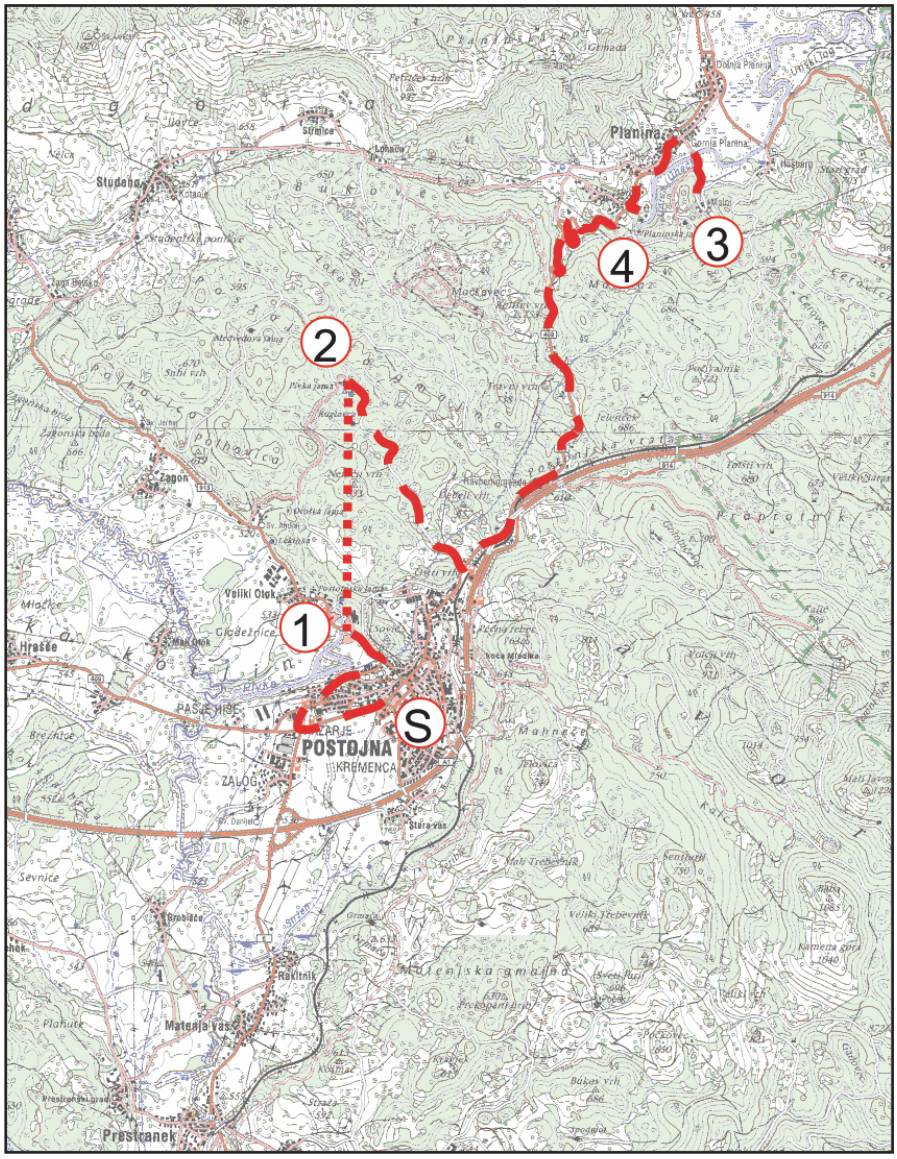


Fig. 3.01: Field trip stops.

Motivation

The idea behind this field trip is to cross-sect the karst system between Postojna and Planina from ponors to the springs and discuss how flow and the interactions between water and air control the carbon flux through the karst massif.

Settings

Postojnska Jama (Postojna Cave) and Planinska Jama (Planina Cave) are among the principal landmarks of the classical karst between the Pivka Basin and Planinsko Polje (Fig. 3.02). Postojnska Jama is a cave system more than 24 km long, with five known entrances and the ponor of the Pivka River. Planinska Jama, located on the southern margin of Planinsko Polje, is a spring cave extending over 6.8 km.

Although the physical connection between the two systems has not yet been fully explored by cave divers, and at least one deep phreatic loop remains unexplored, numerous dye-tracing experiments and indirect observations leave no doubt that they form a single hydrological/ speleological system. For this reason, the combined network is often referred to as the Postojna–Planina Cave System. Postojnska Jama is undoubtedly one of the world's most famous show caves, while Planinska Jama is widely regarded as one of the most scenic karst springs.

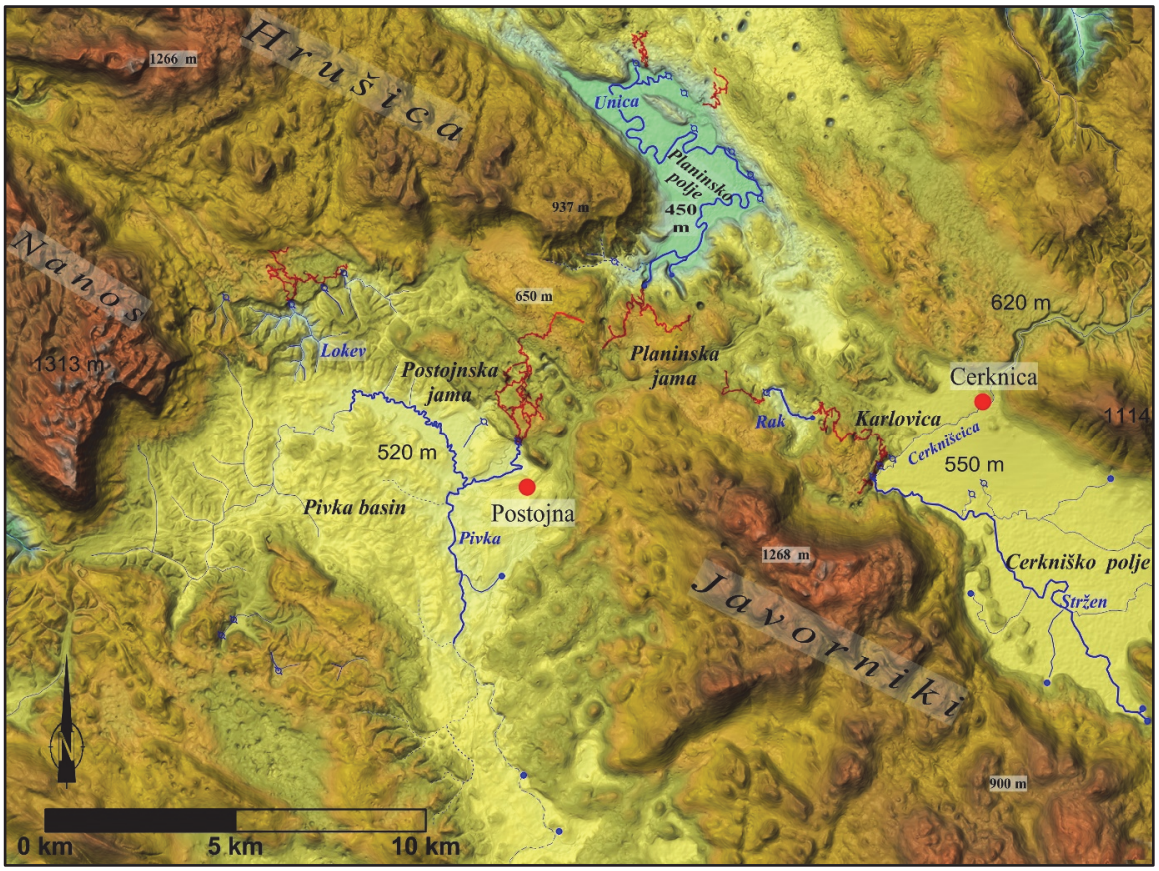


Fig. 3.02: A geomorphological map of Postojnski kras (Postojna Karst) between the Pivka Basin and Planinsko polje (Planina Polje) with the location of major caves (A. Mihevc).

The Pivka River flows through impermeable Eocene flysch and sinks into the Postojnska Jama cave at the contact with limestones (Figs. 3.01, 3.02). The Pivka flows underground to the Planinska Jama (Planina Cave), from which the Unica River then emerges.

The karst between Postojna and Planina is formed within Cretaceous limestones and dolomites. The entire cave is formed in a 800-metre-thick sequence of limestones confined by two distinct dextral strike-slip fault zones in the Dinaric direction (Predjama and Idrija faults). Carbonate beds of different thicknesses are overthrusted, folded and faulted due to regional tectonics (Placer 1996). Important structural elements of folding are the Postojna anticline and the Studeno syncline, which trend toward SE–NW. Significant faults are in Dinaric direction (SE–NW; dextral strike-slip fault) and in Cross-Dinaric direction (sinistral strike-slip fault); some of them are vertical.

The formation of caves is conditioned by allogenic recharge from the Pivka basin. The karst surface at an altitude of 600 to 650 m a.s.l. is characterized by numerous solution dolines and sixteen large collapse dolines, which formed above the cave passages, and block some of them.

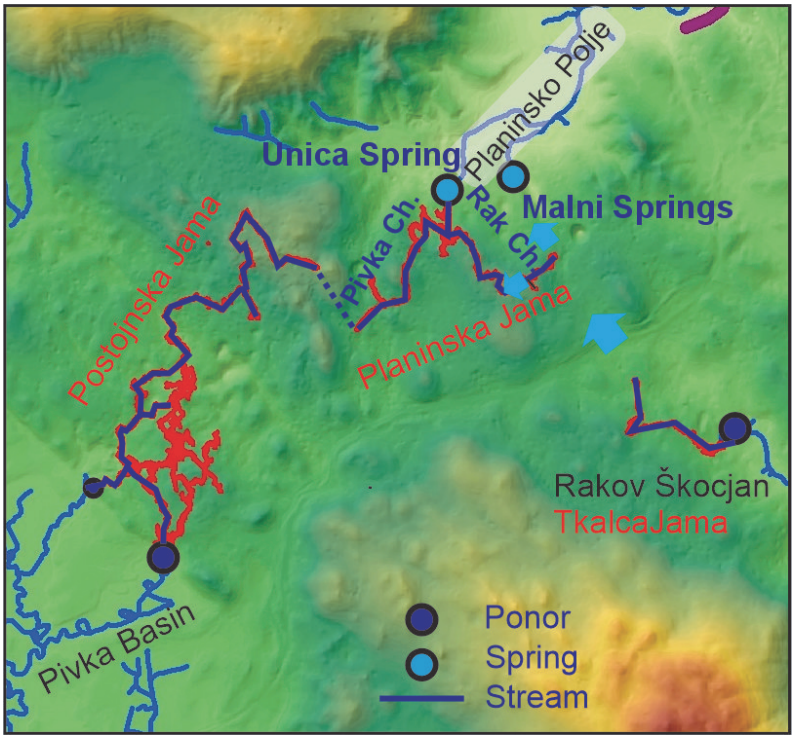


Fig. 3.03: Spatial relationships between the Postojna–Planina Caves System and associated underground streams, ponors, and springs.

Hydrological System

The recent ponor of the sinking Pivka River lies at 511 m a.s.l. on the contact between the impermeable Eocene flysch rocks of the Pivka Basin and the karstified limestone, while several abandoned ponors occur at elevations of up to 529 m a.s.l. The active river flows northward toward the first sump in Pivka Jama at 477 m a.s.l. From there, the river continues through known and unexplored passages before reappearing in Planinska Jama at 460 m a.s.l. Explorations conducted in 2015 revealed new passages, indicating that approximately 800 m of cave passages between Postojnska and Planinska Jama remain unexplored.

The Pivka River represents the principal allogenic recharge to Postojnska Jama from the adjacent flysch basin (Q_{min} < 0.01 m³/s, Q_{max} > 60 m³/s, Q_{av} = 5 m³/s). The active underground flow can be

followed without diving for most of the initial 3.5 km; farther downstream, the river continues through a series of sumps interconnected by open river passages toward Planinska Jama.

In addition to the Pivka inflow, Planinska Jama receives water from the Notranjska poljes system and from the Javorniki aquifer. The cave is well-known for the underground confluence of two streams, as well as for the merging and bifurcation of flow at the distal end of Rak Channel, where waters from Rakov Škocjan and the Javorniki Mountains converge and subsequently diverge toward the Malni Springs and the Rak Channel. The Unica Springs constitute the principal discharge point during high-water conditions, with a minimum discharge (Q_{min}) of 0.1 m³/s and peak discharges (Q_{max}) exceeding 90 m³/s. In contrast, the Malni Springs maintain a consistently high baseflow and a comparatively limited maximum discharge, characterized by Q_{min} = 1.0 m³/s and Q_{max} = 11.2 m³/s. Owing to this stable high baseflow, the Malni Springs serve as an important regional drinking water source.

Microclimatic Characteristics

The climate of Postojnska Jama is determined by the external weather conditions, the geometry of the cave and position of its entrances. The topography of the karst system allows the action of the chimney effect, which enforces natural year-round ventilation of the cave. The ventilation shows two different seasonal regimes (Fig. 3.4); winter (typically upward) and summer (typically downward).

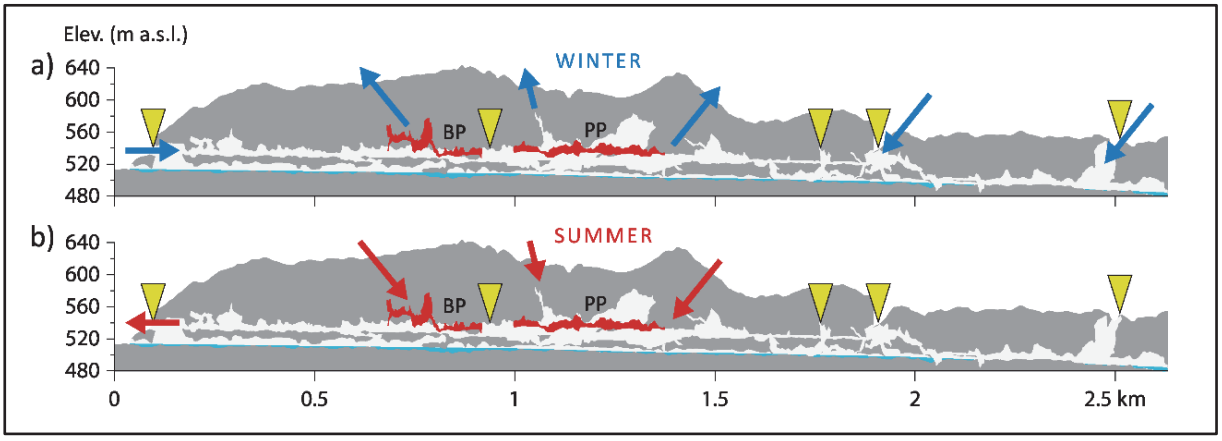


Fig. 3.4: Extended profile of Postojna Cave showing typical ventilation regimes – winter (a) and summer (b). Legend: Yellow triangles – cave entrances; blue arrows – updraft; red arrows – downdraft; BP – Brezimeni Passage; PP – Pisani Passage. The horizontal scale is reduced by 50%. In addition to the known entrances, many breathing holes, which are not explicitly shown, allow efficient ventilation throughout the year.

Postojna is also known for its windiness, particularly in colder months with frequent periods influenced by the cold katabatic wind, known as the *Bora*, blowing from NNE. The Bora has characteristic strong gusts, where wind speed frequently exceeds 20 m/s. It has been shown that dynamic pressure differences at the surface, caused by Bora wind events, may reverse the airflow directions otherwise governed by the chimney effect (Kukuljan et al., 2021a).

All karst massifs exhibit a characteristic temperature, which is a result of long-term external climatic conditions and long-term heat exchange between the rock, infiltrating water and air. In the Postojna region the equilibrium temperature is between 8.5°C and 9.0°C.

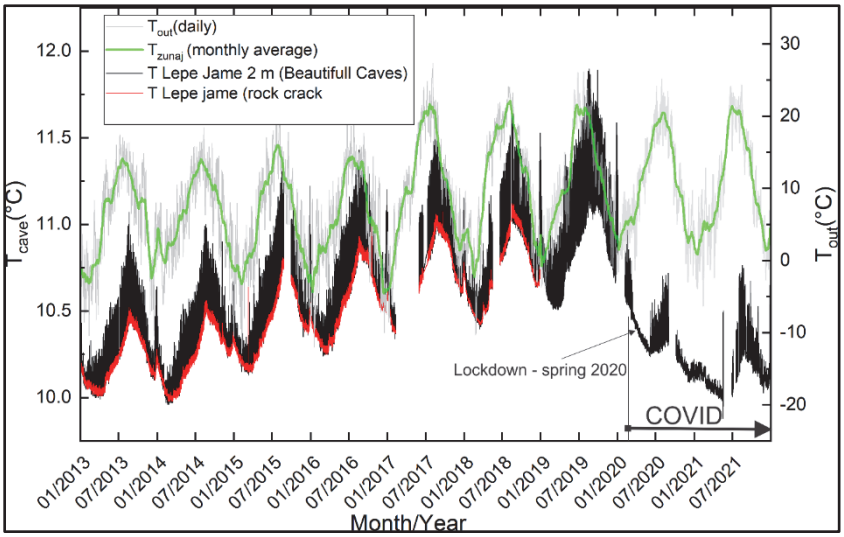


Fig. 3.5: Temperature variations in Lepe Jame (Beautiful Caves) and external temperature between 2013 and 2021.

CO_2 in the Vadose Zone

CO_2 concentrations within the cave exhibit strong spatial and temporal variability. In well-ventilated inner sections, concentrations may decrease to 600 ppm or lower during winter, whereas in summer they can exceed 10,000 ppm (1%). A characteristic example is the dead-end passage Pisani Rov (Fig. 3.6), where, during summer, air enters the passage from the vadose zone above the cave through a network of fractures containing elevated concentrations of CO_2 (and radon), resulting in a substantial influx of both gases into the passage. In contrast, during the cold season, airflow into the passage originates predominantly through the well-ventilated main cave passages connected to the entrance, and therefore, carries much lower CO_2 concentrations. This pattern is common: CO_2 levels at a given location depend primarily on the airflow pathway between the surface and the cave passage. Air entering through numerous small fractures in the vadose zone—where CO_2 concentrations are elevated—transports substantial amounts of CO_2 into the cave. By contrast, airflow routed through large, well-ventilated passages generally carries much lower CO_2 concentrations with significant input from the outside atmosphere (Fig. 3.7) (Kukuljan et al., 2021b).

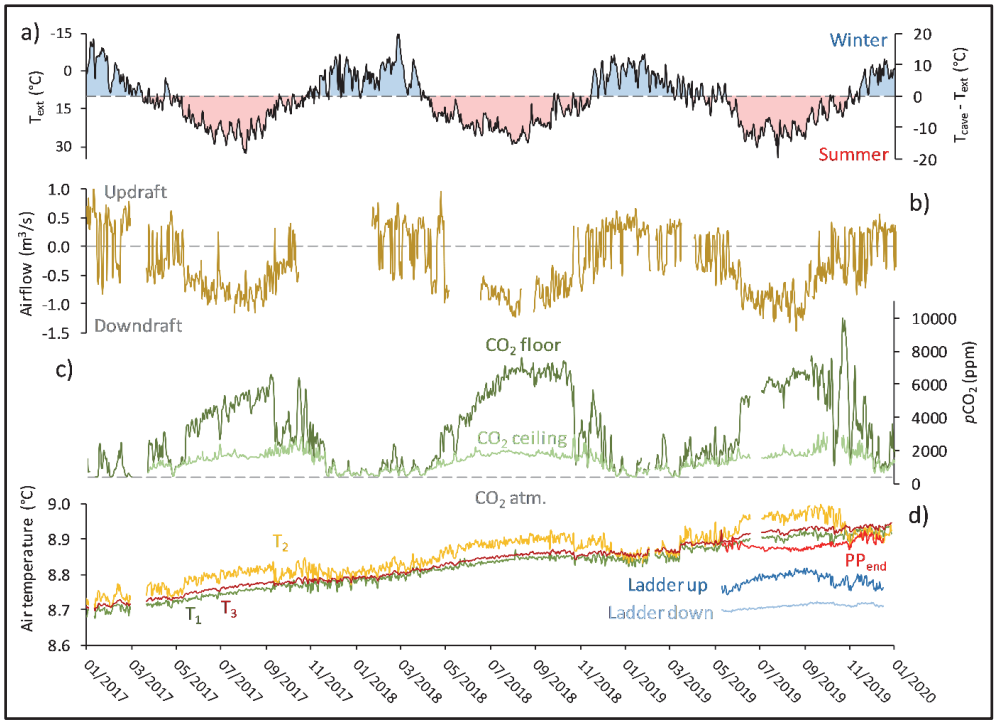


Fig. 3.6: Time series of the cave air parameters in the Pisani Passage. (a) Difference between cave (T_3 in the "Red Hall" (RH) in the terminal chamber of the Pisani Passage) and outside temperature (negative values typical in the summer season, positive values in winter); (b) airflow at the entrance to the Pisani Passage (PP_{ent}) (negative = downdraft, positive = updraft); (c) pCO_2 in the RH at the floor and the ceiling stations (atmospheric pCO_2 = 410 ppm); (d) temperature dynamics in the RH at three different heights (T_1 is the highest, T_3 is the lowest) and above and below a ladder placed at a constriction in the passage, a short distance before reaching the terminal chamber.

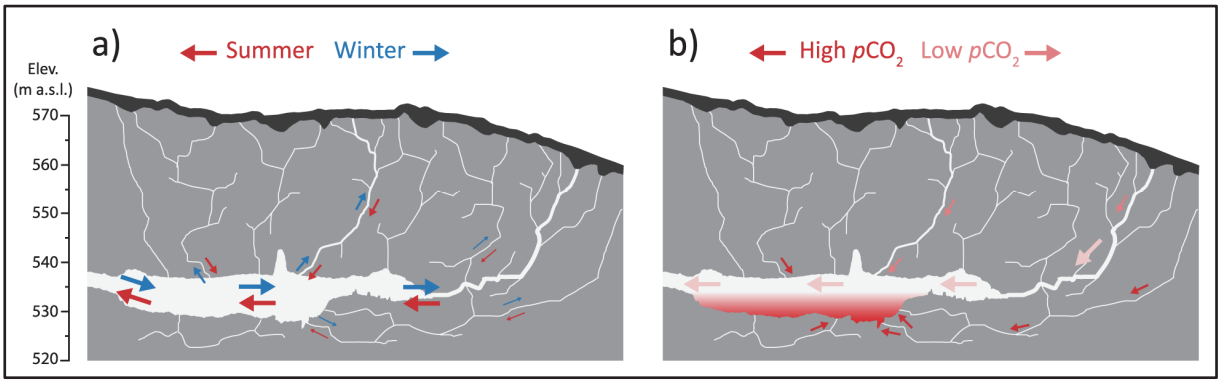


Fig. 3.7: Conceptual diagram showing the relation between the airflow direction and resulting CO_2 concentration in the terminal chamber of the Pisani rov passage.

An interesting insight into the vadose zone CO_2 gives a small time-window of observations within a borehole above Planinska jama (Fig. 3.8). The borehole penetrates the vadose zone above the cave from the surface to the Mysterious lake in Rak Channel. Access to the lower end of the borehole and measurements of the exhaling air are only possible during periods of low water level and are limited in duration. We took advantage of such a period in August 2024 to measure airflow at the upper mouth of the borehole, and CO_2 concentrations in the exhaled air just above the Mysterious Lake in the cave. The results show a positive correlation between airflow and CO_2 concentration: the highest CO_2 values were recorded around midday, when the chimney effect (downdraft) is strongest due to peak external temperatures.

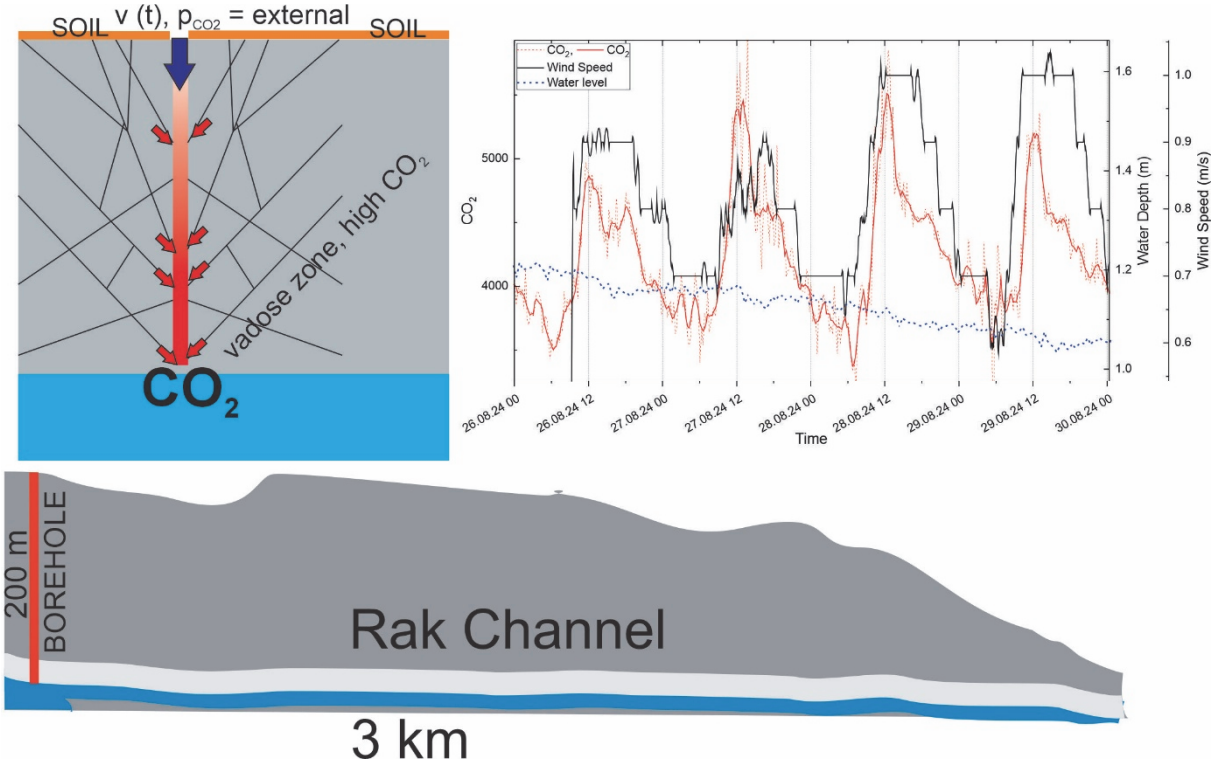


Fig. 3.8: Borehole through the vadose zone above Planinska Jama with time series of external temperature, CO_2 concentration of the air at the cave outlet and water level in August 2024.

Characteristics of Streamflow: Preliminary Results

The physical and chemical parameters of the Pivka stream undergo significant changes along its flow path between the ponor in Postojnska Jama and the springs of the Unica in Planinska Jama. These changes reflect ongoing physical and chemical interactions among the water, the atmosphere, and the surrounding rock. Water temperature indicates the degree of thermal equilibration, whereas specific electrical conductivity (SEC) reflects the extent of geochemical equilibration.

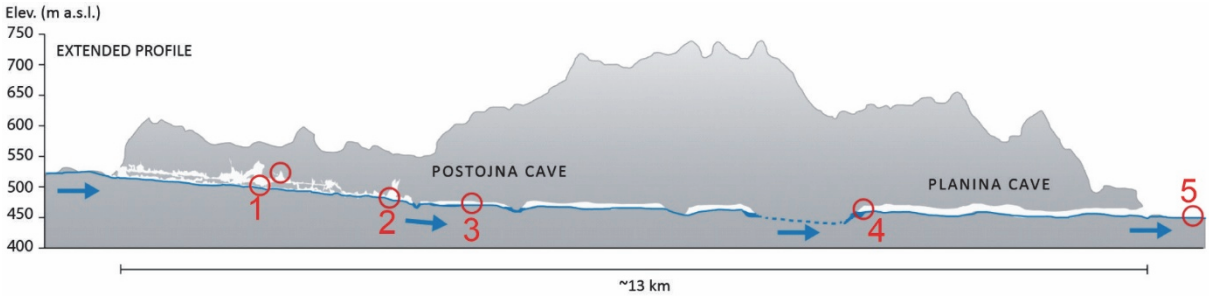


Fig. 3.9: Extended profile through the massif between Postojnska Jama and Planinska Jama with observation points referenced in the text. 1-Tartatus, 2-Magdalena Jama, 3-Pivka Jama, 4-Inflow-Planinska Jama, 5-Unica Spring.

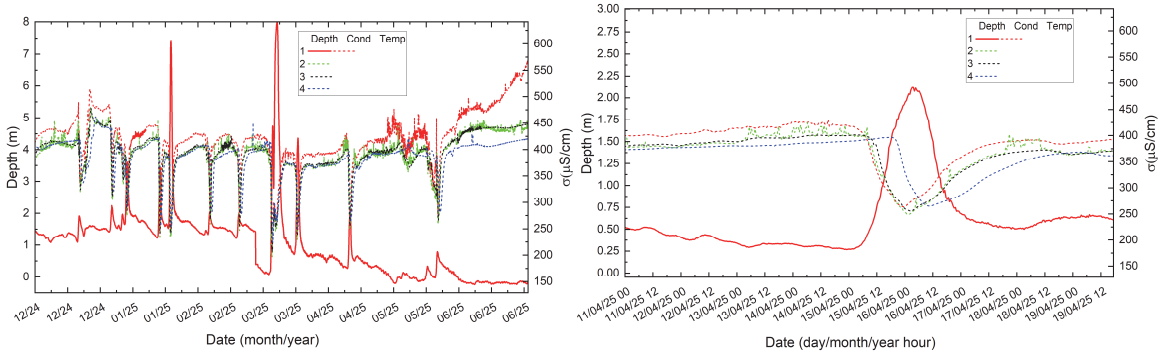


Fig. 3.10: Left: time series of water level at Tartarus (1) and specific electric conductivity (σ) at points 1–4 (in Fig. 3.9). Right: Same as in the left figure but for a medium size rain event.

Fig. 3.10 shows the SEC time series between December 2024 and July 2026, including a rain event in April 2025. As expected, SEC decreases during rainfall events and exhibits a phase lag along the flow. Spot measurements of SEC and geochemical analyses indicate that Ca+Mg and bicarbonate concentrations show good linear correlation for SEC values below 400 µS/cm, whereas the data become more scattered at higher SEC values.

To estimate the potential for CO_2 exchange between water and the atmosphere, we used NDIR instruments (Vaisala) to simultaneously measure dissolved CO_2 in the water and CO_2 concentrations in the atmosphere. Measurements were taken at various locations along the Pivka flowpath from the ponor, through the caves, to the springs. Fig. 3.11 shows the results of spot measurements, indicating that CO_2 concentrations in the water are consistently above the equilibrium line predicted by Henry's law.

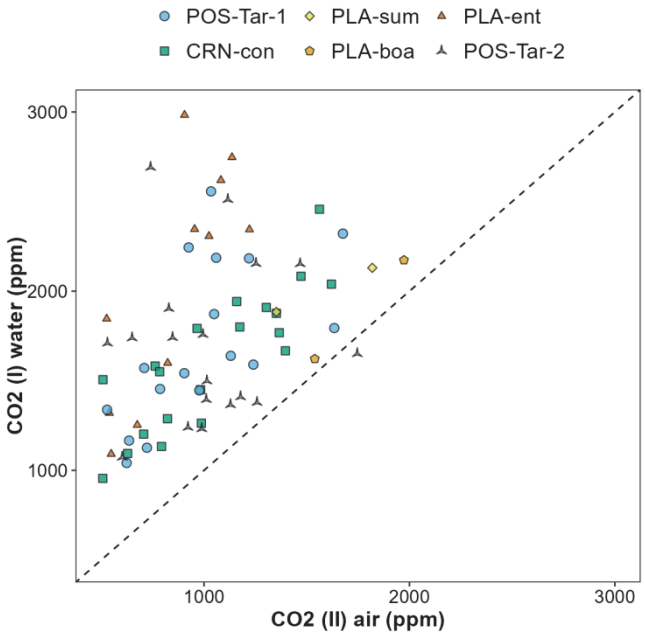


Fig. 3.11: Spot measurement data of CO_2 concentrations in air versus water. The dashed line shows a 1:1 relationship. Certain sites correspond to the locations in Fig. 3.9: (1) POS-Tar-1, (3) CRN-con, (4) PLA-sum, (5) PLA-ent. POS-Tar-2 is a cave pool unconnected to the Pivka flow.

At the same time as the spot CO_2 measurements (data in Fig. 3.11), physicochemical parameters (including temperature, pH, SEC) were measured and samples were collected for laboratory analyses of major and minor ions. Using the chemical speciation software PHREEQC (Parkhurst and Appelo, 2013), geochemical speciation and thermodynamic equilibrium calculations were performed to determine parameters including the gas-phase saturation index of CO_2 (SI CO_2 (g); equivalent to log pCO_2 at equilibrium) and the saturation index of calcite (SI_C). The calculated pCO_2 values, derived from measured water chemistry, showed a positive trend with dissolved CO_2 concentrations measured directly in the river and pool waters; however, the measured values were consistently slightly lower (Fig. 3.12a). Since the water exhibited higher CO_2 concentrations than the surrounding air (see Fig. 3.11), this offset between the pCO_2 calculated from the geochemistry versus that measured directly (Fig. 3.12a) suggests that the waters are out of equilibrium, both internally within the carbonate system and with the cave air. This likely reflects ongoing CO_2 degassing from the water to the air, potentially occurring more rapidly than carbonate re-equilibration. However, despite this apparent disequilibrium and CO_2 degassing, the data do not indicate an overall decrease in dissolved CO_2 concentrations as the water moves through the cave system. Instead, dissolved CO_2 concentrations generally increase from the ponar (POS-pon) towards the Unica Springs (PLA-ent and MAL-spr) (Fig. 3.12). Importantly, this suggests that cave air is not the source of the additional dissolved CO_2; rather the extra CO_2 must originate from another source, possibly from the decomposition of organic matter or generated within the water–rock geochemical system.

The waters were, for the most part, oversaturated with calcite ($SI_C > 0$; Fig. 3.12b) indicating that the water has the potential to precipitate calcite. As the water flows through the cave system it trends towards carbonate equilibrium ($SI_C = 0$), inferring that calcite precipitation may have occurred along the flow path. In carbonate systems, calcite precipitation and CO_2 degassing are closely coupled processes, although the relative importance of each process within the cave system remains uncertain. There were, however, a few instances where the SI_C was substantially negative, indicating conditions favourable for calcite dissolution. These corresponded to high-water events. However, given the limited number of data points for these conditions, it remains unclear to what extent dissolution reactions occurred in this fast-flowing water. Overall, the geochemical processes within the cave system are likely much more complex than described here, particularly because the river flows through markedly different hydrological and microclimatological settings, including large highly ventilated passageways and phreatic sumps.

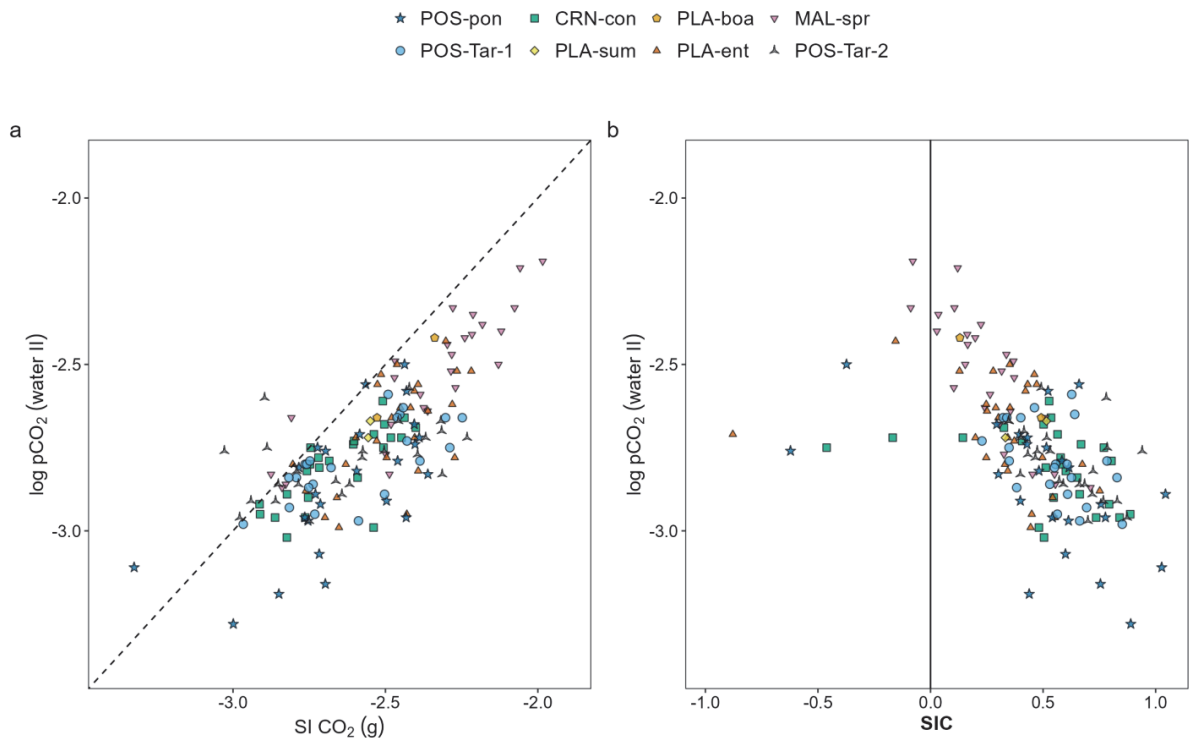


Fig. 3.12: Saturation index with respect to CO_2 and calcite. a) Saturation index of CO_2 (g) in the water as calculated by phreeqc against the log_{10} partial pressure of CO_2 measured in the water. The dashed line shows a 1:1 relationship. b) Saturation index with respect to calcite (SI_C) against the log_{10} partial pressure of CO_2 measured in the water. Certain sites correspond to the locations in Fig. 3.9: (1) POS-Tar-1, (3) CRN-con, (4) PLA-sum, (5) PLA-ent. POS-Tar-2 is a cave pool unconnected to the Pivka flow.

At the inflow sump in Planinska Jama (Point 4 on Fig. 3.9) we observed dissolved CO_2 using a submersible NDIR CO_2 probe (AMT). Fig. 3.13. shows results for the winter/spring 2024/2025 period. Figure 3.13 also shows a time series of SEC and depth from an InSitu Troll 2000 installed at the same position and CO_2 recorded in the air above the sump. The records show an abrupt response to the rain events, with slow recession, reasonably well-correlated with depth; details of these results are still matter of analysis and will be (hopefully) presented to the public soon.

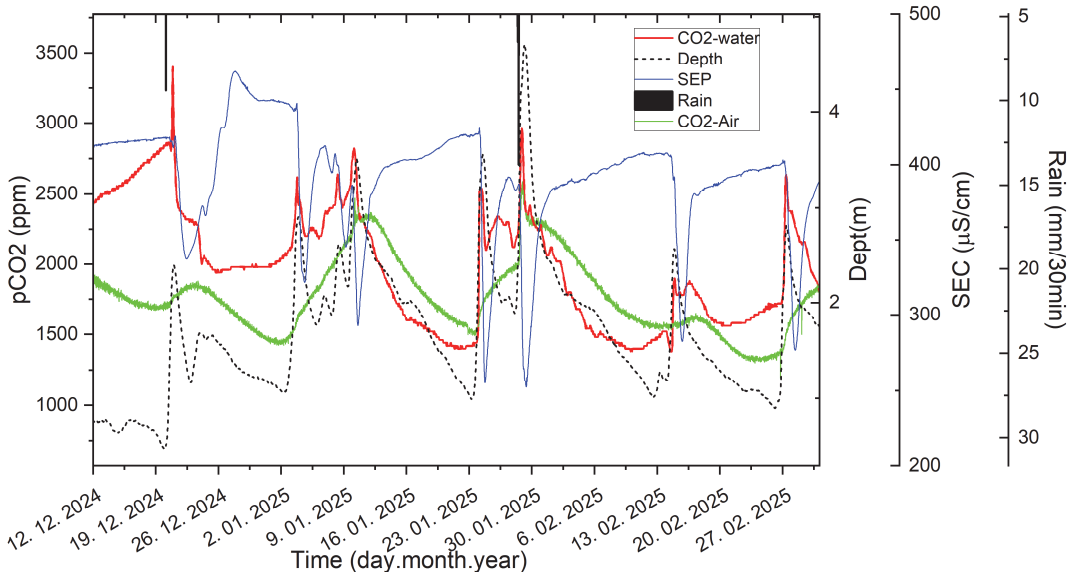


Fig. 3.13: Time series of depth, specific electric conductivity (SEC), concentrations of CO_2 dissolved in water and CO_2 in the air at the sump of the Pivka Channel in Planinska Jama.

Much of the presented data presented was collected within the project Dynamics and distribution of CO_2 in karst vadose and epiphreatic zone (CARDIKARST) (J7-4630) funded by Slovenian Research and Innovation Agency (ARIS).

REFERENCES

- Parkhurst, D.L., and Appelo, C.A.J., 2013:. Description of Input and Examples for PHREEQC Version 3—A Computer Program for Speciation, Batch-Reaction, One-Dimensional Transport, and Inverse Geochemical Calculations. U.S. Geological Survey Techniques and Methods, Book 6, Chapter A43, 497 pp. https://doi.org/10.3133/tm6A43
- Kukuljan, L., Gabrovsek, F., Covington, M.D., 2021: . The relative importance of wind-driven and chimney effect cave ventilation: Observations in Postojna Cave (Slovenia). International Journal of Speleology, 50(3), 275-288. https://doi.org/10.5038/1827-806X.50.3.2392
- Kukuljan, L., Gabrovšek, F., Covington, M.D., Johnston, V.E., 2021: CO_2 dynamics and heterogeneity in a cave atmosphere: role of ventilation patterns and airflow pathways. *Theoretical and Applied Climatology*, 146, 91–109. https://doi.org/10.1007/s00704-021-03722-w

Whole-day field trip (D):

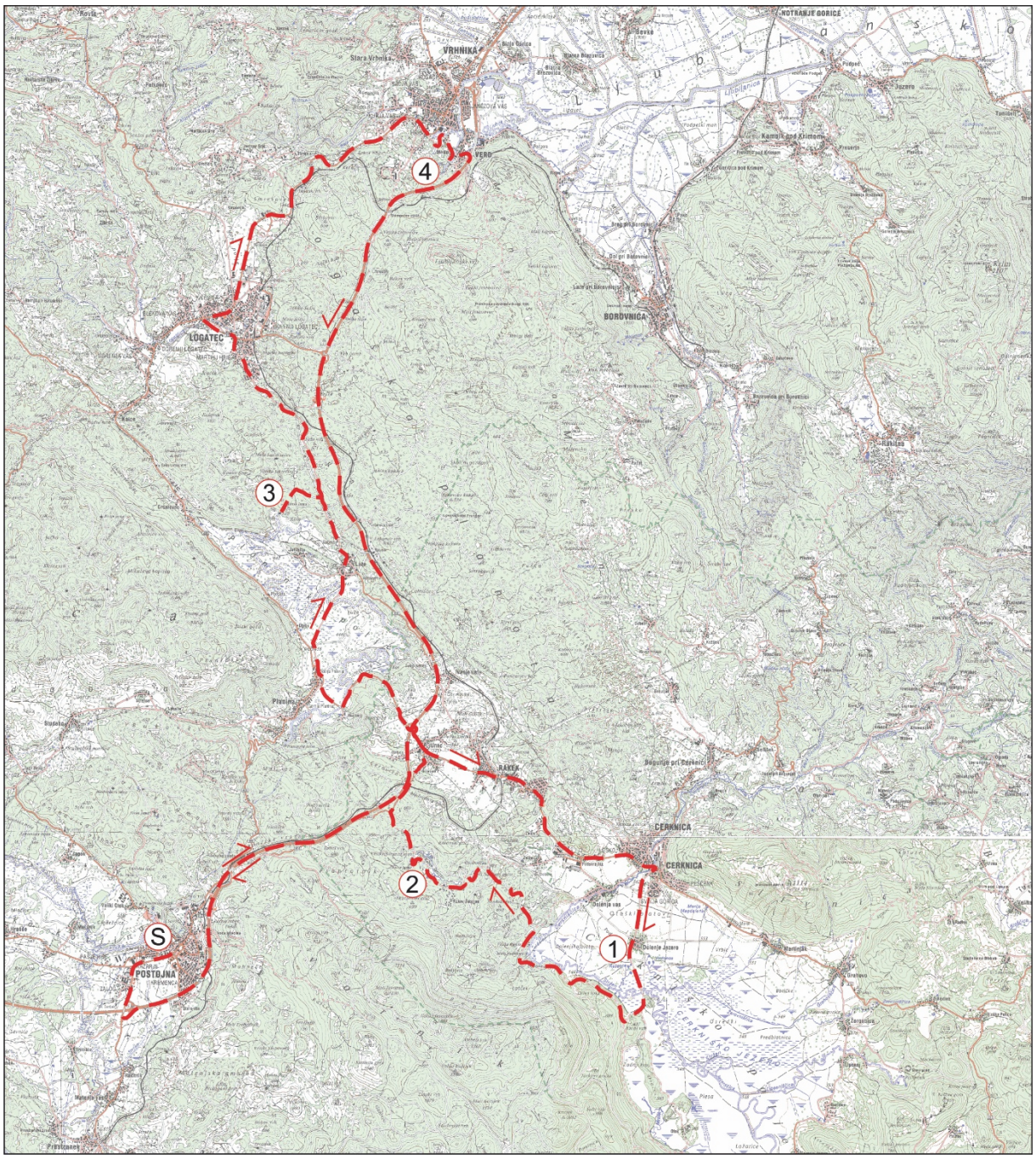
GROUNDWATER FLOW IN THE LJUBLJANICA RECHARGE AREA

Friday, 19th June, 2026, 9:00–17:00

Cyril Mayaud, Blaž Kogovšek, Matej Blatnik, Nataša Ravbar, Metka Petrič, Franci Gabrovšek

Stops:

1 – Outflows of the Cerkniško Polje
2 – Hydrology of the Rakov Škocjan karst valley
3 – Ponor zone of the Planinsko Polje
4 – Springs of the Ljubljanica River near Vrhnika



General Introduction: Hydrogeology of the Ljubljanica River Recharge Area

The central part of the Slovenian Dinaric Karst drains to the springs of the Ljubljanica River, located on the southern edge of the Ljubljana Basin (Fig. 4.01). Although the area is about 26 km of straight-line distance close to the Adriatic Sea, intense tectonic activity has triggered drainage into the Sava-Danube river basin, which flows to the Black Sea. The karst part the Ljubljanica recharge area measures about 1100 km^2.

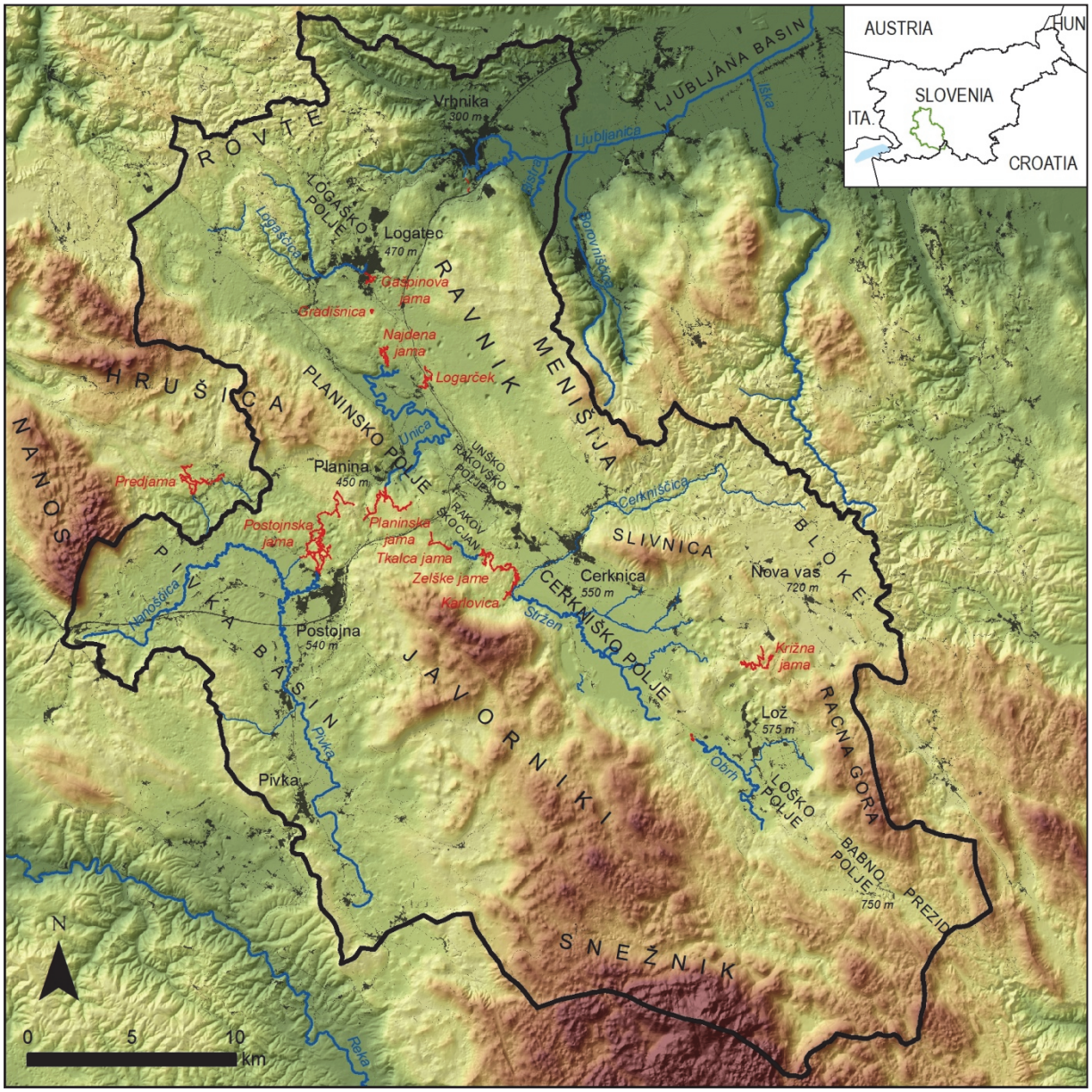


Fig. 4.01: Ljubljanica River recharge area with high karstic plateaus, karst poljes and surface rivers. The main caves are shown with red polygons.

The karst rocks are mostly of Mesozoic age. They are generally micritic, locally oolitic limestones and predominantly late-diagenetic dolomites. They formed on the Dinaric platform under conditions of continuous sedimentation. The total thickness of the carbonate sequence is almost 7 km.

Structurally, the entire Ljubljanica catchment belongs to the Adriatic Plate. The area consists of several nappes that were overthrust during the peak of the Alpine orogeny in the Oligocene in a NE to SW direction (Placer 2008; Placer et al. 2010). A later change in the direction of plate movement led to the formation of the Idrija Fault Zone, a dextral strike-slip fault that crosses the area in the direction

of NW–SE (Fig. 4.02) (Vrabec 1994). The Idrija Fault Zone largely determines the direction of regional flow (Fig. 4.02). In general, the steepest hydraulic gradient is oriented northwards, from the Notranjska region towards the Ljubljana Basin, which represents a regional base level. However, the fault zone acts as a barrier to groundwater flow and forces the water to surface in the poljes. At the same time, it diverts the flow in the Dinaric direction (SE–NW) (Šušteršič 2006).

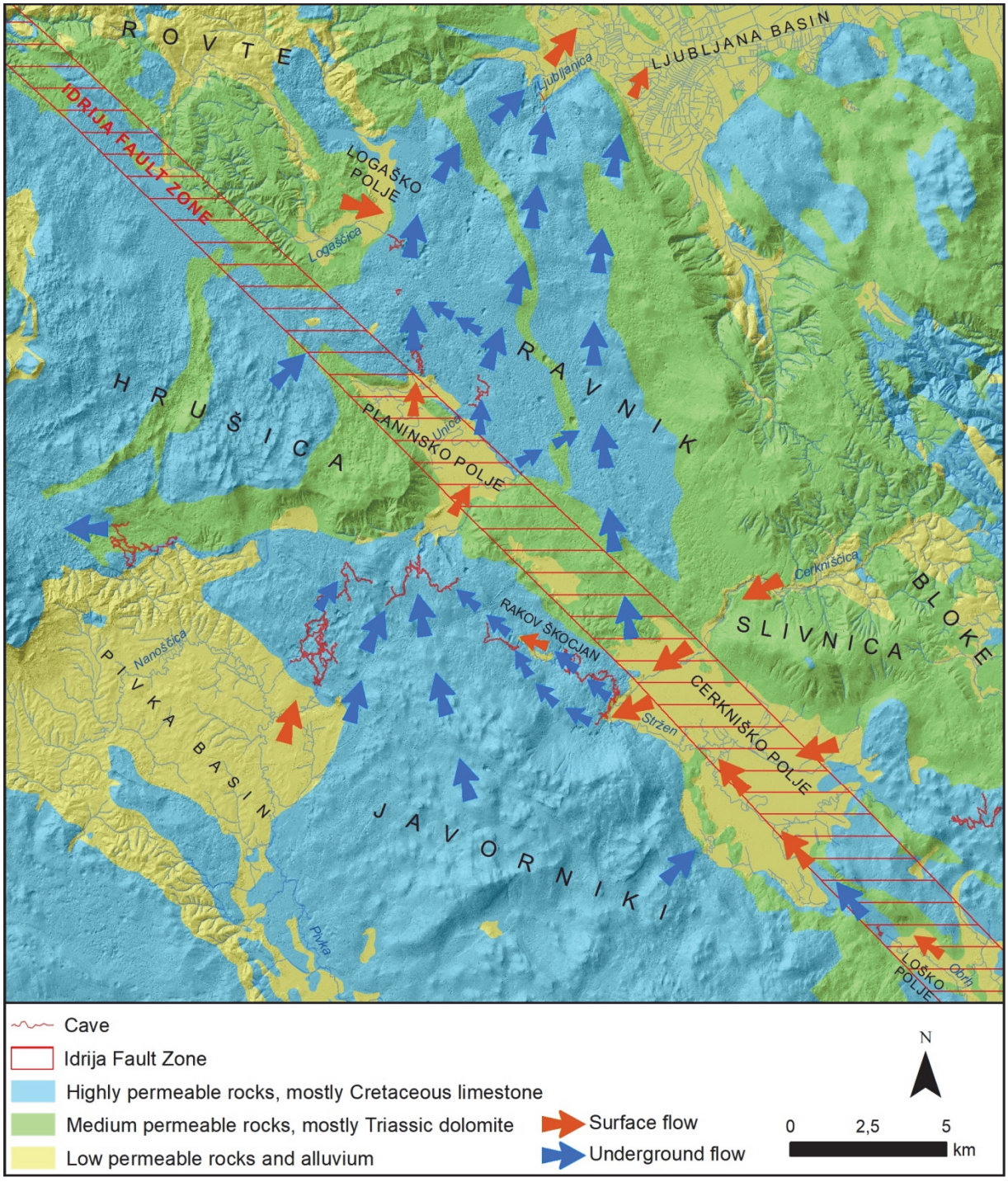


Fig. 4.02: Geology and hydrology of the Ljubljanica recharge area (adapted from Krivic et al. 1976).

Several poljes have developed along the Idrija Fault Zone (Gams 1965, 1978; Šušteršič 1996). These large flat-bottomed depressions are regularly flooded and are often the only areas where water appears at the surface. The formation of poljes is preconditioned by tectonics, in this case by the

structures within the Idrija strike slip fault (e.g., pull-apart zones), but the forming mechanism is the corrosional planation at the groundwater level.

In general, the water follows the SE–NW direction with surface flow on the poljes and groundwater flow in-between (Fig. 4.03). Additional water enters the flow system at numerous springs draining the areas of the Snežnik and Javorniki mountains in the south of the Idrija Fault Zone. Several sinking rivers draining dolomite or flysch areas also contribute to this system (Gams 2004). The altitude of the poljes drops from about 750 m to 450 m a.s.l. Apart from a relatively small amount of water flowing directly from Cerkniško Polje to the springs of Ljubljanica, most of the water comes to the surface along the southern edge of Planinsko Polje. The average annual discharge of the Ljubljanica springs is 38.6 m^3/s, with part of the water coming from from the Rovte region and from ponors of Logaško Polje.

There are over 1,600 known caves located in the recharge area of the Ljubljanica River, most of them are accessible fragments of a fossil underground drainage system. However, the largest cave systems are water-active and sum a total of about 80 km of epiphreatic channels (Fig. 4.03).

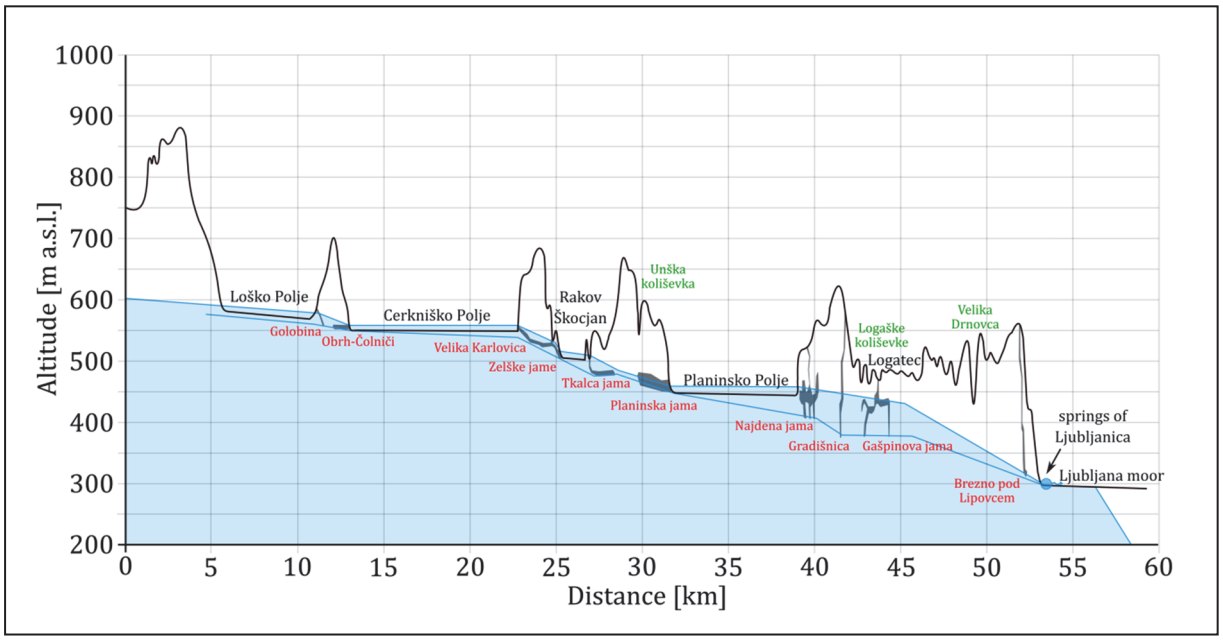


Fig. 4.03: Cross section of the Ljubljanica River recharge area following an initially SE–NW trend along the Idrija Fault Zone between Loško and Planinsko Polje, and turning N from Planinsko Polje toward the Ljubljanica springs near Vrhnika. The major caves are indicated in red, large collapse dolines in green.

Cerkniško Polje

Cerkniško Polje is the largest karst polje in Slovenia (Gams 1978, 2004). It is often called Cerkniško Jezero (Lake of Cerknica) because of its regular floods (Fig. 4.04a). When full, the intermittent lake covers up to 26 km^2 out of 38 km^2 of the polje's total area. The bottom of the lake is at an altitude of 550 m a.s.l. Its intermittency has attracted many scholars since the beginning of the New age, including the polihistorian Valvasor, who published his famous study of the Cerkniško Jezero in 1689 (Shaw & Čuk 2015). The main part of the polje is underlained by Upper Triassic dolomite at its N, E and SE borders. The areas to the W and NW, on the other hand, are mainly underlain by Cretaceous limestone (Fig. 4.02).

Fig. 4.04: (a) Flooded Cerkniško Jezero (Spring 2013) (Photo: C. Mayaud). (b) Ponors of Rešeta during low flow conditions (Summer 2017) (Photo: M. Blatnik).

The polje is regularly flooded for several months (Fig. 4.5), mostly in autumn, winter and spring (Kovačič & Ravbar 2010). On average, the water is above the level of 550.3 m a.s.l. on 10.2 days per year, which corresponds to a flooded area of 21.84 km^2 (Ravbar et al. 2021). The main inflows into the polje come from a series of karst springs called Žerovniščica, Šteberščica and Stržen, located on its eastern and southern borders. The springs on the SW side (e.g., Suhadolca, Vranja jama) add a lot of water during floods. In addition, an important allogenic component comes from the Cerkniščica River, which drains a dolomitic area of about 44 km^2 in the east (Gams 2004). Finally, several estavelles (e.g., Vodonos) also contribute to the inflow into the polje.

In addition to the estavelles, several ponor zones located in the inner part of the polje drain a certain amount of water directly to the springs of Ljubljanica (Krivic et al. 1976) (Fig. 4.04b) while the main ponors are aligned along the W side of the polje, with Velika and Mala Karlovica being the most prominent. Both caves extend for over 8.5 km between Cerkniško Polje and the Rakov Škocjan karst valley. So far, only a small section between Velika Karlovica and Zelške Jame (located in Rakov Škocjan) is unexplored as an important collapse zone is located there. Recent studies have shown that at low to medium water levels (Gabrovšek et al. 2010; Ravbar et al. 2012, Kogovšek 2022), a large part of the

water sinking into the ponor of Mala Karlovica reaches the Kotliči springs in the middle of Rakov Škocjan and a smaller part reaches Zelške Jame, which would be the most logical direction.

In the last centuries, several plans were made to change the hydrological behaviour of the polje, but none were completed. In the 1960s, a plan to transform the Cerkniško Jezero into a permanent lake was initiated. The entrances to the caves Velika and Mala Karlovica were closed with concrete walls and a 30 m tunnel was built to connect Karlovica to the surface. However, a minor impact on water retention during dry periods was found assessed (Shaw & Čuk 2015).

Rakov Škocjan Karst Valley

Before reaching Planinsko Polje, the water sinking in the main ponors of Cerkniško Polje surfaces in an about 1.5 km-long and 200 m-wide karst valley called Rakov Škocjan (Fig. 4.05). On the upstream side (SE) the water emerges as the Rak River from the cave Zelške Jame. Zelške Jame is about 5 km-long and ends in the large collapse doline of Velika Šujca, where the water arrives from Cerkniško Polje via the Karlovica Cave system. The entrance area of Zelške Jame is a fragmented system of channels and collapse dolines. The most prominent feature is Mali Naravni Most (Small Natural Bridge) where an impressive narrow arch, which was part of the former cave ceiling, crosses the collapse doline (Gams 2004).

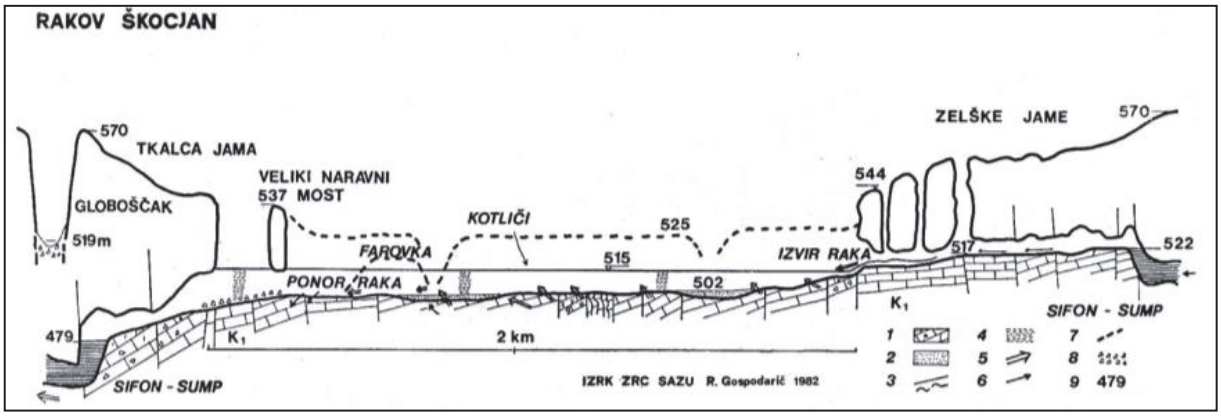


Fig. 4.05: Cross-section of the Rakov Škocjan karst valley between the Rak spring at Zelške Jame and the terminal ponor in Tkalca Jama. Legend: 1. rocky bottom; 2. alluvia; 3. fault zone; 4. flood level in 1982; 5. karst spring: 6. water flow directions; 7. terraces; 8. boulder rocks; 9. altitude.

Downstream, the valley widens and several springs located along the SW side of the valley (e.g., Kotliči, Prunkovec) form perennial or intermittent tributaries of the Rak River. The valley narrows an impressive natural bridge called Veliki Naravni Most (Big Natural Bridge). The height of the bridge is between 9.5 and 17 m, its width is between 15 and 23 m and it is 56 m-long. The rocky arch is made of thick-bedded and anticline-folded Lower Cretaceous limestone.

After Veliki Naravni Most, the channel opens into a 150 m-long canyon that ends at the entrance to Tkalca Jama, an almost 3 km-long cave that drains the water towards Planinsko Polje. The connections of the Rak with the water from Cerkniško Polje and with the Unica springs at Planinsko Polje have been proven by several tracer campaigns under different hydrological conditions (Gabrovšek et al. 2010; Ravbar et al. 2012). An important flow constriction is present before the first siphon of Tkalca Jama and allows flooding to occur regularly. The floods can reach a height of 19 m above the cave entrance (located at 496 m a.s.l.), and large parts of the Rakov Škocjan karst valley are frequently inundated (Drole 2015). Before World War 1, Rakov Škocjan was a private park owned by the Windischgrätz family, while between the First and Second World Wars the Italians used it as a military site. Since 1949, Rakov Škocjan has been is a Landscape Park open to the public.

Planinsko Polje

Planinsko Polje is a typical example of an overflow structural polje (Gams 1978; Šušteršič 1996). Its springs are located on one side and recharge the Unica River that sinks in two major outflow zones located along the polje eastern and northern borders (Savnik 1960) (Fig. 4.06). The polje surface is slightly undulating and about 10 km^2 large, with a bottom elevation mostly comprised between 444.5 m and 450 m a.s.l (Blatnik *et al.* 2017). Apart from the wetlands close to the Unica, the polje is used for field crops and grass. Three settlements are located on the elevated slopes around Planinsko Polje, which is surrounded by forested karst plains at elevations between 520 m and 600 m a.s.l. and by mountains reaching up to 1,000 m a.s.l. after.

Planinsko Polje has formed along the Idrija Fault Zone. Its southern and western borders mostly consist of Upper Triassic main dolomite, while its two main springs are located within a band of Cretaceous limestone in the south. The average thickness of the alluvium cover is about 4 m (Breznik 1961; Ravnik 1976). The polje bedrock base is dominantly Upper Triassic main dolomite, whereas its eastern and northern sides include most of the ponors and are composed of highly karstified Cretaceous limestone (Čar 1982).

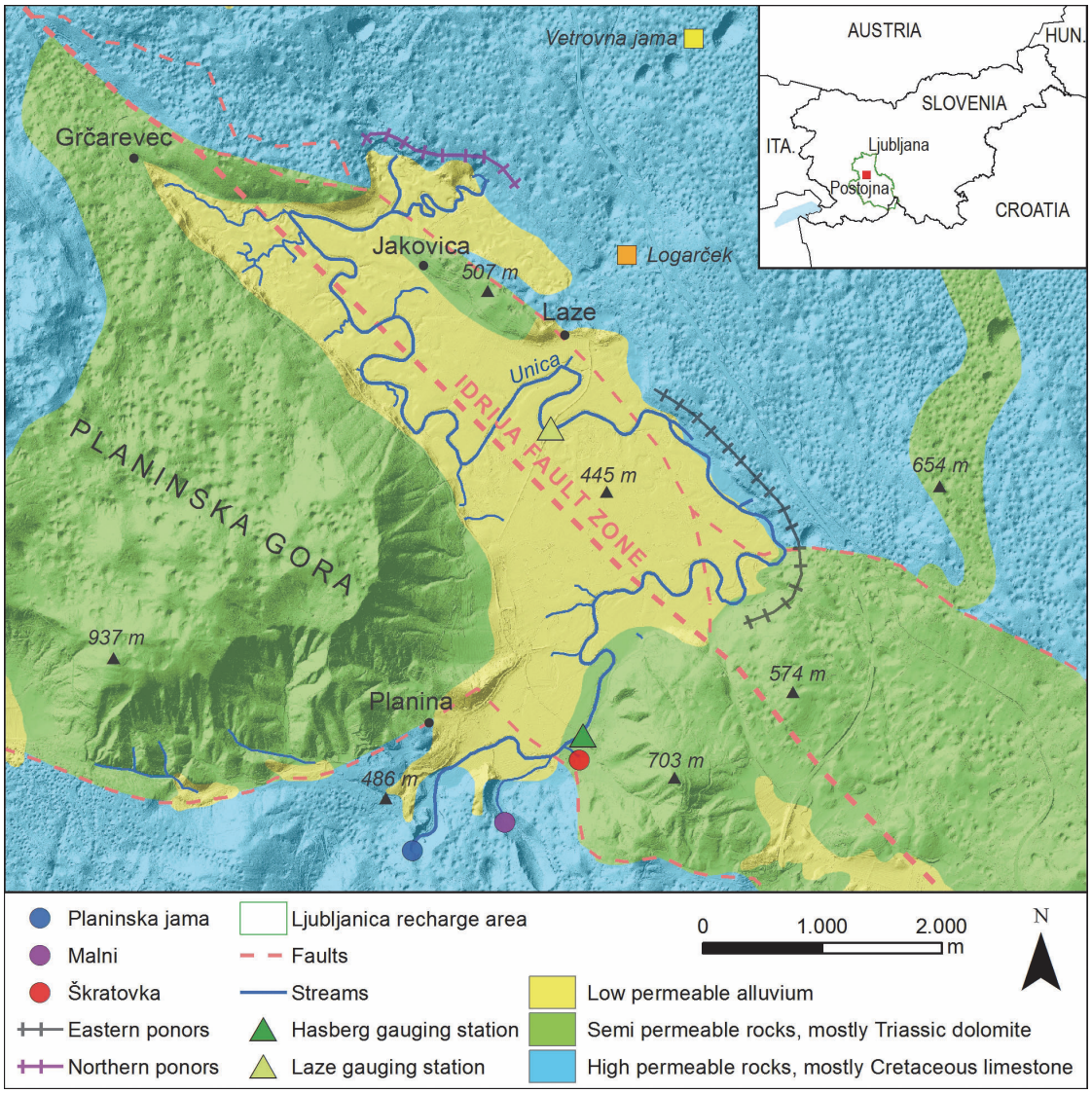


Fig. 4.06 Planinsko Polje and its surrounding area with the position of caves, springs, ponor zones and main gauging stations. The upper right insert shows the regional position of the area in Slovenia.

Besides Planinska Jama, the most important recharge input is the Malenščica spring (Q_{min} = 1.1 m^3/s, Q_{mean} = 6.7 m^3/s, Q_{max} = 9.9 m^3/s; Frantar 2008), which receives water from Rakov Škocjan and the Javorniki mountains. The Malenščica Spring is used as a water supply for more than 20,000 inhabitants (Petrič 2010). The Unica River flows rather uninterrupted over the polje's surface for the first 7 km. Along its course in proximity to the eastern border, it loses water along a 2 km-long reach due to the presence of several groups of ponors and zones of intense leakage (Fig. 4.06). The water sinks into well-expressed ponors, along lines of diffuse discharge into fractures and small dissolutional openings, as well as into small blind valleys entrenched into the sediment (Blatnik *et al.* (2017) revealed new details on the location and capacity of the eastern ponor zone, with a total outflow capacity of about 18 m^3/s and individual outflow ranging between 1.0 and 5.6 m^3/s at each group of ponors. After 2 km of flow along the eastern border, the river crosses the polje and follows the western border. Then the Unica turns northeast towards the second ponor zone that are distributed along the polje northern border. The capacity of the northern group of ponors was estimated between 40 and 60 m^3/s (Šušteršič 2002).

Similarly to Cerkniško Polje, Planinsko Polje can be flooded up to several times per year (Kovačič & Ravbar 2010). The period with the greatest probability that an extreme flood occurs is the coldest part of the year, tied to the mid-autumn rainfall peak, winter rains and snowmelting. Although historical data are difficult to compare to current regular measurements, several extreme floods have been recorded in the past, such as in 1801 and 1851/52; when the water level presumably reached an elevation between 456 and 458 m a.s.l.; and in 1923 when the water level reached 453.4 m a.s.l. (Gams 1980). In February 2014, the floods reached an altitude of 453.2 m a.s.l. and 72 Mm^3 of water were stored in the polje (Frantar & Ulaga 2015). The lake extended over 10.3 km^2 and more than forty houses and other facilities were flooded (Mihevc 2014).

Figure 4.07: Two of the many ponors draining Planinsko Polje. Left: Velike Loke located at the eastern border. Right: So-called Putick's Well (Putickova štirna) located at the terminal outflow zone at the northern border (Photos: M. Blatnik).

During the period between 1954 and 2014, high waters on the polje occurred on average 37.9 days per year (Ravbar *et al.* 2018). The longest periods the polje has been overflown were recorded in 1960 (altogether 137 days) and in 2014 (altogether 126 days). An event of high waters lasts on average for ten days, but can also be as long as 78 days, such as the flood that occurred in autumn and winter 2000/01 (Ravbar *et al.* 2018). To prevent extreme flooding in Planinsko Polje, different measures have been undertaken in the beginning of 20th century (Putick 1889). They consisted to

increase the outflow capacity of the ponors zone by mean of different constructions to prevent their plugging by flotsam (Fig. 4.07).

Mayaud *et al.* (2019) listed and tested the parameters that could potentially control flooding in poljes. If the method is applied on Planinsko Polje, focusing on the high flood event of February 2014, the role of the ponor zones can be emphasized. Due to the sudden arrival of an important quantity of melted water carrying a lot of flotsam, all the ponors were plugged. This can explain the high amplitude and long duration of the flood. This result is confirmed when comparing this flood with the high flood of November 2014. Despite a much higher amount of precipitation released within a similar time span, the maximum stage in the polje was three meters lower than the flood of February 2014. The only explanation to justify such difference is that all ponor zones have been cleaned in between (Mayaud *et al.* 2019).

Water level and temperature have been monitored in all active caves between Planinsko Polje and Ljubljana basin in years from 2006 to 2009 and from 2015 on (Turk 2010; Gabrovšek & Turk 2010; Blatnik *et al.* 2019; Blatnik *et al.* 2020). Data loggers are installed in eight caves (Logarček, Vetrovna Jama, Najdena Jama, Gradišnica, Gašpinova Jama, Brezno pod Lipovcem, Andrejevo Brezno 1, Veliko Brezno v Grudnovi Dolini) and three ponors on the rim of Planinsko Polje (Velike Loke, Pod Stenami, Škofov Lom). Figure 4.08 presents the recorded dynamics of underground water in March and April 2018.

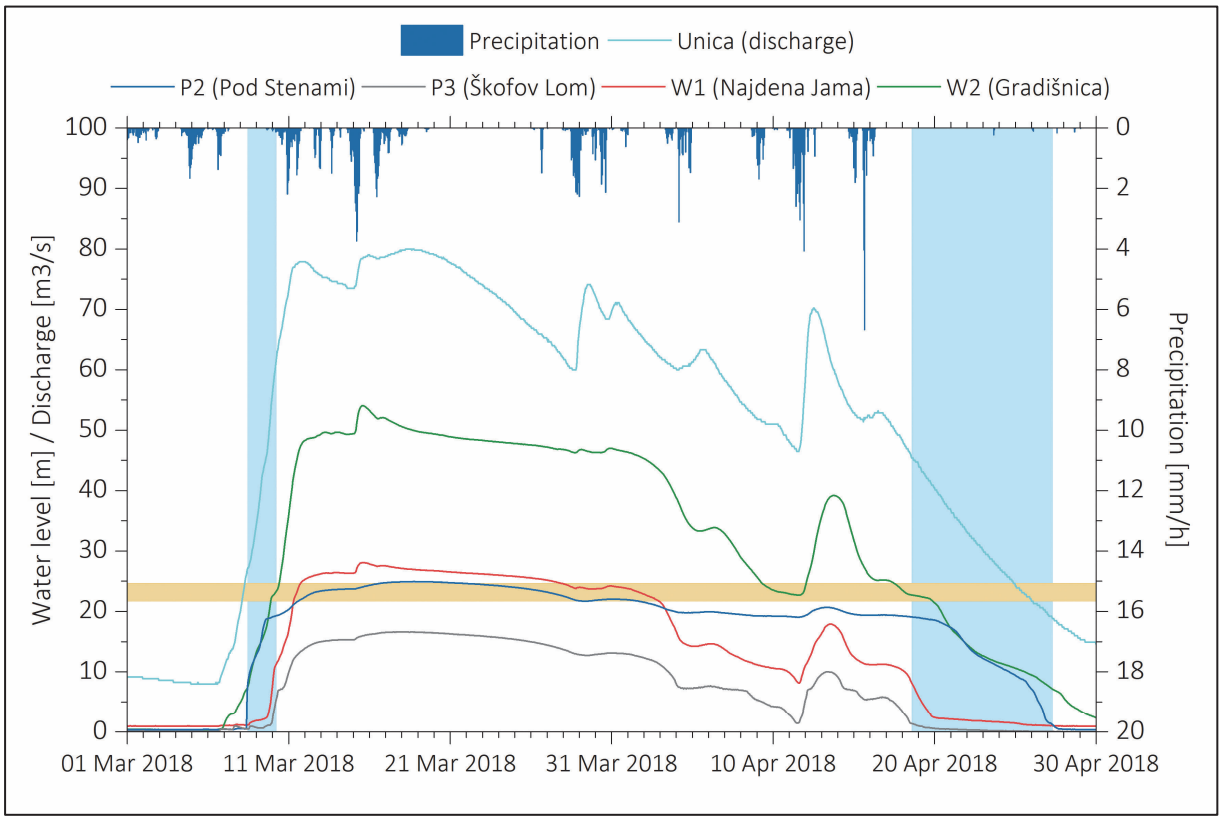


Figure 4.08: Records of water level in selected caves between Planinsko Polje and Ljubljanica springs during a high water event in March and April 2018. Blue areas denote different responses of water level change; orange area denotes temporal slower increase (decrease of water level in Gradišnica Cave).

Water level measurements showed complex dynamics in water level variations (up to 60 m, Fig. 4.08 and different rates of changes of groundwater level (from several hours during increase to several weeks during decrease). The duration of the high water event is dependent on the duration of flooding of Planinsko Polje During all high water events there is a different response in water level increase. When the discharge of the Unica River is increasing, water reaches different ponor zones at different times (in Planinsko Polje first eastern, then northern ponors), resulting in a different response

in downstream located caves. This dynamic explains the late response in cave Najdena Jama in comparison to the nearby located ponor zone Pod Stenami. There, water bypasses cave Najdena Jama, which is recharged through a more apparent ponor zone Škofov Lom (Fig. 4.9). Considering the geological structure, this explanation is plausible (Blatnik *et al.* 2019). Water level hydrographs also shows inflection points, presenting temporal slower increase/decrease of the water level. This dynamic indicates the presence of overflow passages at certain levels. Temperature and EC hydrographs have been interpreted for the travel time estimation between successive observation points. Finally, a direct connection between the caves located on the Hrušica Plateau (Veliko Brezno v Grudnovi Dolini and Andrejevo Brezno 1) and the caves Gradišnica and Gašpinova Jama has been proven by the analysis of several hydrological events of different amplitude and duration (Blatnik *et al.* 2019, Blatnik *et al.* 2020).

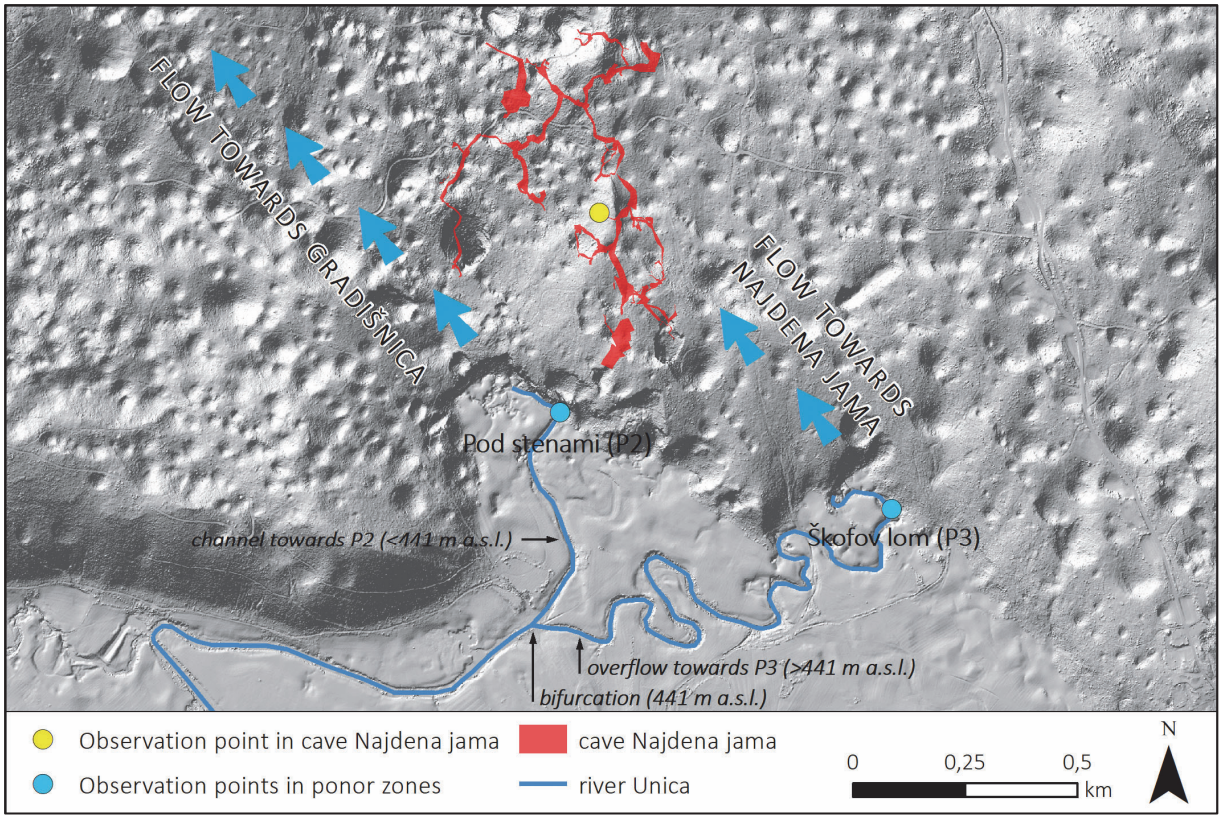


Figure 4.9: Interpretation of the groundwater flow directions between the northern ponors (Pod Stenami and Škofov Lom) and Najdena Jama and Gradišnica.

The Springs of Ljubljanica

The water of the Ljubljanica karst catchment emerges at many springs located near Vrhnika, at the rim of the Ljubljana Basin. The line of springs generally follows the contact of Jurassic limestone and Quarternary sediments underlain by Triassic dolomite (Celarc *et al.* 2013). The most important springs are aligned along the gradually retreating pocket valleys of Močilnik and Retovje. The springs at Močilnik (Q_{av}≈ 6–7 m^3/s) feed Mala (=small) Ljubljanica and springs at Retovje (Q_{av}≈ 16 m^3/s) feed Velika (= big) Ljubljanica, the main tributaries related to karst springs of the Ljubljanica River. Easterly, another tributary Ljubija (Q_{av}≈ 6–7 m^3/s) is also fed by several springs. The eastern-most set of springs at Bistra are already positioned in Triassic dolomites and add on average 7 m^3/s to the last true karstic tributary of Ljubljanica. Mean annual discharge of the Ljubljanica karst springs is about 24 m^3/s (Gospodarič & Habič 1976).

Temperature monitoring at the springs have shown that the major springs exhibit similar temperature dynamics, however, the easternmost spring at Bistra differs quite substantially from the others. The temperature lag is longer and the hydrograph lacks short-time disturbances, which

indicates longer retention time (Blatnik *et al.* 2019). Water tracing in in 1970s also revealed that the direct flow from the Cerkniško Polje mostly goes to the Bistra springs (Gospodarič & Habič 1976).

Springs have been explored by diving since 1936, but the major breakthrough was done in 2020s, when divers have explored more than 1 km of submerged passages (Fig. 4.11).

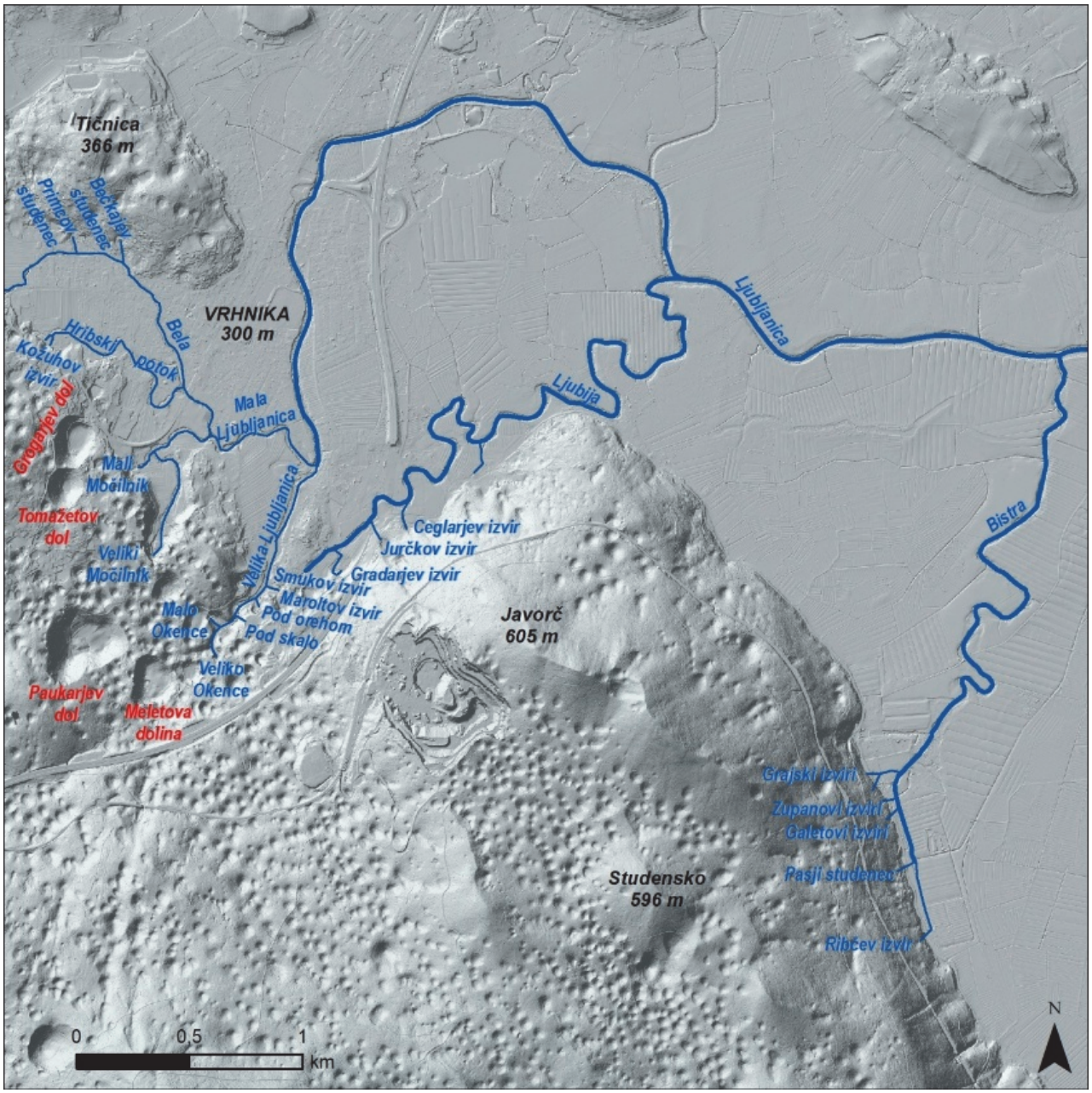


Fig. 4.10: Location of collapse dolines and Ljubljanica springs near Vrhnika.

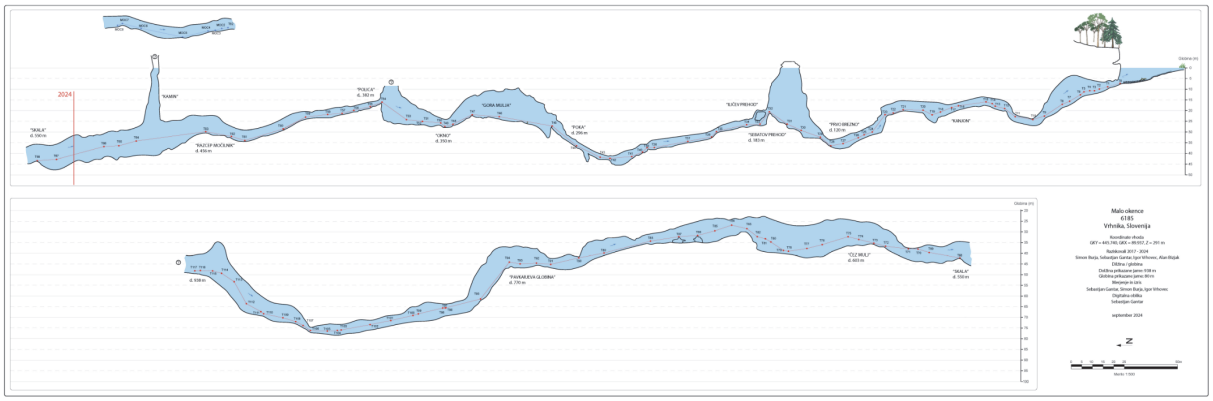


Fig. 4.11: Profile (extended ečlevation) of Malo Okence Spring Cave, most of it explored in 2024 (Authors: Sebastjan Gantar, Simon Birja, Igor Vrhovec)

References (and further reading)

- Blatnik, M., Mayaud, C. & F. Gabrovšek, 2019: Groundwater dynamics between Planinsko Polje and springs of the Ljubljanica River, Slovenia. Acta Carsologica, 48/2, 199-226.
- Drole, F., 2015: Rakov Škocjan in Planinsko polje 2014. Proteus, 76, 6, 275–281.
- Gabrovšek, F. & J. Turk, 2010: Observations of stage and temperature dynamics in the epiphreatic caves within the catchment area of the Ljubljanica river. Geologia Croatica, 63, 2, 187–193.
- Gabrovšek, F. & U. Stepišnik, 2011: On the formation of collapse dolines: a modelling perspective. Geomorphology, 134, 1-2, 23–31.
- Gabrovšek, F., Kogovšek, J., Kovačič, G., Petrič, M., Ravbar, N. & Turk, J., 2010: Recent results of tracer tests in the catchment of the Unica River (SN Slovenia). Acta Carsologica, 39, 1, 27–38.
- Gabrovšek, F., Petrič, M., Ravbar, N., Blatnik, M., Mayaud, C., Prelovšek, M., Kogovšek, B., Mulec, J., Šebela, S. & G. Vižintin, 2019: Raziskave možnih rezervnih vodnih virov za oskrbo občin Postojna in Pivka. Project report, pp. 84.
- Gams, I., 1965: On the Quarternary geomorphogenesis of the area among the karst poljes of Postojna, Planina and Cerknica (In Slovene, English Summary). Geografski vestnik, 37, 61–101.
- Gams, I., 1978: The polje: the problem of definition: with special regard to the Dinaric karst. Zeitschrift für Geomorphologie, 22, 170–181.
- Gams, I., 2004: Kras v Sloveniji v prostoru in času. Inštitut za raziskovanje krasa ZRC SAZU, pp. 515, Ljubljana.
- Gospodarič, R., 1981: Morfološki in geološki položaj kraških votin v ponornem obrobju Planinskega polja. Acta Carsologica, 10, 157–172.
- Gospodarič, R. & P. Habič, (ed), 1976: Underground water tracing: Investigations in Slovenia 1972–1975. Third International Symposium of Underground Water Tracing (3. SUWT), pp. 312, Ljubljana, Bled.
- Habič, P., (ed) 1973: Speleološka karta – List Vrhnika 2-D. Inštitut za raziskovanje krasa ZRC SAZU, pp. 156, Postojna.
- Habič, P., 1984: Vodna gladina v Notranjskem in Primorskem krasu Slovenije. Acta Carsologica, 13, 37–78.
- Kaufmann, G., Gabrovšek, F. & J. Turk, 2016: Modelling flow of subterranean Pivka River in Postojnska Jama, Slovenia. Acta Carsologica, 45, 1, 57−70.
- Kaufmann, G., Mayaud, C., Kogovšek, B. & F. Gabrovšek, 2020: Understanding the temporal variation of flow direction in a complex karst system (Planinska Jama, Slovenia). Acta Carsologica, 49, 2/3, 213–228.
- Kogovšek, B., 2022: Characterization of a karst aquifer in the recharge area of Malenščica and Unica springs based on spatial and temporal variations of natural tracers. PhD thesis. University of Nova Gorica, pp. 242.

- Kogovšek, J., 1999: Nova spoznanja o podzemnem pretakanju vode v severnem delu Javornikov (Visoki kras). Acta Carsologica, 28, 1, 161–200.
- Kovačič, G., 2010: An attempt towards an assessment of the Cerknica Polje water balance. Acta Carsologica 39, 1, 39–50.
- Kovačič, G., 2011: Kraški izvir Malenščica in njegovo zaledje : hidrološka študija s poudarkom na analizi časovnih vrst. Univerza na Primorskem, Znanstveno-raziskovalno središče, Univerzitetna založba Annales, pp. 408, Koper.
- Kovačič, G. & N. Ravbar, 2010: Extreme hydrological events in karst areas of Slovenia, the case of the Unica River basin. Geodinamica Acta, 23, 1–3, 89–100.
- Krivic, P., Verbovšek, R. & F. Drobne, 1976: Hidrogeološka karta 1: 50 000. In: Gospodarič, R. & P. Habič (eds.): Underground water tracing: Investigations in Slovenia 1972–1975. Inštitut za raziskovanje krasa ZRC SAZU, Postojna.
- Mihevc, A., Prelovšek, M., & N, Zupan Hajna, 2010: Introduction to Dinaric Karst. Inštitut za raziskovanje krasa ZRC SAZU, pp. 71., Postojna.
- Petrič, M., Kogovšek, J., & N. Ravbar, 2018: Effects of the vadose zone on groundwater flow and solute transport characteristics in mountainous karst aquifers–the case of the Javorniki–Snežnik massif (SW Slovenia). Acta Carsologica, 47, 1, 35–51.
- Placer, L., 2008: Principles of the tectonic subdivision of Slovenia = Osnove tektonske razčlenitve Slovenije. Geologija, 51, 2, 205–217.
- Placer, L., Vrabec, M. & B. Celarc, 2010: The bases for understanding of the NW Dinarides and Istria Peninsula tectonics. Geologija, 53, 1, 55–86.
- Ravbar, N., Barberá, J.A., Petrič, M., Kogovšek, J. & A. Bartolomé, 2012: The study of hydrodynamic behaviour of a complex karst system under low-flow conditions using natural and artificial tracers (the catchment of the Unica River, SW Slovenia). Environ Earth Sciences, 65, 2259–2272.
- Ravbar, N., Mayaud, C., Blatnik, M. & M. Petrič, 2021: Determination of inundation areas within karst poljes and intermittent lakes for the purposes of ephemeral flood mapping. Hydrogeology Journal, 29, 1, 213–228.
- Savnik, R., 1960: Hidrografsko zaledje Planinskega polja. Geografski vestnik, 32, 212–224.
- Shaw, T. & A. Čuk, 2015: Slovene karst and caves in the past. Inštitut za raziskovanje krasa ZRC SAZU, pp. 464, Postojna.
- Šušteršič, F., 1996: Poljes and caves of Notranjska. Acta Carsologica, 25, 251–290.
- Šušteršič, F., 1999: Speleogenesis of the Ljubljanica River Drainage Basin, Slovenia. In: Klimchouk, A.B., Ford, D.C., Palmer, A.N. & W. Dreybrodt (Eds.): Speleogenesis: Evolution of Karst Aquifers. NSS, Huntsville, Alabama, 397–406.
- Šušteršič, F., 2002: Where does Underground Ljubljanica Flow? RMZ Materials and Geoenvironment, 49, 1, 61–84.
- Šušteršič, F., 2006: Relationships between deflector faults collapse dolines and collector channel formation. International Journal of Speleology, 35, 11–12.
- Vrabec, M., 1994: Some thoughts on the pull-apart origin of karst poljes along the Idrija strike-slip fault zone in Slovenia. Acta Carsologica, 23, 155–167.

ABSTRACTS
IZVLEČKI

*sorted according to the family names of the first authors
**for any grammatical errors is responsible the corresponding author
*razporejeno glede na priimke navedenih prvih avtorjev
**za slovnične napake je odgovoren glavni avtor prispevka

Karst Distribution in Ethiopia: An Overview
Razširjenost krasa v Etiopiji: Splošen pregled

Yohannes Asaye[1], Cyril Mayaud[2,3], Abraham Mechal[4]

[1] *University of Nova Gorica, Glavni trg 8, 5271 Vipava, Slovenia*
[2] *Karst Research Institute ZRC SAZU, Titov trg 2, 6230 Postojna, Slovenia*
[3] *UNESCO Chair on Karst Education, University of Nova Gorica, Glavni trg 8, 5271 Vipava, Slovenia*
[4] *Department of Geology, College of Natural and Applied Sciences, Addis Ababa Science and Technology University, P.O. Box 16417, Addis Ababa, Ethiopia*

This study presents an overview of Karst distribution in Ethiopia based on reconnaissance field survey and synthesis of existing literatures. The most important karst regions are located in the Mekele Basin in northern Ethiopia, the Abay Basin in central and northwestern Ethiopia, and the Ogaden Basin in southeastern Ethiopia. Karst landscapes area primarily associated with Mesozoic carbonate rocks, which occur within the broader Paleozoic–Mesozoic sedimentary successions. These successions typically comprise older Paleozoic clastic units overlain by Adigrat Sandstone, followed by Jurassic Antalo Limestone that host the main karst development and are locally overlain by younger basaltic rocks. The Mekelle Basin (~8,000 km²) comprises Paleozoic–Mesozoic sequences up to ~2,250 m-thick, with the Antalo Limestone Formation (700–800 m). The Abay Basin (~120,000 km²) comprises approximately 1,400 m-thick Paleozoic–Mesozoic successions, with the Antalo Limestone formation (420 m). In contrast, the Ogaden Basin, the largest sedimentary basin in Ethiopia (~350,000 km²), contains up to 10,000 m of Paleozoic and Mesozoic sedimentary sequences, with carbonate rocks distributed across multiple formations, including the Hammanlei, Gabredarre, Gorrahi, Ferfer, and Belet Uen formations, where the Hammanlei limestone reaches a thickness of approximately 500–800 m. Despite containing the largest volume of carbonate rocks, the Ogaden Basin displays comparatively limited surface karstification, mainly due to arid conditions and burial of carbonate units. Karst is mainly subdued at the surface but may occur in subsurface or paleo-karst forms, with local examples such as the Sof Omar Cave system (15.1 km long) in the Bale area and the Mechara Karst system (7.1 km long) in the Western Hararghe region. Other karst landforms include subterranean rivers, sinking streams (ponors), karst springs, sinkholes and collapse dolines, dry valleys, karren, and speleothems (stalactites, stalagmites, and columns). These karst systems offer considerable potential for geo-tourism development due to the presence of cave systems and have important implications for future hydrogeological studies.

Keywords: *Ethiopia, sedimentary basins, karst distribution, carbonate rocks, Antalo Limestone, Hammanlei Limestone*
Ključne besede: *Etiopija, sedimentacijski bazen, razširjenost krasa, karbonatne kamnine, apnenec Antalo, apnenec Hammanlei*

CO_2 and radon variability in a karst cave: Insights from Nova Grgosova Cave, Croatia
Variabilnost CO_2 in radona v kraški jami: Spoznanja iz jame Nova Grgosova, Hrvaška

Petra Bajo[1], Andrej Stroj[1], Maja Briški[1], Vlatko Brčić[1], Iva Palatinuš[1]

[1] *Croatian Geological Survey, Zagreb, Croatia*

Karst caves play an important role in carbon cycling by facilitating the exchange of CO_2 between the atmosphere and the subsurface. Here we present a multiyear dataset from Nova Grgosova Cave in Croatia aimed at understanding the controls of cave air CO_2 variability. Cave air CO_2 concentration, temperature, relative humidity, and airflow were monitored at hourly resolution, while radon activity was measured at monthly intervals with occasional high-resolution campaigns.

The data demonstrates almost constant temperature and relative humidity. In contrast, the CO_2 record is characterised by pronounced seasonal variability, ranging from low concentrations in the cooler seasons to periods of accumulation in the summer months. Cave ventilation, primarily driven by temperature differences between the cave interior and the external atmosphere, is the main control of CO_2 variability at this site. Periods of limited ventilation and elevated CO_2 concentrations are also characterised by increased radon activity, indicating a stronger contribution from soil and epikarst sources than the atmosphere. In contrast, enhanced airflow promotes mixing with outside air, leading to lower CO_2 concentrations and lower radon activities.
This study shows the value of long-term, high-resolution cave monitoring for understanding carbon dynamics in karst systems. The inclusion of radon monitoring further assists in the better interpretation of the origin and mixing of the cave air.

Keywords: *Cave monitoring, cave air CO_2, radon, Nova Grgosova Cave*
Ključne besede: *Spremljanje jam, CO_2 v jamskem zraku, radon, jama Nova Grgosova*

In situ determination of the CO_2 content of cave air with community science methods
In situ določanje vsebnosti CO_2 v jamskem zraku z metodami državljanske znanosti

Viktória Bernadett Balázs[1], Ádám Teil[1], Dénes Szieberth[1]

[1] *Budapest University of Technology and Economics, Hungary*

In cave environments measuring the concentration of CO_2 in cave air can help us determine the carbon output, the rate of ventilation and the periodicity of air movements. Furthermore, it can be useful to determine the breathability of air spaces above water-filled passages, which can be particularly important for divers; at surface fissures we can help identify potential exploration sites.
Instruments suitable for this purpose must meet several criteria. Dust, splash and shock resistance are important, also small size and low power consumption are beneficial. Commercial rugged devices are expensive, while cheap indoor varieties are of questionable quality. In order to explore the possibilities available for community science we developed and tested cost-effective instruments and compared them with classical analytical methods.
While classical chemical analysis can provide accurate results (0.1 mg/l), the implementation in cave-compatible format is challenging. We have also constructed and tested electronic instruments from readily available and inexpensive components. The selected sensors utilize the unique absorption band of the CO_2 molecule in the infrared range. With these sensors the measurement range can reach up to 40000 ppm, with an accuracy of ±50 ppm + 5%. Test measurements were conducted primarily in the air-filled chambers of the Molnár János Cave.

Keywords: *CO_2 sensing, community science*
Ključne besede: *Merjenje CO_2, državljanska znanost*

Modeling of aerological, energy, and condensation volume balance. Chameau Cave, Zegzel, Morocco

Modeliranje aerološke, energijske in kondenzacijske prostorninske bilance. Jama Chameau, Zegzel, Maroko

Lionel Barriquand[1], Philippe Audra[2], Mohamed El Kadiri Boutchich[3], Vasile Heresanu[4], Michel Renda[5]

[1] *Université Savoie Mont Blanc, EDYTEM, UMR 5204, Bâtiment « Pôle Montagne », 5 bd. de la mer Caspienne, 73376 Le Bourget-du-Lac cedex, France*
[2] *Polytech'Lab UPR 7498, Université Côte d'Azur, 930 route des Colles, 06903 Sophia-Antipolis, France*
[3] *Zegzel Valley Foundation, Morocco*
[4] *CINaM, CNRS – Aix Marseille University, Campus de Luminy, case 913, 13288 Marseille cedex 9, France*
[5] *Ifreemis, France*

The Chameau Cave is located in the Zegzel Valley, in the Oriental Region of Morocco. It consists of several tiered galleries, two of which open to the surface. Its terminal section ends in a sump. This is partly fed by low thermal water, giving it a temperature of around 24–27°C. The area between the two entrances, with a 33 m difference in elevation, acts as a wind tunnel, while convection loops flow through the secondary galleries. This configuration, with a hot spot at the confined upstream end of the cave, a wind tunnel between both entrances, and intermediate tiered galleries, gives the cave a complex aerological system. In winter, cold outside air is drawn in through the lower entrance. Some of it rises directly to the upper entrance, where it warms up. Another part is distributed in convection loops in the secondary galleries and up to the upstream sump. In summer, warm outdoor air sinks from the upper entrance to the lower entrance, also forming loops in the secondary galleries.
Aerological measurements taken between March 2018 and June 2019 have made it possible to model and quantify these various exchanges. The original method used (multipoint measurements of air temperature and velocity, and relative humidity of the air in different sections of the galleries) and the mathematical treatments used (statistical treatment using a multiple correlation method) make it possible to visualize the thermal flows in the cave through the velocities and temperatures of the air masses. Combined with calculations based on latent heat, these models provide a preliminary estimate of the volumes of water evaporated and condensed daily in the cave and offer an initial assessment of the aerological dynamics of the cave.
We show that air flows vary seasonally—and probably also at shorter intervals—depending on the temperature gradient between the cave and outdoor. Beyond the internal flows, air flow rates at the system boundaries reach 4 to 7 m^3/s in winter, but are limited to 1.2 m^3/s in summer due to lower temperature gradient. The CO_2 flow remains modest, with a few tens of ppm being extracted, thanks to the permanent dilution of the internal air limiting accumulations. The energy dissipated from the slightly thermal sump at the end of the cave, including the latent heat of vaporization, produces an energy input of between 21 and 56 kW/s for the two periods measured. The condensed water masses vary between 1,360 L/day in summer conditions and 2,095 L/day in winter conditions, when the thermal gradient is stronger. These contributions of condensation water, combined with the diffusion of CO_2, contribute significantly to the corrosion of the walls, which have receded by several decimeters and sometimes more than 1 m, shaping specific morphologies, notably deep notches sculpted by megascallops.

Keywords: *Chameau Cave, cave air flow, latent heat, condensation corrosion, Morocco*
Ključne besede: *Jama Chameau, pretok zraka v jami, latentna toplota, kondenzacijska korozija, Maroko*

Unlocking karst archives: Lipid biomarkers as underutilized paleoclimate proxies in speleothems and cave sediments

Odklepanje kraških arhivov: lipidni biomarkerji kot premalo izkoriščeni paleoklimatski kazalniki v sigi in jamskih sedimentih

James Bendle[1], Patthapong Chaiseanwang[1], Aifeng Zhou[2], Huiling Sun[3], Akkaneewut Jirapinyakul[4], Vasile Ersek[5], Sarah Greene[1], Michael L. Griffiths[6]

[1] *School of Geography, Earth, and Environmental Sciences, University of Birmingham, United Kingdom, B15 2TT*
[2] *School of Earth and Environment Sciences, Lanzhou University, Lanzhou, Gansu, P.R. China 730000*
[3] *Faculty of Geography, Yunnan Normal University, Chenggong, Kunming, Yunnan, P.R. China 650500*
[4] *Department of Geology at Chulalongkorn University, Thailand*
[5] *Department of Geography and Environmental Sciences, Northumbria University, United Kingdom, NE1 8ST*
[6] *Department of Environmental Science, William Paterson University, New Jersey, USA, 07470*

Karst archives are central to terrestrial palaeoclimate reconstruction, yet remain dominated by inorganic proxies (stable isotopes, trace elements) which often integrate multiple environmental signals. Lipid biomarkers offer a complementary and potentially more diagnostic approach, but remain underutilized across both speleothems and cave sediments.

Here, we evaluate the application of lipid biomarkers—including bacterial 3-hydroxy fatty acids (3-OH-FAs), plant-wax n-alkanes, and branched GDGTs—as proxies for reconstructing temperature, hydrology, vegetation, and soil microbial processes in karst systems. Speleothem studies demonstrate that these compounds can resolve coupled vegetation–microbial dynamics and provide independent constraints on terrestrial carbon cycling. Moreover, 3-OH-FA-based proxies enable reconstruction of both temperature and hydrological variability from a single archive, helping to deconvolve signals that are often conflated in conventional oxygen isotope records.

We extend this framework to cave clastic sediments, an archive that remains largely unexplored despite its widespread occurrence. Recent work in Southeast Asia demonstrates that lipid biomarkers are well preserved in cave sediments and form stratigraphically coherent records capable of reconstructing hydroclimatic variability in monsoon-dominated systems. These deposits integrate catchment-derived organic matter, microbial inputs, and event-driven sedimentation, with the potential to capture both gradual environmental change and extreme processes.

By combining insights from speleothems and cave sediments, I will highlight the broader applicability of lipid biomarkers across karst archives. Key challenges include low organic concentrations, diagenetic alteration, and uncertainties in proxy calibration. However, continuing analytical and methodological advances provide clear pathways to overcome these limitations.

We argue that lipid biomarkers represent a critically underutilized proxy system in karst science, with the potential to significantly enhance the resolution, specificity, and process-level understanding of palaeoclimate reconstructions.

Keywords: *Lipid biomarkers, speleothems, cave sediments, paleoclimate reconstruction*
Ključne besede: *Lipidni biomarkerji, siga, jamski sedimenti, paleoklimatska rekonstrukcija*

IS 6 climate variability in Central Europe recorded in a speleothem from Prekova Cave (Central Slovenia)

Spremenljivost podnebja med MIS 6 v Srednji Evropi, zapisana v sigi iz Prekove jame (osrednja Slovenija)

Marcin Błaszczyk[1], Andrzej Tyc[2], Beata Gebus-Czupyt[1], Filp Šarc[3], Krzysztof Gaidzik[2], Bojan Otoničar[3]

[1] Institute of Geological Sciences Polish Academy of Sciences, Twarda 51/55, 00-818 Warszawa, Poland
[2] Faculty of Natural Sciences, University of Silesia in Katowice, Będzińska 60, 41-200 Sosnowiec, Poland
[3] Karst Research Institute ZRC SAZU, Titov trg 2, 6230 Postojna, Slovenia

This study presents a high-resolution paleoclimate record derived from a newly investigated speleothem from the Prekova jama cave (Central Slovenia). The cave lies in a transitional area between two major karst regions—the Dinaric and Alpine karst. Preliminary screening indicated high calcite purity and a growth interval spanning MIS 6, a period generally characterized as cold and often considered unfavourable for speleothem deposition.

Motivated by these promising initial results, a detailed investigation combining high-resolution U–Th dating and continuous stable isotope ($\delta^{18}O$ and $\delta^{13}C$) profiles was conducted. The U–Th chronology reveals that the speleothem grew approximately between ~176 and ~123 ka, with relatively low detrital contamination, confirming the reliability of the age model. Stable isotope values show a broad range of variability, with $\delta^{18}O$ values spanning roughly −8.1‰ to −5.5‰ VPDB and $\delta^{13}C$ values ranging from about −6.9‰ to +0.6‰ VPDB, indicating significant environmental fluctuations during growth and a dominant low vegetation activity throughout most of the period.

The obtained record suggests that MIS 6, despite its overall glacial character, was marked by substantial internal variability. At least two distinct phases can be identified: an earlier interval (~167–147 ka) characterized by more negative $\delta^{18}O$ values, interpreted as colder conditions, followed by a phase (~147–130 ka) showing a gradual increase in $\delta^{18}O$, indicative of relatively warmer conditions and/or changes in moisture source and atmospheric circulation. These findings suggest that the Central European climate during MIS 6 was more dynamic than commonly assumed.

Although the presented results are preliminary, they provide valuable new insights into a poorly documented time interval in Central Europe. The record contributes to a growing database of high-resolution speleothem-based reconstructions and offers potential for comparison with recently published datasets (e.g., Błaszczyk et al., 2025).

The research was funded by the National Science Centre (Poland), grant No. 2020/39/I/ST10/02357 and the Slovenian Research Agency (Slovenia), grant No. N1-0226.

Błaszczyk M., Pawlak J., Hercman H. 2025. Paleoclimatic implications of the Tatra Mountains in Central Europe during MIS 9–6 based on multiproxy speleothem records. Quat. Sci. Rev., Vol. 367, 109544.

Keywords: *Speleothem, paleoclimate, MIS 6, stable isotopes, Prekova jama, Central Slovenia*
Ključne besede: *Siga, paleopodnebje, MIS 6, stabilni izotopi, Prekova jama, osrednja Slovenija*

Long-term monitoring of CO_2 concentration in cave air using the CM-0018 1% CO_2 Data Logger (CO_2 Meter) instrument (Upper Barać Cave, Croatia)

Dolgoročno spremljanje koncentracije CO_2 v jamskem zraku z uporabo instrumenta CM-0018 1 % CO_2 (CO_2 Meter): primer Zgornja Baraćeve špilje, Hrvaška

Neven Bočić[1], Slaven Vuković[2]

[1] *University of Zagreb, Croatia*
[2] *Public Institution Barać Caves, Rakovica, Croatia*

Monitoring was carried out in Upper Barać Cave in Croatia. The cave is located near the world-famous well-known karst phenomenon of the Plitvice Lakes National Park.

Given the tourist use of the cave, the goal was to conduct regular monitoring of carbon dioxide concentration in order to monitor the condition in the cave and to detect possible negative impact of visitors. The CM-0018 1% CO_2 Data Logger (CO_2 Meter) instrument was used for this task. The main advantage of this instrument is that it does not require a mains power supply but uses replaceable and rechargeable batteries (4 x type AA). However, the instrument also has several important limitations for cave monitoring.
Taking this into account, a three-instrument strategy was designed for this research. We had three identical instruments available. Instead of measuring at three points with one instrument each, all instruments measured at one point, but in a way that we regularly changed them. The principle is to measure with two instruments while one instrument is in the office. The change was carried out in a circular manner. In this way, we ensured: (i) continuous measurement at one point, (ii) regular drying of the instrument to prevent the negative impact of moisture, and (iii) double measurement, which we used to try to ensure a continuous series even if one instrument were to shut down.
Measurements were taken hourly over the period from 21 May 2020 to 14 June 2024. The instruments operated in the cave for a total of 35,640 hours, producing 33,118 valid readings (93%). The average CO_2 concentration was 1801.25 ppm, with values ranging from 599.5 ppm to 5084 ppm, showing pronounced seasonal variability.

Keywords: *Cave air, carbon dioxide concentration, cave monitoring, Barać Caves, Croatia*
Ključne besede: *Jamski zrak, koncentracija ogljikovega dioksida, spemljanje jam, Baraćeve jame, Hrvaška*

Insights into karst from monitoring heritage caves

Spoznanja o krasu na podlagi monitoringa jam naravne in kulturne dediščine

François Bourges[1]

[1] *Géologie-Environnement-Conseil 30, rue de la République, F-09200 Saint-Girons, France*

Since the 1990s, high-performance sensors and data loggers requiring minimal maintenance over long periods have been deployed in cultural and natural heritage caves in southern France. Such monitoring is mainly focused on cave microclimates which result from the dynamics of energy and matter (water and gas) transfers through karst permeability. Measurements of underground temperature and cave atmospheric composition allow the assessment of conditions that support optimal conservation. Over time, the quality of measurements has improved and new parameters have become accessible revealing an unexpected complexity of underground atmospheres. These properties and dynamics reflect fundamental processes active in karst systems, some of which are presented hereafter.

Multiparameter monitoring provides insights into CO_2 sources and transfer processes. In Chauvet Cave, the seasonal decrease in CO_2 concentration is associated with autumn rains and coincides with the activation of drip rates in the cave; water infiltration into the fissural network reduces air permeability, thereby limiting the transfer of CO_2-enriched air to the cave. In the nearby Aven d'Orgnac, the CO_2-O_2 time series over a complete seasonal cycle showed an inverse relationship with a 1:1 molar ratio consistent with biogenic production (as confirmed by $\delta^{13}C$ isotopic measurements). The long-term evolution of CO_2 concentration in cave air (+0.8% over 25 years in Chauvet and about +1% over 30 years in the deep parts of Aven d'Orgnac) has been mainly attributed to changes in the production processes but also to increasing external temperatures. Such strong increases in CO_2 concentration in the cave atmosphere significantly alter its aerology as a denser air induces an additional confinement associated with higher radon activity. However, if sanitary thresholds for these contaminants are reached, remediation measures may be implemented by increasing ventilation (Saint-Marcel cave, Aven d'Orgnac) to restore previous atmospheric conditions.
The current temperature drift in many karst systems has been revealed in detail by monitoring; it has been attributed to regional surface climate forcing. The drift rates are roughly dependent on depth within the same cave. Nevertheless, in some places (Gargas Cave), the natural seasonal variations are dampened with depth but not phase shifted as expected. Similar drift values (0.15 °C/decade) are observed at 33 m depth in Pech Merle Cave and at 125 m depth in Aven d'Orgnac, suggesting that diffusive heat transfer through rock is not the only driver and that heat is also transported by fluids, mainly via air convection. An accurate monitoring also reveals the karst response to extreme weather events. Thus, heavy rains in Gargas Cave not only trigger transient responses in infiltration drips, CO_2 concentration, aerosol content in the air, but also cause a permanent shift in air and wall temperatures eventually integrated into the long-term thermal drift.

Keywords: *CO_2, temperature, cave microclimate monitoring, France*
Ključne besede: CO_2, temperatura, spremljanje jamske mikroklime, Francija

Microplastics in pristine caves of the Timavo karst system: contamination patterns and spatial heterogeneity

Mikroplastika v neokrnjenih jamah kraškega sistema Timave: vzorci onesnaženosti in prostorska heterogenost

Raffaele Bruschi[1,2], Manuela Piccardo[3,4], Tecla Bentivoglio[5], Serena Anselmi[5], Patrice Cabanel[6†], Stanislao Bevilacqua[3], Lucia Gardossi[1], Monia Renzi[3]

[1] *Department of Chemical and Pharmaceutical Sciences, University of Trieste, Italy*
[2] *Società Adriatica di Speleologia, Trieste, Italy*
[3] *Department of Life Sciences, University of Trieste, Italy*
[4] *CoNISMa, Rome, Italy*
[5] *Bioscience Research Center, Orbetello, Italy*
[6] *Fédération Française d'Études et de Sports Sous-Marins (FFESSM), France*
[†] *Deceased*

Microplastic (MP) contamination has been documented across a wide range of environments, yet data from pristine subterranean systems remain extremely limited. Here, we investigate MP occurrence in sediments from two newly discovered and virtually inaccessible caves (Maucci and Luftloch) within the Classical Karst (NE Italy), hydraulically connected to the Timavo River, and compare them with a frequently visited cave (Trebiciano Abyss).
Sediments were collected along standardized river-to-slope transects and analyzed using density separation and µFT-IR spectroscopy. MP concentrations were comparable across caves, ranging from ~85 to 106 items kg^{-1} (dry weight), with no significant differences between pristine and non-pristine

systems. Polymer composition was dominated by polypropylene (PP), polyethylene (PE), and polyethylene terephthalate (PET), with similar distributions across sites.
In all caves, MP abundance increased significantly along the river-to-slope gradient, with concentrations up to 4–12 times higher in elevated depositional zones compared to river-proximal sediments. This pattern reflects flood-driven transport and sorting processes within the karst system, where slackwater conditions during high-flow events promote particle retention on higher sediment benches, while lower zones are subject to re-entrainment.
Importantly, MP distribution showed strong spatial heterogeneity at small scales, highlighting the need for structured, multi-point sampling designs in cave environments to avoid biased estimates. The similarity in MP abundance and composition between pristine and frequently visited caves indicates that indirect inputs via the Timavo River dominate over direct human contamination.
These findings provide one of the first quantitative baselines for MP contamination in inaccessible karst environments and emphasize the strong coupling between surface processes, hydrodynamics, and subsurface pollution in karst systems.

Keywords: *Microplastics, karst caves, pristine environments, Reka/Timavo River, spatial heterogeneity, sediment contamination, flood dynamics*
Ključne besede: *Mikroplastika, kraške jame, neokrnjena okolja, reka Timava, prostorska heterogenost, onesnaženje sedimentov, poplavna dinamika*

Beyond the "dogma" of mean annual cave air temperature: Rethinking cave microclimate monitoring

Onkraj »dogme« o povprečni letni temperaturi jamskega zraka: ponoven razmislek o spremljanju jamske mikroklime

Nenad Buzjak[1]

[1] *Department of Geography, Faculty of Science, University of Zagreb, Croatia*

Cave microclimate research has become one of the essential components of contemporary speleology. Its importance extends across a wide range of scientific and practical needs, including the interpretation of physical and geomorphological processes, palaeoclimate records, and ecological conditions, while also supporting cultural heritage protection, biodiversity conservation, and show-cave management. Yet, despite this importance, both terminology and methodology remain unevenly defined. Clear distinction between cave climate, cave microclimate, and cave meteorology is essential, because these concepts refer to different levels of atmospheric organization and cannot be used interchangeably without obscuring the processes they describe. Particular attention must also be given to the persistent "dogma" that mean annual cave air temperature equals the mean annual air temperature of the surrounding region. Although this approximation may hold in some settings, it cannot be treated as a general rule, because caves are internally differentiated into zones with distinct thermal characteristics shaped by seasonally selective coupling with the external atmosphere, cave morphology, rock thermal inertia, ventilation, and hydrological, biological, and anthropogenic inputs. Reliable interpretation of cave microclimate requires appropriate monitoring design. Instantaneous measurements, continuous monitoring, and hybrid strategies combining long-term records with targeted field campaigns do not provide equivalent information; they capture different dimensions of cave-atmosphere dynamics and are most powerful in combination. The same applies to spatial design. Zonation based only on longitudinal measurements along the main passage remains inadequate in many caves, where strong vertical gradients in temperature, humidity, and gas composition may control the internal atmospheric structure. Vertical profiling should therefore be treated as an essential part of monitoring strategy rather than as a methodological refinement. In this framework, CO2 is not

merely an accompanying parameter, but a key indicator of ventilation efficiency, seasonal decoupling from the surface atmosphere, and internal redistribution processes.

Keywords: *Cave climate, cave microclimate, monitoring strategies*
Ključne besede: *Jamsko ozračje, jamska mikroklima, strategije spremljanja*

Geochemical and mineralogical modifications in speleothems associated with past bat occupations (Demoiselles and Roquette caves, Gard, France)

Geokemične in mineraloške spremembe v sigi zaradi pretekle prisotnosti kolonij netopirjev (jame Demoiselles in Roquette, Gard, Francija)

Hélène Cassagne[1,2], Edwige Pons-Branchu[1], Jocelyn Barbarand[2], Éric Douville[1], Delphine Thomas[1], Julius Nouet[2], Maxime Leblanc[2], Laurent Bruxelles[3]

[1] *Laboratoire des Sciences du Climat et de l'Environnement (LSCE), CEA, CNRS, UVSQ, Université Paris-Saclay, Gif-sur-Yvette, France*
[2] *Laboratoire Géosciences Paris-Saclay, UMR 8148, CNRS, Université Paris-Saclay, 91405, Orsay, France*
[3] *Institut Français d'Afrique du Sud IFAS-Recherche, USR 3336 and Evolutionary Studies Institute, University of the Witwatersrand, Johannesburg, South Africa*

Cave morphologies can be significantly altered by the presence of bats. These modifications arise from both the direct mechanical effects of bats and environmental changes induced by respiration and guano deposition. Increased temperature, humidity, CO_2 levels, and the introduction of acids (nitric, sulfuric and phosphoric) from respiration, guano and urine lead to the walls and speleothems dissolution. Beyond the morphological changes, a suite of specific minerals, primarily sulphates and phosphates, is associated with guano and acidic fluids. All these modifications, collectively referred to as biocorrosion, are observed in caves with both current and past bat occupations.
The objective of this study is to understand the chemical and mineralogical modifications due to bat presence occurring in speleothems that serve as records used for dating or reconstructing paleoenvironments. Samples were collected from the Demoiselles cave (Gard, France) and from the Roquette cave (Gard, France), where biocorrosion alterations are observed. Bat occupation phases were identified through mineralogical analysis by SEM and XRD, revealing the preservation of phosphates in speleothems such as apatite and crandalite.
Trace element analyses were conducted on speleothems, revealing elevated concentrations of certain elements (e.g., U, Mg, Cu, Zn, Mn and REE) in phosphate phases. These elements may be hosted by phosphates or by the detrital phases associated with biocorrosion, which remobilizes insoluble elements within the cave. Furthermore, strong correlations exist between U, Mn, REE and P.
Evidence of bat occupation phases in speleothems is preserved through phosphate mineralogy, appearing as distinct bands or grains, always linked to a detrital phase. Geochemical analyses highlight associated modifications, leading to the mobilization and/or introduction of specific elements. This can compromise at least in the levels affected, the use of trace elements in speleothem as a proxy for paleoclimate or their precise chronology.

Keywords: *Speleothems, trace elements, guano, phosphates, biocorrosion*
Ključne besede: *Siga, elementi v sledovih, gvano, fosfati, biokorozija*

Resilience of Nettuno tourist cave (Alghero, Italy) to CO_2 pressure: multi-year monitoring of tourist flow and meteomarine disturbance

Odpornost turistične jame Nettuno (Alghero, Italija) na obremenitve s CO_2: večletno spremljanje turističnega obiska in meteorološko-morskih motenj

Daniela Cinus[1], Quirico Antonio Cossu[1], Angelo Arca[1], Stefano Arrizza[1], Leonarda Fadda[1], Roberto Ferrara[1], Pierpaolo Masia[1], Andrea Ventura[1], Pierpaolo Zara[1], Bachisio Arca[1]

[1] *National Research Council of Italy (CNR), Institute of BioEconomy (IBE), Italy*

Show caves are fragile geoheritage sites whose conservation is threatened by growing tourist pressure and by complex interactions with natural factors. This study presents results from a long-term multi-parameter environmental monitoring programme (May 2021–December 2023) conducted in the Nettuno Cave (Alghero, Sardinia), a Mediterranean coastal show cave receiving over 200,000 visitors per year, with daily peaks of up to 3,000 visitors in summer. Air temperature, relative humidity, CO_2 concentration, and air flow were collected by three automatic stations along the tourist path and the speleological branch. Meteorological and meteomarine data from an offshore buoy were collected. The aim of the work was to quantify the impact of tourism and extreme weather events on cave air chemistry.

Three distinct CO_2 signals were identified by the study. The tourism-driven signal that shows clear daily cycles, with CO_2 peaking at 750–850 ppm during visiting hours and recovering to ~460 ppm overnight, driven by gravitational drainage of CO_2-enriched air along the outward-descending conduit toward the marine entrance. The meteomarine disturbances affect the main signalduring storm events (waves 6–7 m, winds >10 m s^{-1}), when wave pressure on the entrance disrupts natural ventilation, causing the accumulation of elevated CO_2 levels that persist for days after cave closure. A natural background regime, recorded in the deep speleological branch during prolonged closures, shows concentrations progressively increasing with distance from the entrance, probably reflecting endogenous geogenic and biotic sources.

Despite intense tourist loads, CO_2 levels remained well below occupational safety thresholds (750–850 ppm vs. 1,000–1,500 ppm, European guidelines), demonstrating significant microclimatic resilience of the cave. However, effective carrying capacity is dynamically modulated by external meteomarine conditions, which suggest the need of constant adaptive management of this Mediterranean coastal show cave.

Keywords: *Cave microclimate, tourist carrying capacity, gravitational drainage, resilience*
Ključne besede: *Jamska mikroklima, nosilna zmogljivost jame za turistični obisk, gravitacijski odtok, odpornost*

Understanding ventilation dynamics and CO_2 concentration variability of the permanent outflowing cave of Los Pilones (Spain)

Razumevanje ventilacijskih dinamik in variabilnosti koncentracije CO_2 v jami s stalnim zračnim iztokom Los Pilones (Španija)

David Domínguez-Villar[1], Kristina Krklec[1,2], Željka Zgorelec[2], Sonja Lojen[3]

[1] *Department of Geology, Faculty of Science, Universidad de Salamanca, Plaza de los Caídos s/n, 37008, Salamanca, Spain*
[2] *Department of Soil Science, Faculty of Agriculture, University of Zagreb, Svetošimunska 25, 10000 Zagreb, Croatia*
[3] *Department of Environmental Sciences, Jožef Stefan Institute, Jamova 39, SI-1000, Ljubljana, Slovenia*

The cave of Los Pilones (Spain) is a horizontal ~300 m long cave with a single entrance, located in the slope of a narrow canyon. The cave has a subtle but permanent outflow of air by the entrance all year round. This singular ventilation regime limits the impact of advection on temperature records of the

cave interior, that are dominated by thermal conduction and show spectacular thermal signals. Cave air CO2 concentration shows a seasonal variability ranging from 800 to 1600 ppmv, with maxima and minima values during spring and autumn respectively. Cave relative humidity is high all year round (~100%) and cave air pressure oscillates in phase with the external pressure variations. However, a constant pressure difference of 0.6 hPa was measured between cave and external atmospheres at the same elevation.
The calculated cave air density is fairly stable. The external air is denser than the cave when $T_{ext}<T_{cave}$ and vice versa. However, CO_2 concentration is not controlled by air density gradients. We suggest that ventilation of this cave is controlled by a baric (pressure) and not thermic (air density) mechanism. The pressure difference is caused by a permanent thermal inversion at the bottom of the valley due to lack of insolation. Concentrations of CO_2 and $\delta^{13}C$ values from potential sources of cave air CO_2 were studied (soil, dripwaters, groundwater and external air). Preliminary results support that cave air CO_2 originates from air fluxes that interact with groundwater. So, we propose the existence of a permanent convection cell where the air enters to the massif at the bottom of the canyon, ascends through rock porosity/cracks until encounters the cave, uses it as a preferential conduit, and flows out to the valley. In this case, the forcing mechanisms of the convection cell are pressure gradients caused by the thermal inversion.

Keywords: *Karst, isotope, carbon, pressure, source*
Ključne besede: *Kras, izotop, ogljik, tlak, vir*

Hydrogeological drought assessment under semi-arid climate for the highly karstified Western Mountain Aquifer

Hidrogeološka ocena suše v polsuhem podnebju v močno zakraselem Zahodnem gorskem vodonosniku

Irina Engelhardt[1], Micha Gebel[2], Martin Sauter[3]

[1] *Technical University of Berlin, Hydrogeology Department, Berlin, Germany*
[2] *VisDat, Germany*
[3] *LIAG-Institute for Applied Geophysics, Hannover, Germany*

A process-based integrated method for determining droughts in the vadose zone and in groundwater for a highly karstified aquifer, the Western Mountain Aquifer, which is a transboundary between Israel and Palatine was developed. The goal was to support water management in karstified aquifers located in semi-arid regions. Drought assessment is based on two hydrogeological indices: GRI and GWI, which are integrated into the early warning system. Furthermore, two meteorological indices SPI and SPEI were also integrated. The early drought warning system is publicly accessible web-based drought monitor and are continuously updated. The four indices display both: forecasts up to six months into the future and long-term assessments up to the year 2100 based on climate projection data. The early warning system for drought serves as a source of information for stakeholders to plan water resource management and to inform the public, whose awareness of the impending water shortage needs to be raised. In addition to interactive drought assessments for sub-basins, wells and aquifers in the form of maps and diagrams for the four indices have selectable calculation intervals of 3, 6, 9, 12 or 24 months. An interactively generated management catalogue provides a verbal description of the drought status, possible impacts and possible options for mitigating the impacts of drought. The products and tools developed in this way will enable water users and local authorities to improve regional resilience to extreme climate events and reduce water stress.

Keywords: *Water management, early drought warning system, water stress*
Ključne besede: *Upravljanje voda, sistem zgodnjega opozarjanja na sušo, vodni stres*

Origin of organic matter present in the karst system in the Rovte area, Central Slovenia

Izvor organske snovi v kraškem sistemu na območju Rovt, osrednja Slovenija

Monika J. Fabiańska[1], Justyna Ciesielcyuk[1], Beata Gebus-Czpyt[3], Magdalena Misz-Kennan[1], Filip Šarc[2], Andrzej Tyc[1], Vanessa E. Johnston[2], Krzysztof Gaidzik[1], Bojan Otoničar[2]

[1] *Faculty of Natural Sciences, University of Silesia in Katowice, Będzińska 60, Sosnowiec, Poland*
[2] *Karst Research Institute ZRC SAZU, Titov trg 2, 6230 Postojna, Slovenia*
[3] *Institute of Geological Sciences, Polish Academy of Sciences, Twarda 51/55, 00-818 Warszawa, Poland*

Organic matter was investigated in the Rovte area (Central Slovenia), where Triassic carbonate rocks underwent dolomitization and dedolomitization. Dark-colored, petrographically varied host rocks and spring water were analyzed for organic matter thermal maturity, biogenic origin, and depositional environment features.
The results show that both the organic matter present in rocks and the organic compounds found in spring water have the same origin: marine biogenic material sedimented in a relatively deep, anoxic basin in an environment poor in sulfates. Such conditions led to the formation of kerogen IIa of a planktonic/bacterial origin, with planktonic material degraded by bacteria in a water column. The resulting rocks were poor in organic carbon. In the following depositional history, this kerogen was further altered hydrothermally. This increased its maturity, leading to the expulsion of hydrocarbons. These compounds were leached and are now found in spring water. Highly graphitized organic matter reached the end of the gas window.

These studies are funded by the Polish National Science Centre (grant No. UMO-2020/39/I/ST10/02357) and the Slovenian Research Agency (No. N1-0226), within OPUS-20 (LAP).

Keywords: *Organic matter, Rovte area, carbonate rocks, spring water, Central Slovenia*
Ključne besede: *Organska snov, Rovte, karbonatne kamnine, izvirska voda, osrednja Slovenija*

Early Warning Systems as dynamic karst groundwater protection tools: the case of Sierra de Ubrique aquifer (S Spain)

Sistemi zgodnjega opozarjanja kot dinamična orodja za zaščito kraške podtalnice: primer vodonosnika Sierra de Ubrique (južna Španija)

Jaime Fernández-Ortega[1], Juan Antonio Barberá [1], Bartolomé Andreo[1]

[1] *Department of Geology and Centre of Hydrogeology, University of Malaga (CEHIUMA), 29071 Malaga, Spain*

Karst waters are widely used for drinking water supply but is highly vulnerable to contamination due to the rapid groundwater flow systems through conduits and fractures. Early Warning Systems (EWS) have emerged as effective dynamic protection tools to detect contamination events in real time at drinking water capture points. This study addresses the development and implementation of an EWS in the drinking water system of Ubrique, a rural mountainous area with Mediterranean influence in S Spain. The investigated permanent springs, captured for drinking water supply, face rapid water quality challenges following intense rain events due to turbidity variations over the threshold established by Spanish legislation (4 NTU), which forces the temporary shutdown of groundwater abstraction. In the upstream recharge area, the leakage of an insufficiently treated WWTP effluent containing faecal bacteria infiltrates directly into the aquifer through a swallow hole, leading to high faecal bacteria activity at karst springs used for drinking water supply. A multi-technique approach was applied to (i) characterise contamination episodes at the scale of individual spring flood events, (ii) identify the main

contaminants, (iii) integrate protection and modelling tools, and (iv) design, test, and validate an early-warning protocol to support decision-making. A comprehensive monitoring network was established, collecting environmental, hydrodynamic, physico-chemical, chemical, and microbiological data, including Escherichia coli, during nine flood events between 2020 and 2023. Statistical analyses and time-series evaluation enabled the identification of optimal proxy parameters for each spring, main sediment and contaminant transport mechanisms and mixing processes. A decision-tree workflow was developed to assess groundwater quality on an hourly basis using spring-specific warning thresholds. These thresholds trigger alarms when critical parameters are exceeded. In parallel, hydrodynamic modelling and Machine Learning tools were implemented to forecast spring responses and assess sanitary risk in real time. Overall outcomes demonstrate the effectiveness of this integrated framework for implementing early-warning strategies to safeguard public health in karst water supply systems worldwide.

Keywords: *Karst, early warning, contamination, protection tool*
Ključne besede: *Kras, zgodnje opozarjanje, onesnaženje, orodje za zaščito*

Determining the water storage capacity of different types of limestone and dolomite using ERT
Določanje zmogljivosti zadrževanja vode različnih tipov apnenca in dolomita z uporabo ERT

Barbara Funk[1,2], Clemens Moser[2], Adrian Flores Orozco[2]

[1] *Natural History Museum, Karst and Cave Group, Burgring 7, 1010 Vienna, Austria*
[2] *TU Wien, Research Unit Geophysics, Wiedner Hauptstraße 8, 1040 Vienna, Austria*

Improving our understanding of the water storage capacity of solid rocks is crucial for future water availability in context of changes in precipitation patterns due to climate change. In our study, we aim to measure the water storage capacity of various limestone and dolomite formations in the catchment area of the Vienna High-Altitude Water Supply Lines I and II using electrical resistivity tomography (ERT). The ERT method allows to resolve the electrical resistivity of the medium under investigation and is linked with water content. We conducted laboratory ERT imaging measurements on rock samples collected at the Hochschwab, Schneealpe, Rax and Schneeberg massive to examine the storage capacity of the rock matrix. The rock samples were cut into cuboid-shaped blocks and saturated in a tap water bath for one month. To measure the water storage capacity, we dried the sample at a constant temperature of 25°C while we monitored changes in electrical resistivity over time at 30-minute intervals. Additionally, the weight of the sample was measured to determine the actual amount of water retained and to calibrate the resistivity data. The composition and porosity of the rock samples were measured to calculate the ideal Ca-Mg ratio for reaching the maximum water storage capacity. Information on the relationship between resistivity and saturation are key for interpretation of field signatures, allowing to estimate bedrock water saturation from resistivity measurements.

Keywords: *Karst, hydrology, ERT, water storage capacity, laboratory measurements*
Ključne besede: *Kras, hidrologija, ERT, zmogljivost zadrževanja vode, laboratorijske meritve*

Landslide Hazard Zonation in a cut slopes along Sohag- Safaga highway based on slope properties and rock mass classification

Coniranje nevarnosti zemeljskih plazov v vkopih ob avtocesti Sohag–Safaga na podlagi lastnosti pobočja in klasifikacije hribinske mase

Ahmed Gaber[1]

[1] *Geography Department, Sohag University, Egypt*

Landslide and especially rock fall hazard widely occurs along cut slopes in mountainous regions. The risk assessment of mass movements is still one of most challenging problems in slope engineering geology. I propose a routine method to assess rock slide and rock fall risk of cut slopes essentially based on slope properties and rock mass structure.
The method is a lean low-cost path to a risk estimate. Rock block size is simplified into two classes, {small} with a volume less than 1.0 m^3 and {large}, greater than 1.0 m^3. Studies indicate that for a slope with n small-medium rock blocks, the possibility of rock falls can be estimated by 1 - (1 - P) n, in which P is the likelihood of one {small} rock block fall. The possibility of other types of mass movement can be determined by the first order second-moment (FOSM) method. Based on this, an exponent equation was adopted to evaluate the consequence and the risk. The methodology is demonstrated by a case study from the Sohag – Safaga highway. Based on the investigations of geological conditions (i.e., lithology, weathering and rock mass structure) and some historical mass movement data of the cut slopes, a zonation map for rock fall and rock slide risk along the cut slope sections.

Keywords: *Landslides, rock fall, rockslide risk, cut slope, highway*
Ključne besede: *Zemeljski plazovi, skalni podori, nevarnost skalnega podora, vkop, avtocesta*

Diurnal CO_2 Variability in Air Exhaled from a Deep Vadose Borehole in Planinska Jama

Dnevna variabilnost CO_2 v zraku, izhajajočem iz globoke vrtine v Planinski jami

Franci Gabrovšek[1]

[1] *Karst Research Institute ZRC SAZU, Titov trg 2, 6230 Postojna, Slovenia*

About 35 years ago, a 200 m-deep borehole was drilled connecting the surface above Planinska jama with the Mysterious Lake in the remote part of the cave. The borehole penetrates the vadose zone above the cave. According to a 1991 report, most of the borehole is uncased, allowing unrestricted air exchange between the borehole and the surrounding limestone massif. Access to the lower end of the borehole and measurements of the exhaling air are only possible during periods of low water level and are limited in duration. We took advantage of such a period in August 2024 to measure airflow at the upper mouth of the borehole, and CO_2 concentrations in the exhaled air just above the Mysterious Lake in the cave. The results show a positive correlation between airflow and CO_2 concentration: the highest CO_2 values were recorded around midday, when the chimney effect is strongest due to peak external temperatures. At first glance, this result appears counterintuitive, since one would expect minimum diurnal CO_2 concentrations when the inflow of external air is greatest. However, considering that the borehole intersects a fracture/conduit system that also enables advective CO_2 transport, the observations become more consistent with expectations. We present a simple model to test several hypotheses and to interpret the observed results.

Keywords: *CO_2, karst, borehole, vadose zone, Planina Cave*
Ključne besede: *CO_2, kras, vadozna cona, Planinska jama*

New preliminary oxygen stable isotope results of carnivore coprolites from Biśnik Cave (southern Poland)

Novi preliminarni rezultati stabilnih izotopov kisika iz fosiliziranih iztrebkov mesojedcev iz jame Biśnik (južna Poljska)

Beata Gebus-Czupyt[1], Greta Brancaleoni[1], Krzysztof Stefaniak[2], Adrian Marciszak[2], Magdalena Sudoł-Procyk[3], Krzysztof Cyrek[3], Maciej T. Krajcarz[1]

[1] Institute of Geological Sciences, Polish Academy of Sciences, Twarda 51-55, 00-818, Warsaw, Poland
[2] Department of Paleozoology, University of Wroclaw, Sienkiewicza 21, 50-335, Wrocław, Poland
[3] Institute of Archaeology, Nicolaus Copernicus University in Toruń, Szosa Bydgoska 44/48, 87-100, Toruń, Poland

Coprolites, or fossilised faeces, are a valuable source of information on the diet, behaviour, and physiology of animals, as well as predator-prey interactions. During coprolite formation, fresh faecal components are mineralised, typically through replacement by carbonate or phosphate phases. The best-preserved coprolites are commonly found in caves and rock shelters.

Here, we present the first phosphate-related oxygen isotope results obtained from coprolites collected in Biśnik Cave (southern Poland). This cave represents an important Middle Palaeolithic site where the presence of carnivores has been repeatedly recorded. The analysed coprolites originate from Layer 7, dated to MIS4-MIS3, and are primarily of carnivore origin, as supported by apatite-rich matrices, the presence of bone fragments, and micro-spherulitic structures.

For this pilot study, we selected 11 coprolite samples that had been well characterized in previous studies. The oxygen isotopic signal was measured in calcium phosphate, a main component of these coprolites. The $\delta^{18}O\text{-}PO_4$ values obtained from the phosphate fraction range from +16.5 to +18.5 ‰ VSMOW, falling within the range reported for guano-derived deposits (from +15.0 to +19.5 ‰, Smith et al. 2021).

Further research will focus on other potential phosphate source within the cave, including bones, guano, and bedrock, to better understand the source of phosphates and sedimentary processes occurred during and after deposition of the sedimentary record in the Biśnik Cave and to build a reference database of oxygen stable isotope values in cave phosphates.

Isotope research was financed by the IGS PAS statutory project "Jaskinie", the remaining research was financed by the National Science Centre, Poland, MINIATURA grant 2024/08/X/ST10/01585.

[1] Smith, A.C.; Pfahler, V.; Tamburini, F.; Blackwell, M.S.A.; Granger, S.J. A review of phosphate oxygen isotope values in global bedrocks: Characterising a critical endmember to the soil phosphorus system. J. Plant Nutr. Soil Sci. 2021, 184, 25–34.

Keywords: *Coprolites, phosphates, stable isotopes, Biśnik Cave*
Ključne besede: *Fosilizirani iztrebki, fosfati, stabilni izotopi, jama Biśnik*

Karst and Wind Energy Development in British Columbia, Canada: Implications of a Regulatory Transition

Kras in razvoj vetrne energije v Britanski Kolumbiji, Kanada: Vplivi regulativnega prehoda

Paul A. Griffiths[1], Carolyn L. Ramsey[1]

[1] *Independent karst researchers, Canada*

Carbon dioxide is the predominant greenhouse gas (GHG) in British Columbia (BC), Canada, accounting for nearly 85% of the province's annual emissions, which total 61.1 million tonnes of carbon dioxide equivalent ($MtCO_2e$).
Wind energy development, aimed at reducing GHG emissions by shifting energy demand toward low carbon electricity, is a central component of BC's decarbonization and electrification strategy.
As onshore wind energy development expands, projects are expected to occasionally intersect karst landscapes of conservation value, particularly in coastal islands and mountainous regions of BC where wind conditions are favourable.
The Government of British Columbia has recently announced that major wind energy projects will be exempt from review under the Environmental Assessment Act, shifting oversight from a coordinated, effects-based environmental assessment (EA) process to a streamlined, permitting-led regulatory model with lifecycle compliance. The new framework includes an explicit legislated objective requiring that energy resource activities avoid damaging karst systems as a resource feature. However, achieving outcomes comparable to those of the EA process will depend on early identification and field verification of karst features, delineation of recharge areas, avoidance-based siting of turbines, careful routing of linear infrastructure, and enforceable long-term monitoring and maintenance.
We examine the implications of this regulatory shift for karst through a comparative review of the two regulatory models. Our findings identify key challenges in applying a permitting-led approach to karst and offer transferable insights for renewable energy development in karst settings both within British Columbia and in other jurisdictions.

Keywords: *Karst, wind energy, British Columbia, environmental assessment, regulatory transition*
Ključne besede: *Kras, vetrna energija, Britanska Kolumbija, presoja vplivov na okolje, regulativni prehod*

Morphology and speleogenesis of the Vrlovka Cave (Kamanje, Croatia)

Morfologija in speleogeneze jame Vrlovka (Kamanje, Hrvaška)

Klara Grošanić[1], Neven Bočić[1], Uroš Barudžija[2], Lea Okički[3]

[1] *University of Zagreb, Faculty of Science, Department of Geography, Croatia*
[2] *Department of Mineralogy, Petrology and Mineral Resources, Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb*
[3] *Croatian Biospeleological Society, Zagreb*

The Vrlovka Cave is located in the Kupa River valley in Kamanje near Ozalj (Croatia). Its entrance is located on a steep rocky cliff on the right side of the Kupa River canyon. The cave consists of a main channel with several shorter branches, and is 474 m long in total. It is formed in Cretaceous limestone. The values of this cave were recognized early, so it was declared a protected geomorphological monument of nature in 1962. Since then, no further geospeleological research was carried out in the cave, so the goal of this research was to determine the basic morphological characteristics of the cave and to define phases of its speleogenesis. The research was conducted in several steps: 1) a new cave survey was carried out, 2) morphometric, as well as macro- and mesomorphological characteristics were determined, 3) detailed geospeleological mapping was performed, including mapping of

structural elements (faults and fractures), speleogens and other denudational features, water bodies and sediments. Based on the collected data, the main conditions and phases of speleogenesis were defined: (1) passage enlargement in the phreatic zone; (2) lowering of the erosion base and formation of the cave in epiphratic and vadose conditions (3) clastic sediment fills the part of the passages in the epiphreatic conditions; (4) paragenesis (antigravitative corrosion) and formation of branches and (5) further lowering of the erosion base, erosion of the sediment infillings, accumulation of speleothems and development of the channel in vadose conditions. In addition to the carbonate structure and fracture porosity, the relative position of the Kupa River level in relation to the level of the cave conduit played an important role in controlling the speleogenesis process.

Keywords: *Vrlovka Cave, speleogenesis, karst geomorphology, Dinaric karst, Croatia*
Ključne besede: *Jama Vrlovka, speleogeneza, kraška geomorfologija, Dinarski kras, Hrvaška*

CO_2 around Milandre Cave (Jura, Switzerland)
CO_2 v jami Milandre (Jura, Švica)

Philipp Häuselmann[1], Pierre-Yves Jeannin[1], Marc Luetscher[1]
[1] *Swiss Institute for Speleology and Karst Studies, CH-2300 La Chaux-de-Fonds, Switzerland*

Milandre Cave is an active river cave that is used as a laboratory for decades already in order to understand karst hydrogeology. In recent years, CO_2, its generation, its effect on the cave, and the effect of the cave (ventilation) on CO_2 has gained more interest. The presentation shows summarily the measurements, possibilities, and open questions.

Keywords: *Milandre Cave, CO_2, Switzerland, ventilation, hydrogeology*
Ključne besede: *jama Milandre, CO_2, Švica, prezračevanje, hidrogeologija*

A field-inspired, systematic investigation of conduit network impacts on flow and transport in karst aquifers
Terensko zasnovana sistematična raziskava vplivov omrežja kanalov na tok in prenos snovi v kraških vodonosnikih

Jenny Huang[1], Jannes Kordilla[2], Marco Dentz[2], John Barry[3], Christian Langevin[4], Peter K. Kang[1]

[1] *University of Minnesota, Department of Earth and Environmental Sciences, Minneapolis, MN, USA*
[2] *Institute of Environmental Assessment and Water Research, Barcelona, Spain*
[3] *Minnesota Department of Natural Resources, St. Paul, MN, USA*
[4] *S.S. Papadopulos & Associates, St. Paul, MN, USA*

Karst aquifers are particularly vulnerable to contamination due to direct surface connectivity via sinkholes and rapid transport through conduits and fractures. Effective management of these groundwater systems necessitates accurate characterization of flow and transport. However, accurate modeling of karst aquifers is challenging due to the high heterogeneity of these systems. This heterogeneity produces complex partitioning of recharge between bedrock and embedded conduit network. Additionally, conduit networks serve as both preferential flow paths and storage reservoirs, producing spatial and temporal variability in behavior. Thus, the properties of conduit networks impact flow and transport, but there has not been a systematic, quantitative study of how conduit network structure and geometry impact spring hydrographs and breakthrough curves in naturalistic field conditions. In this field-inspired modeling study, we attempt to identify key geometric and structural properties of conduit networks that control flow in karst aquifers and use these insights to constrain our understanding of a nitrate and chloride-impacted karst aquifer in Southeastern Minnesota.

We systematically vary network structure, geometry, and recharge distribution for a field-inspired conduit network. We model conduit flow with the model openKARST coupled with a linear reservoir model to represent matrix controls on conduit flow. To identify key properties that impact spring flow, we quantify the differences in spring hydrograph behavior as a function of network properties, with a particular focus on identifying the conditions under which conduit geometry can be simplified or ignored when modeling spring flow. Based on the simulation results of synthetic yet realistic conduit systems, we attempt to characterize the key properties of a karst aquifer conduit network in Southeastern Minnesota and validate these properties by recreating observed spring hydrographs. Future work will incorporate solute transport to investigate the impact of conduit network properties on breakthrough curve behavior.

Keywords: *Modeling, aquifer, spring, hydrographs, conduit network, Minnesota*
Ključne besede: *Modeliranje, vodonosnik, izvir, hidrogrami, mreža kanalov, Minnesota*

Holocene variability of internal carbon cycling in a karst Lake Velo Blato (Pag Island, Croatia) inferred from stable isotopes in lake sediments

Holocenska variabilnost notranjega kroženja ogljika v kraškem jezeru Velo Blato (otok Pag, Hrvaška) na podlagi stabilnih izotopov v jezerskih sedimentih

Ivona Ivkić Filipović[1,2], Nikolina Ilijanić[1], Ivan Razum[3], Melanie J. Leng[4,5], Jack H. Lacey[4], Slobodan Miko[1], Tamara Marković[1], Martina Šparica Miko[1]

[1] *Croatian Geological Survey, Sachsova 2, 10000 Zagreb, Croatia;*
[2] *Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Pierottijeva 6, 10000 Zagreb, Croatia*
[3] *Croatian Natural History Museum, Demetrova 1, 10000 Zagreb, Croatia*
[4] *British Geological Survey, Nottingham NG12 5GG, United Kingdom*
[5] *School of Biosciences, University of Nottingham, Sutton Bonington, Loughborough LE12 5RD, United Kingdom*

Lake Velo Blato is a shallow coastal karst lake on Pag Island (Croatia) on the eastern Adriatic coast. It is characterized by wetland vegetation in an otherwise barren karst landscape, resulting in minimal terrestrial input from the catchment. This makes it an ideal site to study past changes in the internal (aquatic) carbon cycle. In this study, we used stable isotope analyses of lacustrine organic matter ($\delta^{13}C_{om}$) and lake carbonates ($\delta^{18}O_{calcite}$, $\delta^{13}C_{calcite}$) to reconstruct climate changes, organic matter sources, and variations in the carbon pool throughout the Holocene. The $\delta^{18}O_{calcite}$ record implies the wettest climate conditions between 8100 and 7500 cal yr BP, followed by a progressive aridification trend with pronounced dry phases during the Roman and Medieval Warm Periods, and a return to wetter conditions during the Little Ice Age. $\delta^{13}C_{calcite}$ broadly follows this pattern, suggesting common controls on both isotopes related to evaporation and CO_2 exchange with the atmosphere. However, from ca. 2100 cal yr BP, $\delta^{18}O_{calcite}$ and $\delta^{13}C_{calcite}$ are decoupled, with continued enrichment in $\delta^{18}O_{calcite}$ but decreasing $\delta^{13}C_{calcite}$, implying changes in the $\delta^{13}C_{DIC}$. The $\delta^{13}C_{om}$ record reveals changes in aquatic vegetation, from submerged macrophytes and algae (higher $\delta^{13}C_{om}$) during the Middle Holocene to more emergent macrophytes and palustrine plants (lower $\delta^{13}C_{om}$) during the Late Holocene, reflecting progressively lower lake levels and enroachment of wetland vegetation. Together, the $\delta^{13}C_{om}$ and $\delta^{13}C_{calcite}$ reflect variable $\delta^{13}C_{DIC}$ throughout the Holocene, with higher values indicating progressive $\delta^{13}C_{DIC}$ enrichment from karst and CO_2 outgassing, and lower values suggesting enhanced sediment respiration at the lake bottom, typical of organic-rich shallow lakes. This record demonstrates that in karst settings with negligible terrestrial input, lake sediments can capture a signal of internal carbon cycling, offering rare insight into how aquatic systems and karst alone regulate carbon pathways over millennial timescales.

Keywords: *Holocene, lake sediments, karst lake, organic carbon, stable isotopes*
Ključne besede: *Holocen, jezerski sedimenti, kraško jezero, organski ogljik, stabilni izotopi*

GIS-Based Analysis of Dinaric Karst Poljes: An Integrated Approach and Preliminary Results

GIS-analiza dinarskih kraških polj: integriran pristop in preliminarni rezultati

Matej Jelovčan[1], Nadja Zupan Hajna[1], Rok Mihevc[2]

[1] Karst Research Institute, Titov trg 2, 6230 Postojna, Slovenija
[2] 1370 Logatec, Slovenija[2]

Poljes are among the largest karst depressions and represent key natural laboratories for understanding interactions between dissolution, tectonics, sedimentation, and hydrogeology (e.g., groundwater level oscillation). Despite extensive research, the definition and conceptual framing of poljes remain debated, particularly regarding the relative roles of morphometric versus hydrogeological factors. This research aims to develop a GIS-based framework for analysing Dinaric karst poljes by integrating geomorphological, geological, hydrogeological information with remote sensing data, using high-resolution LiDAR datasets where available and comparable digital elevation models elsewhere. Our approach emphasizes the role of hydraulic regulation at the karst groundwater table as a key factor linking polje morphology with hydrogeological functioning.

The first phase focuses on the automated detection and delineation of karst poljes from topography and lithology using a machine learning segmentation model. The model is trained on Copernicus DEM 30 m resolution, producing probability masks and boundary geometries for subsequent GIS analyses. Predicted polje polygons are enriched with their dominant lithology class to support rapid manual review and the filtering of false positives in non-karst terrain. Subsequent work will address the hydrogeological regime of poljes, including permanent and seasonal flooding and dry systems, as well as the effects of anthropogenic drainage works (hydromelioration). Time-series remote sensing (Sentinel-1 SAR, Landsat/Sentinel-2) will be used to reconstruct inundation dynamics and their temporal variability. Selected case studies, particularly Planinsko and Cerkniško polje will serve as key case studies, benefiting from extensive tracer tests, hydrological monitoring, and modelling datasets. Later phases will reconstruct developmental stages of selected poljes and place them in a geological time framework through detailed geomorphological mapping, sedimentary archives, and tectonic analysis.

Expected outcomes include: (1) a standardized and openly documented GIS database of Dinaric poljes; (2) a process-based understanding of polje functioning that links geomorphology and hydrogeology; (3) improved understanding of tectonic and groundwater controls on polje evolution; and (4) applied contributions to karst water-resource management, flood-hazard assessment, and spatial planning in the Dinaric Karst.

Keywords: *Karst polje, Dinaric karst, automated detection with machine learning, geomorphology, hydrogeology, paleoreconstruction*

Ključne besede: *Kraško polje, Dinarski kras, avtomatizirano zaznavanje s strojnim učenjem, geomorfologija, hidrogeologija, paleorekonstrukcije*

Rock–water–air carbon exchange along the Postojna–Planina caves system

Izmenjava ogljika med kamnino, vodo in zrakom vzdolž jamskega sistema Postojna–Planina

Vanessa E. Johnston[1], Youjun Jiao[1,2,3,4], Franci Gabrovšek[1]

[1] *Karst Research Institute ZRC SAZU, Titov trg 2, 6230 Postojna, Slovenia*
[2] *Beijing Key Laboratory of Water Resources and Environmental Engineering, School of Water Resources and Environment, China University of Geosciences (Beijing), Beijing 100083, China*
[3] *Institute of Karst Geology, CAGS/ Karst Laboratory of karst Dynamics, MNR & GZAR/ International Research Center on Karst under the Auspices of UNESCO, Guilin, Guangxi 541004, China*
[4] *Pingguo Guangxi, Karst Ecosystem, National Observation and Research Station, Pingguo, Guangxi 531406, China*

When water enters the underground it encounters an environment that often has higher CO_2 concentrations in the vadose zone air than what the water was previously exposed to in the outside atmosphere. This permits CO_2 to dissolve into the water, forming a weak carbonic acid that can lead to the dissolution of carbonate minerals. The dissolution of calcite consumes CO_2, and thus acts as a net CO_2 sink. However, under different conditions, CO_2 can degas from the water, driving calcite precipitation. The concentration of CO_2 in the vadose zone air is highly variable; both spatially and temporally. Therefore, CO_2 exchange between groundwater and the vadose zone works in both directions, fluctuating water–rock interactions between the states of carbonate dissolution or precipitation as the water travels through the karst system.
As part of the CardiKarst project, we carried out simultaneous CO_2 monitoring of cave air and cave water. Additionally, we analysed the water geochemistry at a biweekly resolution for one year to inform about the carbonate saturation state. We chose specific locations along the water travel path through the Postojna–Planina caves system, throughout which the water encounters diverse cave environments. At all sites the CO_2 concentration dissolved in the water was greater than that of the air, with the smallest difference at the sites in the middle of the cave system. Comparing the water entering to that exiting the caves system, the dissolved CO_2 concentration increased and the saturation of calcite decreased as the water travelled through the cave system, indicating a greater possibility to dissolve calcite and act as a CO_2 sink. However, the fate of the dissolved CO_2 after exiting the cave system is an open question.
This work has been co-financed by the Slovenian Research and Innovation Agency (ARIS; J7-4630) and the Croatian Science Foundation (IPS-2022-02-2260) under the bilateral project "Dynamics and distribution of CO_2 in karst vadose and epiphreatic zone (CARDIKARST)".

Keywords: CO_2, water geochemistry, Postojna–Planina caves system, Pivka River, water–rock interactions
Ključne besede: *CO_2, geokemija vode, sistem Postojnsko-Planinske jame, reka Pivka, interakcije voda-kamnina*

Use of ^{13}C to trace the origin of dissolved inorganic carbon in water and organic carbon in sediments: a case study of the permanent subsurface flow of the karstic Reka River

Uporaba ^{13}C za sledenje izvoru raztopljenega anorganskega ogljika v vodi in organskega ogljika v sedimentih: študija primera trajnega podzemnega toka kraške reke Reke

Tinkara Kepic[1], Luka Serianz[1]

[1] *Geological Survey of Slovenia, Slovenia*

In this study, we investigate the spatial variability of carbon sources in water and sediments within the permanent subsurface flow of the karstic Reka River. In karst systems, carbon sources reflect the interaction of geochemical and biological processes, including carbonate weathering and microbial

activity. We particularly focus on an extended karst system in which carbon sources evolve along the flow path from the river sink and are further modified by in-situ biological processes, providing first insight into the complexity of the carbon cycle within this system. Samples were collected at five sampling sites along the flow path: the Škocjan II ARSO hydrological station (located upstream of the river sink), Škocjan Caves, Kačna Cave, and Grotta di Trebiciano. Additionaly, the Timavo Spring was sampled as the main discharge from the karst system. To determine the sources of carbon, two complementary $\delta^{13}C$ proxies were applied. In water samples, $\delta^{13}C$ of dissolved inorganic carbon (DIC) was measured in combination with total organic carbon (TOC), while in sediments, $\delta^{13}C$ of organic carbon (OC) was analysed together with the TOC/TN ratio. The isotopic composition of organic carbon reflects the preferential assimilation of lighter or heavier carbon isotopes during metabolic processes.

Keywords: *Carbon sources, karst rivers, stable isotopes, Reka River*
Ključne besede: *Viri ogljika, kraške reke, stabilni izotopi, reka Reka*

Karst conduit network generation conditioned by geology, geomorphology, and hydrodynamic behaviour

Nastanek mreže kraških kanalov pod vplivom geologije, geomorfologije in hidrodinamičnih razmer

Attila Kovács[1]

[1] *University of Miskolc, Hungary*

Recent advances in karst conduit network modelling enable generating ensembles of plausible subsurface geometries constrained by geological structures, hydrological data, and surface karst features like springs, sinkholes, and mapped cave passages. These stochastic methods quantify uncertainty in conduit location and connectivity, propagating it into flow and transport simulations. Techniques include fast marching and rule based growth algorithms, probability map ensembles from soft data, modular simulators, skeleton pattern generators, and deep generative graph models. Most condition on observed fractures or explored cave segments, though these represent only a fraction of hydraulically active conduits. Hydrogeological evidence indicates most conductive pathways follow conjugate fracture sets, with mapped bifurcations marking the most enlarged sections. In unconfined aquifers, effective drainage requires spatially coherent conduit networks, emphasizing structural density over enlargement for hydrodynamic function.

This method introduces two key innovations: (1) conceptualizing conduit systems as maze like networks rather than hierarchical branching trees, and (2) constraining conduit spacing using hydrodynamic behaviour inferred from hydrograph analysis. This geometric conditioning is vital to reproduce transient hydraulic responses in natural karst systems. The workflow involves spatial identification of conductive features (e.g., caves, sinkholes, springs), directional analysis of conduit families via von Mises distributions, and hydrograph based estimation of characteristic conduit spacing. Monte Carlo sampling and least squares optimization align conduits with observed features along dominant orientations, followed by stochastic generation of cross conduits based on spacing and orientation statistics.

This structural statistical framework integrates geological realism with hydrodynamic consistency through three stages: (1) extraction of structural patterns from karst features, (2) statistical characterization of directional and spacing distributions, and (3) stochastic conduit generation conditioned by structural and hydraulic constraints. Implemented with Python and GIS libraries, it supports spatial conditioning and ensemble production.

Keywords: *Conduit network, hydrograph analysis, monte-carlo process, modelling*
Ključne besede: *Mreža kanalov, analiza hidrogramov, metoda Monte Carlo, modeliranje*

Cave air ventilation dynamics in Eagle Cave (Spain): Unraveling the controls and sources of cave air CO_2

Dinamika prezračevanja jamskega zraka v jami Eagle Cave (Španija): Razkrivanje dejavnikov in virov CO_2 v jamskem zraku

Kristina Krklec[1,2], Željka Zgorelec[2], Sonja Lojen[3], David Domínguez-Villar[1]

[1] *Department of Geology, Faculty of Sciences, University of Salamanca, Salamanca, Spain*
[2] *Faculty of Agriculture, University of Zagreb, Zagreb, Croatia*
[3] *Department of Environmental Sciences, Jožef Stefan Institute, Ljubljana, Slovenia*

Concentration of CO_2 in cave atmospheres is an important factor controlling karst underground geochemical processes. Although soil CO_2 is the trigger of most karst processes, other sources of CO_2 such as degassing/equilibration with karst waters or the external atmosphere also contribute to cave air CO_2. Variability of CO_2 concentration in caves is often related to ventilation rates that depend on air density or pressure gradients between the external and cave atmospheres.
In Eagle Cave (central Spain), we monitored soil and cave CO_2 concentration at daily resolution. Also, we collected monthly air and water samples for hydrochemical and $\delta^{13}C$ analyses. Additionally, we monitored soil and cave basic meteorological parameters at daily resolution. Since Eagle Cave is a show cave, we excluded periods when CO_2 concentrations show obvious impact of tourists to understand the natural cave CO_2 variations. We used virtual temperature (T_v) to calculate air density of soil and cave atmospheres.
We found a strong correlation (r^2=0.82) between soil air density and cave CO_2 concentration, supporting that Eagle Cave is a thermic cave (controlled by air density gradients) with summer and winter ventilation modes. It is the soil air, rather than external atmosphere (in comparison to cave air) that drives the ventilation regime. Extreme air density gradients are recorded during maxima and minima in cave CO_2 concentrations, suggesting that CO_2 concentrations are not related to ventilation rates but with CO_2 concentrations from different sources. The $\delta^{13}C$ signal of cave air CO_2 differs between ventilation modes, with dominant sources from soil in summer and interaction with karst water in winter, both of having certain mixing with the external atmosphere.
Our research confirms that maxima cave air CO_2 values typically recorded in summer should not be necessarily related to low ventilation rates, and that cave airflows can be more complex than previously anticipated.

Keywords: *cave ventilation; cave air CO_2; karst; Eagle Cave; air density; carbon isotopes*
Ključne besede: *jamska prezračenost, jamski zrak CO_2, kras, jama Orel, gostota zraka, ogljikovi izotopi*

Forms of calcium carbonate precipitation in Pleistocene glacial sediments of Poland

Oblike obarjanja kalcijevega karbonata v pleistocenskih ledeniških sedimentih na Poljskem

Bogusz Kulus[1]

[1] *Doctoral School of Exact and Natural Sciences, University of Warsaw, ul. Stefana Banacha 2c, 02-097, Warsaw, Poland*

Poland's territory is largely covered by Pleistocene glacial sediments, such as till, sand, gravel, silt and clay. Although these sediments do not undergo karst processes *sensu stricto*, they do contain numerous carbonate erratics (limestones, dolomites, chalk), which are subject to dissolution. Waters containing dissolved calcium carbonate migrate through the sediments and as a result of precipitation, concentrations on single pebbles (coatings, knobstones) and forms of sediment cementation (concretions in tills, sub-pebble cementation forms, conglomerates and sandstones) are formed.

Conglomerates and sandstones form particularly interesting rock formations, from small lumps to large blocks, layers, and columns. They have been the subject of discussion regarding their origin and the conditions of their formation. It has been repeatedly suggested that meteoric waters infiltrated calcium carbonate-rich tills, dissolving $CaCO_3$. When such waters flowed into the sands, changes in porosity led to degassing of waters and precipitation of calcite under vadose conditions. Suitable conditions for this process occur during warm periods, when organic matter decomposition occurs on the surface, acidifying the water. Others suggest that calcium carbonate precipitation in the intergranular spaces of sands and gravels occurred during cold periods (glacials), as a result of changes in subglacial water pressure. Studies of sandstone layers from several profiles have revealed a diversity of cement morphologies. However, the predominant cement generation consists of cements characteristic of phreatic conditions (isopachous, equant). Together with the oxygen and carbon isotope records, they indicate that these layers formed in shallow groundwater during interglacial and/or Holocene conditions. Currently, these formations (conglomerate and sandstone tors) are undergoing karstification, and speleothems are forming within them.

Keywords: *Cements, erratics, groundwater, sandstones*
Ključne besede: *Cementi, ledeniški balvani, podzemna voda, peščenjaki*

Towards a systematic stratigraphy of Croatian cave sediments: the QUEECAD project
Proti sistematični stratigrafiji jamskih sedimentov na Hrvaškem: projekt QUEECAD

Tomislav Kurečić[1], Lara Wacha[1], Neven Bočić[2], Hrvoje Cvitanović[3], Petra Bajo[1], Filip Šarc[4], Marijan Kovačić[5], Nadja Zupan Hajna[4], Robert Lončarić[6], Maša Surić[6]

[1] *Croatian Geological Survey, Department of Geology, Milana Sachsa 2, Zagreb, Croatia*
[2] *University of Zagreb, Faculty of Science, Department of Geography, Trg Marka Marulića 19/II, Zagreb, Croatia*
[3] *Public Institution Barać Caves, Nova Kršlja 47 a, Rakovica, Croatia*
[4] *Karst Research Institute ZRC SAZU, Titov trg 2, 6230 Postojna, Slovenia*
[5] *University of Zagreb, Faculty of Science, Department of Geology, Horvatovac 102 b, Zagreb, Croatia*
[6] *Department of Geography, University of Zadar, F. Tuđmana 24 i, Zadar, Croatia*

The project Quaternary Environmental Evolution Archived in Croatian Cave Deposits (QUEECAD) investigates the complementarity between speleothems and clastic (allogenic and authigenic) cave sediments, that reflect distinct speleogenetic phases. It aims to reconstruct the origin, depositional environments, and geochronology of cave sediments using a multi-proxy approach that integrates mineralogical, geochemical, and sedimentological data from clastic deposits and flowstone intercalations. Chronological constraints will be established using U-Th, OSL, and/or IRSL dating, complemented by the first application of detailed magnetostratigraphy in Croatian caves to constrain depositional timing. Due to specific methodological requirements, detailed investigations will focus on sedimentary profiles in three of the five caves included in the QUEECAD project: Gornja Cerovačka špilja (Upper Cerovac Cave), Donja Baraćeva špilja (Lower Barać Cave), and Gornja Baraćeva špilja (Upper Barać Cave).
Initial work has been carried out in Gornja Baraćeva špilja, where a 2-m-thick clastic sequence interlayered with flowstone has been excavated, described, and sampled. Preliminary results provide insight into alternating intervals of authigenic and allogenic detritus deposited in various settings (e.g., diamicton, slackwater deposits, and entrance talus), interrupted by more stable phases characterised by flowstone deposition. Grain-size analysis, XRF data, and heavy and light minerals assemblages identified within the profile indicate a shift from allogenic input to authigenic deposition, correlating with the evolution of the local landscape. Initial U-Th results suggest that sediment deposition within the sequence continued until approximately 106.3 ka. The site is considered particularly promising for detailed palaeomagnetic analysis, with high-resolution sampling planned as part of the project. The same methodological framework will be applied to Donja Baraćeva špilja and Gornja Cerovačka špilja.

The resulting data and reconstructions will enable comparison and correlation with well-characterised cave deposits from the Slovenian Dinaric Karst, particularly Račiška pečina (Račiška Cave), which represents one of the most significant cave archives of geomagnetic field variations over the last 3.4 million years.

Project *Quaternary Environmental Evolution archived in Croatian Cave Deposits* – QUEECAD IP-2025-02-6560 is funded by the Croatian Science Foundation (2025-2028).

Keywords: *Caves, clastic sediments, mineralogy, magnetostratigraphy, Croatia*
Ključne besede: *Jame, klastični sedimenti, mineralogija, magnetostratigrafija, Hrvaška*

Impact of "parasitic phenomena" on the microclimate of the show caves: A case study from the Balcarka Cave (Moravian Karst, Czech Republic)

Vpliv »parazitskih pojavov« na mikroklimo turističnih jam: študija primera jame Balcarka (Moravski kras, Češka)

Marek Lang[1]

[1] *Department of Geological Sciences, Faculty of Science, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic*

In addition to popular tourist destinations, show caves are also frequently used for cultural events, therapeutic purposes, and/or scientific research. Therefore, effective protection of caves is a classical karst problem that has been solved continuously for several decades. The anthropogenic impact in the show caves was documented by many studies focused on various microclimatic parameters; however, the main indicator is generally considered to be carbon dioxide (CO_2), because anthropogenic CO_2 contributes to the total cave CO_2 level by the net positive flux derived from visitor exhalation. In principle, instantaneous cave CO_2 is given by the balance of input and output CO_2 fluxes. Whereas the input fluxes are associated with soil/epikarstic sources, the output fluxes are controlled by cave airflow. In this context, visitors can induce the "parasitic phenomena" that affect cave ventilation and disturb or even inverse the expected CO_2 increases. Two examples of these phenomena, (i) the visitor movement in low-profile passages and (ii) the opening of the doors that close the cave or its individual passages, were studied in the Balcarka Cave (Czech Republic) and the results were presented in Acta Carsologica (44/1, 71–80) and the International Journal of Speleology (46/3, 345–358). The study of visitor movement showed that anthropogenically induced airflows exceeded natural airflows by a factor of more than 60. These airflows caused a switch of actual ventilation mode and a significant drop in CO_2 fluxes/levels. The effect of door opening differed with ventilation modes. Under upward airflow, an increase in output advective CO_2 fluxes from the cave was evident with a decrease of CO_2 levels near the cave entrance, but deeper in the cave, this effect was suppressed. Under downward airflows, changes in airflow paths resulted in an increase in CO_2 level in the entrance passages, but a decrease in the deeper passages.

Keywords: *Anthropogenic impact, carbon dioxide, cave airflow, door opening, show cave, visitor movement*
Ključne besede: *Antropogeni vpliv, ogljikov dioksid, pretok jamskega zraka, odpiranje vrat, turistična jama, gibanje obiskovalcev*

Long-Term Monitoring in the Vadose Zone of a Karst System: Investigating Environmental Drivers of CO_2 Transport Dynamics Using Machine Learning

Dolgočasovni monitoring vadozne cone krasa: analiza okoljskih dejavnikov prenosa CO_2 z uporabo metod strojnega učenja

Vivien Langhans, Leon Keim, Holger Class, Sergey Oladyshkin[1]

[1]*Department for Hydromechanics and Modelling of Hydrosystems, University of Stuttgart, Germany*

CO_2 transport and dissolution processes in karst systems play a fundamental role in karstification and the global carbon cycle, yet some processes like density-driven CO_2 dissolution in temporary stagnant cave water bodies as a carbon sink remain insufficiently quantified. Recent work has shown that density-driven enhanced dissolution of gaseous CO_2 at the karst water table is a key mechanism driving rapid increases in aqueous CO_2 concentrations during periods of elevated cave-air CO_2, and that deep, stagnant water bodies may act as efficient CO_2 traps [1, 2]. Establishing the boundary conditions for this process is therefore a prerequisite for credible numerical simulations of karst carbon dynamics.

CO_2 enters the cave atmosphere through two main pathways: dissolved in percolating drip water passing through the vadose zone, and in the gas phase driven by cave ventilation dynamics. These processes are governed by a complex interplay of environmental drivers, including atmospheric temperature, pressure, wind, precipitation, and soil moisture as well as temperature. For example, soil moisture and temperature clearly act as important controls on the vertical transport of CO_2 in the vadose zone, resulting in the accumulation or dilution of gaseous CO_2 in the cave atmosphere. Disentangling these complex interactions and their temporal structure calls for data-driven approaches. Machine learning methods, particularly time-series forecasting models, offer a promising framework for identifying dominant environmental drivers and characterising the inertia terms of the system. A persistent challenge, however, is the treatment of data gaps in long-term monitoring records. Data logger or network failures can introduce gaps of varying length into time series, and the majority of forecasting models cannot proceed with missing training data, making robust gap-filling a critical preprocessing step. This work therefore also addresses and compares statistical and machine learning methods for imputing missing values in environmental cave monitoring data.

The study site is the Laichinger Tiefenhöhle, a karst cave in the Swabian Alb, Southern Germany. Since 2021, a monitoring campaign has recorded cave air CO_2 concentrations at one-minute resolution. Repeated hardware failures in the network and data logger system produced data gaps ranging from minutes to several months. In 2025, the measurement infrastructure was completely renewed: a new network system ensures reliable data transfer, and a new data logger based on Raspberry Pi with Ansible deployment now operates two parallel CO_2 sensors for redundancy [3]. In addition, a radon (Rn) sensor has been installed alongside the CO_2 sensors, as both gases can serve as tracer gases detecting transport processes in a karst system.

[1] H. Class, P. Bürkle, T. Sauerborn, O. Trötschler, B. Strauch, and M. Zimmer. “On the role of density-driven dissolution of CO2 in phreatic karst systems”. Water Resources Research 57 (2021), e2021WR030912. doi: 10.1029/2021WR030912.

[2] H. Class, L. Keim, L. Schirmer, B. Strauch, K. Wendel, and M. Zimmer. “Seasonal Dynamics of Gaseous CO2 Concentrations in a Karst Cave Correspond with Aqueous Concentrations in a Stagnant Water Column”. Geosciences 13.2 (2023). doi: 10.3390/geosciences13020051.

[3] L. Keim, S. Hägele, V. Langhans, and H. Class. A Flexible Raspberry Pi-Based Data Logger Platform for Modbus Sensors with Ansible Deployment. 2026. arXiv: 2605.10454 [cs.CE]. url: https://arxiv.org/abs/2605.10454

Keywords: karst CO_2 dynamics, density-driven dissolution, vadose zone, machine learning, long-term monitoring

Ključne besede: *dinamika ogljikovega dioksida v krasu, z gostoto pogojeno, vadozna cona, trojno učenje, dejavniki, dolgočasovni monitoring*

How to Professionally "Sell" a Cave? Speleological Marketing of the Demänová Caves Association (1924–1954)

Kako profesionalno "prodati" jamo? Speleološki marketing Društva Demänovskih jam (1924–1954)

Łukasz Lewkowicz[1]

[1] *Maria Curie-Skłodowska University, Poland*

A true breakthrough in the history of Slovak speleology and cave tourism, came with the discovery of the Demänová Cave of Liberty (Demänovská jaskyňa Slobody, "Temple of Liberty") in the summer of 1921. It was discovered on 3 August by Moravian teacher Alois Král. Due to the exceptional value of the cave, it was placed under state protection the same year, and work began on making it accessible to visitors. In 1922, the Commission for the Opening of the Demänová Caves (Komisia pre zverejnenie Demänovských jaskýň) was established. A year later, temporary electric lighting was installed. A section of the cave - from the entrance adit to the Golden Lake - was opened to visitors in August 1924.
In 1924, the Demänová Caves Association (Družstvo Demänovských jaskýň) was founded, taking over the commission's responsibilities and continuing the exploration and development of further parts of the "Temple of Liberty". Due to insufficient transport infrastructure, visitor numbers were initially very low: in the first season of 1924, only 2,634 tourists visited the cave. From the early 1930s, attendance gradually increased following the construction of a road from Liptovský Mikuláš, the development of tourist infrastructure (including restaurants), and the redesign of the cave route.
The Association also carried out intensive and professional marketing campaigns within Czechoslovakia and abroad. Czech cultural figures such as Rudolf Těsnohlídek and Leoš Janáček actively supported promotional efforts. The caves were also widely advertised in Polish tourist guidebooks, including those published by well-known speleologists, the Zwoliński brothers. In 1928, the world's first speleological film, titled "Demänová", was produced. The Association extensively named sections of the cave after Czechoslovak and international politicians, as well as well-known businessmen. By the early 1930s, annual visitor numbers exceeded 20,000, reaching over 30,000 in peak years such as 1936–1937.
Following the dissolution of Czechoslovakia in 1938 and the Second World War, tourist numbers declined sharply, particularly in 1944 and 1945. After the Communist takeover in 1948, improved living standards and the mass expansion of tourism led to a severalfold increase in visitation. At the same time, due to political changes, the Association was dissolved in the early 1950s and the caves were taken over by the state.

Keywords: *Show caves, speleohistory, Slovakia, Demänovská Cave of Liberty*
Ključne besede: *Turistične jame; speleozgodovina; Slovaška; Demänovská jama svobode*

MOKRO project - Environmental changes of the littoral karst during the late Quaternary

Projekt MOKRO - Okoljske spremembe obalnega krasa v poznem kvartarju

Robert Lončarić[1], Maša Surić[1], Tvrtko Dražina[2], Krešimir Žganec[3], Ozren Hasan[4], Filip Šapina[1], Aurora Varda[1]

[1] *Department of Geography, University of Zadar, F. Tuđmana 24i, Zadar, Croatia*
[2] *Department of Biology, Faculty of Science, University of Zagreb, Savska cesta 32, Zagreb, Croatia*
[3] *Department of Teacher Education Studies in Gospić, University of Zadar, Ulica dr. Ante Starčevića 12, Gospić, Croatia*
[4] *Department for Mineral Resources and Marine Geology, Croatian Geological Survey, Milana Sachsa 2, Zagreb, Croatia*

The Mediterranean is globally recognized as a hot spot in terms of environmental effects of the recent climate changes and within the region the Dalmatian coast is considered as a particularly vulnerable area. Since the adaptation to future climate changes relies on understanding the complex environmental changes in recent geological past, we have launched a project Environmental change of the littoral karst during the late Quaternary (MOKRO) which encompasses multi- and interdisciplinary research of the coastal environment near the village of Modrič, on the foothill of the Velebit Mt. (Croatia). The research area, although small (ca. 2 km^2), is known for its geo- and biodiversity and during the Quaternary it experienced extreme hydro(geo)logical changes caused by climate changes accompanied by the sea-level fluctuations.

The project's aim is to reconstruct paleoenvironmental conditions of the littoral karst during: a) Quaternary glacial periods exhibiting lower sea levels (analysis of submerged speleothems from nearby submarine spring), b) sea level rise (analysis of marine sediments), and c) submergence of coastal karst ecosystems (analysis of the brackish shallows and the coastal pond habitats), and to estimate d) the current state of subaerial cave environments (biospeleological inventory, monitoring of the cave atmosphere), and e) cause-and-effect relationships between variations in environmental conditions and historical socio-economic changes.

There are four key directions in the methodological approach: i) reconstruction of geomorphology of submerged areas using MBES/SBP, and of environmental changes based on different proxies in absolutely dated (U-Th, ^{14}C) sediments, ii) monitoring of physical and chemical properties (T, pH, Rn concentration) which affect ecological conditions, iii) determination of the current state of biocenoses of brackish shallows, coastal ponds and caves that reflect current ecological conditions, and iv) compilation of various archival historical documents.

The synthesis of these results will provide a basis for predicting how ongoing climate trends may drive future changes in littoral karst environments.

The project MOKRO (IP-UNIZD2025-28060) is funded by the European Union – NextGenerationEU.

Keywords: *Karst, coastal environments, climate change, Quaternary, Croatia*
Ključne besede: *Kras, obalna okolja, podnebne spremembe, kvartar, Hrvaška*

Carbon and oxygen stable isotope composition of speleothems from Čulejca Cave (N. Macedonia): preliminary insight on Holocene paleoclimate changes

Stabilni izotopi ogljika in kisika v sigi jame Čulejca (Severna Makedonija): preliminarni vpogled v holocenske paleoklimatske spremembe

Ali Mammadov[1], Marjan Temovski[1,2]

[1] *Department of Mineralogy and Geology, University of Debrecen, Egyetem tér 1, H-4032 Debrecen, Hungary*
[2] *HUN-REN Institute for Nuclear Research (ATOMKI), Bem tér 18/c, H-4026 Debrecen, Hungary*

Two broken stalagmites were collected from two locations in Čulejca Cave (N. Macedonia), the bases of which remain in the cave. CU5, collected in a niche in the Upper Room, is ~35 cm long, and CU6, collected from the end of the Poolfinger Room, is ~10 cm long. Preliminary age-depth models were established based on 5 and 17 U-Th ages for CU5 and CU6, respectively. CU5 formed continuously between 3573 ± 184 and 2030 ± 80 years BP, while the lower part at CU6 formed between 7843 ± 196 and 6190 ± 134 and the upper part between 1731 ± 275 and 474 ± 85 years BP, with a ~4500 years hiatus in-between. The stalagmites show significantly different growth rate, with values ranging at 160–183 µm/year for CU5 and 6–81 µm/year for CU6. Low-resolution (5 mm steps) carbonate stable isotope composition ($\delta^{13}C$, $\delta^{18}O$) was determined on 70 samples at CU5 and 17 samples at CU6. They have similar range of $\delta^{13}C$ values (−9.32 to −5.64 ‰ for CU5 and −8.01 to −5.58 ‰ for CU6), with CU6 having somewhat lower $\delta^{18}O$ values (−9.65 to −6.84 ‰ for CU5 and −10.47 to −8.09 ‰ for CU6). At CU6, an excursion to lower $\delta^{18}O$ and $\delta^{13}C$ values is found between 7.5 and 6.5 ka, coeval with an increase in growth rate. This is consistent with proxy data from Ohrid Lake, which indicates colder winter and likely wetter conditions during this period, that switches to warmer/drier conditions after 6.5 ka.

Keywords: *Stalagmite, U-Th dating, stable isotopes, Holocene*
Ključne besede: *Stalagmit, U-Th datiranje, stabilni izotiopi, holocen*

Identification of organic compounds in moonmilk-forming waters by Liquid Chromatography High-Resolution Mass Spectrometry (LC-HRMS)

Identifikacija organskih spojin v vodah, ki tvorijo jamsko mleko, s tekočinsko kromatografijo – visokoločljivostno masno spektrometrijo (LC-HRMS)

Andrea Martín Pérez[1], Vanessa E. Johnston[2], Adrijan Košir[1] and Janez Mulec[2]

[1] *Institute of Palaeontology ZRC SAZU, Novi trg 2, 1000, Ljubljana, Slovenia*
[2] *Karst Research Institute ZRC SAZU, Titov trg 2, 6230 Postojna, Slovenia*

Water samples from moonmilk speleothems from two karstic caves in Slovenia have been analysed by Liquid Chromatography High-Resolution Mass Spectrometry (LC-HRMS) to identify the organic compounds.

Calcite moonmilk is a very peculiar, highly hydrated type of speleothem composed of fibrous microcrystalline calcite, which has been shown to host abundant microbial biomass. Many authors have considered moonmilk as biogenic in origin, but the exact role of microorganisms in mineral precipitation is still under debate. Based on previous petrographic and geochemical analysis, our working hypothesis is that organic matter could play a passive role in moonmilk precipitation, where the distinctive, fibrous microcrystalline habit of calcite is determined by the presence of certain organic compounds in the water, and that mineralization is not necessarily induced by any specific microbial metabolic pathway.

To gain information about the presence and distribution of organic compounds, 18 water samples have been analysed by LC-HRMS from the Snežna jama (1556 m a.s.l.) and Košelevka cave (634 m a.s.l.), both located in relatively remote, forested areas. Here we show the distribution of the organic molecules in moonmilk—forming waters, control water samples, subaqueous moonmilk deposits, and subaerial moonmilk for each cave, and discuss the possible origins of the identified synthetic and natural molecules.
This is a contribution of the project J1-50028 “Exploring the potential of moonmilk speleothems as archives of palaeo-environmental information”, financed by the Slovenian Research and Innovation Agency (ARIS).

Keywords: *Speleothems, fibrous microcrystalline calcite, biologically influenced mineralisation, organic geochemistry*
Ključne besede: *speleotemi, vlaknati mikrokristalni kalcit, biološko vplivana mineralizacija, organska geokemija*

Coastal karst geomorphology and submerged archaeological features at Ras Alam El-Rum, northwest coast of Egypt

Obalni kras geomorfologija in potopljene arheološke oblike na rtu Ras Alam El-Rum, severozahodna obala Egipta

Samah Moustafa Abozeid[1]

[1] *Bloom International Academy, 22 El-Ghorfa El-Tegareya St, Mahatet El-Raml, Alexandria, Egypt*

This research focuses on the unique coastal karst manifestations at the ancient submerged harbor sites of Ras Alam El-Rum on the Northwest Coast of Egypt. The study area is characterized by Pleistocene limestone ridges (Oolitic Limestone) that have undergone significant karstification processes.
Field observations and underwater documentation reveal various coastal karst landforms, including solution pans, kamenitzas, and intricate dissolution features carved directly into the submerged archaeological structures and rock-cut harbor installations. These features are the result of the complex interplay between freshwater dissolution and marine erosion (Bio-erosion and Mixing-zone Corrosion). By analyzing these karst forms within the submerged port context, this study aims to reconstruct the palaeo-environmental conditions and coastal evolution of the region. The presence of these karstified features provides crucial evidence for sea-level changes and the long-term geomorphological stability of the limestone coastline, offering new insights into the preservation of maritime cultural heritage in karstified environments.

Keywords: *Coastal karst, submerged archaeological sites, Ras Alam El-Rum, Pleistocene limestone, dissolution features, northwest coast of Egypt*
Ključne besede: *Obalni kras, potopljena arheološka najdišča, Ras Alam El-Rum, Pleistocenski apnenec, korozijske oblike, severozahodna obala Egipta*

Using FloodWatch on the field: a first assessment
Uporaba FloodWatch na terenu: prva ocena

Cyril Mayaud[1,2], Žan Kafol[1,3], Žiga Kokalj[4,5,6] and Jaroslav Obu[1,2]

[1] *Karst Research Institute ZRC SAZU, Titov trg 2, 6230 Postojna, Slovenia*
[2] *UNESCO Chair on Karst Education, University of Nova Gorica, Glavni trg 8, 5271 Vipava, Slovenia*
[3] *Kafol.net, Žan Kafol s.p., 6230 Postojna, Slovenia*
[4] *Institute of Anthropological and Spatial Studies ZRC SAZU, Novi trg 2, 1000 Ljubljana, Slovenia*
[5] *Postgraduate school ZRC SAZU, Novi trg 2, 1000 Ljubljana, Slovenia*
[6] *University of Vienna, Franz-Kleingasse 1, 1190 Wien, Austria*

This work presents a first assessment of the use of the citizen science mobile application FloodWatch on the field. The application has been officially released in November 2025 and aims at measuring the flood dynamics of karst poljes and intermittent lakes using a simple smartphone. Since its release, FloodWatch has been used to monitor the water level dynamics of the Upper Pivka Valley during two floods. The first flood focused on catching the flooding dynamics of the intermittent lake Petelinjsko jezero. During the second event, flooding of the intermittent lakes Petelinjsko, Parsko and Palško jezero were completely monitored. In both cases, the water levels measured with the application were compared to the water levels monitored by automatic stations installed in each lake. The results showed that FloodWatch is able to catch accurately the flood dynamics if the user makes a few measurements along the lake shore during each field trip. Thanks to a promotion campaign including several interviews at different regional and national Slovenian radios, newspapers, TVs combined with an intense advertisement on social networks, FloodWatch has now 200 registered users. About a quarter of them did already one measurement. This allowed water level data to be obtained from 13 of the 17 Pivka intermittent lakes during the last flood that occurred in the valley. The application has, therefore, the potential to become a state-of-the-art tool used by both the scientific and public communities, enhancing the potential to collect data from poljes and intermittent lakes that do not have an automatic monitoring network.

Keywords: *Karst areas, floods, citizen science, mobile application, FloodWatch*
Ključne besede: *Kraška območja, poplave, državljanska znanost, mobilna aplikacija, FloodWatch*

ZRC SAZU and EPOS ERIC: Data provision and seismic monitoring in the Slovenian karst
ZRC SAZU in EPOS ERIC: Zagotavljanje podatkov in potresni monitoring na slovenskem krasu

Magdalena Năpăruş-Aljančič[1], Uroš Novak[1], Stanka Šebela[1]

[1] *Karst Research Institute ZRC SAZU, Titov trg 2, 6230 Postojna, Slovenia*

Since 2025, the Karst Research Institute ZRC SAZU has acted as a server and data provider for the EPOS ERIC data portal (https://www.ics-c.epos-eu.org/), representing an important milestone in the integration of Slovenian karst-related geoscientific infrastructure into the European research area. In the same year, ZRC SAZU also became an official member of the International Federation of Digital Seismograph Networks (FDSN; https://fdsn.org/networks/detail/S5/), further enhancing the international integration, interoperability, and accessibility of seismic and environmental data from the Slovenian karst.
Central to this development is the Slovenian Karst Near Fault Observatory (SLO KARST NFO; https://slo-karst-nfo.si/), established in 2020–2021 by the Karst Research Institute ZRC SAZU within the RI-SI-EPOS project (https://izrkp.zrc-sazu.si/sl/programi-in-projekti/ri-si-epos). The observatory consists of a seismic network of seven stations (in cooperation with the Slovenian Environment Agency (ARSO)) monitoring approximately 2.000 km² of the southwestern Slovenian karst. This area overlies an

extensive karst aquifer that constitutes a critical water resource for SW Slovenia and is also subjected to continuous hydrological, surface, and subsurface monitoring. Additional to seismic data, geochemical data (air T, CO_2, air pressure) are part of EPOS NFO FRIDGE data portal (https://fridge.ingv.it/, https://doi.org/10.5281/zenodo.15599149).
The primary objective of SLO KARST NFO is detection and analysis of seismic activity in the karst region, providing high-quality data for seismic and tectonic investigations in the NW Dinarides. These observations contribute to a better understanding of crustal deformational processes and structure. In the long term, the generated data and research outcomes will support improved earthquake hazard, and future development early earthquake warning in SW Slovenia and neighboring Croatia and Italy, thereby contributing to more effective hazard mitigation. Despite its recent establishment, the observatory is already integrated into major European projects EPOS ON and TRANSFORM2, confirming its scientific relevance and strategic role within the broader European geoscientific research infrastructure.

Keywords: *SLO KARST NFO, karst, earthquakes, EPOS ON, TRANSFORM2*
Ključne besede: *SLO KARST NFO, kras, potresi, EPOS ON, TRANSFORM2*

Modeling CO_2 concentration of a karstic soil from Dalmatia (Croatia) and implications for endokarst CO_2 dynamics

Modeliranje koncentracije CO_2 v kraški prsti Dalmacije (Hrvaška) in pomen za dinamiko CO_2 v endokrasu

Diego A. Nunes-Alvarado[1], Jimena Gómez-Encinas[1], Daniel Martín-Santos[1], Inés Bouzón-Saavedra[1], Kristina Krklec[1,2], David Domínguez-Villar[1]

[1] *Department of Geology, Faculty of Sciences, Universidad de Salamanca, Plaza de los Caídos s/n, 37008 Salamanca, Spain*
[2] *Department of Soil Science, Faculty of Agriculture, University of Zagreb, Svetošimunska 25, 10000 Zagreb, Croatia*

Soil CO_2 is a key component in the carbon cycle, since it includes complex processes that enable atmospheric CO_2 fixation to rocks. In addition, it is important to understand carbonate dissolution and precipitation processes. During a two-year period (March 2020 to February 2022), a Red Mediterranean Soil was monitored above Stara Jametina Cave in the region of Dalmatia (Croatia). Collected data includes soil CO_2 concentration, soil temperature, soil water content (SWC) that were measured at a depth of 20 cm with a daily resolution. Also, meteorological data and a hydrological model that quantifies SWC and recharge are available. Concentration of soil CO_2 has two clear periods of maxima values each year, recorded in spring and autumn. This is an uncommon seasonal variability, since most soil studies available in the literature show a single annual cycle. Monitoring data suggests a non-linear behavior of controls affecting soil CO_2. During periods without hydric stress, soil CO_2 is dominated by soil temperature, whereas during periods with soil water deficit, SWC dominates its variability. A model accounting for soil CO_2 concentration at a depth of 20 cm was conducted. The record was divided into continuous wet or dry periods every year, implementing for each period the respective equations calculated using multiple regression analysis that consider soil temperature and SWC as variables. The model explains 61% of soil CO_2 variability. Part of the unexplained variability is related to preferential flows. When the periods with preferential flows are discarded, the model explains 80% of the observed variability. This study improves the understanding of CO_2 dynamics in karst soils developed above caves such as Stara Jametina. This research opens the possibility to study the implications that certain soils with complex seasonal dynamics have in the hydrochemistry and CO_2 concentration in caves.

Keywords: *Monitoring, Terra Rossa, CO_2 cycle, soil water content, karst*
Ključne besede: *Spremljanje, jerovica, kroženje CO_2, vsebnost vode v prsti, kras*

Surface climatic processes as a key to interpreting carbon pathways in karst and caves: the example of Northern Velebit, Croatia

Površinski podnebni procesi kot ključ za razumevanje poti ogljika v krasu in jamah: primer Severnega Velebita (Hrvaška)

Dalibor Paar[1]

[1] *Faculty of Science, University of Zagreb, Department of Physics, Croatia*

When interpreting carbon pathways in karst and caves, it is essential to consider climatic processes at the surface, although their interpretation is often more complex than it may initially appear. Monitoring climate change is currently one of the central focuses of contemporary science. An increasingly dense network of meteorological stations equipped with advanced instruments, together with satellite and other data sources, provides a solid basis for understanding surface climate. However, using the example of Northern Velebit, we demonstrate that such data are often insufficient for an adequate interpretation of processes in karst and caves, and we propose ways to complement them.

Northern Velebit is a highly dynamic mountain karst system in which extreme climatic events are shaped by the complex interaction of relief, climate, and atmospheric dynamics. Steep slopes, deep dolines, and ice caves, together with Velebit's position at the boundary between continental and Mediterranean climates and the strong influence of the bora as the dominant dry and cold wind, create pronounced local variability in atmospheric conditions. As a result, local extremes frequently occur, including strong winds, intense precipitation, and heat waves.

Such localized mountain processes are poorly captured by standard meteorological measurements because of their coarse spatial resolution. The complex interaction between topographically controlled atmospheric processes and subterranean systems therefore highlights the need to establish dense local microclimatic monitoring networks integrated with cave monitoring systems. In this presentation, we will present examples of local disturbances, analyze their effects on surface and subsurface processes, and provide guidelines for further, broader research. Such networks are crucial for recording fine spatial and temporal variations, improving understanding of the links between surface and subsurface processes, and enhancing the prediction of extreme events in sensitive mountain karst systems under climate change conditions.

Keywords: *Karst, caves, microclimate, climate extremes, Northern Velebit*

Ključne besede: *Kras, jame, mikroklima, podnebni ekstremi, Severni Velebit*

Dynamic patterns and resilience of cave air CO_2 under tourism interferences in the Lushan National Geopark, north China (npj Heritage Science | (2026)14:31)

Dinamični vzorci in odpornost jamskega CO_2 v zraku pod vplivom turističnih motenj v nacionalnem geoparku Lushan (severna Kitajska) (npj Heritage Science | (2026)14:31)

Shengxin Peng[1,*], Wen Liu[2,3,*], Tao Zhang[1], Junbing Pu[1], Zhiqiang Zhao[2], Haoran Liu[2], YanhaoZhai[2], Nataša Ravbar[4], Alena Gessert[5], Eko Haryono[6]

[1] *Karst research team, Chongqing Key Laboratory of Carbon cycle and Carbon regulation of Mountain Ecosystem, School of Geography and Tourism, Chongqing Normal University, Chongqing, China*

[2] *Shandong Provincial Geo-mineral Engineering Exploration Institute, 801 Institute of Hydrogeology and Engineering Geology, Shandong Provincial Bureau of Geology & Mineral Resources, Ji,nan, China*

[3] *Institute of Groundwater Management, Dresden Universities of Technology, Dresden, Germany*

[4] *Karst Research Institute ZRC SAZU, Titov trg 2, 6230 Postojna, Slovenia*

[5] *Institute of Geography, Faculty of Science, P. J. Šafarik University, Košice, Slovakia*

[6] *Karst Research Group, Faculty of Geography, Universitas Gadjah Mada, Yogyakarta, Indonesia*

** These authors contributed equally: Shengxin Peng, Wen Liu*

Cave-air CO_2, one of the key indicators of cave ecosystem stability and human disturbance, plays a significant role in regional carbon cycles but has long been overlooked. Existing studies have primarily focused on cave resource development and restoration, resulting in an insufficient understanding of tourism-induced CO_2 dynamics. This study conducted high-resolution monitoring in Jiutian Cave (northern China) for the first time and integrated tourist data. The results showed that the air CO_2 concentration in Jiutian Cave was lower during summer–autumn and winter–spring, with soil CO_2 identified as the primary carbon source. However, tourism activities disrupted the synergistic relationship between soil CO_2 and cave-air CO_2, causing pulsed increases in cave-air CO_2 concentration. From the perspective of cave resilience, factors such asthe duration of tourist visits, the structural characteristics of different internal cave regions, and ventilation status all infiuence the recovery rate of cave-air CO_2 concentration.

Keywords: *Cave air CO_2, dynamic patterns, resilience, karst carbon cycle, Jiutian Cave*
Ključne besede: *Jamski zrak, CO_2, dinamični vzorci, odpornost, kroženje ogljika v krasu, jama Jiutian*

Modelling and observation of CO_2 and temperature in an intermittently-visited showcave
Modeliranje in opazovanje CO_2 in temperature v turistični jami z občasnim obiskom

Matija Perne[1,2], Boštjan Grašič[3], Marija Zlata Božnar[3], Franci Gabrovšek[4,5]

[1] *Faculty of Mathematics and Physics, University of Ljubljana, Jadranska ulica 19, 1000 Ljubljana, Slovenia*
[2] *Jožef Stefan Institute, Jamova cesta 39, 1000 Ljubljana, Slovenia*
[3] *MEIS d.o.o., Mali Vrh pri Šmarju 78, 1293 Šmarje–Sap, Slovenia*
[4] *Karst Research Institute ZRC SAZU, Titov trg 2, 6230 Postojna, Slovenia*
[5] *Faculty of Mathematics and Physics, University of Ljubljana, Jadranska ulica 19, 1000 Ljubljana, Slovenia*

The study uses model simulations to interpret field measurements. CO_2 and heat transport along a cave passage are simulated using an idealised model. It assumes a passage of a uniform cross-section with constant air velocity. It takes into account heat conduction through the boundary layer and inside the surrounding rock while neglecting dispersion along the passage and treating CO_2 as a conservative tracer. A CO_2 and heat source, which can be switched on and off, extends over part of the passage. CO_2 concentration and temperature time series downwind from the source are calculated. The obtained results inspire the analysis of almost 3 years of time-series measurements from Lepe Jame, Postojna Cave, Slovenia. The model partly explains the observations, while discrepancies between the data and predictions are further investigated. These discrepancies provide insight into processes governing the cave atmosphere.

Keywords: *Showcave, modelling, measurement, time series, carbon dioxide, heat*
Ključne besede: *Turistična jama, modeliranje, meritve, časovne vrste, ogljikov dioksid, toplota*

Climate Signals and Historical Ice Exploitation in a High-Altitude Mountain Karst: Crna ledenica Ice Cave (Croatia)

Podnebni signali in zgodovinsko izkoriščanje ledu v visokogorskem krasu: Ledena jama Crna ledenica (Hrvaška)

Aurel Persoiu[1,2,3], Nenad Buzjak[1,4], Silvia Bekavac[5], Željko Miletić[6], Christos Pennos[1,3]

[1] *Emil Racoviţă Institute of Speleology, Cluj-Napoca, Romania*
[2] *Ștefan cel Mare University, Suceava, Romania*
[3] *School of Geology, Department of Physical Geography, Aristotle University of Thessaloniki, Thessaloniki, Greece*
[4] *Department of Geography, Faculty of Science, University of Zagreb, Zagreb, Croatia*
[5] *Department of History of Art, Univeristy of Zadar, Zadar, Croatia*
[6] *Department of Archaeology, University of Zadar, Zadar, Croatia*

Crna ledenica Ice Cave is situated on the northern slope of the highest ridge of Biokovo Mountain (1762 m a.s.l.) in southern Croatia. This high-mountain karst area is characterized by numerous large dolines and deep shafts, many of which host perennial snow and ice deposits.

Crna ledenica is a complex vertical cave system with four entrances located at around 1500 m a.s.l., connected by a vertical passage leading to a large chamber with a volume of ~20,000 m^3. The cave is developed in strongly karstified Cretaceous limestones. Following initial speleogenetic phases dominated by corrosion, subsequent evolution was strongly influenced by collapse processes and cryogenic weathering (cryofraction), which contributed (and still contributing) to the enlargement of the passages.
The cave hosts one of the southernmost perennial cave ice deposits in Europe, radiocarbon dated to be over 1000 years old. Historically, this ice represented an important resource for local populations inhabiting the Biokovo plateau since at least the Bronze Age. In the absence of permanent surface water, communities relied on a combination of temporary doline ponds and harvested snow and cave ice for water supply and food preservation. Ice extraction from Crna ledenica and similar shafts was an established practice until the advent of modern refrigeration technologies in the 20th century.
This study examines the relationship between past human activities, water resource use, and environmental variability on the Biokovo plateau. Stable isotope analysis of the radiocarbon-dated cave ice is used to reconstruct winter air temperature variability, snow accumulation rates, and changes in moisture sources feeding precipitation in the area. In addition, recent microclimate monitoring data provide a contemporary process-based framework that supports the interpretation of the palaeoclimatic signals, further enhancing our understanding of the long-term interactions between climate dynamics and human adaptation in high-altitude karst environments.

Keywords: *Crna Ledenica, ice cave, Holocene, climate, ice harvesting*
Ključne besede: *ledena jama Crna ledenica, holocen, podnebje, nabiranje ledu*

Speleogens formed by locally produced sulphuric and carbonic acid in large epigene caves of the NCA (Austria)

Nastanek jamskih skalnih oblik pod vplivom lokalno tvorjene žveplove in ogljikove kisline v velikih epigenih jamah Severnih Apneniških Alp (Avstrija)

Lukas Plan[1], Marjan Temovski[2,3], Michael Nagl[1], Jo De Waele[4]

[1] *Karst and Cave Group, Natural History Museum, Burgring 7, 1010 Vienna, Austria*
[2] *Isotope Climatology and Environmental Research Group, HUN-REN Institute for Nuclear Research (ATOMKI), Bem tér 18/c, 4026 Debrecen, Hungary*
[3] *Department of Mineralogy and Geology, University of Debrecen, Egyetem tér 1, 4032 Debrecen, Hungary*
[4] *Department of Biological, Geological and Environmental Sciences, Via Zamboni 67, 40126 Bologna, Italy*

A set of peculiar cave wall and roof morphologies are reported from several large epigenic cave systems in the Northern Calcareous Alps (NCA) in Austria. These shapes include variously sized and shaped pockets and holes, decametric niches with rims or teeth, some with flat ceilings, larger (metric) portions of flat solutional ceilings, and vertical conical ceiling holes. Although some of these have occasionally been reported from other karst areas, their widespread occurrence in the NCA karst systems and the fact they often are found in association with each other is remarkable and worth investigating. Based on morphometric data including Structure from Motion (SfM) photogrammetry, petrographic, mineralogical, and geochemical (stable isotope) analyses of cave sediments and rocks, we present a model for the origin and the formation of most of these special features including condensation corrosion-enhanced oxidation of sulphide minerals deriving from interbeds of the km-thick limestone layers of the NCA, and successive corrosion of the limestone walls by the produced sulphuric and additional carbonic acid often below a thin sediment veneer. Other morphologies (e.g., vertical conical ceiling holes) appear to be related to localised condensation corrosion created by underground mixing clouds or other mechanisms. Many small-to-medium-sized morphologies found in many other epigenic karst systems might be explained by this combination of sulphuric acid production and condensation corrosion phenomena.

Keywords: *Speleogens, sulphuric acid speleogenesis, epigene caves, Northern Calcareous Alps*
Ključne besede: *Jamske skalne oblike, speleogeneza z žveplovo kislino, epigene jame, Severne apneniške Alpe*

Physics based modeling of speleogenesis in openKarst - preliminary results

Fizikalno zasnovano modeliranje speleogeneze v programu openKarst - preliminarni rezultati

Prune Roche[1], Philippe Renard[1], Julien Straubhaar[1], Jannes Kordilla[2], Franci Gabrovšek[3]

[1] *University of Neuchâtel, Neuchâtel, Switzerland*
[2] *Institute of Environmental Assessment and Water Research (IDAEA-CSIC), Barcelona, Spain*
[3] *Karst Research Institute ZRC SAZU, Titov trg 2, 6230 Postojna, Slovenia*

Predicting flow and water quality in karstic environments is a challenging task due to the complex structures and high heterogeneity of karstic reservoirs. Numerical tools to simulate flow and transport in these systems need to resolve dynamic free-surface and pressurized states including complex turbulent-laminar flow transitions. openKARST is a Python-based open source flow and transport simulator under transient conditions (Kordilla et al. 2026). The simulator solves the Darcy-Weisbach flow equations under consideration of suitable friction descriptors such as the Churchill equation. To represent karstic networks, we use a graph based numerical framework. Although real human accessible networks can be mapped, most often only the geology and main faults are known, without any detailed information about the conduit network topology and geometry.

Therefore, the general objective of the research presented in this poster is to create a tool allowing karstic networks to be created by simulating the speleogenetic processes. In a second step, we want to employ it to extract the statistical features of the simulated networks at a scale that is usually not accessible by caving exploration.
Here, we provide an overview of the main speleogenetic phenomena and modeling approaches that were proposed in the scientific literature so far. This includes a synthesis of the equations that govern speleogenesis through the dissolution of limestone in groundwater enriched with CO_2 (e.g., Buhmann and Dreybrodt 1985, Groves and Howard 1994). It also summarises the usual simplifications of equations and numerical models of dissolution that can be applied along a 1D fracture or pipe (e.g., Dreybrodt 1990, Liedl et al. 2003) or for 2D and 3D modeling (e.g. Kaufmann 2016, Wang et al. 2020).
We proceed to demonstrate how these equations can be implemented in combination with openKARST to establish a physics-based model for the large scale simulation of speleogenesis, as well as show the first tests comparing the resulting simulations with previously published studies.

Keywords: *Speleogenesis, calcium carbonate dissolution, dissolution kinetics, physics-based modeling, openKarst*
Ključne besede: *Speleogeneza, raztapljanje kalcijevega karbonata, kinetika raztapljanja, fizikalno zasnovano modeliranje, openKarst*

Towards a calibration of the infiltrability potential of the geological substratum on the Aix-Marseille Provence Metropole (SE, France)

Proti kalibraciji infiltracijskega potenciala geološke podlage na območju metropole Aix–Marseille–Provence (JV Francija)

Lilas Ruttyn[1], François Fournier[1], Philippe Léonide[1], Jean Borgomano[1], Bruno Arfib[1], Sophie Viseur[1], Laurent Goulet[2], Narimane Zaabar[2], Olivier Vignoulle[2]

[1] *Aix Marseille Univ., CNRS, IRD, INRAE, CEREGE, Aix-en-Provence, France*
[2] *Métropole Aix Marseille Provence - service Gestion des milieux aquatiques et prévention des inondations*

Aix Marseille Provence Metropolis (AMPM) faces flooding issues increasing rapidly as a consequence of global warming. Due to population growth and rapid urbanization, sealing of the substratum prevents water infiltration and limits groundwater recharge. Therefore, removing impermeable anthropogenic materials could enhance water penetration into soils and the unsaturated zone, raising questions about karst vulnerability.
The goal of this study is to develop a method to predict infiltration capacity of the geological substratum and to produce an infiltrability map of the Aix-Marseille Provence Metropolis. The study is based on: (1) local acquisition of hydraulic behaviour of geological units, (2) laboratory proxies of infiltration capacity measurements, and (3) watershed water mass balances.
The geological substratum of AMPM consists of heterogeneous sedimentary formations including lacustrine and marine limestones or dolomites affected by karstification, as well as sandstones that undergone polyphased tectonic events. To address this large-scale heterogeneous system, a naturalistic rock classification approach is used. “Hydraulic Types” (HT) are defined as follows: HT-1 represents impermeable rocks or soils where infiltration is absent; HT-2 represents thin soils with variable porosity and permeability; HT-3 describes rocks with low to high matrix porosity influenced by clay content and variable permeability; HT-4 corresponds to fractured and/or karstified rocks with permeability controlled by fracture or cavity density, with variable porosity.
Using geolocated data points, a map is produced in QGIS to upscale hydraulic types over a regional grid. Calibration of the method allows quantification and definition of thresholds within the Hydraulic Types classification.

In this context, we will discuss the influence of karst network distribution on flood-risk management at the metropolitan scale.

Keywords: *Infiltration, runoff, GIS mapping, geological substratum, karst, quantification, petrophysical properties, absorption coefficient, heterogeneity*
Ključne besede: *Infiltracija, odtok, GIS kartiranje, geološka podlaga, kras, kvantifikacija, petrofizikalne lastnosti, absorpcijski koeficient, heterogenost*

Denudation processes in isolated karst: a case study of the Rovte region in Central Slovenia
Denudacijski procesi na osamelem krasu: študija primera na območju Rovt v osrednji Sloveniji

Kewin Rzadkowski[1], Andrzej Tyc[1]

[1] *Faculty of Natural Sciences, University of Silesia in Katowice, Poland*

This study presents the dynamics and intensity of denudation processes in the lithologically diverse catchments of the Rovte region in Central Slovenia. This area, representing a pre-alpine isolated karst, is characterized by highly diverse and varied conditions over short distances, with belts and patches of various carbonate rocks (dolomites, limestones, marly limestones and marls) interbedded or laterally contacting clastic and siliciclastic rock formations. The main objective of the study was to identify the structural conditions that control denudation rate.
The research applied two independent, complementary methodological approaches. The first was the assessment of contemporary chemical denudation based on hydrochemical analyses and calculations of ionic runoff in surface streams and karst springs. The second approach involved determining the long-term rate of terrain lowering through geomorphometric modelling using the Minimum Eroded Volume (MEV) index, based on a high-resolution digital elevation model (1×1 m) obtained from ARSO Geoportal.
The results showed that the intensity of contemporary chemical denudation is strictly dependent on the volume of circulating water (discharge) and the functioning of deep groundwater drainage zones, and does not show a simple correlation with the surface proportion of carbonates. In contrast, long-term denudation, quantified by the MEV index, is strongly structurally and tectonically controlled. The greatest rock material losses were recorded along main dislocation zones, which are used by the river network for intense incision into the massif as a response to its active tectonic uplift.
The integrated analysis proves the exceptional complexity of denudation processes in this fluviokarst system. Morphogenetic evolution results from spatial interactions between overlapping tectonic, hydrogeological, lithological, and geomorphological factors. Therefore, surface erosion alone does not fully account for the total denudation potential. As significant morphogenetic activity shifts underground into heterogeneous karst systems, fully understanding these degradation processes requires a comprehensive approach assessing both topographic changes and subsurface dynamics.
The research was funded by the National Science Centre of Poland (No. 2020/39/I/ST10/02357) and the Slovenian Research Agency (No. N1-0226) under OPUS-20 (LAP) programme.

Keywords: *Isolated karst, denudation rate, Minimum Eroded Volume index, ionic runoff, Central Slovenia*
Ključne besede: *Osameli kras, stopnja denudacije, Indeks minimalne erodirane prostornine, osrednja Slovenija*

Near-surface CO_2 dynamics in a karst vadose zone: insights from a tectonically stable setting

Dinamika CO_2 v kraški vadozni coni blizu površja: spoznanja iz tektonsko stabilnega okolja

Laura Sanna[1]

[1] *National Research Council of Italy CNR, Cagliari, Italy*

The natural geological accumulation of carbon dioxide (CO_2) in rocks is documented worldwide. In most settings, the CO_2 is produced at great depths in the lithospheric mantle and/or in volcanic and seismically active areas. However, CO_2 rich-fluids are also storage underground in evaporites and limestones. Understanding these natural reservoirs is critical for quantifying the global carbon pool and for supporting climate change mitigation efforts. Some of these CO_2 reservoirs are sealed by caprock and/or aquifers, while others leak gas to the surface through fracturing and/or secondary porosity. Among the latter, natural CO_2 accumulations in carbonate rocks provide a unique opportunity to study gas-water-rock interaction mechanisms, gas migration near the surface, and to quantify geosphere-atmosphere exchanges. The aim of this study was to investigate the behaviour of CO_2 in the karst vadose zone in a volcanically inactive and relatively stable tectonic setting. Temporal variations of CO_2 gas migration were measured in near-surface using standard micrometeorological techniques over a karst area in NW Sardinia (Italy). This island is considered one of the most geologically stable regions of the western Mediterranean, where the last volcanic activity occurred during the Plio-Pleistocene time. The results show that cave CO_2 concentration does not exhibit a daily cycle as observed at the surface; instead, in the underground atmosphere, peaks are observed, sometimes isolated, other times occurring as a continuous series of smaller peaks. The increase and decrease in gas concentration during these plumes are always sharp, while their duration is variable. The peaks are sometimes synchronized with the change in density between the air mass inside the cave and the external air, but more often they are negatively correlated with atmospheric pressure. Finally, monitoring near-surface CO_2 flux is shown to be a broadly tool for quantifying the role of karst in the net carbon budget.

Keywords: *Carbon dioxide, cave micrometeorology, barometric pressure pumping, density-driven circulation*

Ključne besede: *Ogljikov dioksid, jamska mikrometeorologija, barometrično tlačno črpanje, kroženje zraka, pogojeno z njegovo gostoto*

The karst vadose zone – infiltration dynamics and storage

Kraška vadozna cona – dinamika infiltracije in skladiščenja

Martin Sauter[1,2], Ulrich Maier[2], Peter Dietrich[3], Alireza Kavousi[1], Tobias Geyer[4], Irina Engelhardt[5]

[1] *LIAG-Institute for Applied Geophysics, Hannover, Germany*
[2] *University of Göttingen, Göttingen, Germany*
[3] *Helmholtz-Zentrum für Umweltforschung, Leipzig, Germany*
[4] *Landesamt für Geologie, Rohstoffe und Bergbau, Freiburg, Germany*
[5] *Technical University of Berlin, Hydrogeology Department, Berlin, Germany*

Field and modelling investigations have shown the karst vadose zone to act as an important compartment in the recharge infiltration process particularly in karst regions characterised by thick unsaturated zones. In semi-arid regions of the Eastern Mediterranean, very wet years have shown to have prolonged effects of elevated groundwater discharge as well as elevated groundwater levels, compared to long-term average hydraulic conditions.

The above prolonged storage effects can generally be attributed either to delayed groundwater discharge or the sustained infiltration processes in the matrix of the vadose zone.

The research focused on the analysis of the geohydrological processes in the field, i.e. the analysis of spring discharge and groundwater hydrograph records, both for humid-temperate as well as semi-arid conditions, the analysis of water tracers (Krypton and T/He; trace organics) as well as the coupled modelling of saturated / unsaturated flow, employing a double-continuum approach.
Our findings show that in less maturely karstified aquifer systems, the contribution of delayed seepage from the vadose zone can reach up to 40% of total spring discharge which is of particular importance in regions with prolonged drought periods, expected for semi-arid environments. The analysis of the tracer information allowed the discrimination of the source of the delayed discharge, in particular Krypton tracer analysis demonstrated the extended residence time of infiltrating water in the vadose zone.

Keywords: *Karst vadose zone, infiltration, modelling, drought*
Ključne besede: *Kraška vadozna cona, infiltracija, modeliranje, suša*

Carbon Footprint of the Loess–Karst Aquatic Continuum: Organic Matter Sources, Transformation, and Carbon Sink Effects

Ogljični odtis puhličasto-kraškega vodnega kontinuuma: viri organskih snovi, transformacija in učinki ponora ogljika

Mingyu Shao[1], Zaihua Liu[1]

[1] *Institute of Geochemistry, Chinese Academy of Sciences*

Surface waters distributed across the Chinese Loess Plateau and karst regions, including rivers, reservoirs, and lakes, are key interfaces linking carbonate weathering, aquatic primary production, and organic matter transformation. Based on recent studies in river–reservoir systems on the Loess Plateau, semi-arid aquatic continua, and karst surface waters, this presentation examines the “carbon footprint” of loess–karst waters from the perspective of coupled inorganic–organic carbon cycling. Existing results indicate that aquatic primary production in these systems is often constrained by inorganic carbon availability, while dissolved inorganic carbon (DIC) derived from carbonate weathering can stimulate autochthonous production through a CO_2/DIC fertilization effect. Hydrological conditions, especially residence time and connectivity, further regulate DOM composition, reactivity, and stability, thereby influencing its downstream transport and long-term fate. In addition, damming and hydrochemical heterogeneity can substantially alter the relative contributions of allochthonous versus autochthonous organic matter, the efficiency of the biological carbon pump, and the stability of aquatic carbon sinks. Overall, the carbon footprint of loess–karst aquatic systems is not merely a balance between carbon uptake by weathering and carbon release from inland waters, but also reflects the redistribution, transformation, and preservation of organic carbon along the aquatic continuum. These findings provide new insights into inland-water carbon cycling, stabilization of weathering-related carbon sinks, and the co-benefits of carbon sequestration and eutrophication mitigation.

Keywords: *Chinese Loess Plateau, karst, carbon footprint, dissolved organic matter, autochthonous organic carbon*
Ključne besede: *Kitajska Puhlična planota, kras, ogljični odtis, raztopljena organska snov, avtohtoni organski ogljik*

Both enhanced carbonate and silicate weathering strategies improve soil carbon sequestration via different pathways

Pospešeno karbonatno in silikatno preperevanje izboljšujeta sekvestracijo ogljika v prsti po različnih poteh

Liangxing Shi[1]

[1] *Institute of Geochemistry, Chinese Academy of Sciences*

Enhanced rock weathering (ERW) is a vital CO_2 removal strategy, yet its impact on terrestrial carbon sinks remains under-explored. Using a large-scale field platform in Southwest China, we evaluated the effects of applying limestone, dolostone (ECW), and basalt (ESW) powders on soil carbon sequestration through seasonal monitoring and advanced modeling (Bayesian, CDOM fluorescence, and Monte Carlo).Our results reveal distinct mechanisms for carbon enhancement:
ECW (Carbonates): Significantly increases soil inorganic carbon via biotic processes. Notably, it triggers a shift in soil organic carbon (SOC) sources from plant-dominated (~60–85%) to microbe-dominated (~85–95%). This microbial surge is driven by high Ca^{2+} release and is confirmed by increased biogenic CDOM components (C3, C5).
ESW (Silicates): Enhances sequestration primarily through direct nutrient inputs and the addition of stable, humus-like carbon pools (C1, C2, C4). Overall, both methods amplify soil carbon sinks. Monte Carlo simulations suggest that integrating nutrient-rich ESW with ECW can boost SOC by over 42.6%. We propose that synergistic ECW-ESW applications offer a superior pathway for large-scale atmospheric CO_2 removal and soil carbon management.

Keywords: *CO_2 removal, enhanced rock weathering, enhanced carbonate weathering, soil carbon sequestration, nutrient fertilization*
Ključne besede: *odvzem CO_2, pospešeno preperevanje kamnin, pospešeno preperevanje karbonatov, sekvestracija ogljika v tleh, gnojenje s hranili*

Stone forests, developed from subsoil karren

Kamniti gozdovi, ki se razvijajo iz podtalnih škrapelj

Tadej Slabe[1], Martin Knez[1]

[1] *Karst Research Institute ZRC SAZU, Titov trg 2, 6230 Postojna, Slovenia*

Many karren, in which the development of the karst surface is clearly etched, first form as subsoil, below the sediment and soil. Due to the frequent, diverse, fast or gradual denudation of sediment and soil, we can trace the development of their morphology and rock relief. Their development is also influenced by the rock, its structure, stratification and fissuring. Development traces of the subsoil shaping and reshaping of the rock relief exposed to rain have also been analysed with laboratory tests on plaster.
We have highlighted three development models of the most characteristic and most often studied variants, and traced the reshaping of the most distinct rock features.
We have learned a great deal by examining the stone forests and subsoil karren, composed of diverse rocks, in Yunnan. Stone forests in Shilin are one of the most typical examples of the shaping of the karst surface. Due to the lengthy process of formation, their subsoil rock relief is very distinct. On the cracked rocks, the water percolates through the crevices, eventually shaping subsoil stone teeth and in the long run a subsoil stone forest. Of course, the transitions differ, which influences their shape and rock relief.

We must know how individual subsoil rock features and the rock relief as a whole are reshaped in order to better understand the development of karren.
Broad knowledge of such examples in different karst areas of the world and building on this with laboratory modelling on plaster enable us to propose development models.

Keywords: *Stone forests, rock relief, rock features, lithology*
Ključne besede: *Kamniti gozdovi, skalni relief, skalne oblike, litologija*

Who Needs to Know about Karst? From Awareness to Policy and Protection
Kdo mora poznati kras? Od ozaveščenosti do politike in varstva

Limaris Soto[1], Ira D. Sasowsky[2]

[1] *University of Nova Gorica, Slovenia*
[2] *Department of Geosciences, The University of Akron, Akron, OH 44325-4101, USA*

Informed citizens are generally better able to make good decisions about environmental issues, both in their personal lives and in how they engage with society and politics. A basic challenge to this is that many people have a limited scientific background, or only a rough understanding of how Earth systems work. This is especially true in karst areas, where complex and interconnected surface and subsurface drainage systems are difficult to visualize and where contaminants can be rapidly transmitted through groundwater. Improving understanding of caves and karst systems is therefore essential for supporting responsible land-use practices, groundwater protection, and evidence-based policy and regulation.
In the USA, a broad network of federal agencies, non-governmental organizations (NGOs), academic institutions, and volunteer caving groups contribute to public awareness and learning related to caves and karst landscapes. Several NGOs offer hands-on education, technical training, and STEM programs to increase participation, while academic institutions add further depth through instruction and research that build long-term capacity in karst science. Volunteer cavers also provide critical contributions through mapping, monitoring, and restoration activities that directly support management and research.
As pressures on karst landscapes increase, driven by groundwater demand, land-use change, wildfire impacts, and ecosystem pressures, the need for broader understanding becomes more urgent. Karst underlies approximately one fifth of the USA and supplies an estimated 40 percent of its groundwater, yet its vulnerability to contamination and geohazards remains poorly appreciated. Improving public scientific literacy related to karst processes can support better personal and political decisions, increase public support for protective regulations, and strengthen long-term stewardship. Greater awareness among residents, landowners, planners, and policymakers can also improve compliance with regulations and encourage proactive protection of vulnerable karst resources before impacts occur. Coordinating USA initiatives with UNESCO's International Day of Caves and Karst provides an opportunity to connect these approaches with similar initiatives worldwide.

Keywords: *Karst, caves, public awareness, scientific literacy, stewardship, science communication*
Ključne besede: *Kras, jame, ozaveščenost javnosti, znanstvena pismenost, skrbništvo, komuniciranje znanosti*

QUEECAD - Quaternary Environmental Evolution archived in Croatian Cave Deposits

QUEECAD – Kvartarni okoljski razvoj, zabeležen v jamskih sedimentih na Hrvaškem

Maša Surić[1], Petra Bajo[2], Neven Bočić[3], Tomislav Kurečić[2], Robert Lončarić[1], Lara Wacha[2], Nadja Zupan Hajna[4]

[1] *Department of Geography, University of Zadar, F. Tuđmana 24 i, Zadar, Croatia*
[2] *Croatian Geological Survey, Department of Geology, M. Sachsa 2, Zagreb, Croatia*
[3] *University of Zagreb, Faculty of Science, Department of Geography, Trg Marka Marulića 19/II, Zagreb, Croatia*
[4] *Karst Research Institute ZRC SAZU, Titov trg 2, 6230 Postojna, Slovenia*

Reconstruction of Quaternary environment evolution is the principal source of information upon which the anticipation of future changes relies. Cave deposits, both clastic and speleothems, are well established as reliable archives of hydroclimate- and tectonically related Quaternary palaeoenvironmental changes. Here, we present a scientific project Quaternary Environmental Evolution archived in Croatian Cave Deposits – QUEECAD (IP-2025-02-6560) funded by the Croatian Science Foundation (2025-2028) which is grounded on the complementarities of speleothems and clastic (allogenic and authigenic) cave sediments, given that their geneses are related to completely different dynamic conditions, i.e., speleogenetic phases. The main premise is that in the same cave, environmental changes associated with dynamic phases (e.g., tectonics), accompanied by geomorphological processes such as intensified weathering, base-level incision, changes in water flow, and sediment accumulation are recorded in clastic (allogeneic and authigenic) cave sediments. This record is further controlled by the hydrological position of the cave, i.e. whether the depositional environment is in the vadose, epiphreatic or phreatic zone. In contrast, calmer phases that favour speleothem deposition more precisely record regional hydroclimatic conditions at the surface and related local vegetation changes. Since the eastern Adriatic realm, exposed to both North Atlantic and Mediterranean air masses, has experienced significant environmental changes during the glacial cycles along with changes in dominant hydroclimatic and tectonic influences, our research focuses on the transect from the eastern Adriatic coast, via the Dinaric mountain range to the continental Lika region. Based on previous research, we chose three caves distinguished by their geographical locations (Modrič Cave on the Adriatic coast, Cerovačke Caves in Velebit Mt. and Baraćeve Caves in the northernmost part of Lika) and by positions (different altitudes, distance from the sea and geological setting). The geochronological framework will be determined by U-Th and OSL / IRSL dating and by palaeomagnetism, and based on a multi-proxy approach, the results of geochemical, mineralogical and sedimentological analyses of speleothem and clastic sediments samples will be comprehended. Monitoring of hydroclimate variability and the cave-surface interactions will support a robust interpretation of the palaeoclimate and speleogenesis.

Keywords: *Environmental changes, caves, sediments, speleothems, Quaternary, Croatia*
Ključne besede: *Okoljske spremembe, jame, sedimenti, siga, kvartar, Hrvaška*

Challenges and methods for sampling gas-rich thermal springs discharging into water bodies - case studies from Slovenia and Hungary

Izzivi in metode vzorčenja termalnih izvirov z visoko vsebnostjo plinov, ki se izlivajo v vodna telesa – študije primerov iz Slovenije in Madžarske

Dénes Szieberth[1], Viktória Bernadett Balázs[1], Ádám Teil[1], Kaja Šušmelj[2], Petra Žvab Rožič[2]

[1] *Budapest University of Technology and Economics, Faculty of Chemical Technology and Biotechnology; H-1111 Budapest, Műegyetem rkp. 3, Hungary*
[2] *University of Ljubljana, Faculty of Natural Sciences and Engineering, Department of Geology, Aškerčeva 12, 1000 Ljubljana, Slovenia*

Thermal springs often carry significant amounts of gases (e.g., CO_2, H_2S) in both dissolved and free phases. The composition and concentration of these gases, together with other geochemical parameters (including carbon species), provide valuable information on the origin of the water, as well as the conditions and characteristic geochemical processes along its underground pathway.
In some settings, gas-rich waters discharge directly into a different surrounding water body. For example, in Izola (Slovenia), sulfidic thermal groundwater discharges into the sea through fine-grained sediments, either as focused submarine springs or as diffuse seepage. Another example is the Fényes Springs at Tata (Hungary), where gas-rich thermal groundwater discharges through sandy sediments into a freshwater lake.
Sampling such systems presents significant methodological challenges. The immediate mixing of spring water with the surrounding water requires careful selection of sampling locations. In cases of highly diffuse discharge, direct sampling may be impossible, therefore the development of new sampling approaches and equipment is necessary. Additional complications can be caused by phase separation (bubble formation) in the spring: the inhomogeneity of the flow makes representative sampling challenging. Due to the volatility and reactivity of the dissolved gases, careful handling and special sample conservation methods are required.
This contribution presents field experiences and best practices for investigating gas-rich thermal groundwater discharges into aquatic environments based on case studies from Slovenia and Hungary.

Keywords: *Thermal spring, dissolved gas, underwater sampling, submarine discharge*
Ključne besede: *Termalni izvir, raztopljeni plin, podvodno vzorčenje, podmorski iztok*

Coupled ventilation and hydrogeological controls on seasonal radon dynamics in Vrelo Cave (Croatia)

Vpliv prezračevanja in hidrogeoloških dejavnikov na sezonsko dinamiko radona v jami Vrelo (Hrvaška)

Filip Šarc[1], Nina Trinajstić[2], Gordana Žauhar[3], Franci Gabrovšek[1], Uroš Novak[1], Marija Čargonja[3], Nenad Buzjak[4], Jagoda Ravlić Gulan[5], Ivana Rogić[6]

[1] *Inštitut za raziskovanje krasa, ZRC SAZU, Titov trg 2, Postojna, Slovenija, filip.sarc@zrc-sazu.si*
[2] *Croatian Geological Survey, Sachsova 2, Zagreb, Croatia*
[3] *Faculty of Physics, University of Rijeka, Radmile Matejčić 2, 51000 Rijeka, Croatia*
[4] *Department of Geography, Faculty of Science, University of Zagreb, Marulićev trg 19/II, 10000 Zagreb, Croatia*
[5] *Faculty of Medicine, University of Rijeka, Braće Branchetta 20/1, 51000 Rijeka, Croatia*
[6] *Public Institution "Priroda", Grivica 4, 51000 Rijeka, Croatia*

Vrelo Cave, located in Gorski Kotar (Croatia), is a show cave developed in Mesozoic carbonate rocks near their contact with Permo-Triassic clastic rocks. The cave represents an active karst system with a permanent siphon that occasionally overflows during high groundwater stages, causing partial flooding of the cave passages. To investigate interactions between cave microclimate, groundwater dynamics and radon behaviour, a multidisciplinary monitoring program was established. The monitoring system currently includes continuous measurements of radon concentration, air temperature in the cave and outside, CO_2 concentration, air flow and hydrological parameters in the siphon. In parallel, hydrochemical sampling of selected waters (sump, cave spring, dripping water and nearby karst springs) has been initiated. Preliminary results indicate pronounced seasonal variability of radon concentrations. Higher values were recorded during summer and early autumn, when reduced thermal gradients between the cave and outside air likely suppress ventilation and enable radon accumulation. In contrast, winter values were considerably lower, reflecting enhanced air exchange. The radon signal also shows a delayed response to external temperature changes, indicating thermal and aerodynamic inertia of the cave system. Short-term radon peaks not directly related to temperature suggest an additional influence of hydrogeological events, particularly fluctuations of the active siphon, temporary flooding, and possible radon degassing from groundwater. Hydrochemical measurements show

generally similar carbonate signatures in waters hydraulically connected to the cave system, while nearby external springs display slightly different ionic compositions, likely reflecting local lithological and flow-path controls. These first results demonstrate that radon variability in Vrelo Cave is governed by coupled ventilation and groundwater processes. Continued monitoring will allow more detailed quantification of relationships between meteorological forcing, groundwater dynamics, cave microclimate and radon behaviour, contributing both to karst process understanding and sustainable management of a show cave environment.

Keywords: *radon dynamics, cave microclimate, groundwater dynamics, karst system, ventilation*
Ključne besede: *dinamika radona, jamska mikroklima, dinamika podzemne vode, kraški sistem, prezračevanje*

Spatial variation in carbon dioxide concentrations between the entrance and deeper parts of Postojna Cave, Slovenia

Prostorske razlike v koncentracijah ogljikovega dioksida med vhodom in globljimi deli Postojnske jame, Slovenija

Stanka Šebela[1]

[1] *Karst Research Institute ZRC SAZU, Titov trg 2, 6230 Postojna, Slovenia*

In Slovenia's most visited show cave, Postojna Cave (940,000 visitors in 2025), carbon dioxide concentration monitoring in cave air is conducted at several locations. For the period from 23 October 2019 to 25 March 2026, hourly concentrations were compared between the cave entrance (Biospeleološka Postaja) and deeper cave sections (Lepe Jame 2 and 3 sites). All three sites are strongly affected by the presence of visitors. Seasonal and hourly variations in carbon dioxide concentrations were observed at all three sites and compared with cave air temperatures, outside temperatures, and precipitation. Monitoring during the COVID-19 closure period in 2020–2021 provided additional information on the natural seasonal behaviour of carbon dioxide concentrations in the show cave without human presence. Based on multi-year hourly datasets (2019–2026) of carbon dioxide concentrations, it was possible to distinguish between natural and human-induced levels of carbon dioxide during summer and winter cave ventilation regimes. We were able to provide sustainable guidelines for cave management regarding the impact of visitors on carbon dioxide concentrations. This study is part of the EU projects EPOS ON (101131592) and TRANSFORM2 (101188365), as well as the ARIS infrastructure programme (I0-E017).

Keywords: *Carbon dioxide, show cave, cave management, Slovenia*
Ključne besede: *Ogljikov dioksid, turistična jama, upravljanje jam, Slovenija*

Reconstructing hydrological changes in contact karst using tectonic uplift phases (Postojna Contact Karst, W Slovenia)

Rekonstrukcija hidroloških sprememb v kontaktnem krasu z uporabo faz tektonskega dviga (kontaktni kras Postojnske kotline, Z Slovenija)

Astrid Švara[1], Nadja Zupan Hajna[1,2]

[1] *Karst Research Institute ZRC SAZU, Titov trg 2, 6230 Postojna, Slovenia*
[2] *UNESCO Chair on Karst Education, University of Nova Gorica, Glavni trg 8, SI-5271 Vipava, Slovenia*

The Classical Karst of Slovenia represents a key tectonically active area for understanding karst evolution. Hydrological changes and cave formation in the Postojna Karst were primarily attributed to

climatic fluctuations. However, recent multidisciplinary research demonstrates that karst development is controlled by a combination of factors, among which tectonic activity may play a dominant role. This study reconstructs hydrological changes in the contact karst of the Postojna Basin (W Slovenia) by linking them to tectonic uplift phases recorded in cave systems. The region is influenced by the compressional tectonic regime of the External Dinarides and the counter-clockwise rotation of the Adria Microplate since ~6 Ma. These processes have fragmented karst blocks and altered drainage patterns, as evidenced by studies of cave allogenic sediments. Contact karst at the boundary between carbonate and non-carbonate rocks is characterized by ponor systems, blind valleys, and extensive levelled cave systems formed under varying hydrological conditions. Two main sedimentary records are preserved in caves: allogenic clastic sediments deposited under (epi)phreatic conditions and speleothems formed in vadose environments. Their succession provides a chronological framework for interpreting hydrological shifts. Dating techniques, including paleomagnetism, U-Th methods, and cosmogenic nuclides, enable the timing of transitions between these depositional environments. Results indicate that major hydrological changes in the Postojna Basin, particularly the redirection of the Nanoščica River, occurred between 3.59 Ma and 1.77 Ma and were driven by tectonic uplift rather than climate. Periods of horizontal cave development with allogenic sedimentation correspond to tectonically stable phases, whereas vertical percolation and speleothem formation reflect uplift phases. By integrating geomorphological mapping, cave analysis, sedimentology, and geochronology, this approach establishes tectonic uplift as the primary driver of hydrological evolution in tectonically active areas of contact karst, such as the Dinaric Mountains. The methodology provides a robust framework applicable to similar karst systems worldwide.

Keywords: *Neotectonics, contact karst, Loza Cave System, Postojna Cave System, paleo-Nanoščica, electrical resistivity tomography*
Ključne besede: *Neotektonika, kontaktni kras, jamski sistem Loza, Postojnski jamski sistem, paleo-Nanoščica, električna upornostna tomografija*

Cave monitoring at Drenska Peštera (N. Macedonia): Insight from carbon isotopes
Spremljanje jamskega okolja v jami Drenska Peštera (Severna Makedonija): Vpogled iz izotopov ogljika

Marjan Temovski[1,2], Kata Molnár[1], István Major[1], Tamás Varga[1], Mihaly Molnár[1], István Futó[1], László Palcsu[1]

[1] *HUN-REN Institute for Nuclear Research (ATOMKI), Bem tér 18/c, H-4026 Debrecen, Hungary*
[2] *Department of Mineralogy and Geology, University of Debrecen, Egyetem tér 1, H-4032 Debrecen, Hungary*

Cave monitoring has been conducted between October 2018 and March 2022 (3.5 years) at Drenska Peštera, an old fossil cave located at 1150 m a.s.l., with relatively simple morphology and total depth of ~40 m. The monitoring, carried out at three locations inside the cave, and one location outside, consisted of continuous monitoring of cave air temperatures and humidity, that was expanded for two years with monthly monitoring of hydrology, chemical (T, pH, EC, major ions) and geochemical properties of cave dripwater (δ^2H, $\delta^{18}O$, ^3H, $\delta^{13}C_{DIC}$, $^{14}C_{DIC}$). Stable carbon and oxygen isotopes were also measured on farmed calcite, and on several occasions CO_2 and ^{14}C content of cave air was also measured. We will present the results of the monitoring with special emphasis on the carbon isotopes, their sources and pathways from the surface to the speleothems.

Keywords: *Dripwater, cave air, carbon isotopes*
Ključne besede: *kapnica, jamski zrak, izotopi ogljika*

Karst bauxites as archives of Paleogene volcanism: Evidence from the Dinarides

Kraški boksiti kot arhivi paleogenskega vulkanizma: dokazi iz Dinaridov

Nina Trinajstić[1], Vlatko Brčić[1], Sanja Šuica[2], István Dunkl[3], Duje Kukoč[1], Mihovil Brlek[1], Hilmar Von Eynatten[3]

[1] *Croatian Geological Survey, Sachsova 2, Zagreb, Croatia*
[2] *Croatian Natural History Museum, Demetrova 1, Zagreb, Croatia*
[3] *Department of Sedimentology and Environmental Geology, Georg-August-University Göttingen, Goldschmidtstraße 3, Göttingen, Germany*

Paleogene karst bauxites of the Dinarides have been widely studied in terms of weathering, reworking, and provenance; however, their potential to record regional volcanoclastic input remains insufficiently explored.

This study integrates data from bauxite occurrences along a north–south transect of the Dinarides, including the Promina area, the Gljev deposit near Sinj, and the Imotski region. Despite their spatial separation, these deposits exhibit consistent geochemical and mineralogical characteristics, including enrichment in high field strength elements (HFSE; e.g., Zr, Nb, Hf), LREE-enriched patterns with negative Ce and Eu anomalies, indicating a dominant felsic continental source, accompanied by elevated Cr contents suggesting a subordinate mafic contribution. The dominance of euhedral zircon grains further supports a primary volcanogenic origin.

Detrital zircon U–Pb ages from Promina and Gljev reveal pronounced Paleogene populations with peaks at ~45–32 Ma, indicating temporally constrained volcanic input. The absence of nearby volcanic centers suggests that this signal reflects distal ash dispersal rather than local sources.

The formation of bauxites in karst depressions characterized by low detrital input enabled the preservation of this volcanogenic signal, effectively turning karst systems into sensitive archives of regional eruptive activity.

These results demonstrate that karst bauxites can provide indirect evidence of Paleogene volcanism in the Alpine–Balkan region, offering new insights into the geodynamic evolution of the Dinarides beyond the scope of traditional geomorphological approaches.

This research was funded by the GEACAP project (Global events in the Adriatic Carbonate Platform), supported by the Ministry of Science and Education of the Republic of Croatia and the National Recovery and Resilience Plan 2021–2026 (NextGenerationEU).

Keywords: *Karst bauxite, Paleogene, volcanoclastic input, detrital zircon U–Pb*
Ključne besede: *Kraški boksiti, paleogen, vulkanoklastični vnos, U-Pb datiranje detritnega cirkona*

Carbonate weathering turns karst waters into carbon sinks via a biological carbon pump

Preperevanje karbonatov spreminja kraške vode v ponore ogljika prek biološke črpalke ogljika

Xu Wang[1,2], Zaihua Liu[1,*], Haibo He[1,*], Sibo Zeng[1], Yongqiang Han[1]

[1] *Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, China*
[2] *University of Chinese Academy of Sciences, Beijing, China*

Carbonate weathering is typically treated as an inorganic driver of CO_2 supersaturation and evasion from inland waters. Yet the characteristically low CO_2 emissions of karst lakes suggest that weathering products can also be routed into biological pathways. Here we propose that weathering-derived dissolved inorganic carbon (DIC) sustains a biological carbon pump that suppresses CO_2 degassing. Using a global compilation of 938 lakes and reservoirs, we show that karst aquatic systems emit less than half the CO_2 of non-karst counterparts (median 20.9 versus 53.8 g C m^{-2} yr^{-1}). Karst waters also contain a higher fraction of autochthonous organic matter (>80%) and exhibit elevated autochthonous

burial rates (38.4 g C m^{-2} yr^{-1}). Structural equation modeling indicates that catchment lithology increases pH and DIC, stimulates primary productivity via a "DIC fertilization effect", and is associated with reduced emissions (path coefficient = 0.387). Radiocarbon ($\Delta^{14}C$) and C/N evidences further show that primary producers directly assimilate weathering-derived inorganic carbon, while Ca-rich conditions enhance organic-matter preservation through a calcite ballasting effect. Together, these findings identify a coupled weathering–photosynthesis pathway that transfers geological carbon into buried organic carbon, advocating for its explicit representation in Earth system models.

Keywords: *Carbonate weathering, karst waters, karst lakes/reservoirs, carbon sinks, biological carbon pump, radiocarbon ($\Delta^{14}C$) and C/N*
Ključne besede: *Preperevanje karbonatov, kraške vode, kraška jezera/zbiralniki, ponori ogljika, biološka črpalka ogljika, radioaktivni ogljik ($\Delta^{14}C$) in C/N*

A greening Earth has increased the trend of karst-related carbon sink under a warming climate

Ozelenitev Zemlje je v razmerah segrevanja podnebja okrepila trend kraškega ponora ogljika

Sibo Zeng[1], Zaihua Liu[2,3], Yongjun Jiang[1], Nico Goldscheider[4], Yan Yang[1], Min Zhao[2], Hailong Sun[2], Haibo He[2], Mingyu Shao[2], Liangxing Shi[2]

[1] *Chongqing Key Laboratory of Karst Environment & School of Geographical Sciences, Southwest University, Chongqing, China*
[2] *State Key Laboratory of Environmental Geochemistry (SKLEG), Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, China*
[3] *CAS Center for Excellence in Quaternary Science and Global Change, Xi'an, China*
[4] *Institute of Applied Geosciences, Division of Hydrogeology, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany*

The response of karstification (carbonate weathering) and its related carbon sink for atmospheric CO_2 ($WS_{atm\text{-}CO2}$) to global vegetation greening are not well understood. After applying different biogeochemical models and a field experiment to investigate the influence of vegetation greening and warming on the variations of karsitification (carbonate weathering) and $WS_{atm\text{-}CO2}$ on regional and global scales, we show a significant positive relationship between global carbonate weathering intensity ($[HCO_3^-]$ as a proxy) and vegetation greenness. During 1982–2018, under a warming climate, $[HCO_3^-]$ and $WS_{atm\text{-}CO2}$ increase by 5.8% and 6.1%, respectively, due to vegetation greening, in the karst areas of Southwest China. Meanwhile, the $[HCO_3^-]$ in global karst areas increases by +2.4% during the same period. By contrast, the $[HCO_3^-]$ in global karst areas decreases by −1.3% without a vegetation function due to the warming. Moreover, we estimated that the karsitification (carbonate weathering) enhancements due to vegetation restoration at the global scale could reach 43.8%. Our results demonstrate that future vegetation restoration is important for the carbon capture by karst process.

Keywords: *Carbonate weathering, climate change, global vegetation green, carbon capture*
Ključne besede: *Preperevanje karbonatov, podnebne spremembe, svetovna ozelenitev, zajem ogljika*

From UNESCO proclamation to global implementation: The International Day of Caves and Karst

Od razglasitve pri UNESCO do globalne prepoznavnosti: Mednarodni dan jam in krasa

Nadja Zupan Hajna[1,2]

[1] *Karst Research Institute ZRC SAZU, Titov trg 2, 6230 Postojna, Slovenia*
[2] *UNESCO Chair on Karst Education, University of Nova Gorica, Glavni trg 8, 5271 Vipava, Slovenia*

The International Day of Caves and Karst (IDCK), to be celebrated annually on 13 September, was proclaimed by UNESCO in November 2025 at its General Conference in Samarkand. This international observance represents a major step towards recognising the global importance of caves and karst within the context of water resources, biodiversity, geoheritage, and sustainable development. The year 2026 marks its first global celebration. The initiative originated within the International Union of Speleology (UIS), headquartered in Postojna, Slovenia, and was formally submitted to UNESCO by the Republic of Slovenia. Its development was the result of a multi-year process combining scientific groundwork, international coordination, and broad global support from more than 150 organisations. At its final stage, the initiative was co-sponsored by 67 UNESCO Member States, reflecting strong international consensus. This contribution outlines the transition from scientific initiative to UNESCO recognition and implementation, highlighting the role of the international karst research community in establishing a permanent global platform for awareness and action. Beginning in 2026, the IDCK will serve as an annual framework to promote research, conservation, education, and public engagement related to karst environments. The first official celebration will take place in Slovenia between 10 and 13 September 2026, centred in Postojna. The programme includes an international scientific conference co-organised by the Karst Research Institute ZRC SAZU and UIS, thematic field excursions, and a formal ceremony in Postojna Cave, held under the honorary patronage of the President of the Republic of Slovenia and the patronage of UNESCO. The scientific conference will focus on the sustainable management of caves and karst, emphasising protection, research, and education as key pillars of sustainable development. Participants are warmly invited to engage with the initiative and its activities. Further information is available at: https://izrkp.zrc-sazu.si/en/dogodki/international-day-of-caves-and-karst-idck

Keywords: *Caves and karst, UNESCO recognition, global awareness, karst aquifers, sustainable management*
Ključne besede: *Jame in kras, priznanje UNESCO, globalna prepoznavnost, kraški vodonosniki, trajnostno upravljanje*