30th INTERNATIONAL KARSTOLOGICAL SCHOOL "Classical Karst"

KARST – APPROACHES AND CONCEPTUAL MODELS

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30th INTERNATIONAL KARSTOLOGICAL SCHOOL
"Classical Karst"

30. MEDNARODNA KRASOSLOVNA ŠOLA "KLASIČNI KRAS"

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KRAS – RAZVOJNI PRISTOPI IN KONCEPTUALNI MODELI

ABSTRACTS & GUIDE BOOK

POVZETKI & VODNIK

30th INTERNATIONAL KARSTOLOGICAL SCHOOL
"CLASSICAL KARST"

30th ANNIVERSARY

30. MEDNARODNA KRASOSLOVNA ŠOLA "KLASIČNI KRAS"
30. OBLETNICA

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ABSTRACTS & GUIDE BOOK

POVZETKI & VODNIK

Postojna
2023

Editors / Uredniki:
Astrid Švara, Nadja Zupan Hajna, Franci Gabrovšek

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CONTENTS

VSEBINA

GENERAL INFORMATION

SPLOŠNE INFORMACIJE

PROGRAM

Monday, June 19th, 2023 Ponedeljek, 19. junij 2023		
08:00–13:00	**REGISTRATION** / PRIJAVA UDELEŽENCEV	Cultural Centre Postojna Kulturni dom Postojina
09:00–10:15	**30TH ANNIVERSARY CEREMONY*** / SLOVESNOST OB 30. OBLETNICI*	
10:15–10:45	*Coffee break* / *Odmor za kavo*	
	SESSION 1: SPELEOLOGY, SPELEOGENESIS & MODELS (*Chair: F. Gabrovšek)* SKLOP 1: SPELEOLOGIJA, SPELEOGENEZA in MODELI	
10:45–11:05	*1st Keynote lecture* / *1. Plenarno predavanje* F. Gabrovšek & W. Dreybrodt: Models of Speleogenesis: What have we learned so far?	
11:05–11:20	M. D. Covington: Do existing conceptual models of critical zone processes apply to karst?	
11:20–11:50	*2nd Keynote lecture* / *2. Plenarno predavanje* A. N. Palmer & M. V. Palmer: Advances in karst science since the founding of the Karst School in Slovenia	
11:50–12:05	*Invited lecture* / *Vabljeno predavanje* A. Tyc et al.: Hypogene speleogenesis and the origin of collapse dolines in travertines of the Central Andes – interdisciplinary approach	
12:05–12:20	R. Tásler et al.: Complex evaluation of caves in the Krkonoše Mountains (N Bohemia, Czechia)	
12:20–12:35	S.-E. Lauritzen: Dynamics of Glacier Ice-Contact Speleogenesis and CO_2 Sequestration: the pressure story	
12:35–14:15	*Lunch break* / *Odmor za kosilo*	
	SESSION 2: HYDROLOGY & CAVE CLIMATE (*Chair: N. Ravbar)* SKLOP 2: HIDROLOGIJA in JAMSKA KLIMA	
14:15–14:45	*Keynote lecture* / *Plenarno predavanje* J. Doummar: Different approaches of process-based modelling to simulate flow in karst systems: application on pilot sites	
14:45–15:00	P. W. Williams: Arthur Marble Aquifer and Te Waikoropupu Springs, New Zealand: modelling flow contributions and nitrate sources	
15:00–15:15	N. Kalantari et al.: Groundwater exchange between the Izeh alluvial aquifer and the surrounding karst aquifers in the NE of Khuzestan province, Iran	
15:15–15:30	H. Scherzer & H. Class: Nerochytical Speleogenesis (NERO): mobile CO_2 as driving force for karstification. A new thesis	
15:30–15:45	P.-Y. Jeannin & A. Malard: Building hydrogeological 3D conceptual models of karst aquifers with visual KARSYS	
15:45–16:00	*Break* / *Odmor*	
16:00–16:15	V. Gajović & N. Ravbar: Karst digital twin – evaluation of remote sensing spatiotemporal data for modelling the karst systems	
16:15–16:30	L. Plan: What do we know about the “karst water table”? – Insights from caves in the Eastern Alps	
16:30–16:45	O. Koit et al.: Exploring the hydrological sensitivity of surface water and groundwater resources in the Boreal region of Estonia	
16:45–17:00	R. Lončarić: When karst hydrology models were young – the concepts of karst water flow in the works of Albero Fortis (1741 – 1803)	
17:00–17:15	N. Buzjak et al.: Monitoring strategies in cave microclimate monitoring studies – Dos, Don`ts, Maybes	
17:15–17:30	*Break to move* / *Odmor za premik*	KRI IZRK
	POSTER SESSION / POSTERJI	
17:30–19:00	Quick poster presentations / Hitra predstavitev posterjev	
19:00–21:00	Poster display / Ogled posterjev	
19:00–21:00	**ICE BREAKER and KARST JAM** UVODNO DRUŽENJE in KRAŠKE DEBATKE	

Tuesday, June 20th, 2023 **Torek, 20. junij 2023**		
08:00–11:00	**REGISTRATION / PRIJAVA UDELEŽENCEV**	Cultural Centre Postojna Kulturni dom Postojna
	SESSION 3: GEOMORPHOLOGY & CAVE MORPHOLOGY (*Chair: N. Zupan Hajna)* **SKLOP 3: GEOMORFOLOGIJA in JAMSKA MORFOLOGIJA**	
08:30–09:00	*Keynote lecture / Plenarno predavanje* A. Persoiu: Development and evolution of models in geomorphology	
09:00–09:15	U. Sauro: Traces of ancient glaciations in karst environment – a case study in the Venetian Prealps	
09:15–09:30	A. Gessert: Identification of karst depressions based on LiDAR – challenges from the Slovak karst region	
09:30–09:45	U. Stepišnik: Multiphase Development of Ponor-Type Contact Karst on the Zrenj Plateau, Istria, Croatia	
09:45–10:00	M. Kázmér et al.: Terrain uplift recorded by hypogenic karst features – the case of Peninsular Malaysia	
10:00–10:15	M. Lipar et al.: A discovery and study of limestone depositional form on the Nullarbor Plain, Australia	
10:15–10:30	A. Rajačić & N. Bočić: Geomorphology of the alluvial fans in selected Dinaric Karst poljes in Croatia	
10:30–10:45	N. Zupan Hajna et al.: Atypical cave sediments from Grofova jama (Kras Plateau) and their connection with the eruption of the Smrekovec stratovolcano	
10:45–11:15	*Coffee break / Odmor za kavo*	
	SESSION 4: KARST GEOLOGY (*Chair: S. Šebela)* **SKLOP 4: KRAŠKA GEOLOGIJA**	
11:15–11:45	*Keynote lecture / Plenarno predavanje* I. Sasowsky: Role of geologic history and basic factors in karst models	
11:45–12:00	D. Ford: And now for something completely different! – Morphology and deposition of the Main (sulphide) Ore in Proterozoic dolomites at Nanisivik Mine, Baffin Island, Canada	
12:00–12:15	D. Szieberth et al.: Sediments in a hypogenic underwater cave – an indication of high flow periods in the past	
12:15–12:30	A. Mladenović & Ćalić: To what extent reactivated faults are (not) responsible for karst processes: example from Serbian Carpatho-Balkanides?	
12:30–12:45	L. Slapnik et al.: Reddish Paleokarst Multiphase Infillings in the Megalodontid Bivalves and Solution Voids in the Julian Alps	
12:45–13:00	B. Rožič et al.: The enigma of the oldest allogenic sediments of the Unroofed Cave Loza – preliminary results (Slavinski ravnik, W Slovenia)	
13:00–14:30	*Lunch break / Odmor za kosilo*	
14:30–20:00	**Afternoon field trip (A) / Popoldansko terensko delo (A)** Active and Relict features and sediments of the Slavinski ravnik Contact Karst with the Rakuliščica Stream. *Bus drive and walk (several km).* Aktivne in reliktne oblike ter sedimenti kontaktnega krasa Slavinskega ravnika s potokom Rakuliščica. *Vožnja z avtobusom ter hoja (nekaj km).*	

Wednesday, June 21st, 2023 Sreda, 21. junij 2023		
08:00–09:00	**REGISTRATION / PRIJAVA UDELEŽENCEV**	Cultural Centre Postojna Kulturni dom Postojna
	SESSION 5: SPELEOBIOLOGY & GEOCHEMISTRY (*Chair: J. Mulec)* **SKLOP 5: SPELEOBIOLOGIJA in GEOKEMIJA**	
08:30–09:00	*Keynote lecture / Plenarno predavanje* S. Polak: Studies on the cave animal DNA molecules can help us understand the formation and genesis of karst areas	
09:00–09:15	A. Palandačić et al.: Dispersal of aquatic organisms in karst landscapes	
09:15–09:30	Q. He et al.: The Karst organic carbon sink process in a typical karst surface river, Lijiang, Guilin, China	
09:30–09:45	*Invited lecture / Vabljeno predavanje* M. Hernandez Garcia: Metagenomics in Underground research	
09:45–10:00	I. M. D`Angeli et al.: Sulfuric acid caves of the world: a review	
10:00–10:15	K. Šušmelj et al.: Submerged Izola karst: Investigating submarine sulphur springs	
10:15–10:45	*Coffee break / Odmor za kavo*	
	SESSION 6: OUTREACH OF KARSTOLOGY (*Chair: M. Prelovšek)* **SKLOP 6: OZAVEŠČANJE O KRASU**	
10:45–11:15	*1st Keynote lecture / 1. Plenarno predavanje* P. Griffiths: More than caves: Reflections on advocating a broader concept of karst to government, industry, and the public	
11:15–11:30	D. Cailhol & C. Dioniso: Identification and assessment of karst processes for the studies and the conservation of caves and their heritage	
11:30–12:00	*2nd Keynote lecture / 2. Plenarno predavanje* F. Sauro: Planetary caves: expanding our knowledge about karst and speleogenesis from Earth to the Solar System	
12:00–12:15	M. Năpăruş-Aljančič et al.: Multidisciplinary metadata portal at the Karst Research Institute ZRC SAZU	
12:15–14:30	*Lunch break / Odmor za kosilo*	
14:30–20:00	**Afternoon field trip (B) / Popoldansko terensko delo (B)** Hydrogeology of the Upper Pivka Valley and the cave Jama v Ždinku – a potential drinking water resource? *Bus drive and walk (several km).* Hidrogeologija Zgornje Pivške kotline in Jame v Ždinku – potencialni vir pitne vode? *Vožnja z avtobusom ter hoja (nekaj km).*	

Thursday, June 22nd, 2023 Četrtek, 22. junij 2023		
08:00–17:00	**Whole-day field trip (C) / Celodnevno terensko delo (C)** Škocjanske Jame: caves and karst case studies. *Bus drive and walk (several km).* Škocjanske jame: študije primerov jam in krasa. *Vožnja z avtobusom ter hoja (nekaj km).*	
17:00–19:00	*Break / Odmor*	
19:00–	**Reception with live music with "Geobanda" at 8 p.m.** **Sprejem z glasbo v živo z »Geobando« ob 20:00**	KRI IZRK

Friday, June 23rd, 2023 Petek, 23. junij 2023		
9:00–17:00	**Whole-day field trip (D) / Celodnevno terensko delo (D)** Groundwater flow in the Ljubljanica recharge area. *Bus drive and walk (several km).* Tok podzemne vode v porečju kraške Ljubljanice. *Vožnja z avtobusom ter hoja (nekaj km).*	

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30TH ANNIVERSARY CEREMONY*

The Opening Ceremony will be held on Monday, 19th from 9:00 – 10:15 at the Cultural Centre Postojna. The ceremonial upon the 30th Anniversary of the International Karstological School will be marked by the following speakers:

- Prof. Dr. Tadej Slabe, Head of the Karst Research Institute ZRC SAZU
- Mr. Abou Amani, Director at the Division of Water Sciences, Secretary at the Intergovernmental Hydrological Programme (IHP), UNESCO
- Prof. Dr. Darko Štrajn, Vice President of the Slovenian National Commission for UNESCO
- Prof. Dr. Oto Luthar, Director of ZRC SAZU
- Assoc. Prof. Dr. Nadja Zupan Hajna, President of the International Union of Speleology UIS
- Prof. Dr. Franci Gabrovšek, Karst Research Institute ZRC SAZU, Organizing Committee of 30th IKS
- Prof. Emer. Derek Ford, McMaster University, Canada, long-term collaborator of IZRK
- Prof. Emer. Paul W. Williams, University of Auckland, New Zealand, long-term collaborator of IZRK
- Prof. Dr. Ugo Sauro, University of Padova, Italy, long-term collaborator of IZRK
- Prof. RNDr. Pavel Bosák, Institute of Geology of the Academy of Sciences, Czech Republic, long-term collaborator of IZRK
- Prof. Emer. Stein-Erik Lauritzen, University of Bergen, Norway, long-term collaborator of IZRK.

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Mr Gasper Hrastelj
Secretary General
Slovenian National Commission
for UNESCO
Ministry of Higher Education,
Science and Innovation
Kotnikova ulica 38
Ljubljana 1000
Republic of Slovenia

22 May 2023

The Assistant Director-General
for Priority Africa and External Relations

Ref: SC/HYD/23/2469

Dear Secretary General,

On behalf of the Director-General, I wish to thank you for your letter and the patronage form of 27 February 2023, seeking UNESCO's patronage for the 30th International Karst School "Classical karst" scientific conference devoted to the theme "Karst – Different Approaches and Conceptual Models", to be held from 19 to 23 June 2023 in Postojna, Republic of Slovenia.

UNESCO recognizes the importance of the karstic landscapes, which host high biodiversity, and provide groundwater from karst aquifers. In many countries and regions, it is the major source of fresh water for drinking water supply and water for agricultural irrigation. The hydrogeology of Karst is one of the topics on which UNESCO Intergovernmental Hydrological Programme has worked since its inception. One of the recent activities was the study of the Dinaric Karst Aquifer and the production of two maps: the "World Karst Aquifer Map" and the "Mediterranean Karst Aquifer Map". Considering the value of karst systems, UNESCO was pleased to host the Year of Karst and Caves celebration in September 2021 and the Side event on Karst Aquifers during the UN-Water Summit on Groundwater in December 2022..

The Division of Water Sciences fully supports this international conference whose theme is aligned to the Strategic Plan and activities of the 9th Phase of the Intergovernmental Hydrological Programme (IHP-IX), specifically to Priority Areas 1 (scientific research and innovation), 4 (integrated water resources management under conditions of global change) and 5 (water governance based on science for mitigation, adaptation, and resilience), and in particular as a follow-up of the campaign "Groundwater: Making the Invisible Visible" conducted by UNESCO in 2022. The theme of the scientific conference, "Karst: Difference approaches and Conceptual models" is of great interest for UNESCO as the importance of the karstic systems is also recognized in World Heritage sites, Biosphere Reserves and UNESCO Global Geoparks.

United Nations Educational, Scientific and Cultural Organization
7, Place de Fontenoy 75352 Paris 07 SP France
T: +33 (0)1 45 68 10 00

It is with pleasure that I inform you that the Director-General has decided to grant UNESCO's patronage to the celebration of the 30th International Karst School "Classical karst", together with the scientific conference organized this year under the theme "Karst – Different Approaches and Conceptual Models", and to authorize the use of the Organization's logo, in accordance with the General Conditions enclosed herewith.

Allow me to wish you success for this international conference, and to take this opportunity to express our will to strengthen and to continue our collaboration.

Yours sincerely,

Firmin Edouard Matoko

cc: Permanent Delegation of the Republic of Slovenia to UNESCO

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.

	1st AUTHOR	TITLE
1	Audra Philippe	The Mescla Cave (Alpes-Maritimes, France). Overview of researches in a deep-phreatic cave
2	Bajraktari Fadil	Kosovo Abysses (Vertical caves)
3	Calli Suleyman Selim	The value of satellite-driven snow cover data in the calibration of a karst hydrological model
4	Colton Riannon	How do radon dynamics differ within caves with different airflow mechanisms?
5	Del Gobbo Costanza	The CryoKarst Project: Academic research meets citizen science to study ice deposits within caves
6	Di Muccio Luca A.	Polygenic speleogenesis of Grotta dei Pipistrelli (Matera, southern Italy)
7	Dixit Satish	Assessment of Hydrogeochemical characteristics of Karst Aquifer from a semi-arid region
8	Dušeková Laura	The concept of the caves evaluation methodology in Slovakia
9	Fernández-Ortega Jaime	^{222}Rn as a natural tracer to investigate recharge and groundwater flow dynamics at three Mediterranean karst systems in Southern Spain
10	Gao Shuai	Geological origin and value of karst spring in Jinan, North China
11	Gebus-Czupyt Beata	Geochemical and isotopic approaches in research on dedolomitization and speleogenesis processes
12	Jena Vinod	Physico-Chemical characteristics of Karst Water
13	Johnston E. Vanessa	Hydrogeochemical monitoring in the Rovte region (Slovenia) to assess the potential for dedolomitization
14	Kdýr Šimon	Paleomagnetic and rock magnetic investigations of cave sediments in Lipiška Jama: insight into Classical Karst (SW Slovenia) evolution
15	Knez Martin	Karst rock reading and development models
16	Kurečić Tomislav	The volcanoclastic material in the deep cave sediments of the high karst area on Mt. Biokovo
17	Likar Mojca	Multivariate analysis of environmental and metagenomic data of two Karst water sources
18	Miler Miloš	Fe-oxyhydroxide crusts on carbonates
19	Mušič Maša	Student geological mapping of the Black Olms habitat and its catchment area in Bela krajina
20	Nassery Hamid Reza	Hydrogeology of Quri Qaleh, province Kermanshah, Iran
21	Oarga-Mulec Andreea	Assessing environmental health through monitoring of microbiological parameters and time-series analysis of oxygen in diversity hotspot river

		ecosystems
22	Özdemir Calli Kübra	Revisiting contaminant mixing and transport modeling approaches in karst systems: Model limitations and new prospective
23	Paar Dalibor	Some examples of microclimate research in the Dinaric Karst in the context of climate change
24	Perica Dražen	Investigation of the intensity of surface carbonate corrosion process using rock tablet method in “Northern Velebit” NP (Croatia)
25	Pluta Przemysław	Application of iPhone 13 PRO device for measuring scallops in Mylna Cave in Tatra Mountains using LiDAR and SfM techniques
26	Ratajczak Skrzatek Urszula	Reniferowa Cave – a new research site on the map of Polish caves
27	Rispal Nathan	Contribution of paleokarsts in the understanding of Monts de Vaucluse (France) geological calendar
28	Ruitong Lui	Laboratory and numerical simulations of infiltration processes and solute transport in karst vadose zone
29	Semeraro Rino	Signal examples from different aquifer source areas in the flood events of Davorjevo brezno
30	Skoglund Øvrevik Rannveig	Is the thermal signal a reliable proxy to decipher flow conditions in karst aquifers?
31	Stepišnik Uroš	Morphogenetic interpretation of shallow karst depressions of Upper Pivka, Slovenia
32	Surić Maša	What controls short-term variations in CO_2 and ^{222}Rn concentrations in Modrič Cave atmosphere?
33	Šarc Filip	Lithological characteristics of the dedolomite complex in Mravljetovo brezno v Gošarjevih rupah cave, central Slovenia
34	Šturm Samo	Managing lampenflora growth in Škocjan Caves, a World Heritage Site in Slovenia: a practical approach for show cave conservation
35	Tembe Mwela Valentin	Evaluation of water Resources in the City of Bandundu
36	Temovski Marjan	Hydrogeochemical research of the Klariči water source catchment area – preliminary results
37	Trappe Martin	Sinkholes in the South Franconian Alb (Germany): distribution and relations to geology and geomorphology
38	Turk Domen	Marginal plains on Border Karst Poljes
39	Tuzimek Dominika	The clastic sediments origin of the Głęboka Cave (Kraków-Częstochowa Upland, Poland) in the light of heavy minerals analysis
40	Verbovšek Timotej	Sedimentological and geochemical conditions along the inception horizons influencing the formation of the cave Pečina v Zjatih
41	Zang Yinning	The Value of Stable Water Isotopes for Improving Karst Groundwater Models
42	Zeng Sibo	Natural and Anthropogenic Driving Forces of Carbonate Weathering and the Related Carbon Sink Flux

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) in a separate space in front of the main entrance to the Cultural Centre on the right. **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.
- 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) at the registration desk on Monday, June 19th, 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 excursion (Excursion C) we suggest you take with you some additional snacks.
- Lunch breaks are timetabled into the schedule during the session days (Monday, Tuesday and Wednesday).
- On Thursday a reception dinner will be provided with live music.

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, 19th June 2023 at the registration desk.
- Bus departure for the field trips is from the parking place at 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), v ločenem prostoru pred glavnim vhodom v Kulturni dom, desno. **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 v obliki diapozitivov. Pri tem vse avtorje vabimo k pripravi 2 minuti dolge predstavitve - napovednika (1–2 diapozitiva), 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, 19. junija, do odmora za kosilo.
- Med ogledom posterjev stojte poleg svojega posterja.

Obroki

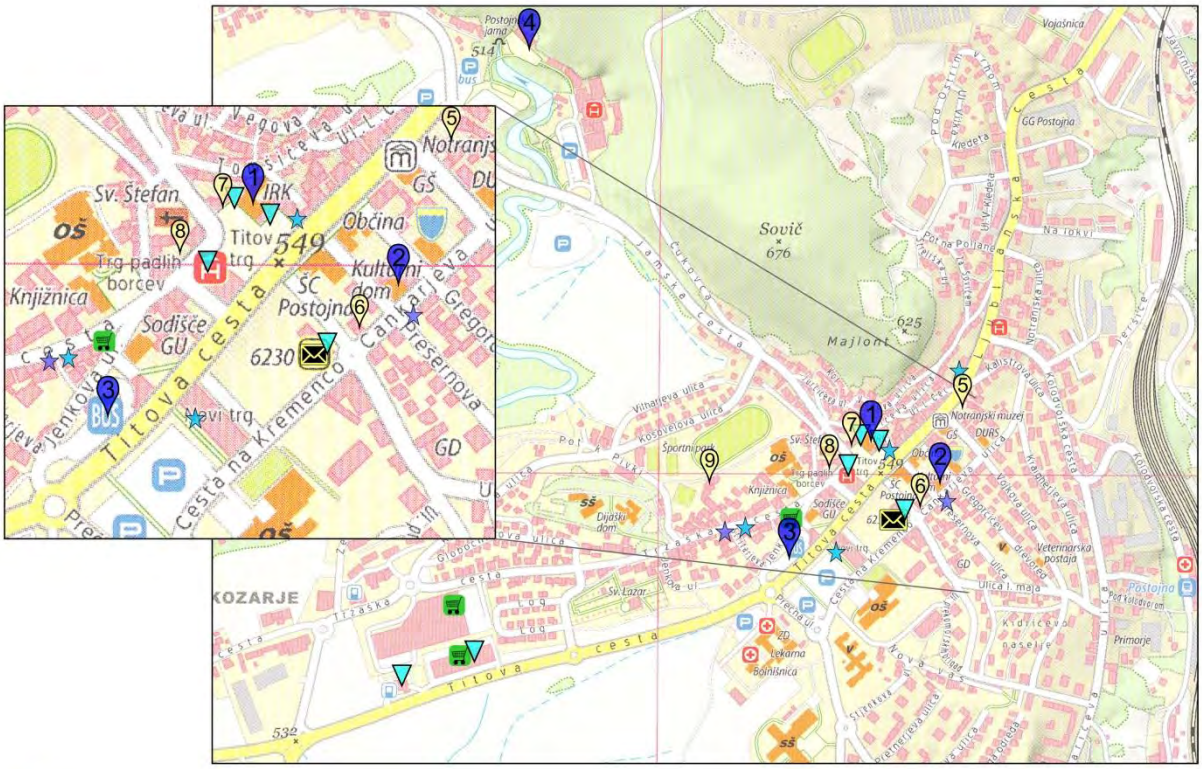
- Kosilo med predavanji in popoldanskim terenskim delom (torek in sreda) ni organizirano.
- Med celodnevnim terenskim delom (četrtek in petek) organiziramo enostavne obroke. Zaradi dolžine četrtkove ekskurzije (Ekskurzija C) priporočamo, da si s sabo vzamete še kakšen dodaten prigrizek.
- Odmori za kosilo so v času predavanj (ponedeljek, torek in sreda) vključeni v program.
- V četrtek je v večernem delu programa planirana pogostitev in glasba v živo.

Strokovne ekskurzije

- Vse ekskurzije bodo kombinirane z avtobusno vožnjo ter hojo (nekaj km/dan).
- Prijave za strokovne ekskurzije bodo mogoče le še v ponedeljek, 19. 6. 2023 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 cave Postojnska jama / Vhod v Postojnsko jamo

Places to eat: / Možnost prehrane:

5. Pizzeria and restaurant „Minutka“ / Picerija in restavracija „Minutka“
6. Bistro „Štorja pod stopnicami“ / Bistro „Štorja pod stopnicami“
7. Restaurant „Proteus“ / Restavracija „Proteus“
8. Bistro „Bar Bor“ / Bistro „Bar Bor“
9. Pizzeria and restaurant „Čuk“ / Picerija in restavracija „Čuk“

- Fast Food / hitra prehrana
- Bakery / pekarna
- Market / trgovina
- ATM / bankomat
- Post Office / pošta

INVITATION TO A SPECIAL SESSION: KARST JAM

(Monday, 19th June 2023)

This year's school will be as always a great meeting point between experienced and new researchers from different parts of the globe.
In the past, a Special Session on Mysteries in Karst science was held which was a successful way to present open research questions and ideas in a form of a short PPT presentation.
This year, we are trying something different. We will hold a "Karst Jam" session, where a debate will be challenged by the moderator and attendees, where different karst topics will be addressed. The idea is to talk about some open/unresolved/ambiguous/problematic topics in a friendly environment with a lot of fun. Young researchers and students will get the possibility to hear both (or several) answers to the unresolved questions within karst science, where recognized scientists will get the possibility to mingle.
No contribution is needed, just your presence, goodwill and constructive ideas.
See you on Monday, 19th of June in the evening at the Karst Research Institute ZRC SAZU!

With best regards,
Astrid Švara and Franci Gabrovšek (moderators and Organizing Committee)

POVABILO NA POSEBNO SEKCIJO: KRAŠKE DEBATKE

(ponedeljek, 19. junija 2023)

Letošnja šola bo kot vedno odlično stičišče izkušenih in novih raziskovalcev iz različnih koncev sveta.
V preteklosti je potekala posebna sekcija o skrivnostih krasoslovja, ki je bila uspešen način za predstavitev odprtih raziskovalnih vprašanj in idej v obliki kratke PPT predstavitve.
Letos poskušamo vpeljati nekaj drugačnega. Izvedli bomo sekcijo "Kraške debatke", kjer bo debata potekala s pomočjo moderatorja in udeležencev, kjer bodo obravnavane različne kraške teme. Ideja je, da se o nekaterih odprtih/nerešenih/dvoumnih/problematičnih temah pogovarjamo v prijaznem okolju z veliko zabave. Mladi raziskovalci in študentje bodo imeli možnost slišati oba (ali več) odgovorov na odprta krasoslovna vprašanja, kjer bodo dobili možnost druženja s priznanimi krasoslovci.

Prispevek ni potreben, le vaša prisotnost, dobra volja in konstruktivne ideje.
Se vidimo v ponedeljek, 19. junija zvečer na Inštitutu za raziskovanje krasa ZRC SAZU!

Z lepimi pozdravi,
Astrid Švara in Franci Gabrovšek (moderatorja in člana organizacijskega odbora)

PILEUS, OKOLJSKE REŠITVE

(from Monday to Wednesday, 19th – 21st June 2023)

"Pileus, okoljske rešitve" is a Slovenian company delivering equipment for energetic, environmental and storage with transport monitoring. They will present their product and service range at a stand at the Cultural Centre of Postojna. Go check them out!

PILEUS, OKOLJSKE REŠITVE

(od ponedeljka do srede, 19. – 21. junija 2023)

"Pileus, okoljske rešitve" je slovensko podjetje, ki dobavlja opremo za energetski monitoring, monitoring okolja in skladiščenja ter transporta. Svojo ponudbo izdelkov in storitev bodo predstavili na stojnici v Kulturnem domu Postojna. Vabljeni k obisku!

LIVE MUSIC WITH GEOBANDA

(Thursday, 22nd June 2023 at 8 p.m.)

The music group Geobanda basically consists of 7 geologist musicians - from graduates to professors, rehearsing and performing purely for pleasure and relaxation. The band members play music full of sound, happy melodies and syncopated rhythm in the style of swing and rhythm & blues. Sometimes they reach for folk songs, follow the idea of New York jazz musicians, explore pop music and arrange it in the style of the group Postmodern Jukebox. The music group has been working within the music section Hic et nunc since 2018. You can dance and sing with Geobanda on Thursday evening at the 30th IKS Reception!

GLASBA V ŽIVO Z GEOBANDO

(četrtek, 22. junija 2023 ob 20:00)

Glasbeno skupino Geobanda v osnovi sestavlja 7 glasbenikov geologov – od diplomantov do profesorjev, glasba pa jim je v veselje in sprostitev. Člani skupine igrajo glasbo polnega zvoka, veselih melodij in sinkopiranega ritma v stilu swinga in rythm & bluesa. Včasih posegajo po ljudskih pesmih, sledijo idejo newyorških jazz glasbenikov, raziskujejo pop glasbo in jo prirejajo v stilu skupine Postmodern Jukebox. Glasbena skupina deluje znotraj glasbene sekcije Hic et nunc od leta 2018.

Z njimi lahko pojete in plešete v četrtek zvečer na sprejemu 30. MKŠ!

Geobanda at the 29th IKS (Photo: Ž. Kafol)

FIELD TRIPS

TERENSKO DELO

Afternoon field trip (A):

ACTIVE AND RELICT FEATURES WITH SEDIMENTS IN THE CONTACT KARST OF THE SLAVINSKI RAVNIK WITH THE RAKULIŠČICA STREAM

Tuesday, 20th June 2023, 14:30–20:00

Astrid Švara, Cyril Mayaud, Nadja Zupan Hajna, Andrej Mihevc

Stops:

1 – Sajevško polje – blind valley, alluvial fans and relict ponors
2 – Rakuliščica stream – active and intermittent ponors
3 – Markov Spodmol
4 – Outcrop of chert pebbles
5 – Unroofed cave Loza
6 – Spodmol v Selški Lozi

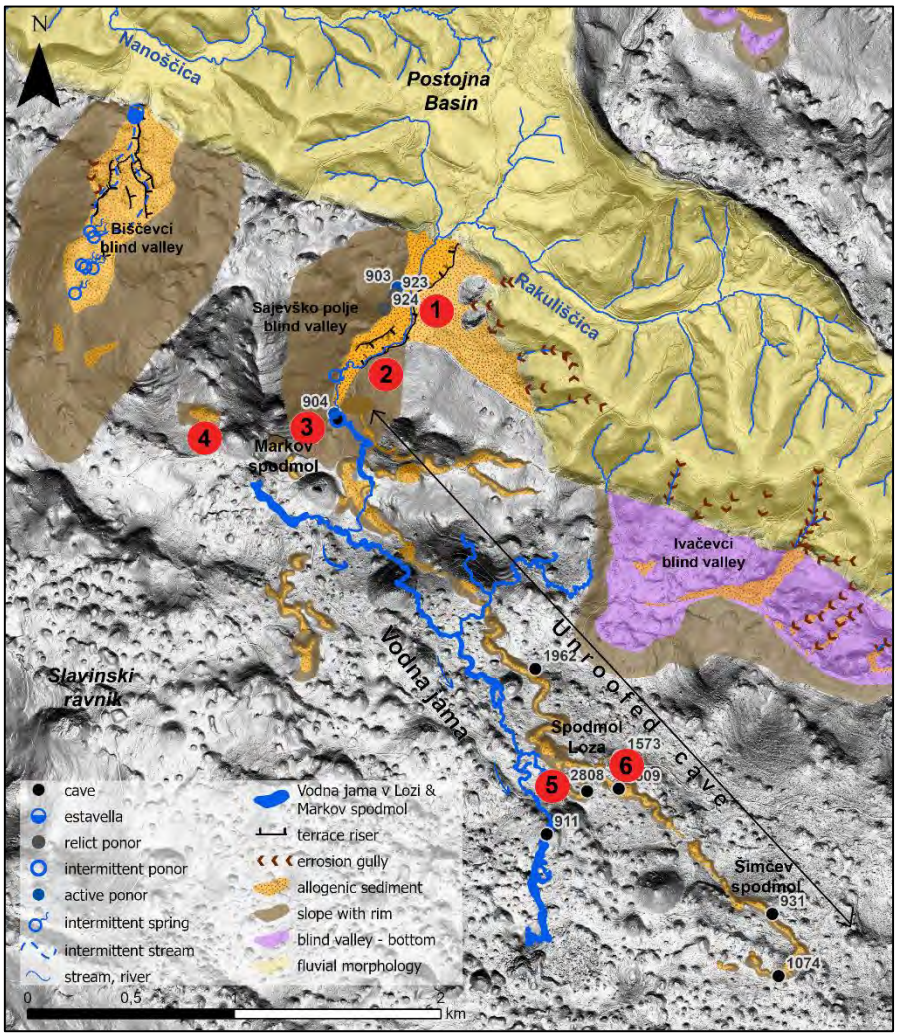


Fig. 1.01: Field stops (1-6) in the contact karst of Slavinski ravnik (DEM: GOV, Cartography: A. Švara).

Rakuliščica ter aktivne in reliktne oblike kontaktnega krasa Slavinskega ravnika

Popoldansko terensko delo (A); torek, 20. junij 2023

Poudarek ekskurzije je kontaktni kras Slavinskega ravnika, kjer se od zgornjega miocena razvijajo geomorfološke in speleološke oblike odvisne od tektonskega in hidrološkega stanja bližnje okolice. Na območju obstajajo številne aktivne in reliktne oblike z dobro ohranjenimi alogenimi sedimenti, ki pričajo o dolgi zgodovini aktivnega naplavljanja in tektonskih premikov.

GENERAL DESCRIPTION

The field trip is headed to a part of the contact karst of Slavinski ravnik, the southernmost contact karst area of the Postojna Basin, located in NW Slovenia. Many active and relict surface and subsurface contact karst features can be observed in the area, proving its complex genesis (Fig. 1.01).

The excursion will review the Sajevško polje blind valley with active and relict ponors of the Rakuliščica Stream (1st stop) as well as different types of surface sedimentation observed in Sajevško polje blind valley and alluvial fan (2nd stop). At the end of the Sajevško polje blind valley, the hydrological measuring station in the riverbed of the Rakuliščica and the entrance to Markov spodmol will be reviewed (3rd stop). The next stop will be at a surface outcrop of old cave sediments (4th stop), followed by the two oldest remains of the Loza Cave System, i.e. the Unroofed cave Loza (5th stop) and Spodmol v Selški Lozi (6th stop) (Fig. 1.01).

SETTINGS

Geological Settings

The Postojna Basin consists of lower to middle Eocene flysch that forms ridges and hills with extensive alluvium cover, that often forms river terraces (Melik, 1951; Pleničar, 1963, 1970; Gospodarič, 1988, 1989). The Slavinski ravnik is in contact with the basin developed in limestones of the Adriatic Carbonate Platform from the Upper Cretaceous to the Eocene (Pleničar, 1963, 1970) (Fig. 1.02). The sedimentary period from the Paleocene to the Eocene is characterized by white, highly karstified limestones with alveolinas and nummulites, while at the transition to the Cretaceous the limestone becomes more greyish and has additional shellfish fauna remains. The Upper Cretaceous is mainly characterized by grey limestones with chert nodules and rudists (Pleničar 1963, 1970). The Slavinski ravnik represents a part of the Komen Thrust Sheet – the lowest thrust unit in the Slovenian part of the External Dinarides, which is the part that travelled the least during the tectonic deformations in the post-Eocene times, while the flysch of the Postojna Basin represents the Snežnik Nappe (Pleničar, 1963, 1970). Slavinski ravnik is located between two major regional Dinaric faults, the Predjama-Avče Fault on the NE and the Raša Fault on the SW (Atanackov et al., 2021). The tectonic composition and indentation of the Adria Microplate strongly influenced the kinematic compression conditions, which were followed by a counter-clockwise (CCW) rotation (Weber et al., 2010), which additionally contributed to the uplift of karst areas between major faults by faulting, thrusting and folding (Pleničar, 1963, 1970; Placer, 1999, 2008).

In the last 25 years of research in Slovenia, a total of three distinctive phases of cave sediment deposition have been observed: 5.4 – 4.1 Ma, 3.6 – 1.8 Ma, and 0.78 Ma to the present, with an end of overthrusting after 1.5 Ma and onset of CCW rotations (e.g. Bosák et al., 1998; Zupan Hajna et al., 2008, 2020). All of this reflects regional uplift associated with CCW domino-like tectonic block rotations between NW-SE-trending dextral strike-slip faults (Vrabec et al., 2018), and consequently environmental changes in the karst system within the Gilbert, Gauss/Matuyama, and Brunhes Polarity Chrones. Rotation over the last few million years can also be recorded in cave sediments, that can grow up to 30° or more in separate tectonic blocks, especially in SW Slovenia (Vrabec et al., 2014, 2018). There also appears to be an episode of accelerated rotations between 1.5 – 3.0 Ma, which may imply increased fault-slip rates possibly driven by large-scale changes in plate motions at about 3 Ma (Calais et al., 2003; Vrabec et al., 2018).

The allogenic and speleothem sediments observed in Slavinski ravnik in caves and surface outcrops represent cave sediments, which are the best chronological evidence of speleogenesis (Zupan Hajna et al., 2008, 2020). The finest and most common allogenic sediments fill the bottom of the blind valley and the ponor caves at all altitudes, from the active passages to the relict exposed channel of the unroofed cave. Pebbles can be observed in all features. Those in the Rakuliščica riverbed are mainly sandstone pebbles from the Eocene flysch, while the pebbles at the highest altitudes are chert pebbles (Mihevc, 1991, 2006), which have been preserved the longest despite severe weathering and represent the oldest allogenic cave sediments still exposed on the surface (Švara et al., 2022) and whose origin we are slowly unravelling (Rožič et al., 2023).

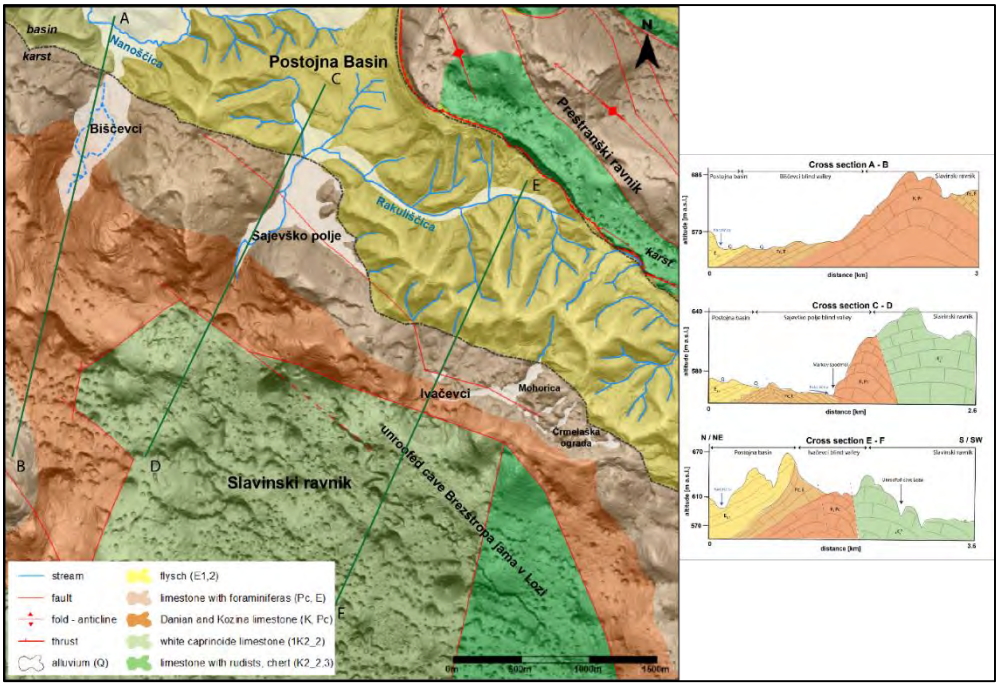


Fig. 1.02: Simplified geological map of Slavinski ravnik study area with schematic cross-sections. Source: DEM – LiDAR data, Geodetic department ARSO; Geology – OGK 1:10000 Postojna, Geological Survey of Slovenia (Pleničar 1963, 1970). Cartography: A. Švara, Karst Research Institute ZRC SAZU (Švara et al. 2022).

Geographic and Geomorphological Settings

The study area represents the N part of the Slavinski ravnik, which is dissected by numerous dolines, bounded by the non-karst Postojna Basin to the N. Slavinski ravnik is a leveled karst area (corrosional plain) with an average elevation of 610 m a.s.l., with the highest elevations reaching 750 m a.s.l. The area is highly affected by allogenic sedimentation from the Postojna Basin, hence it represents a contact karst area, i.e. karst with allogenic input (e.g. Ford & Williams, 2007). In Slavinski ravnik, allogenic waters flow from a non-karst environment and sink into the karst geomorphic system, i.e. where allogenic waters modify karst landscapes by their volume, regime, and sediment load (e.g. Mihevc, 1991, 2001; Sauro, 2001). Typical forms found in this ponor contact karst are ponors (sinkholes), ponor valleys, dry valleys, ponor steepheads, blind valleys, ponor caves and epiphreatic caves. In the karst underground, ponor caves are formed (e.g. Gams, 1995; Ford & Williams, 2007), which can be transformed by paragenetic processes (Roth, 1937; Renault, 1958), as in the case of caves and cave systems in Slavinski ravnik. Caves fed by sinking streams are exposed to severe floods that also bring sediments into the cave. In cases, where allogenic sediment is washed into the karst over time, only inactive or relict geomorphic features remain visible in the relief, such

as unroofed caves, blind and dry valleys (e.g. Mihevc, 2001, 2007, 2010; Sauro, 2002, 2013; Zupan Hajna et al., 2021). Due to karst denudation, caves filled with sediments may be exposed as relief features in the form of unroofed caves (e.g. Mihevc, 1996, 1999, 2001, 2006). The existence and significance of unroofed caves were first discovered and studied in Slovenia (Mihevc, 1996), leading to reassessment and a new understanding of the geomorphological evolution of karst of global significance (e.g. Mihevc 1999).

The extensive water activity in the Postojna Basin enabled the Rakuliščica stream to actively flow into the ponors on the W boundary of the Sajevško polje area (Ogrizkov Spodmol – reg. no. 923, Županov Spodmol – reg. no. 924; Fig. 1.01), which after a certain time overflowed towards the S, with a tendency to shift even further, where at some point, the Sajevško polje blind valley was formed (Mihevc, 1991). The most important processes that enabled the activation of new ponors and the formation of the blind valley are their adaptation to the water level (Mihevc, 2007), which gradually lowered following the tectonic uplift and erosion of the flysch hinterland. The Biščevci blind valley is known W of Sajevško polje blind valley (which is hydrologically inactive with respect to its formation course) and the easternmost Ivačevci blind valley (which is relict, with little or no allogenic sediments or hydrological activity), all pointing to the long-term ponor activity of the area (Mihevc, 1991; Švara et al., 2022).

The Sajevško polje area was first studied by Habe & Hribar (1964), which was followed by the studies of the ponor contact karst with special attention to blind valleys by Mihevc (1990, 1991). The Unroofed cave was first mentioned and recognized by Mihevc (1996, 1999, 2006) and studied by Švara et al. (2022, 2023 – for publication).

Speleological Settings

In the wider research area of the Slavinski ravnik contact karst, 77 caves are known, represented by (sub)horizontal caves, vertical caves, and caves with combined passages (Cave Register 2021), but subhorizontal caves predominate. The majority of vertical caves and passages are vadose shafts related to regional uplift that forced water to follow the movement of the water table. The shift of ponor locations due to the lowering of the water table can still be observed and is best expressed in the Loza Cave System by three horizontal cave levels with side channels, some of which are connected with vertical vadose channels.

The Loza Cave System is represented by the active ponor of Rakuliščica (Ponikve pri Sajevčah – reg. no. 903, Požiralnik pred Markovim Spodmolom – reg. no. 904; Fig. 1.01) and intermittent ponor cave (Markov Spodmol – reg. no. 878; Fig. 1.01), the caves Vodna jamav Lozi or (abb.) Vodna jama (reg. no. 911; Fig. 1.01), Šimčev Spodmol (reg. no. 931; Fig. 1.01), Spodmol v Selški Lozi or (abb.) Spodmol Loza (reg. no. 1573; Fig. 1.01) and Unroofed cave Loza or (abb.) Unroofed cave (Fig. 1.01). Caves Markov Spodmol and Vodna jama were formed under phreatic conditions (proven by typical scallops) and together represent a 7.7 km long active cave. It is partially filled with water and occasionally flooded, whereas, in some other parts, former paragenetic activity can be observed (Švara et al., 2022) (Fig. 1.03c). The entrance to Vodna jama is vertical, through a 43 m deep shaft. As a side passage of the unroofed cave is the Spodmol Loza, a small horizontal cave with only a 1-2 m thick ceiling, located 120 m NE of the main channel (Fig. 1.01), the floor of which is filled with allogenic cave sediments. The uppermost part of the cave system is the longest denuded cave remnant in Slovenia i.e. the Unroofed cave Loza (Fig. 1.01), exposed on the surface as a 4.3 km long cave channel, filled with cave sediments (Mihevc, 1999, 2006; Švara et al., 2022).

Table 1.01: Loza Cave System - altitudes of cave entrances and segments (see locations in Fig. 1.01).

Reg. No.	name of the cave/segment	altitude [m] a.s.l.	approximated height difference [m]	system levels	Exc. stop
-	Unroofed cave	600 - 620	-	3rd level	4
1573	Spodmol Loza – entrance	610	-		5
931	Šimčev Spodmol – entrance	584	30		-
-	Šimčev Spodmol – cave horizontal passage	555		2nd level	-
-	Šimčev Spodmol – shaft entrance	589	30	-	-
878	Markov Spodmol – entrance	560		1st / 2nd level	3
911	Vodna jama – entrance	563	40	1st level	-
-	Vodna jama – horizontal passage	520			-
904	Požiralnik pred Markovim Spodmolom	556	-		2

MARKOV SPODMOL AND VODNA JAMA V LOZI

The cave Markov Spodmol has its entrance at the end of the Sajevško polje blind valley. The cave is 868 m long and 61 m deep and consistent with the cave type of a horizontal intermittent ponor, which acts as a ponor of Rakuliščica only exceptionally and when the water level is very high. The ponor of the stream is now located 26 m N from the entrance to Markov spodmol (reg. no. 904) but was mainly regulated to the ponor further N (reg. no. 903). The wide entrance to the cave is followed by a horizontal dry passage with small lakes (Fig. 1.05a), which vary according to the amount of precipitation. After about 550 m this passage ends with a siphon. The walls and ceiling of the cave passage are full of phreatic relief features (e.g. scallops, pendants; Slabe, 1995). Allogenic sediments are preserved mainly in the higher levels of the passage within several meters of high accumulations (Zupan Hajna et al., 2020; Švara et al., 2021).

The SE part of the cave system is represented by the cave Vodna jama. At about 40 m from the surface entrance, the subhorizontal part is represented by 6,9 km long channels mostly filled by water. A short horizontal passage following the vertical entrance is accessible only with caving equipment when the water level is low. This part is characterized by fine clastic sediment accumulations that cover most of the cave, as fluctuations in the water table still occur. Walls, ceilings, and speleothems are covered with sediments from the last floodings, while ceiling pendants and anastomoses are exposed in some places (Fig. 1.03c). The driest part of the cave (close to Markov Spodmol) can be reached only by divers.

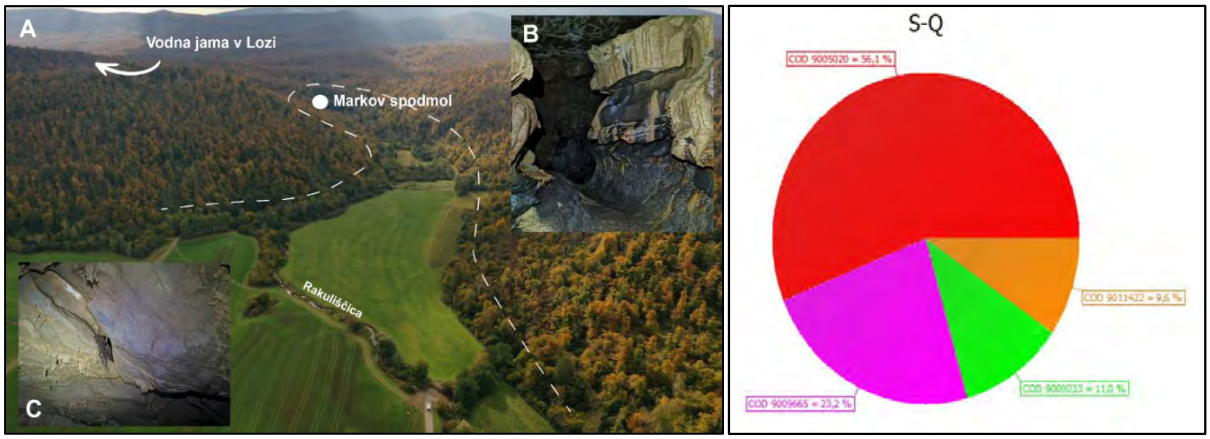


Fig. 1.03: (a) Sajevško polje blind valley photographed towards S; (b) ceiling pendants in Markov Spodmol; (c) anastomoses in Vodna jama v Lozi (Photo: A. Švara, RI-SI drone) – left; XRD results of the semi-quantitative analysis of a sample from the allogenic profile of Markov spodmol: quartz (56.1 %), illite (23.2 %), chlorites (11.0 %) and plagioclase (9.6 %) – right.

Markov spodmol cave encloses older allogenic sediment sections with fine clastic sediments mainly filling side passages at higher elevations as well as younger sediments mainly in the form of sandstone pebbles and wooden debris, filling the riverbed, brought recently by the Rakuliščica stream. The older allogenic sediment is mostly deposited as slackwater facies of a shallow epiphreatic zone. Mineralogical analyses of the allogenic sediment section (Zupan Hajna et al. 2008, 2020) reveal, that more than 50% of the sediment sample is composed of quartz, while the rest of the composition belongs to illite, chlorites and plagioclase (Fig. 1.03 – right).

A dated section of allogenic sediments (Zupan Hajna et al. 2008, 2020) shows that deposition in the Markov spodmol occurred in 2 distinct periods, lower sediment layers are older than 3.34 – 3.60 Ma and upper layers are younger than 0.78 Ma. The two-phased allogenic sedimentation was followed by sedimentation under more vadose conditions with occasional epiphreatic water pulses (Švara et al., 2023 – for publication).

HYDROLOGICAL INVESTIGATIONS IN THE REGION OF SLAVINSKI RAVNIK

The hydrology of the cave system Vodna jama - Markov Spodmol is very interesting. Indeed, results from a tracer test released in the stream flowing toward Markov Spodmol (Habič, 1989) proved that the region of Slavinski Ravnik drains toward the aquifer of the Reka River and further the Timavo Springs. Thus, the area belongs to the watershed of the Adriatic Sea despite being in direct contact with the western border of the Pivka Valley, which drain toward the Black Sea. This result was confirmed later by speleobiological analyses (Konec et al., 2016). These authors compared the aquatic fauna found in the cave system Vodna jama - Markov Spodmol with other water active caves located in the catchments of the Reka and Ljubljanica Rivers. They found out that one species of crustacean dwelling in the cave system Vodna jama - Markov Spodmol was genetically belonging to the group found in the aquifer of the subterranean Reka River.

Fig. 1.04: Lidar of the region of Slavinski Ravnik with locations of the three hydrological stations that have been installed – left; hydrological station measuring water level, specific electric conductivity (SEC) and water temperature in the northern part of the cave Vodna Jama v Lozi (Photo: C. Mayaud) – right.

In order to understand the hydrology of the cave system Vodna jama - Markov Spodmol, three stations measuring water level, specific hydraulic conductivity (SEC) and water temperature at a half hourly interval have been installed since Spring 2022 (Fig. 1.04 – left). The data have not been collected at the moment but will be the first continuous hydrological measures implemented in both caves. They will be compared with hydrological data measured in the Upper Pivka Valley (excursion B) and in the catchment of the Reka River, which will contribute to improving the understanding of the functioning of the cave system at both local and regional scales. Finally, water level and specific electric conductivity (SEC) records are expected to provide substantial information on the dynamic of sediment deposition during flood events.

Fig. 1.05: Measuring specific electric conductivity (SEC) and water temperature along the main conduit in the cave Markov Spodmol (Photo: U. Kunaver) – left; flooded swallow hole in front of the cave Markov Spodmol in November 2021 (Photo: C. Mayaud) – right.

OUTCROP OF COLOURED CHERT PEBBLES

In the following of the Sajevško polje blind valley and its active and relict ponors, the Slavinski ravnik quickly arises, where allogenic sediments frequently appear as outcrops of past cave sediments. At the SE from the Biščevci blind valley and SW of the Sajevše blind valley, a segment of an unroofed cave can be observed (Fig. 1.01; Stop 4). Due to its geomorphological position it suggests the possibility of an occurrence of a ponor cave, once draining the Biščevci blind valley, where water followed the path towards the Loza Cave System from the NW.

The outcrop is composed out of chert pebbles of various colours, sizes and shapes (Fig. 1.06 – left), which upwards finishes with an *in-situ* speleothem deposition (Fig. 1.06 – right). Two speleothem samples were dated with U-Th that revealed, the close cave setting with speleothem deposition occurred at least between 487 ka and > 1.2 Ma ago (Švara et al., 2023 – for publication).

Fig. 1.06: Coloured chert pebbles within the sampling site SSA_SS4 – left; flowstone above the chert outcrop – right (Foto: A. Švara).

NOTICE! The pebble deposit is exceptional in terms of quantity, different sizes and colours of the pebbles and, above all, their age and origin. For this reason, we have proposed the site for inclusion in the List of natural values of Slovenia. So please, do not pick up the pebbles!

UNROOFED CAVE LOZA

The Unroofed cave Loza (Stop 5) is geomorphologically divided in the bottom of the passage (mostly levelled and filled with a variety of sediments; Fig. 1.07) and slope with rim (cave walls and rock rubble from the decomposition of the cave ceiling). From the 1st February 2019, it represents a natural value of national significance. Slope inclination calculations were done in three segments of the Unroofed cave (Table 1.02). The highest is the N segment, while the S segment shows the lowest elevations. The walls of the Unroofed cave are less expressed in the N parts where the cave passage is difficult to detect and the overall allogenic sediment at the surface increases with the proximity of the basin. Slope analyses revealed the steepest inclinations are preserved towards S of the Unroofed cave, while the N segment shows lower mean slope values (Table 1.02). Therefore, surface morphological analyses revealed a slight inclination from the N to the S, as is also the surface of Slavinski ravnik, where the elevation differences in the extremities are about 40 m (Table 1.02). The

walls are more preserved (i.e. slopes are greater) further S (Table 1.02), where the occurrence of collapse material increases (Švara et al., 2023 – for publication).

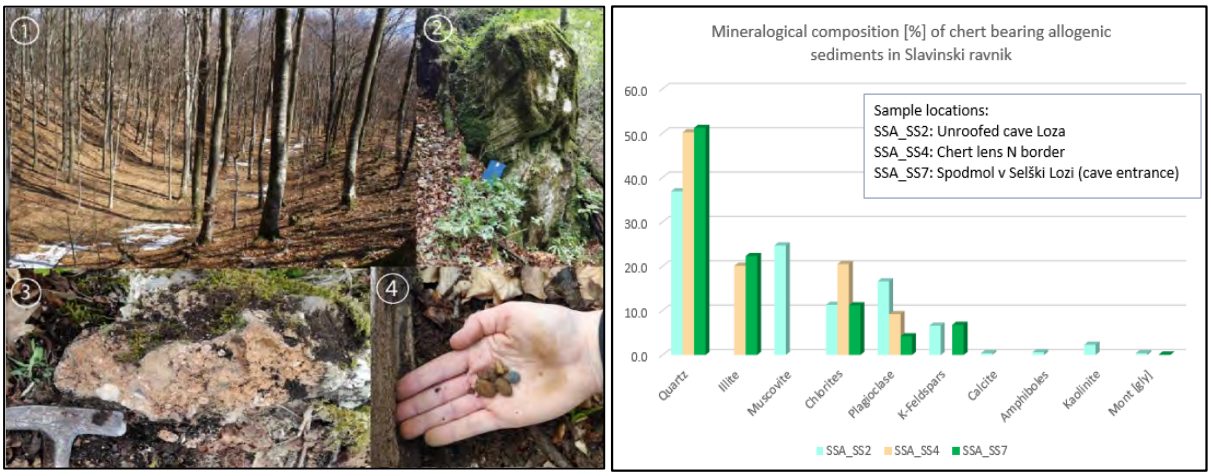


Fig. 1.07: Unroofed cave Loza; (1) the central segment of the channel (Photo: A. Mihevc); (2) fallen stalactite; (3) cemented cave sediment, (4) chert pebbles (Photo: A. Švara) – left; comparison of the mineralogical composition [%] of chert bearing sample locations of the Slavinski ravnik, i.e. Unroofed cave Loza (SS2), Chert outcrop (SS4) and Spodmol v Selški Lozi (SS7) – right.

Table 1.02: Slope inclinations and altitudes of the Unroofed cave segments.

Unroofed cave segment	WGS84 coo. [°E]	WGS84 coo. [°N]	min slope [°]	max slope [°]	mean slope [°]	min alt. [m] a.s.l.	max alt. [m] a.s.l.	mean alt. [m] a.s.l.
north	14.0954	45.7353	0.1	51	18	592	669	631
	14.1097	45.7292						
central	14.1097	45.7292	0.02	81	21	580	650	610
	14.1232	45.7192						
south	14.1232	45.7192	0.2	71	20	567	621	591
	14.1341	45.7106						

The allogenic sediment fill, the morphology of the unroofed cave passage and the proximity of active cave passages were studied with two geophysical methods, i.e. ERT – Electric Resistivity Tomography and GPR – Ground Penetrating Radar. In combination, these two methods can help to understand the connection between surface and subsurface geomorphological forms with a non-invasive approach and in some hard-accessible areas (e.g. Stepišnik & Mihevc, 2008; Čeru & Gosar, 2019). Among 6 ERT and 6 GPR profiles that were studied in the past two years, one profile of both methods was selected for further analysis and interpretation (i.e. profile P1), located at the southernmost part of the Unroofed cave, at the intersection of the unroofed passage and the cave Šimčev Spodmol. A 50 Mhz and a 250 Mhz GPR antennas were used, while with the ERT machine, a setting with 28 electrodes with a 5 m spacing with a dipole-dipole array was used. With both methods, the expected cave passage filled with sediments was observed, while the morphology of the unroofed passage was detected, where the sediment fill was composed out of allogenic sediments and cave rubble/boulders as remains from the cave decomposition. The thickness of the sediment fill in this location was about 20 m, which represents the thickest sediment fill of the Unroofed cave.

During mineralogical studies, 5 sedimentological boreholes were taken with a hand-drilling tool along the main channel of the Unroofed cave Loza. The mineralogical analyses and comparison between borehole samples revealed an increasing quartz content with distance from the ponor point, i.e. Postojna basin. Generally, the southernmost parts of the Unroofed cave contain > 50 % of quartz, while the mean mineralogical composition reveal the majority of samples are composed of quartz (35 %) and muscovite (23 %), followed by plagioclase (15 %), chlorites (11 %) and K-Feldspars (7 %), followed by calcite, amphiboles, kaolinite and montmorillionite in traces (Fig. 1.07 – right).

SPODMOL V SELŠKI LOZI

Spodmol v Selški Lozi (reg. no. 1573; Stop 6) is an almost unroofed side passage of the Unroofed cave (Fig. 1.08), with a levelled floor filled with allogenic sediments and a levelled ceiling. In 2016, a trench was dug up and a cave allogenic section was revealed (Fig. 1.08 – right), sampled for paleomagnetic analyses (Zupan Hajna et al., 2020). The age of the sedimentation was estimated to be 4 Ma (Zupan Hajna et al., 2020). The re-calculation of data with the recent methodology revealed, that the date of deposition is much older than previously thought, confirmed by the clockwise rotation of normal polarity samples. The U-Th analyses of a speleothem sample confirmed, the cave was closed with a thicker ceiling and percolating water activity at least until 205 ka ago (Švara et al., 2023 – for publication).

Fig. 1.08: Entrance to Spodmol Loza with (A) the location of the sedimentological section sampled for paleomagnetic analyses and (B) the location of speleothem sample SL dated with U-Th– left; the 2 m thick allogenic section – right; (Photo: N. Zupan Hajna).

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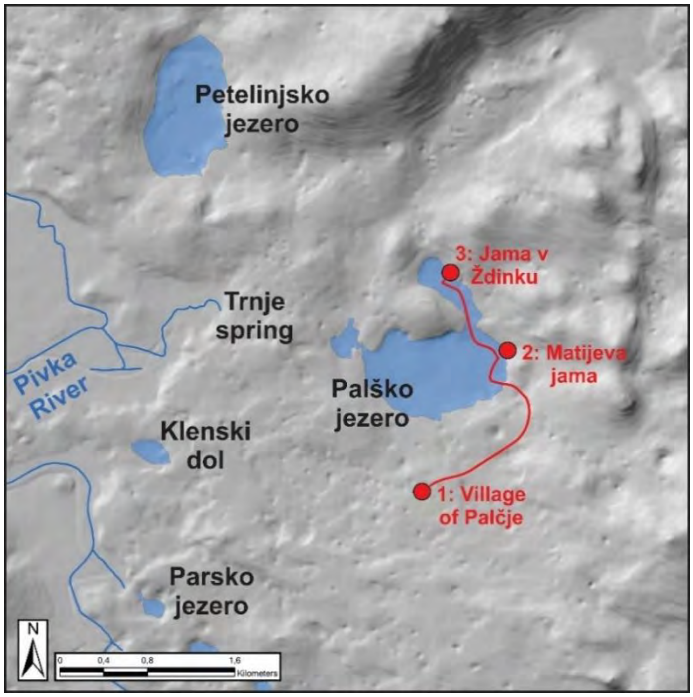
Afternoon field trip (B):

HYDROGEOLOGY OF THE UPPER PIVKA VALLEY. THE CAVE JAMA V ŽDINKU - A POTENTIAL DRINKING WATER RESOURCE?

Wednesday, 21st June 2023, 14:30–20:00

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

Stops:
1 – Village of Palčje – Geology and hydrogeology of the Upper Pivka Valley
2 – The intermittent lake Palško jezero and the cave Matijeva jama
3 – Monitoring the cave jama v Ždinku



Hidrogeologija Zgornje Pivške doline

Popoldansko terensko delo (B); sredo, 21. junij 2023

Poseben hidrološki pojav zahodnega dela kraškega masiva Javornikov so presihajoča Pivška jezera. Za celotno območje je značilna interakcija podzemnih in površinskih voda. V kraškem vodonosniku se vode pretakajo večinoma podzemno, ob močnejših in dolgotrajnejših padavinah pa se nivo podzemne vode dvigne in voda se na številnih mestih preliva na površje. Tako postanejo aktivni občasni kraški izviri ob reki Pivki, z vodo pa se napolnijo tudi kraške globeli in nastane lahko do 17 presihajočih kraških jezer. Nekatera se pojavljajo dokaj pogosto in imajo vodo tudi do pol leta, večinoma pa nastanejo bolj poredko, z vodo pa so zalite le kratek čas ob močnejših poplavah. Vodne jame so na tem območju redek, a dragoceni vir informacij o podzemni vodi. Iz nekaterih so v preteklosti črpali vodo za oskrbo, sedaj pa preverjamo možnosti za njihovo ponovno vključitev kot rezervni vodni vir. Ena takšnih je tudi Matijeva jama, ki leži na vzhodnem robu Palškega jezera. Del nedavnih raziskav je še Jama v Ždinku, ki se nahaja v njeni bližini. V okviru ekskurzije bomo predstavili hidrogeološke značilnosti Palškega jezera in estavel ob robu jezera ter možnosti za rabo vode na tem območju. Podrobno bomo predstavili analize kakovosti vode in druge hidrološke raziskave, ki jih opravljamo v omenjenih jamah. Te vključujejo merjenje vodostajev, temperature in elektroprevodnosti vode. V Jami v Ždinku so nam s pomočjo AquaTrolla merjene vrednosti neposredno dostopne, posebej pa se osredotočamo na nizke vodostaje, ki so pomembni z vidika zagotavljanja varne vodooskrbe.

INTRODUCTION

The Pivka Valley is a large depression laying between the high karst plateaus of the Slovene Dinaric Karst (Nanos, Hrušica, Javorniki; all ~1250 m asl), the lower plateau of Slavenski Ravnik (600 – 700 m asl) and the Snežnik Mountain (1796 m asl). The northern part of the valley, i.e., the Lower Pivka Valley consists of noncarbonate flysch rocks, where superficial drainage prevails. The southern part, i.e., the Upper Pivka Valley is constituted of carbonate Cretaceous layers belonging to the Snežnik thrust sheet that lies over the Palaeocene and Eocene layers of the Komen thrust sheet. The displacement of the Snežnik thrust sheet over the Komen one is estimated to be of about seven kilometres. However, the intensity of the thrusting is less distinctive towards the northwest (Placer 1981).

From a hydrological point of view, the most significant unit is the Javorniki-Snežnik plateau, which is a deep diffuse karst. It is characterised by an immediate infiltration of rainwater underground and fast vertical drainage in different directions towards the springs located on the border of the plateau, where the groundwater generally flows rapidly through karst conduits. Consequently, the Javorniki-Snežnik massif drains towards both Adriatic and Black Seas (Fig. 2.01). The southeastern part of the massif drains in the direction of Croatia and the Riječina River (Biondić et al. 2004; Prestor et al. 2004), whereas the northeastern part belongs to the recharge area of the Ljubljanica River (Habič 1989; Kogovšek et al. 1999; Petrič et al. 2018). In addition, the northern part of the massif also partly drains towards the Vipava springs via several swallow holes (Habič 1989; Kogovšek et al. 1999). Finally, the southwestern part of the massif belongs to the catchment of the Reka River (Habič 1989; Kogovšek 1999; Ravbar & Goldscheider 2007).

In the west of the Upper Pivka Valley, the flysch layer acts as an impermeable barrier for the groundwater that runs from the Javorniki-Snežnik massif (Figs. 2.01 & 2.02). This partly prevents its draining towards the Reka River. Therefore, the major part of the water coming from under the Snežnik Mountain rebounds against the flysch barrier and flows northwards towards the Pivka spring, and further to the Unica and Malenščica springs that recharge Planinsko Polje (Petrič & Kogovšek 2005, Petrič et al. 2018). The underground water level strongly oscillates depending from precipitation and snowmelt: at low water conditions, the hydraulic gradient is inclined solely towards Cerkniško and Planinsko poljes, whereas it is also inclined towards the Pivka Valley at high water levels (Gospodarič 1989).

HYDROGEOLOGY OF THE UPPER PIVKA VALLEY

Because of the underlying flysch rocks, a shallow karst aquifer exists below the Upper Pivka Valley (Fig. 2.02). Under low water conditions, the Upper Pivka Valley is dry and water is assumed to flow towards the Javorniki Mountains to reach the Unica and Malenščica springs. When a hydrological event occurs, the regional groundwater level can rise for more than 50 m and the Pivka River emerges (Figs. 2.03 & 2.04), reaching discharges surpassing 20-25 m^3/s at the gauging station of Prestranek. Up to 17 intermittent lakes might appear due to the rise of the regional groundwater level. In addition, several temporary springs recharging the Pivka River and/or the intermittent lakes are also activated (Kovačič & Habič 2005). Finally, innumerable fissures and voids pour out water from the aquifer and contribute to flood the Valley's depressions. During recession periods, the water sinks back to the underground through the same fissures and voids, which consequently act as small estavelles and greatly contribute to empty the intermittent lakes. Additionally, numerous

swallow holes are activated. Finally, the Pivka River also seeps and sinks underground at different locations in its riverbed.

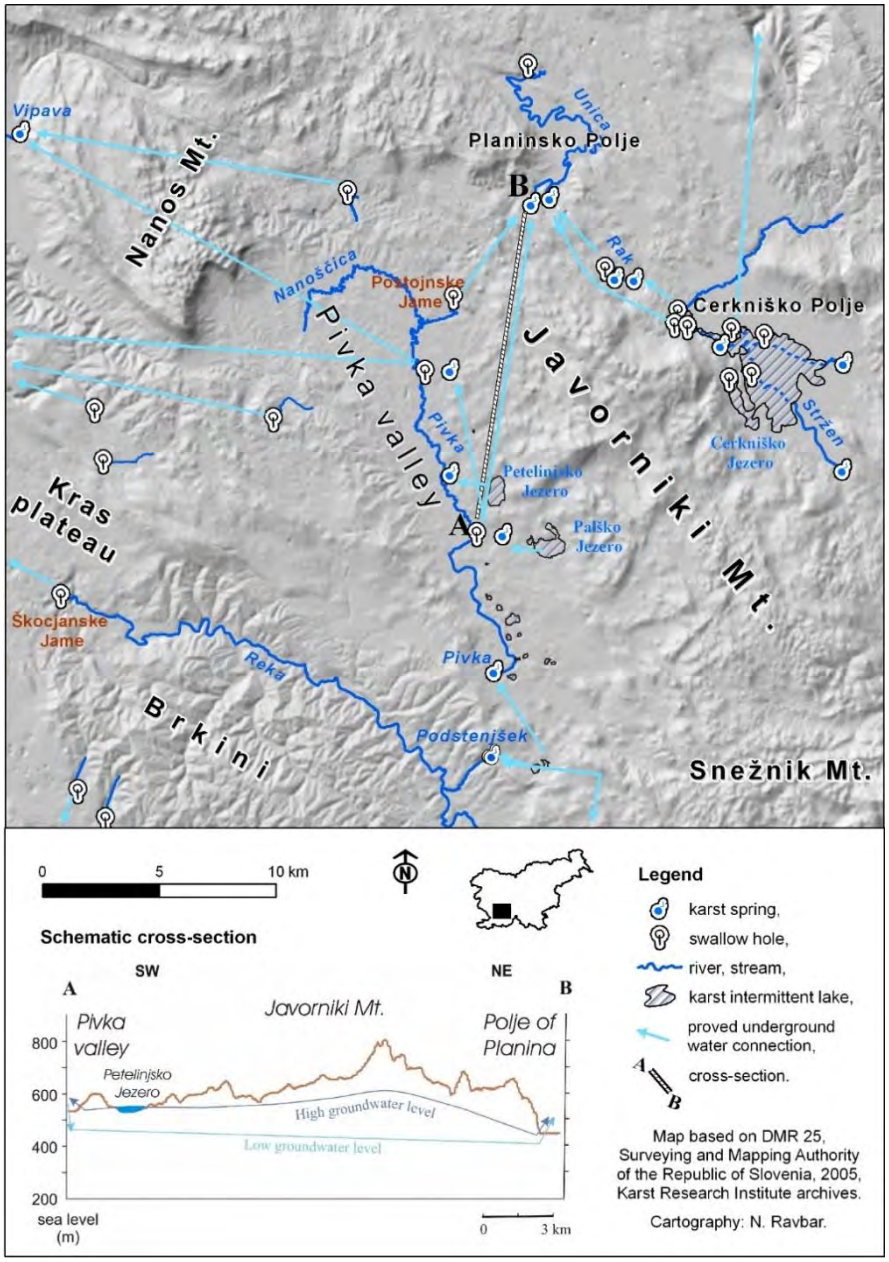


Fig. 2.01: Hydrological map of the region around the Upper Pivka Valley with the underground connections proved by tracer tests, and a schematic cross-section of the area during low- and high-water conditions (Ravbar 2013).

As the Karst Research Institute is involved in the search for a backup drinking water supply for the municipalities of Postojna and Pivka (21.000 inhabitants), hydrogeological investigations in the Upper Pivka Valley started again in Autumn 2016. The cave Matijeva jama was one of the locations selected as a potentially promising candidate due its location upward the main sources of pollution and because water is permanently standing in its large siphon. Therefore, a hydrogeological station measuring automatically the water level, specific electric conductivity (SEC) and water temperature at a 30 min interval had been installed in the siphon of Matijeva jama in October 2016. This station remained the only one installed in the Upper Pivka Valley until August 2018, when

another monitoring station was mounted in the cave jama v Ždinku within the frame of a pumping test investigating the reaction of Matijeva jama under low water levels. However, a malfunction of the data logger recording the pressure prevented retrieving the first year of water levels in jama v Ždinku. Therefore, effective water levels measurements in this cave started only after August 2019.

Since October 2019, the monitoring network operating in the Upper Pivka Valley has been considerably extended to reach currently nine stations monitoring water levels and temperature at a half hour interval (Figs. 2.02 & 2.03). The first station was installed in Petelinjsko jezero, followed by the Trnje spring in June 2020. In February 2021, monitoring was extended again with the installation of two stations in Parsko jezero and at the Mišnik spring, while Malo Drškovsko jezero was monitored for the first time in May 2021. Finally, the borehole of Žeje and the Pivka spring were respectively equipped in March and September 2022. By being the northern and southernmost monitored points, these stations improved the geographical coverage of the monitoring network. Finally, specific electric conductivity is also monitored additionally to water level and temperature at the stations Trnje spring, Parsko jezero, Mišnik spring and at the Pivka spring. These data are interpreted together with the conductivity measured in Matijeva jama and jama v Ždinku.

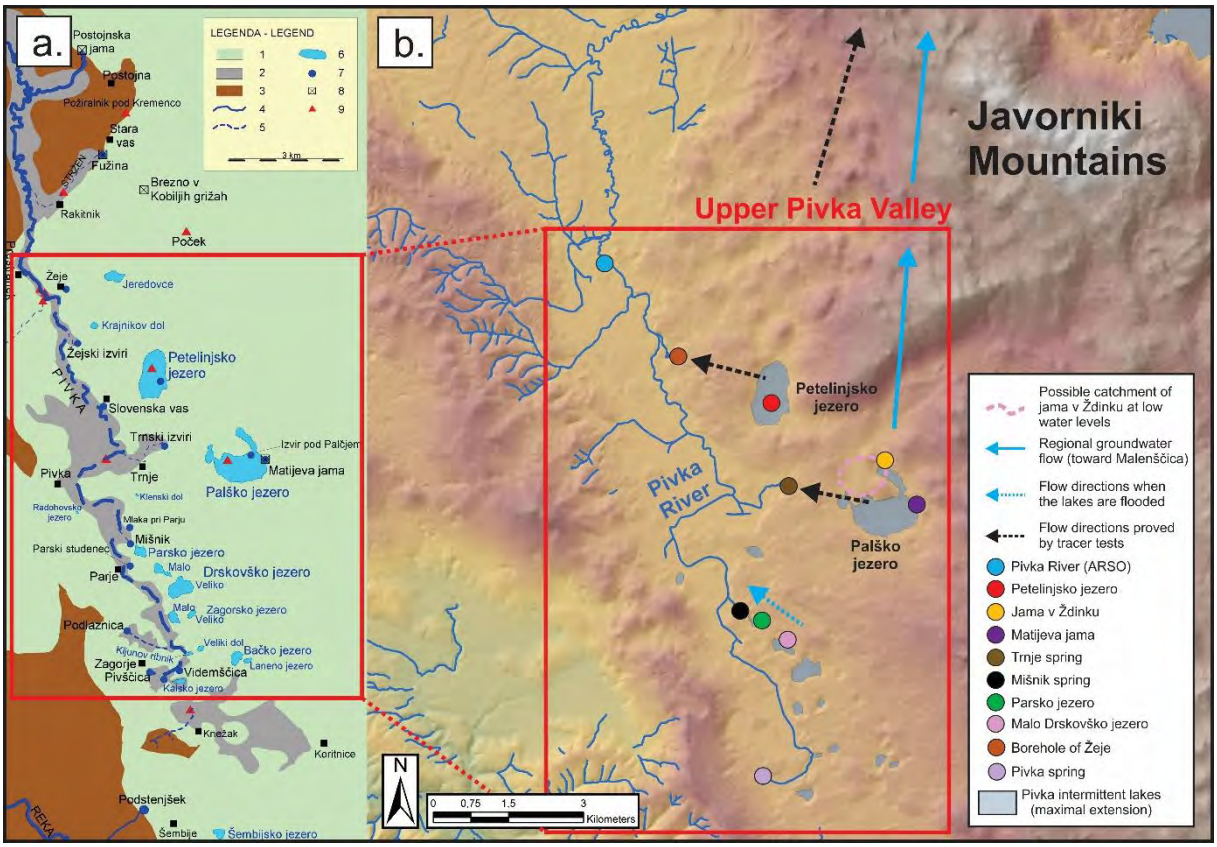


Fig. 2.02: (a) Hydrogeological map of the Pivka Valley (Petrič & Kogovšek 2005). Legend: 1. Karst aquifer, 2. Porous aquifer, 3. Very low permeable rocks, 4. Surface flow, 5. Intermittent surface flow, 6. Intermittent lake, 7. Major spring, 8. Water cave, 9. Injection point. (b) Map presenting the monitoring network currently installed in the Upper Pivka Valley. The maximum extension of the intermittent lakes is drawn after Ravbar et al. (2021).

Because water is temporarily present at the surface of the Upper Pivka Valley, the stations Petelinjsko jezero, Trnje spring, Parsko jezero, Mišnik spring and Malo Drskovško jezero record only the hydrogeological fluctuations occurring during high water periods (Figs. 2.03 & 2.04). Therefore, it has to be kept in mind that the hydrological signal recorded at the surface provides only a partial information compared to the data recorded by the stations located within the aquifer. Moreover, the

lack of appropriate places to fix the data-loggers in the intermittent lakes implies to install the stations only when a high-water period is forecasted. This happens mostly in a period going from autumn to late spring.

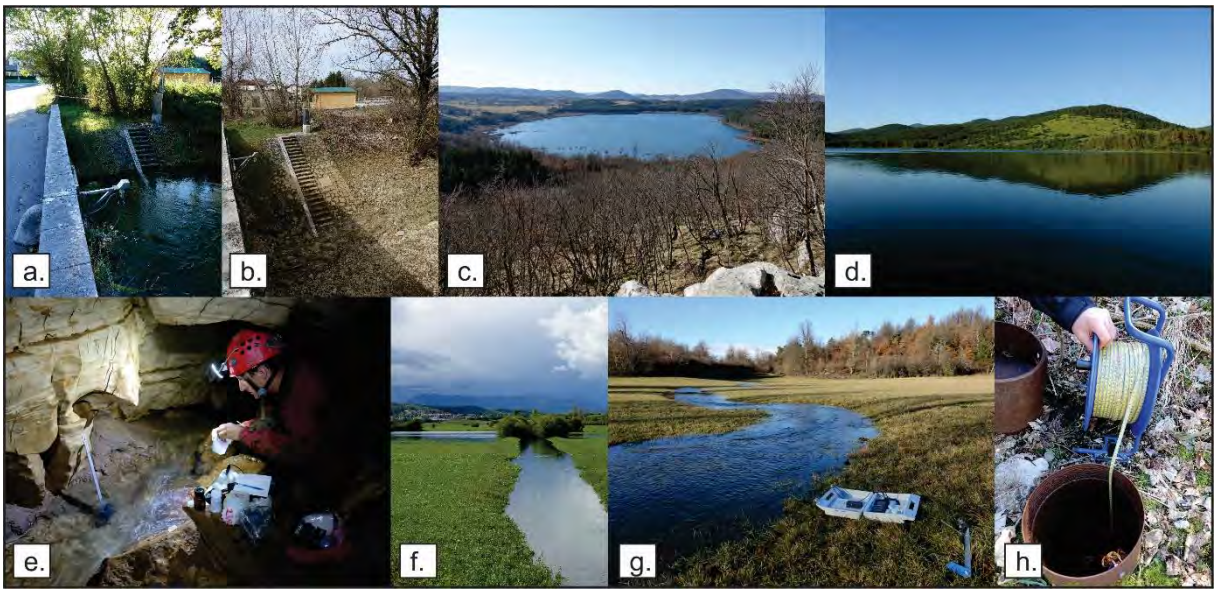


Fig. 2.03: Field impressions of the Upper Pivka Valley (Photos: C. Mayaud). (a) The Pivka River at the station of Prestranek (owned by the Slovenian Environment Agency, ARSO) during a flood. (b) The same station at low water conditions. (c) Flooded Palško jezero. (d) Flooded Petelinjsko jezero. (e) Water sampling in jama v Ždinku. (f) The Mišnik spring during a flood. (g) Parsko jezero at the beginning of a flood. (h) The borehole of Žeje.

Fig. 2.04 shows the water levels recorded in the Upper Pivka Valley for the period going from February to June 2022. On the one hand, the three stations located in the aquifer present important water level fluctuations, which can reach more than 50 m during the strongest floods (Kovačič & Habič, 2005). The similar reaction of these stations proves that the rise of water level is occurring homogeneously at a regional scale. On the other hand, the stations installed in the intermittent lakes and temporary springs activate simultaneously with the rise of water level in the aquifer. However, their behavior during the recession is different, as they last longer at higher level that the stations located in the aquifer. Such difference can be of about two weeks for Petelinjsko jezero and surpass 10 days for the Mišnik spring. The main explanation is that the decrease of the hydraulic gradient reverses the main flow direction underground toward the Javorniki mountains and the Malenščica spring, even if an effect of the alluvial sediments present on the valley floor on the recession should be acknowledged. Finally, the dataset monitored at the Pivka spring will be recovered for the first time in summer 2023. These data are expected to provide meaningful information on the water level fluctuations in the aquifer upper parts.

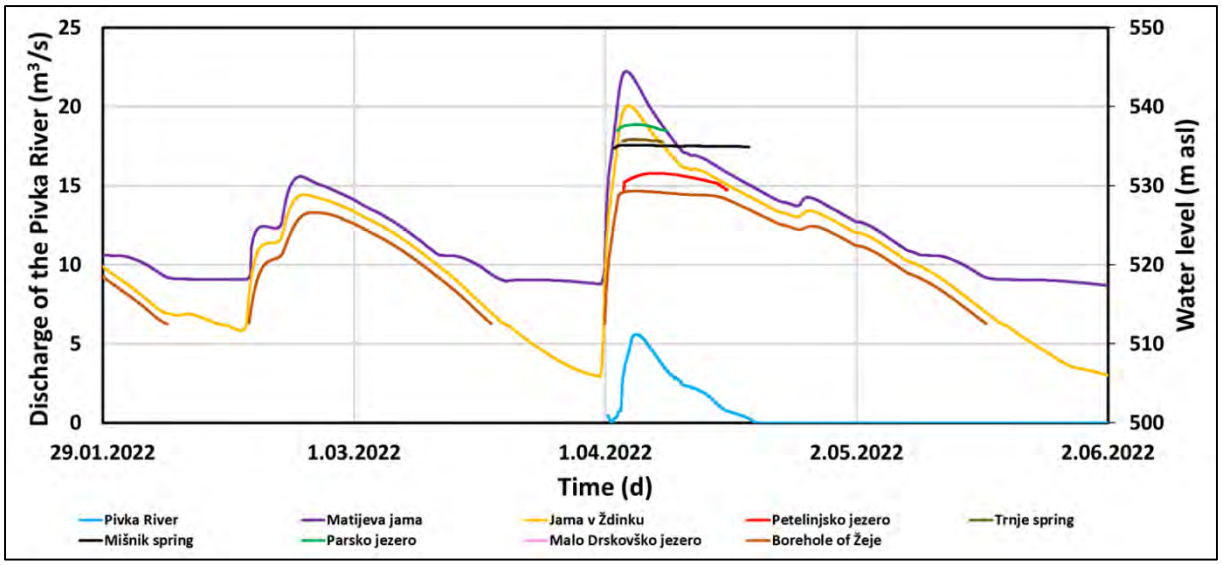


Fig. 2.04: Water level dynamics recorded in the Upper Pivka Valley during the period going from February to June 2022.

THE INTERMITTENT LAKES OF THE UPPER PIVKA VALLEY

The intermittent lakes of the Upper Pivka Valley appear simultaneously with the rise of the regional groundwater level (Figs. 2.02 &Fig. 2.04). The two largest of them are Palško jezero and Petelinjsko jezero, which can respectively cover a maximum flooded surface of about ~1.9 km^2 and ~0.7 km^2 (Kovačič & Habič, 2005). In addition, numerous smaller lakes extend over a few hectares (Ravbar & Šebela 2004). The flood duration and frequency are specific for each lake, mostly depending on the yearly amount of precipitation, on the elevation of the lake bottom and of its location in the valley. Some of the lakes may appear several times per year, while others occur only during exceptionally wet periods, maybe a few times in a decade (Kovačič & Habič 2005; Kirn 2016; Ravbar et al. 2021). Among others, Petelinjsko jezero is the lake with the longest flooding duration, which can last for more than 200 days per year. The flooding duration of the four intermittent lakes monitored is presented in Tab. 2.01 for the hydrological years 2021-2022 and 2022-2023. As it can be seen, the important difference in total precipitation (855 mm registered in 2021 – 2022 opposed to the 1156 mm registered from the 31.08.2022 to the 30.04.2023) strongly correlate with the number of days flooded. Therefore, the flooding duration is up to four times longer for Petelinjsko jezero and Parsko jezero in 2022-2023. Similarly, while Malo Drskovško jezero remained dry in 2021-2022, it was flooded for one and half month in 2022-2023. Such difference in flooding duration shows the extreme importance of the precipitation regime on the appearance of the lakes, which might greatly affect this water-sensitive ecosystem (Ravbar & Pipan 2022). Indeed, many animal and vegetal species rely on the appearance of water to survive.

Hydrological year	01.09.2021 – 31.08.2022	01.09.2022 – 30.04.2023 (ongoing)
Total precipitation (mm)	855	1156
Lake name	**Number of days flooded**	
Petelinjsko jezero	46	147
Palško jezero	1	data currently not available
Parsko jezero	20	87
Malo Drskovško jezero	0	47

Tab. 2.01: Total yearly precipitation measured at the Postojna rain gauge and flooding duration of the lakes Petelinjsko jezero, Palško jezero, Parsko jezero and Malo Drskovško jezero during the hydrological years 2021-2022 and 2022-2023.

Many intermittent lakes represent a unique and precious type of karst groundwater dependent ecosystem. Indeed, floods represent a risk to human health, the environment and economic activity. For this reason, international treaties such as the Ramsar Convention on Wetlands, and regional legislative framework; such as the EU Water Framework Directive and the EU Floods Directive; envisage their management through the preparation of maps of inundation areas. Slovenia has a basis for this in the Water Act. The procedure for determination of intermittently flooded karst areas, which takes into account the extent, duration and frequency of flooding, includes the identification of data sources and processing methods proposed in Ravbar et al. 2021. Accordingly, a map of the flooded areas in the Upper Pivka Valley has been published in this work (Fig. 2.02).

Finally, the water balance of Petelinjsko jezero, Parsko jezero and Malo Drskovško jezero was computed for each recorded flood event (Fig. 2.05) using the technique presented in Mayaud et al. (2022). During the recorded period, the maximum inflow entering Petelinjsko jezero was of about 3.75 m^3/s, while its maximum outflow was of -2.65 m^3/s. For Parsko and Malo Drskovško jezero, these numbers were respectively smaller. The water balance of Palško jezero will be done in the future, as the rating curve of Matijeva jama has to be established at first.

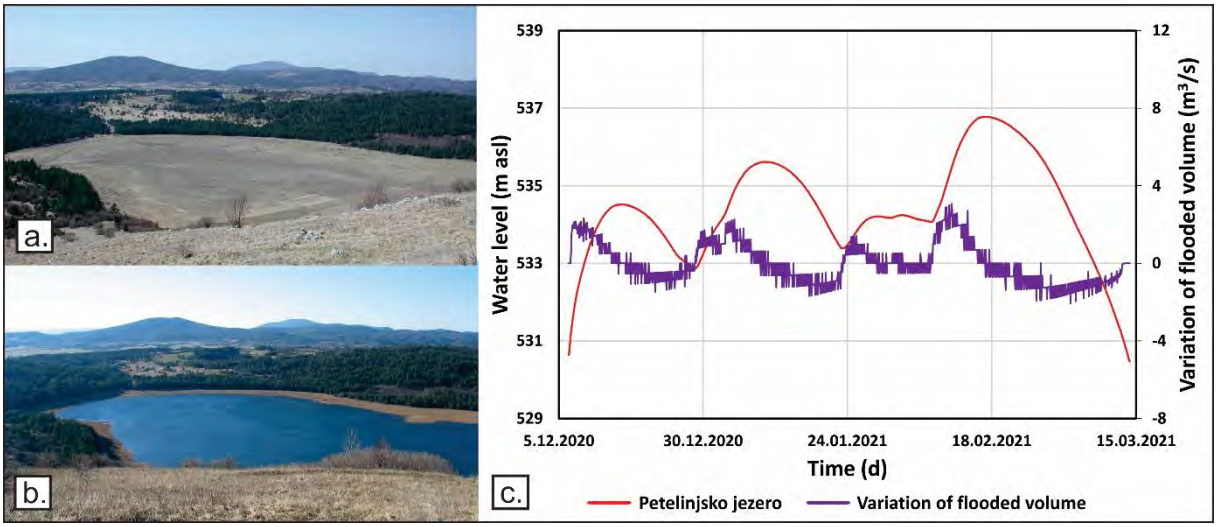


Fig. 2.05: The intermittent lake Petelinjsko jezero (for location see Figs. 2.01 & 2.02). (a) At low groundwater level, the karst hollow is dry. (b) When the groundwater level rises, the depression is flooded and forms a lake (Photos: N. Ravbar). (c) Water level and water balance of the lake for the flood going from December 2020 to March 2021.

THE CAVE MATIJEVA JAMA

Matijeva jama is a large estavelle located on the eastern side of Palško jezero that provides an important part of the lake inflow and outflow (Figs. 2.02 & 2.06). The cave entrance is a 2x2 m large opening, which continues with an approximately 20 m deep shaft. It is followed by a narrow passage that steps down to a larger hall (10x10x10 m) and ends with a siphon. At low water conditions, the water level is located at about 516 m asl. The water level fluctuations at this location might exceed almost 50 m and the cave is able to discharge or swallow several m^3/s of water depending on the hydrological situation (Kovačič & Habič 2005).

Between summer 2017 and summer 2022, four diving actions have been carried out in Matijeva jama (Fig. 2.06). The exploration showed that the cave has an about 100 m long first siphon that is followed by a larger room splitting into two branches. The northern branch terminates immediately with another siphon that is too narrow to be explored, whereas the southern branch ends with a shaft whose bottom goes below the level of the siphon. A team of three cave divers aimed to explore it in summer 2022, but had the surprise to find it without water due to extremely dry conditions. They were able to walk further in the horizontal passage for about 100 m, and were stopped by another 20 m deep shaft that had water at is bottom. Without this dive, the length of the newly explored part of the cave is of about 150 m, which makes the total length of the cave reaching 200 m (Fig. 2.06). Important perspectives for further exploration remain.

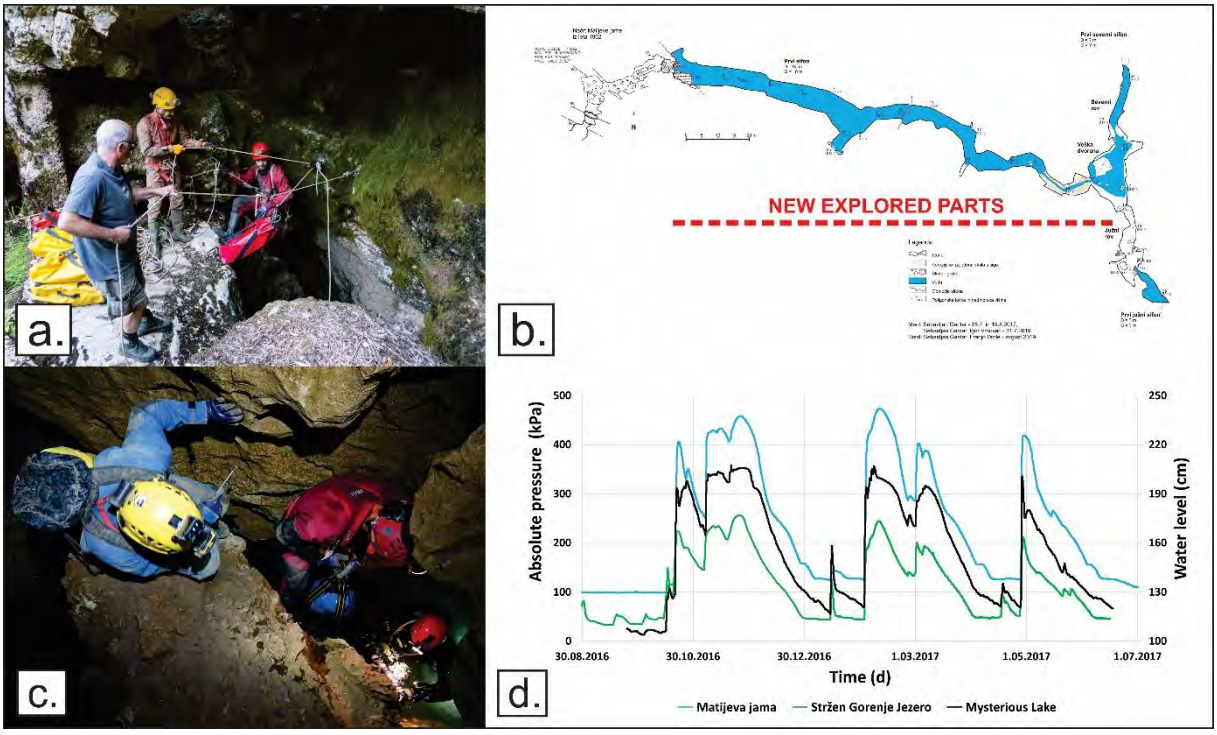


Fig. 2.06: (a) Entrance of Matijeva jama (Photo: B. Kogovšek). (b) Map of Matijeva jama showing the new parts of the cave that were explored during the dives of August 2017 and July 2019 (Cave Register 2023). (c) Diving action in July 2019 (Photo: C. Mayaud). (d) Water pressure registered in Matijeva jama compared to other monitoring stations located in Cerkniško polje and Planinska jama.

Up to eighteen high water periods where Palško jezero was partly or entirely flooded have been registered since August 2016. In general, the flooding begins with a steep rise of the water level in the siphon and responds fast to rain event (Fig. 2.06d). A comparison with other groundwater monitoring stations located on the eastern side of the Javorniki massif (Gorenje Jezero) as well as in

Planinska jama (Mysterious Lake) about 15 km northward, shows that all monitoring points react almost simultaneously, proving that they all belong to the same hydrogeological unit. Palško jezero starts to be flooded when the water level reaches the entrance of Matijeva jama at an elevation of 545 m asl. The flood in the lake can last from a few days to two months, reaching an altitude of 20 m above the cave entrance, as for the floods of December 2000 and February 2014 (Kovačič & Habič 2005; Kirn 2016).

PUMPING TEST IN THE FIRST SIPHON OF MATIJEVA JAMA

A pumping test was performed in Matijeva jama in August 2018 to determine if the siphon represents a perched water body and would be thus less convenient for water exploitation (Gabrovšek *et al.* 2019). Additional purposes were to determine the aquifer permeability as well as the size of the siphon and the rate of filling of the underground channels of Matijeva jama. In order to check if the pumped water would eventually flow back to the cave, and because we were interested in the hydraulic connection of the bottom of Palško jezero with Matijeva jama, a multi-tracer test was simultaneously carried out (Fig. 2.07).

The combined pumping and tracer test showed an immediate flow from the depleted water back into to cave, with a maximum recharge flowrate of almost 9 L/s arriving in the siphon. This proves that the bottom of Palško jezero, where agricultural activity predominates, is very well permeable and has a direct connection to the cave. As soon as the release location of the pumped water was prolonged farther away from the cave entrance (Fig. 2.07c), the recharge flowrate decreased to 0.6 L/s and the drawdown increased again.

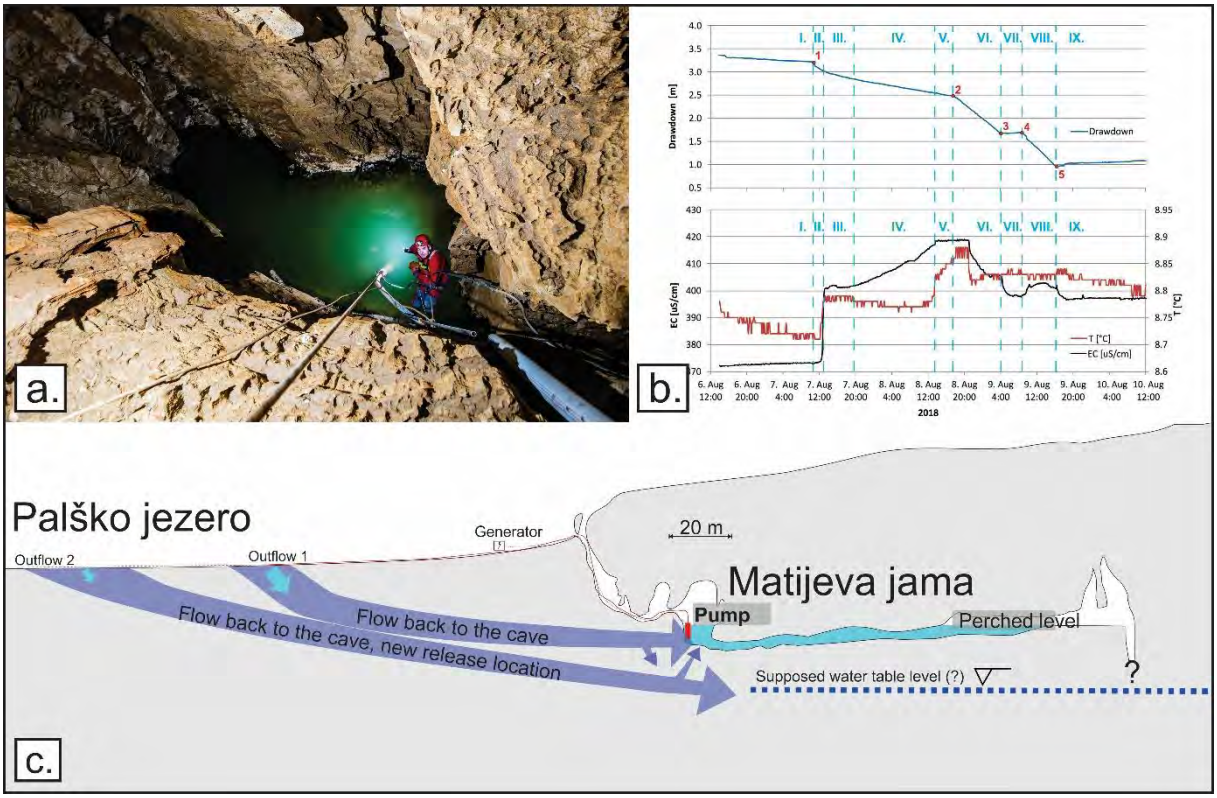


Fig. 2.07: Pumping test in Matijeva jama. (a) View of the siphon. (b) Drawdown and physico-chemical parameters monitored during the different pumping phases. (c) Cross-section of the conceptual hydrogeological model between Palško jezero and Matijeva jama during the pumping test.

The results of the pumping test showed that despite Matijeva jama belongs to the regional water body at high water level, the first siphon of the cave belongs to an isolated perched aquifer under low water conditions (Fig. 2.07). In addition, the proven connection of the siphon with the lake surface makes it vulnerable to any pollution that would occur in the lake vicinity. Therefore, the known water bodies of Matijeva jama are not suitable for exploitation.

MONITORING THE CAVE JAMA V ŽDINKU

Jama v Ždinku is located in a clearing approximately 900 m NW from Matijeva jama. The cave was explored during the pumping test implemented in Matijeva jama in August 2018, where all caves nearby were investigated to check for the presence of water. After discovering its hydrogeological importance, jama v Ždinku was immediately mapped and equipped with a data-logger measuring pressure, SEC and water temperature at a half-hour interval. The cave has a total length of 356 m and a depth of 43 m. The cave begins with a 10 m squeeze followed by a 20 m shaft. Then, a succession of narrow passages interrupted by several small chambers conduct to a 15 m long channel that ends into a collapse at the elevation of 503 m asl. A small stream remains active in this part of the cave during low water periods. Similarly, to Matijeva jama, jama v Ždinku acts as an estavelle. The water level dynamics in both caves is comparable, with an amplitude that might reach 50 m (Fig. 2.04). However, slight differences mostly due to the hydrogeological configuration of both caves exist at low and high water levels.

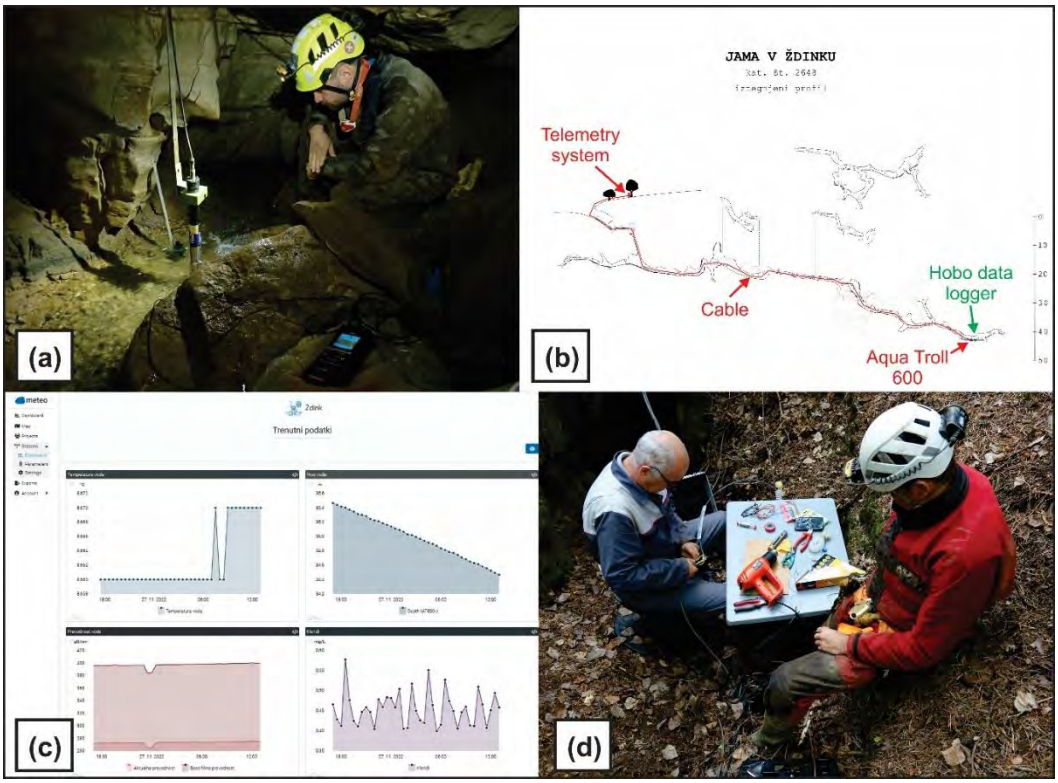


Fig. 2.08: (a) Aqua TROLL 600 multi-parameter probe installed in the active cave stream running at the bottom of jama v Ždinku. (b) Cave profile with location of the instrument and cable up to the surface. (c) Visualization of the recorded data on the website https://meteo.pileus.si/. (d) Maintenance work after the cable connecting the probe to the surface was cut by a wild animal.

Since August 2021, a multiparameter sonde Aqua TROLL 600 has been installed in the active cave stream flowing in the lower parts of jama v Ždinku (Fig. 2.08a). The instrument is fixed at the

same height than the data-loggers measuring since August 2018. Up to 9 parameters (namely water level, temperature, specific electric conductivity, turbidity, salinity, water density, TDS, chloride concentration and rhodamine WT concentration) are continuously measured at a half hourly interval. The probe transmits the recorded data to a VuLink telemetry system located above the cave entrance via a 200 m long cable (Fig. 2.08b). Then, the data are sent at a four-hour interval to an online database stored on the website https://meteo.pileus.si/, and can be accessed by a computer or a smartphone (Fig. 2.08c). The installation of the Aqua TROLL 600 allowed knowing the hydrogeological conditions in the aquifer in an almost-live situation. This is considerably helpful to know when a flood is going to occurs, as it provides crucial information to manage the monitoring network in the Upper Pivka Valley. However, the device is more sensitive than classical data-loggers, especially due to the cable transmitting the data to the surface. The latter was cut by a wild animal in August 2022 and needed some precautious maintenance to work again (Fig. 2.08d).

Period	Summer 2019	Summer 2020	Summer 2021	Summer 2022
Number of days when the water level was below 504.15 m asl	35>20.1	8.0	103.2	94.0

Tab. 2.02: Number of days where the water level in jama v Ždinku passed below the elevation of 504.15 m asl.

Because an active cave stream is still running in the lowest part of jama v Ždinku under low water conditions, this cave was viewed as a good candidate for being the back-up drinking water supply. Therefore, the hydrogeological investigations were completed by an assessment of the water quality and quantity. Discharge measurements of the stream implemented during each visit in the cave ranged between 60.5 L/s and 6.6 L/s. This variability shows the necessity to continue further the hydrogeological analyses to better understand the behavior of the cave and evaluate the sustainability of its groundwater reserves.

Such observation is supported by an analysis of the recorded low water levels (Tab. 2.02). During the summer 2021, the lowest level was of 2.8 cm above the sensor. As the smallest recorded discharge corresponds to a level of 10.8 cm, it can be concluded that the discharge of the cave stream should have been significantly smaller than 6.6 L/s at that time. However, it is surprising to note that the stream remained active after 100 days under extremely low levels. Conversely, the access to the stream at the bottom of jama v Ždinku can become questionable when the hydrological year has a total amount of precipitation significantly higher. This happened in summer 2020 where the water level was only 8 days below 504.15 m asl (Tab. 2.02). Such hydrogeological situation gives only a short interval to access the data logger and retrieve the data.

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Whole-day field trip (C):

ŠKOCJANSKE JAME: CAVES AND KARST CASE STUDIES

Thursday, 22nd June 2023, 8:00–17:00

Nadja Zupan Hajna, Franci Gabrovšek, Martin Knez, Blaž Kogovšek, Peter Kozel, Janez Mulec, Uroš Novak, Bojan Otoničar, Metka Petrič, Tanja Pipan, Mitja Prelovšek, Nataša Ravbar, Tadej Slabe, Stanka Šebela

Stops:

1 – Reka River and its Contact Karst
2 – Smrdljivec Sulphidic Spring (Reka Tributary)
3 – Škocjanske Jame (Škocjan Caves) Case Studies
4 – Lipove Doline Unroofed Cave and Sediments
5 – Kozina – Upper Cretaceous Paleokarst

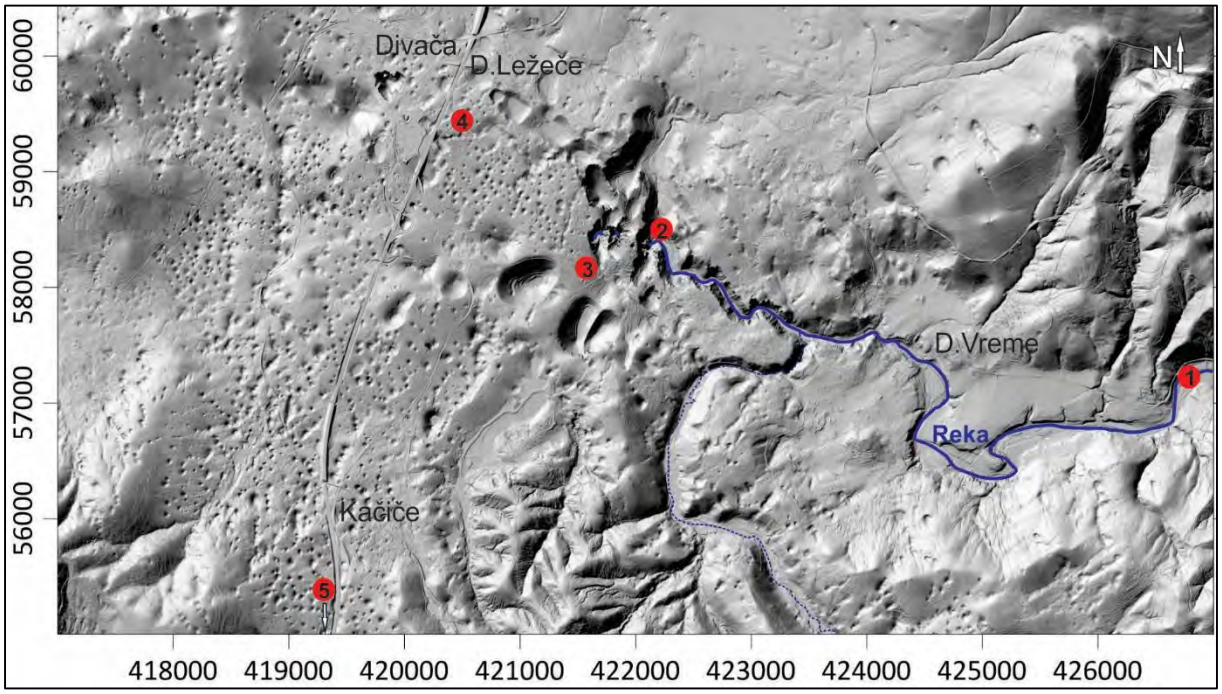

Fig. 3.01: Field stops (1-4) along Reka River contact karst and Up. Cretaceous paleokarst site (5) (DEM: Atlas Okolja http://gis.arso.gov.si/).

INTRODUCTION

The Škocjanske Jame (Škocjan Caves) are a more than 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 World Heritage List UNESCO because of their extraordinary underground canyon - one of the largest in the world. The caves are also of importance for the nineteenth century, which contributed to the understanding of karst phenomena, the development of karst terminology, speleology and karstology as a scientific discipline. The first paths in the cave area were made in 1823, but the construction of paths for exploration and visitors began only in 1884. The exploration of the cave was carried out by speleologists of the DÖAV (Littoral Section of the Austrian Alpine Club) from

Trieste. The most important explorers were Anton Hanke and Joseph Marinitsch. Already in 1891 they reached the last syphon of the cave. In 1999 the caves were included in the UNESCO Ramsar list of wetlands of international importance. The Škocjan Caves Park manages a heritage of outstanding universal value, which in 2004 was included in the World Network of Biosphere Reserves MAB as the Karst Biosphere Reserve.

The location of the Škocjan caves in this area is clearly determined by the proximity of the contact between permeable carbonate rocks of Cretaceous and Paleocene age and impermeable flysch of Eocene age (Fig. 3.02). The area is also defined by the ponor of the Reka River into the Škocjanske Jame at an elevation of 314 m and its approximately 35 km long underground flow to the springs of the Timavo River north of Trieste. The caves consist of extensive cave passages and large collapse chambers in several inclined levels.

REGIONAL SETTINGS

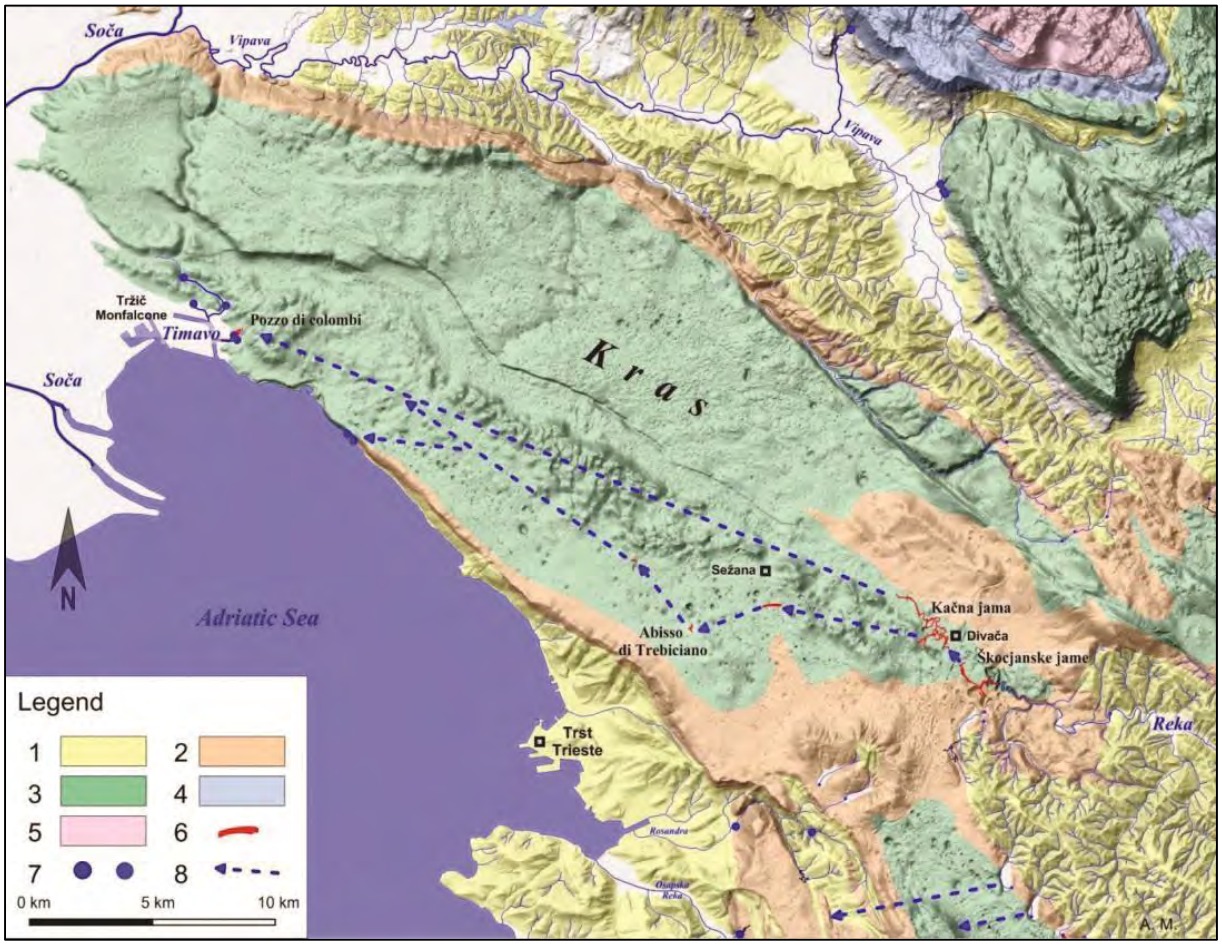

Fig. 3.02: Lithology, hydrology and morphology of the Kras Plateau, with two distinct dry valleys crossing the plateau. *Legend: 1. Eocene flysch; 2. Paleocene limestone; 3. Cretaceous limestone and dolomitic limestone; 4. Jurassic limestone and dolomite; 5. Triassic dolomite; 6. important cave; 7. springs; 8. supposed flow of underground rivers. Source of data: Geodetski oddelek ARSO.*

The Škocjanske Jame are located at the SE edge of the Kras (Karst Plateau; Fig. 3.02). The Reka sinks into the Škocjanske Jame and then flows about 250 - 300 m below the surface. In eight caves (see Fig. 3.03) after Škocjanske Jame the underground river Reka can be reached: Brezno treh generacij,

Kačna Jama, Brezno v Kanjeducah, Jama Sežanske Reke, Jama v Strašinkini dolini, Labodnica (Abisso di Trebiciano), Abisso Skilan and Pozzo di Colombi. Further NW no caves with an open flow of the Reka are known. There are about 300 m of the accessible vadose zone with caves formed at all altitudes from the surface to the sea level and below it.

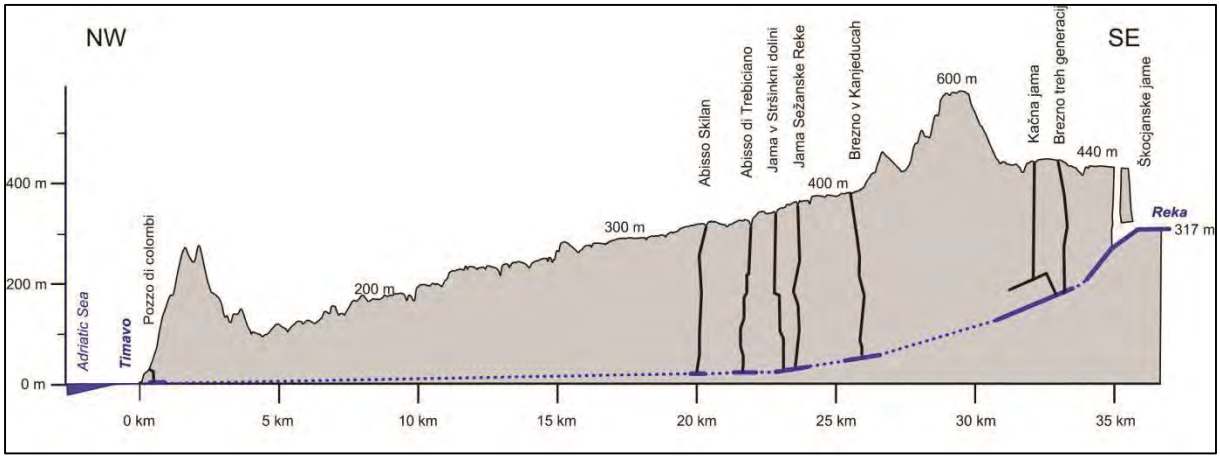

Fig. 3.03: Cross-section of Kras Plateau from the sink of the Reka in Škocjanske Jame, to the springs of Timavo with caves in which the underground water flow can be reached. Source of Lidar data: Geodetski oddelek ARSO.

The Kras Plateau is 40 km long and up to 13 km wide; latitude and longitude 45°45''N and 14°00''E cross the Kras near the village of Divača. The main part of the plateau is essentially leveled, inclined slightly to the northwest, with numerous dolines, caves and other karst features. The Kras plateau became a textbook example of this type of landscape because of its exceptional karst phenomena, and explorations were carried out in the 19th century. The name Kras in the German form of the word (der Karst) became an international scientific term. The plateau consists of Cretaceous and Paleogene limestones and dolomites and is surrounded by flysch sediments of Eocene age (e.g. Gospodarič 1983; Jurkovšek et al. 1996, 2013). The flysch rocks represent the last marine sedimentation in this area (Zupan Hajna et al. 2010). 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). Here, two basic groups of tectonic structures can be distinguished, consisting of (1) Cretaceous-Paleogene NE - SW - directed compression as Dinaric structures (NW - SE -striking regional folds and reverse faults, also cross-dinaric normal faults) and (2) Neogene and Quaternary N - S -directed compression (NW - SE - striking slip faults; Jurkovšek et al. 1996, 2013; Placer et al. 2010; Žvab Rožič et al. 2015).

About 3,500 caves are known on the plateau. Kras is a carbonate plateau 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). The main part of the plateau is essentially leveled, slightly inclined to the NW and has numerous dolines, caves and other karst features. There are about 3,490 known caves on the plateau. The accessible vadose zone with caves at all elevations from the surface to sea level and below is about 300 m long. In seven caves we can reach passages of the underground river Reka, which flows between 200 and 300 m below the surface. In the northwestern part, the plateau drops to below 50 m above sea level; at its edge (SE) the heights are around 500 m above sea level.

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. Due to intensive

pasturing in the past centuries, the Kras was bare, with a rocky and grassy surface. In recent decades, trees have overgrown the landscape.

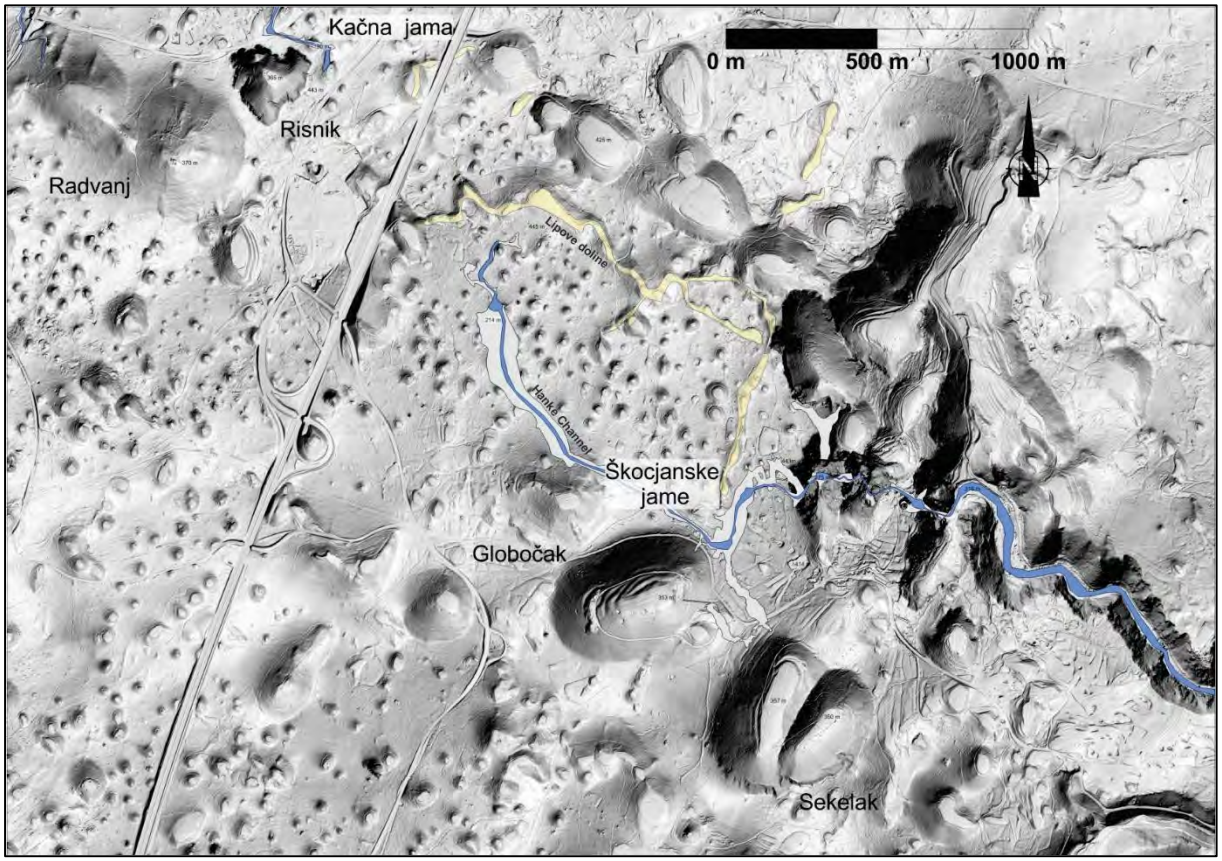

Fig. 3.04: Divaški kras with Škocjanske Jame (grey) unroofed caves (yellow) and the Reka flow (blue) at the surface and in caves. Source of Lidar data: Geodetski oddelek ARSO.

The most important element of Divaški kras is a levelled surface with inclinations of less than 10° (Figs. 3.01, 3.04). This type of surface represents about 87% of the total area. It is intersected by numerous dolines. M ost of them (740) are small, about 50 m in diameter, and about 8 to 10 m deep. We assume that they are solution dolines. They cover about 5% of the area and their total volume is estimated at 6-10 x 10^6 m^3 (Mihevc 2001). There is another group of dolines that are clearly formed by collapse. This is evident from their morphology, size, location above active caves, and recent debris flow or collapses. The largest have a diameter of more than 500 m, and the deepest are more than 150 m deep. The largest collapse doline is Dol Sekelak, 122 m deep, with a volume of 8.5 x 10^6 m^3. Dol Globočak is smaller, 90 m deep and has a volume of 4.8 x 10^6 m^3. Dol Risnik is 86 m deep, and has a volume of 1.7 x 106 m^3. The group of 15 largest collapse dolines occupies only 4% of the area, but their total volume is about 38 x 10^6 m^3. here are also about 20 larger depressions, occupying about 3% of the area, which are most likely old collapse dolines that were already severely affected by the denudation of the relief and the transformation of their slopes.

Numerous caves are known, the largest among them are Škocjanske Jame, Kačna Jama, Divaška Jama and Trhlovca. In several places of the Kras allogenic sediments, quartz sands and pebbles are found on the surface. Their occurrence was erroneously explained in the past as remnants of fluvial deposits from surface "pre-karst" rivers. New interpretations of these localities, in conjunction with geomorphological and sedimentary studies indicate that the allogenic sediments are actually cave sediments that came to the surface because denudation removed the rocks above the caves, leaving

the caves roofless. Unroofed caves and relict caves are very good sediment traps. Analysis of these, especially allogeneic sediments - paleomagnetic, dating, paleontology, mineralogy, and granumelotry - can provide information about the origin of the sediments, the sedimentary environments, the state of allogenic input into the karst, and the later evolution of the karst relief. Therefore, special attention is given to them. The first recognized unroofed cave was a 350 m long cave near the village of Povir, filled with fluvial sediments and speleothems (Mihevc & Zupan Hajna 1996; Mihevc et al. 1998). Morphological analysis of several unroofed caves on Divaški kras (Mihevc 2001) and paleomagnetic properties of sediments in Divaška Jama, Trhlovca and Divača profile (see Bosák et al. 1998, 2000; Zupan Hajna et al. 2008, 2010, 2020) revealed that the age of alluvial sediments is most likely up to 5 Ma. The clastic fillings of the unroofed caves and the extant caves of Divaški kras consist mainly of weathering products of Eocene flysch rocks eroded from the Reka catchment. In all cases, a relatively similar mineral composition prevailed, indicating that the main source was flysch sediments weathered to varying degrees.

1) REKA RIVER AND ITS CONTACT KARST

1.1) HYDROLOGY OF REKA AND GROUNDWATER FLOW CONNECTIONS

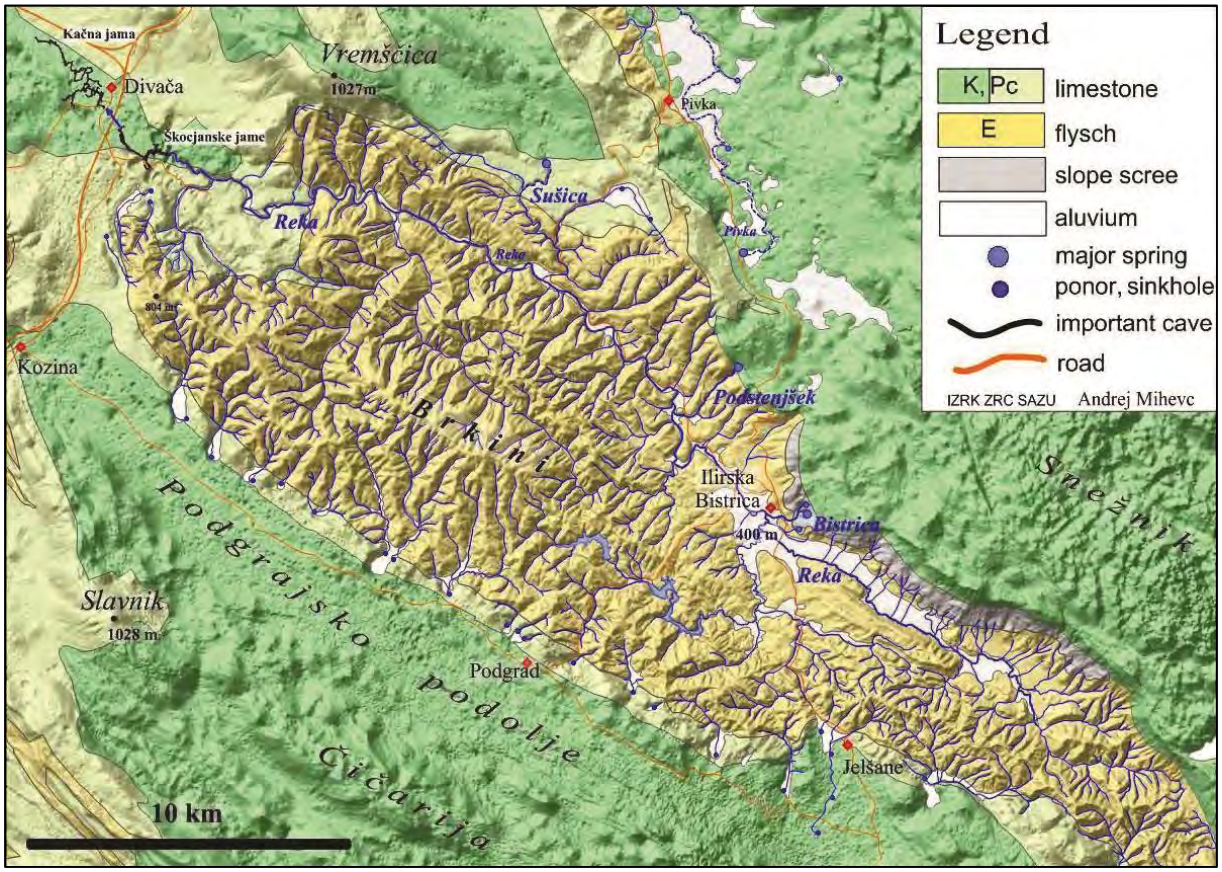

Fig. 3.05: Flysch landscape (Brkini hills) on SE edge of the Kras Plateau with fluvial topography and surface rivers that all sink on the edge into karst. DEM made on 12.5 m grid. Source of DEM data: Geodetski oddelek ARSO.

The development of the currently active part of the Škocjanske Jame is closely related to the Reka sinking stream. Before reaching Škocjan, the river first flows about 50 km through the river valley formed in very low permeability Eocene flysch (Fig. 3.05). The catchment area of the Reka covers more than 365 km^2, with about 60% of the surface runoff on flysch (Peric & Hribar 2010). In the period 1992-

2021, the lowest discharge of the Reka was measured at the hydrological station Cerkvenikov mlin at 0.25 m^3/s, while the mean discharge was 7.89 m^3/s (ARSO 2023). At very high waters the discharge can increase to more than 300 m^3/s. Where the river reaches the limestone base, it begins to lose water in the sinks located immediately downstream of the lithological contact. Only when the water level is very low does the river completely disappear here, otherwise it flows for another 7 km in a limestone valley and then sinks into the cave.

From the cave groundwater flows towards the spring belt between the Nabrežina/Aurisina and Timava/Timavo springs in the Gulf of Trieste (Fig. 3.06). The main springs of the Timava/Timavo River have a minimum discharge of 7.4 m^3/s, a maximum of 158 m^3/s, and a mean of 29.3 m^3/s (Gemiti 1995). The first tracer tests were carried out in the Classical Karst already at the beginning of the twentieth century, and many others followed, showing the connections of the Reka from the Škocjanske Jame to the above-mentioned springs (Timeus 1928; Mosetti 1965; Gemiti 1998; Galli 2012; Peric 2012). Tracers were also recovered in various water caves inbetween (e.g., Jama 1 v Kanjaducah, Labodnica/Abisso di Trebiciano). The determined flow velocities (with regard to duration of tracer transfer and linear distance between the injection point and the point where the tracer emerged), which depend on hydrological conditions, ranged from 47 to 204 m/h (Turpaud et al. 2018).

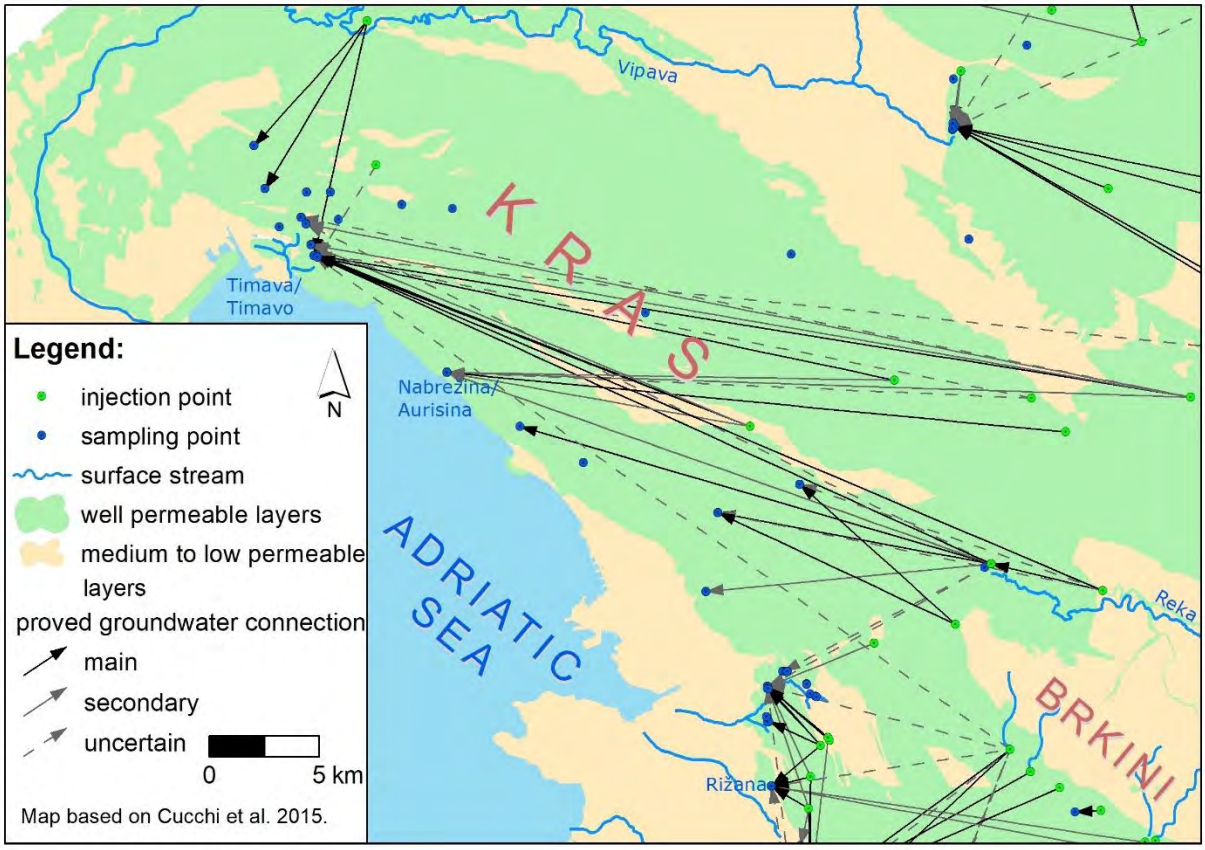

Fig. 3.06: Hydrogeological map of Kras with proved groundwater connections (based on Cucchi et al. 2015).

1.2) CONTACT KARST AND ALLOGENIC SEDIMENTS

At the SE edge of the Kras Plateau is an area of Eocene flysch with developed surface drainage and fluvial morphology. The Reka is the main water source in the valley. Most of the flysch area belongs to the Brkini Hills. All surface waters from the flysch flow and sink into the karst (Figs. 3.02, 3.05). The first ponors of Reka are located at the transition between flysch and limestone (Fig. 3.07).

Vremska dolina is a large blind valley formed by the Reka (Fig. 3.07). It is about 3 km long and 1.5 km wide. Some karstologists count it among the border polje. Blind valleys are formed by allogenic rivers that flow into the karst and sink there. Allogenic rivers with large amounts of water, sediment transport and regime reinforce and change the shape of the karst. However, the shape of the blind valley, especially the width of its bottom, is determined by the drainage system of the karst and the height of the water table. They are the most characteristic forms of contact karst (e.g. the blind valley of Vremska dolina, Fig. 3.07).

The Reka flows through a blind valley at an altitude between 345 m and 335 m. Above the riverbed there are two higher rock terraces at about 360 m and 380 m. On the terraces, thick soils have developed on fluvial sediments containing numerous chert pebbles derived from the flysch. In all studied sediments of the river and its tributary Sušica, quartz predominates with some clay minerals (illite/muscovite group), plagioclase and chlorite (Zupan Hajna et al. 2017).

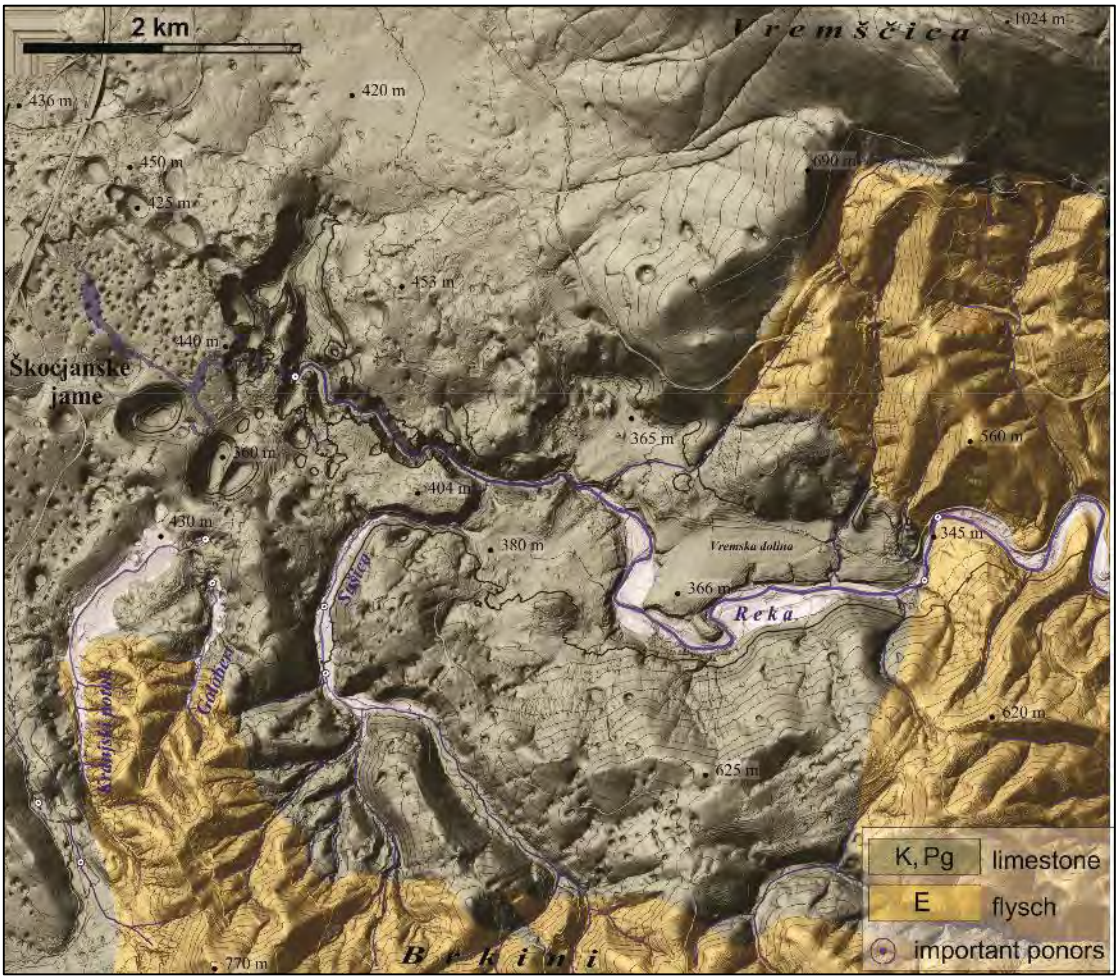

Fig. 3.07: Lithology of the SE edge of Kras with Vremska dolina blind valley. When the Reka crosses the flysch-limestone contact it starts to sink into the karst. The blind valley has a wide bottom and two higher terraces. After about 3.5 km the river enters a canyon which ends with the gaping entrance of Škocjanske Jame. Only main ponors are marked. Source of Lidar data: Geodetski oddelek ARSO.

On the NW edge of the blind valley, the Reka flows into a narrow canyon that joins the Škocjanske Jame at an elevation of 317 m. In the NW direction, above the Škocjanske Jame, there is a higher levelled area of the Kras at an elevation of about 410 - 450 m. There are no fluvial sediments preserved there, but on the surface there are many unroofed caves. The development of the blind

valley was controlled by the water level in the karst and caves (i.e. Škocjanske Jame) and by regional tectonic uplift (Placer et al. 2010).

When the river reaches limestone bedrock in the valley, the river begins to lose water into ponors located immediately at the contact. If the discharge of the Reka at this point is greater than 1 m^3/s, the river continues to flow for 7 km and sinks into the Škocjanske Jame.

1.3) PONOR IN REKA RIVERBED

The first ponors of the Reka are located at the contact of flysch and limestone upstream of the Škocjanske Jame (Figs. 3.07, 3.08).

Fig. 3.08: Injection of tracer into the Reka at the contact, this is about 50 m downstream from the hydrological station ARSO Cerkvenikov mlin (flow measurement location) (photo M. Blatnik, RI-SI-EPOS project). Note that the river completely disappears 20 m downstream from the injection point.

Due to the impermeable flysch, discharge of the Reka gradually increases downstream to the Gornje Vreme settlement, where the river gauging station Cerkvenikov mlin is situated. Here, impermeable bedrock is followed by limestone and first ponors of the Reka appear in the water channel. "Leakage" of water into the karst bedrock is limited only by the occurrence and swallow capacity of karst conduits and very probably discharge-dependent groundwater level. The limestone river bed is not homogeneously karstified, so there are sections with high and negligible permeability; two zones of increased permeability have been identified at the contact having up to 1.0 and 0.2 m^3/s of sinking capacity. At 1.13 m^3/s, the Reka completely sinks and thus does not flow further downstream into the Škocjanske Jame. Due to storage capacity of 3.400 m^3 at the contact, sinking capacity can be up to 1.6 m^3/s during rising limb or weak short-term flood events. At the contact, occasional 22-meters-deep subsidence in the river bed indicate water level already below entrance to the Škocjanske Jame.

However, during complete sink of the Reka, there is discharge of some L/s in the Škocjanske Jame that increases downstream indicating possibility that the Reka partly reenters its channel in the Škocjanske Jame. Therefore, tracing test with 4 kg of uranine has been performed in 2021 from the contact (Fig. 3.08) but it showed no connection with the Reka in the Škocjanske Jame 21 days after injection. Small flood events when water spilled over the contact and from nearby aquifer holding traces of uranine were accompanied with the reentry of uranine into the Reka channel but the concentration and recovery rate (0.15 %) in the Škocjanske Jame were extremely small (Fig. 3.09). This proves water flow that is parallel to the Škocjan Caves but with quite limited capacity (up to 1.1 m^3/s).

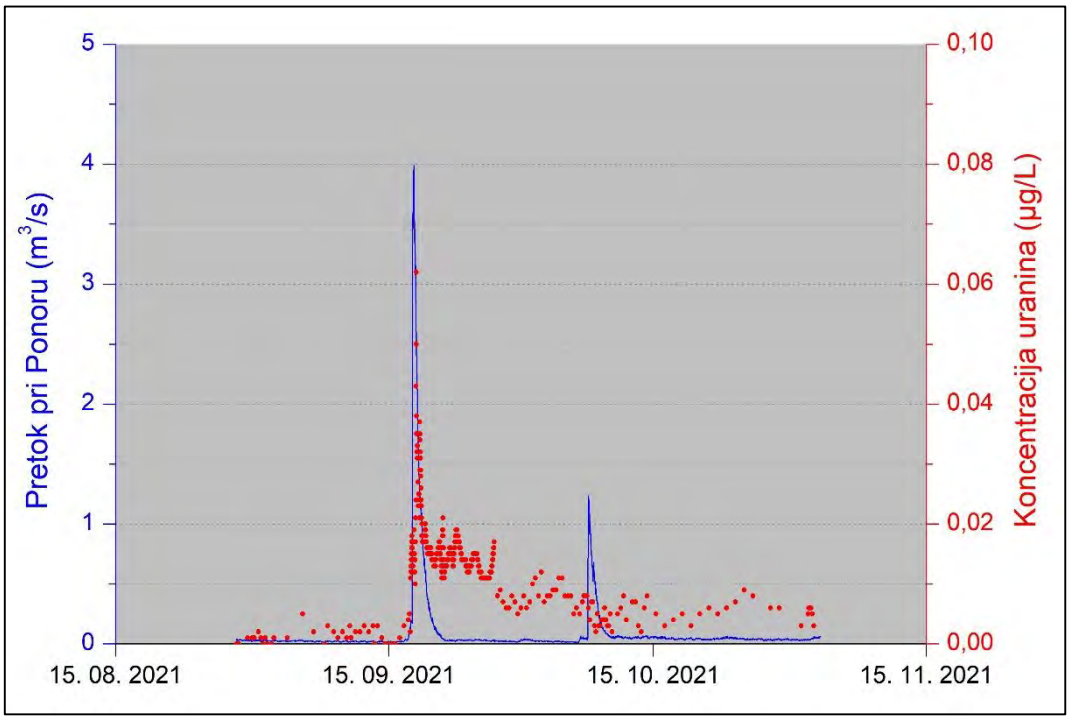

Fig. 3.09: Discharge and uranine concentration in the Škocjan Caves from injection (28/8/2023) till the end of the tracing test. Traced did appear during first flood event but concentrations were extremely low.

When the river in the valley reaches limestone bedrock, the river starts to lose water into ponors which are immediately at the contact. If at that point the discharge or the Reka is larger than 1 m^3/s, the river flows on for another 7 km and sinks into Škocjanske Jame cave.

2) SMRDLJIVEC SULPHIDIC SPRING (REKA TRIBUTARY)

In 2017, the sulphidic spring was discovered about 500 meters upstream, where the Reka sinks at Škocjanske Jame. The spring occurs during long periods without precipitation. It becomes visible in the dry riverbed of the Reka before the river sinks into the karst underground. The time window in which the spring can be studied is limited to the summer and depends on the amount of precipitation. Because of its sulphidic smell, the spring was given the name Smrdljivec, which means “stinker” in English. The sulphur compounds in the Smrdljivec spring probably originate from the coal layers in the surrounding area. The sulphide-rich water that reaches the Smrdljivec spring from the coal layers most likely mixes with a larger volume of water similar to that of the Reka (Mulec et al. 2021).

The iron-sulfidic spring is an example of a short-lived habitat and ecotone for biota. It is a dynamic environment with a biomass that can contribute to additional eutrophication of the Reka ecosystem and karst underground. Microbial communities were studied in the spring water and biofilm. At the genus level, the water was dominated by the methylotroph *Methylotenera*, the morphologically distinct white biofilm was dominated by the sulphur oxidizer *Sulphuricurvum*, and the brown biofilm was dominated by *Aquincola*, previously described as a freshwater organism. The "core" microbiome of the Smrdljivec spring is represented by methylotrophs, in particular *Methylobacter*, *Methylomonas* and *Methylotenera*. In addition, microscopic analysis revealed 26 algal and cyanobacterial taxa in both biofilm types. *Escherichia coli*, which is generally considered an indicator of faecal contamination, was isolated from the sulfidic water (Mulec et al. 2021).

Fig. 3.10: Smrdljivec spring, 30 July 2021 (photo A. Oarga-Mulec)

3) ŠKOCJANSKE JAME (ŠKOCJAN CAVES) STUDIES

3.1) GEOLOGY OF THE CAVES

Geological setting of the Škocjanske Jame area

According to the first geological studies of the Škocjanske Jame, the system has developed in bedded Turonian (K_2^2), massive Senonian (K_2^3) and thin-bedded Paleocene (K_2^{4+Pc}) limestones. The strata dip generally towards the SE, and are cut by fault systems that trend approximately NW–SE and NNE–SSW (Gospodarič 1965, 1983, 1984).

More-recent geological mapping of the surface and subsurface of Škocjanske Jame at 1:50,000 scale, has revealed that the stratigraphical sequence of the researched area is composed of three lithostratigraphical units (Jurkovšek et al. 1996, Jurkovšek 2013). The oldest rocks, belonging to the Sežana Formation (K_2^{2-4}), are 400 to 500 m thick and mostly comprise bedded limestones with rare rudist biostromes. Overlying the Sežana Formation conformably, the Lipica Formation (K_2^{4-5}) is 250 to 400 m in thickness and is represented by bedded and massive limestone with rudist biostromes and bioherms. The youngest lithostratigraphical unit seen in the Škocjanske Jame is the Liburnian Formation (K-Pc), comprising bedded limestones (containing the foraminifera genus *Alveolinae*) with a thickness of 50 to 300 m. The boundary between the older Lipica Formation and the Liburnian Formation is a disconformity, representing a regional discordance.

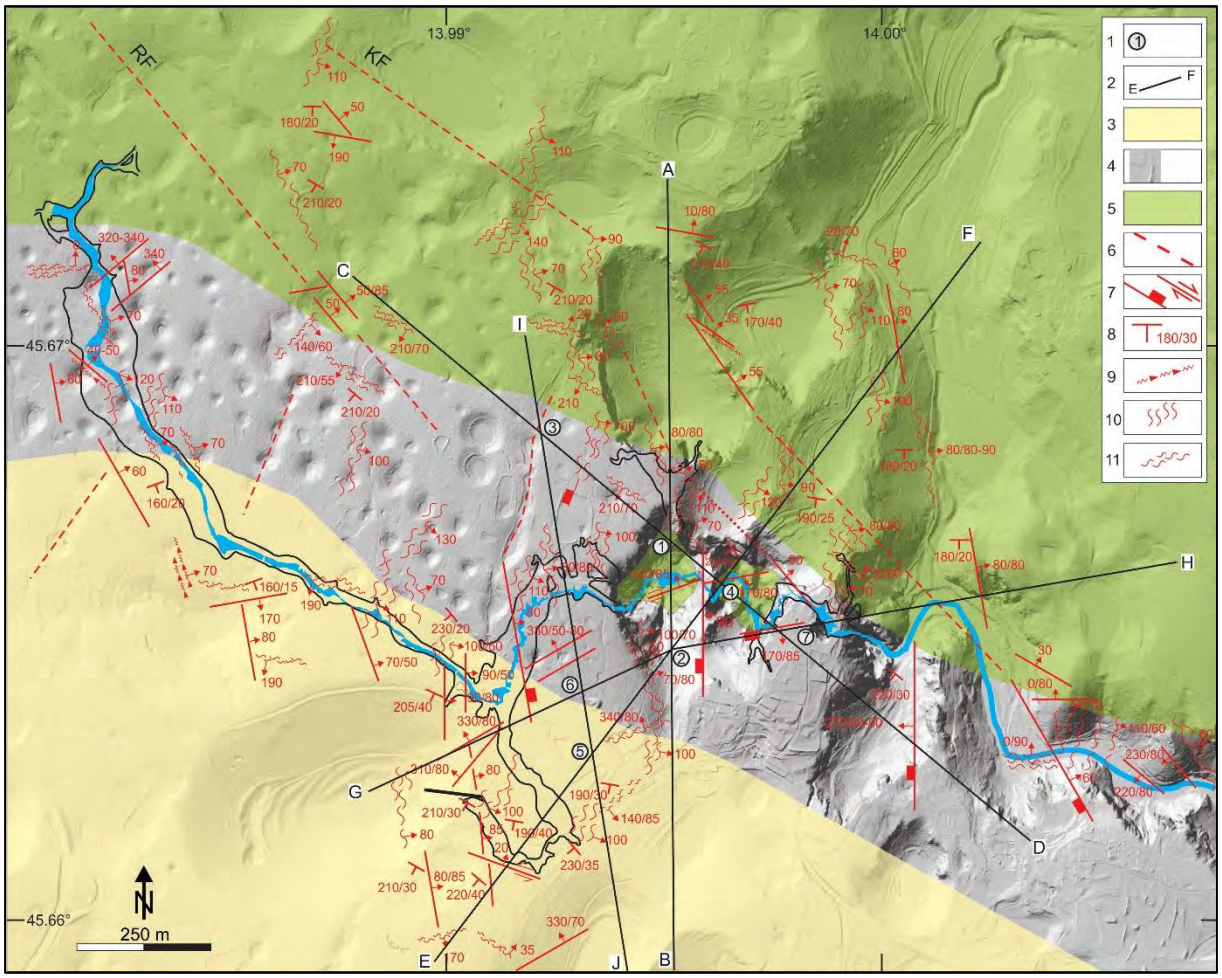

Fig. 3.11: Geological map of the surface above the Škocjan Caves system (Šebela & Novak 2023), hill-shade morphology (ARSO 2022), and Škocjan Caves map with the River Reka. 1 – reference crossing point number of longitudinal profiles on ground-plan and longitudinal profiles, 2 – course of longitudinal profile, 3 – Liburnian Formation (K-Pc), 4 – Lipica Formation (K_2^{4-5}), 5 – Sežana Formation (K_2^{2-4}), 6 – supposed fault trace at the surface, 7 – vertical and horizontal displacements along faults, 8 – dip direction and dip angle of bedding planes, 9 – crushed zone, 10 – broken zone, 11 – fissured zone.

Thus, 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. Bedding planes affected by interbedding slips (Knez 1996, Mihevc 2001, Šebela 2009) appear to have acted as inception horizons, which were especially favourable in guiding the initial development of the earliest cave passages.

Strata in the Škocjanske Jame area have a Dinaric strike orientation trending NW–SE and generally dipping towards the SW. The area is part of the geotectonic unit known as the Trieste–Komen Plateau; more specifically it lies on the SW wing of a regional anticlinal fold structure (Gospodarič 1965, Jurkovšek 2013). Many faults run parallel to the bedding strike (NW–SE), with some also cutting across the strike (NE–SW).

The area of Škocjanske Jame belongs to the Adria Microplate, which was overthrust by the External Dinaric thrust belt at the end of the Eocene (Celarc et al. 2012). During the Miocene the Adria Microplate underwent segmentation and rotation in a counter-clockwise sense, with underthrusting

beneath the Dinarides. Degradation of the Adriatic–Dinaric carbonate platform and deposition of clastic flysch rocks occurred during the Eocene (Celarc et al. 2012).

The most important regional faults in the area are the Dinaric-oriented (NW–SE) Raša and Divača faults. According to Atanackov et al. (2021) both faults remain active. The Raša Fault shows evidence of a multiphase kinematic development. During the first phase it was a reverse fault with its overthrusting tendency directed towards the SW. During subsequent relaxation of regional pressure, individual parts of the fault took on a gravitational character, and in its final phase it evolved into a strike-slip fault (Jurkovšek et al. 1996). The surface trace of the Divača Fault passes about 1 km north of the Škocjan Caves. Examination of its wider deformation zone indicates that it is a shear zone. Evidence of overthrusting, normal subsidence, and horizontal fault movement are all present locally (Jurkovšek et al. 1996).

The study area exhibits two broad groups of tectonic deformations. The first were imposed by Cretaceous–Paleogene compression in a NE–SW direction. They are represented by Dinaric thrusting structures, regional folds with NW–SE-oriented axes and reverse faults with essentially the same strike orientation. Within phases of relaxation some of the original reverse faults were reactivated as normal faults, and at the same time cross-Dinaric normal faults also developed. During the Neogene and Quaternary, the second set of deformations resulted from regional compression in a generally N–S direction, which produced strike-slip faults with a NW–SE orientation (Jurkovšek et al. 1996).

Karst stratigraphical windows of Škocjanske Jame

During detailed structural geological mapping of the Škocjanske Jame and the surrounding land surface, an interesting stratigraphical characteristic (karst stratigraphical window) was found within the Mala and Velika collapse dolines (Šebela & Novak 2023).

The structural-geological map of Škocjanske Jame (Šebela 2009) is based upon structural-geological field mapping (1:500) of cave passages that was carried out during the periods 1991–1992 (Hankejev Kanal, Kranjc et al. 1992) and 1997–2007 (Tiha and Šumeča Jama). Between 2018 and 2022, additional structural-geological mapping was undertaken at 1:500 scale in caves Marhočičeva and Mariničeva Jama and the adjacent Velika Dolina and Mala Dolina collapse dolines. Interaction between massive collapse dolines, the hydrologically active the underground Reka, and cave passages developed within different lithological units resulted in the recognition of particular characteristics that become more evident after the construction of longitudinal cross-sections illustrating the geological structure (Šebela & Novak 2023). The term “karst stratigraphical window” describes a recognizable karst feature that is also characterized by the exposure of a different lithostratigraphical unit that is shown on the geological map (Fig. 3.11).

Karst stratigraphical windows represent an area where older rocks within a conformable stratigraphical succession crop out as inliers beneath younger strata that have been penetrated, in this case because of the effects of karstification processes in deepening collapse dolines (Šebela & Novak 2023).

Stratigraphical windows are not the same as tectonic windows (Fig. 3.12) where, due to the effects of erosion (and corrosion in the case of karst areas), the rocks beneath a thrust fault contact crop out. Although bedding planes with interbed slips are present in Tiha Jama, Mahorčičeva Jama and Mariničeva Jama, such interbed movements represent small displacements (<1 cm) and these cannot be equated with thrust fault movements and tectonic windows. This demonstrates additionally that Velika Dolina and Mala Dolina cannot be considered as being tectonic windows (Šebela, Novak 2023).

Velika Dolina and Mala Dolina are among Slovenia's deeper collapse dolines, with 120 m depth (Mala Dolina) and 165 m depth (Velika Dolina) respectively.

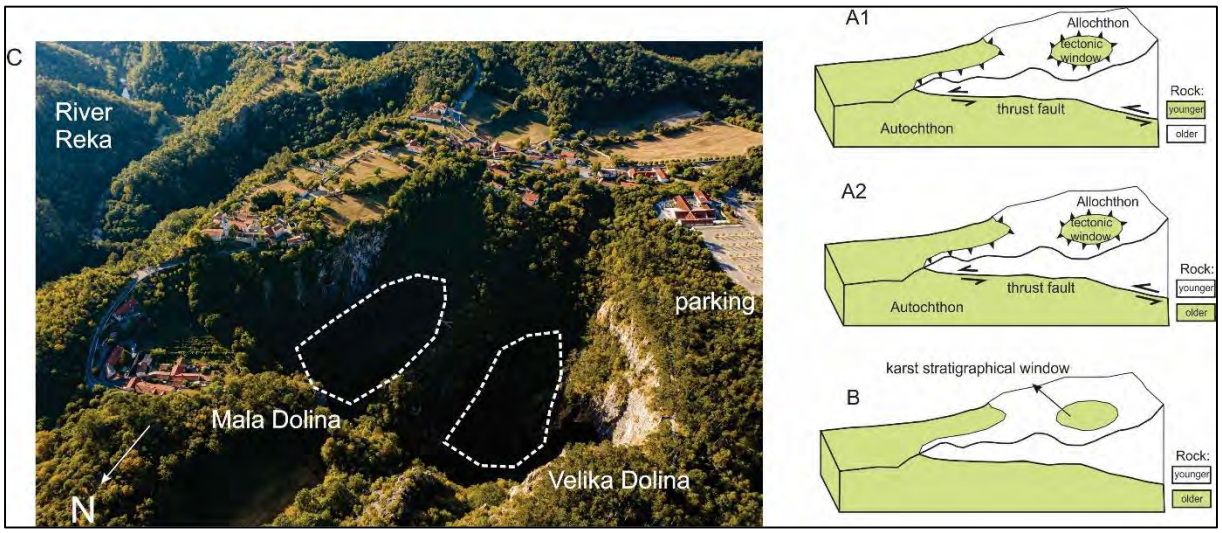

Fig. 3.12: Schematic picture (Šebela, Novak 2023) of: A. tectonic window (A1 – older rocks thrusted over younger rocks, A2 – younger rocks thrusted over older rocks); B. karst stratigraphical window; C. the area around Mala Dolina and Velika Dolina (photo M. Blatnik, RI-SI-EPOS project).

Directly above the passages of the Škocjanske Jame system there are 8 collapse dolines in an area of 4 km^2. In general, the distribution of collapse dolines in karst areas can indicate the presence of "karst stratigraphical windows" with possibly special lithostratigraphical relationships that must be shown clearly on detailed geological maps where inliers of older rocks are exposed beneath surrounding younger rocks due to the erosional effects of karstification.

3.2) SPELEOGENESIS AND COLLAPSE DOLINES

Cave of almost 6 km long passages with dimensions approx. 30 m x 40 m and maximal heights up to 145 m in the underground canyon with flowing river, was scanned by terrestrial laser scanner from 370 stands (Walters & Zupan Hajna 2020). 3D model of the caves produced in a Cloud Compare is shown in Fig. 3.13. Overall cave volume from ponor in collapse doline Velika Dolina to Martelova Dvorana is 6.13 million m^3. Martelova Dvorana (Martel's Chamber) volume was calculated to 2.55 million m^3 with max. length of 314 m and width of 143 m and height of 158 m. Comparison with the largest chambers of the world has shown that the range of the Martelova Dvorana in 2019 reaches 11th place in the world and 2nd in Europe for Salle de la Verna (3.6 million m^3). But in any case, Martelova Dvorana is the largest river passage in Europe. Some of the big chambers collapsed and forming collapse dolines like Velika and Mala Dolina.

The lower, active part of the caves begins with an underground channel located just after the ponor of Reka (Mahorčič and Mariničeva Jama) and has an average size of 30 m x 40 m. After a few hundred meters the cave passage is interrupted by two large collapse dolines - Mala and Velika Dolina. The underground flow of the Reka continues in the 2.6 km long, 10-60 m wide and between 80-145 m high underground canyon (Šumeča Jama and Hankejev kanal) to Martelova dvorana at 214 m a.s.l., from where the river flows to Marchesettijevo Jezero at 190 m a.s.l. (124 m lower of the ponor) and then through completely flooded smaller dimensional passages and unexplored channels to Kačna Jama. The main dry parts are Černigojeca Dvorana l at 345-330 m a.s.l., Brihta Jama at 340-332 m a.s.l.,

Okno at 330 m a.s.l., Tominčeva Jama at 320-312 m a.s.l., Roška Špilja at 387 m a.s.l., Šmidlova Dvorana (Schmidel Chamber) at 307-300 m a.s.l., Dvorana Ponvic at 330-315 m a.s.l., and Tiha Jama (Silent Cave) at 350-330 m a.s.l. with Velika Jama and Paradiž. Occasional floods in the cave are usually up to 30 m high, in exceptional cases up to 100 m, with the highest known flood in the 19th century causing the water level to rise by up to 132 m.

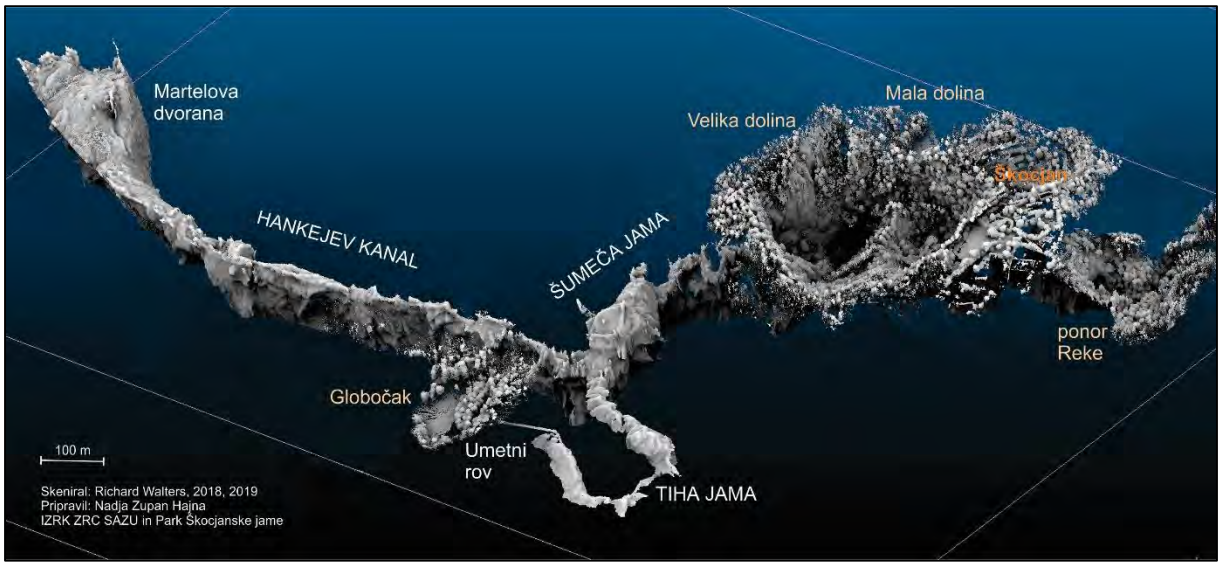

Fig. 3.13: 3D model of Škocjanske Jame made in Cloud Compare. View from NW: collapse dolines Velika and Mala Dolina and Globočak with main parts of the cave: Šumeča Jama, Hankejev Kanal and Martelova Dvorana (from Walters & Zupan Hajna 2020).

Since the beginning of speleological science researchers focused attention on the relation between geological properties (rock and structure) and initial passage development. For a long time, researchers recorded tectonic elements (faults and fissures) on cave surveys; however, lithopetrology and stratigraphy were not considered adequately in studies of cave passage development. Single parameters were partially anticipated, mostly they were guessed. These questions achieved importance when some researchers stressed the distinction between the initial and later stages of speleogenesis. It was tried to cast light on the problem by considering initial passages in collapse doline Velika Dolina at cave Škocjanske Jame. Cave passages, their fragments and other traces of the underground karstification in Velika Dolina do not occur at random in the walls but are controlled by small number of bedding-planes (Knez 1994, 1995, 1996, 1998). Research was concentrated on two basic questions: a) is the concentration of initial channels within limited number of bedding-planes real or just apparent; b) is this "enrichment" - if it exists - associated with the properties of the rock or the bedding-plane? In other words, it was tried to answer the question: Is selective karstification controlled by a rock feature?

Within the area there is not one single passage or segment developed exclusively at a fissure or fault. A probable exception is a breakthrough from a bedding-plane to another; however, they have been entirely removed. Hence, initial phreatic channels are formed at bedding-planes. The larger ones are accompanied by series of smaller ones, corresponding to Curl's (1986) and Worthington's (1991) statements. They may be clearly seen on the flanks of Velika dolina. Briefly, answers on two basic questions: a) In fact former channels are very concentrated along only three initial bedding-planes (4.8%) among 62 observed and this concordance cannot possibly be only apparent; b) Initial bedding-planes differ from the others by the following properties at least: - the rock along these bedding-planes

is typically damaged, indicating an interbedded slip; - the calcite level is slightly (0.33%) however typically, higher than elsewhere; - the rock along them is less porous than elsewhere; - formative bedding-planes are dividing-lines among sedimentary cycles including 19 beds on average.

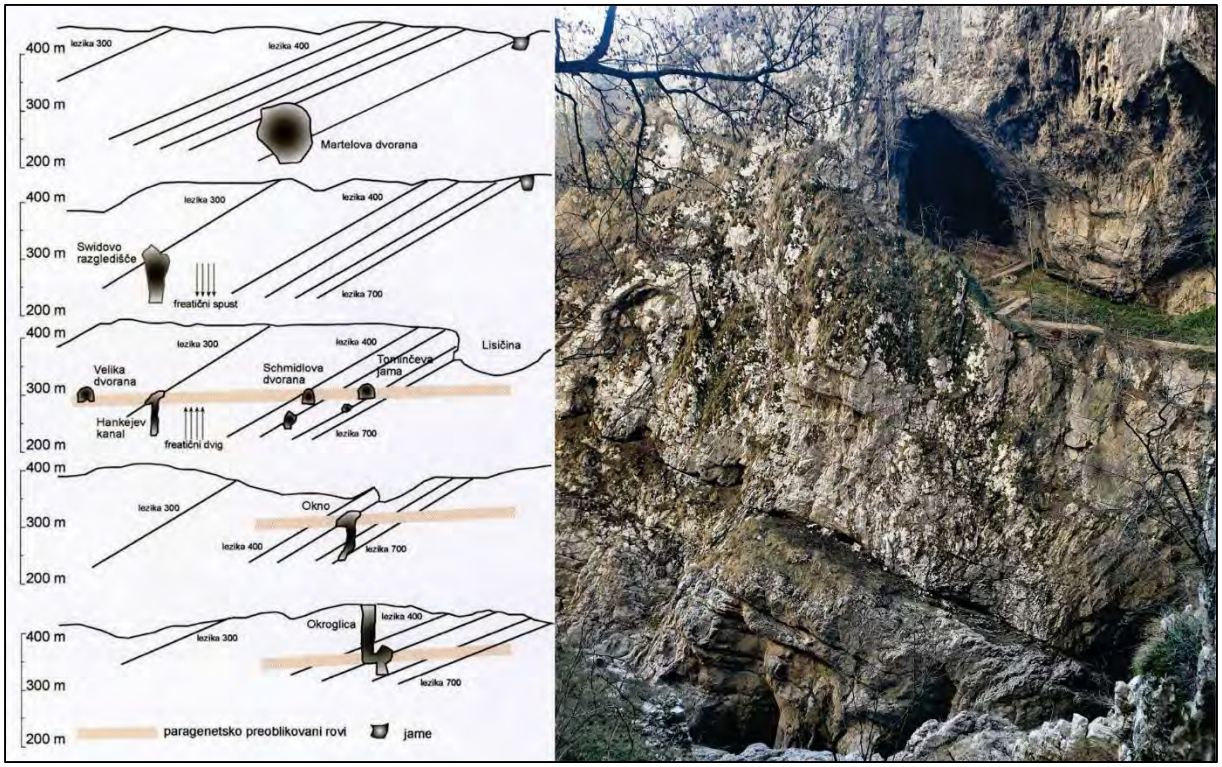

Fig. 3.14: Main tectonised bedding planes (lezika in figure 1) with locations of main cave passages (cross-sections) with view in direction of 220°-40° (from A. Mihevc 2001); and initial channels along bedding planes in collapse doline Velika dolina (photo N. Zupan Hajna).

Cave is now composed of phreatic tunnels and gravitational or paragenetic reshaped galleries. The initial channels of today's cave developed in phreatic conditions, formed along tectonized bedding-planes (Fig. 3.14). Large quantities of water could flow through all these passages, but meanwhile, pebbles were transported through epiphreatic caves, about 150m above them. The water flow demanded a high degree of phreatic rising and falling between individual bedding- planes which are in the area of the chambers Svetinova dvorana and Müllerjeva dvorana approximately 175 m. As these phreatic jumps (i.e. loops) utilize fractured zones they destabilize them with the formation of parallel shafts. Later, when the flow increased, these shafts were the basis for the extensive passages collapses and widenings. In the morphology of the cave there can be seen a long stable period expressed by paragenetic features and the deposition of sand comprised mostly of quartz. Due to the regional low gradient which can be connected to the formation of Vremska dolina also. For a long period of time the water table in the cave was 340–300 m above sea level and the gradient was towards the SW. The Reka formed new passages or adopted old passages by bypassing or paragenesis, respectively. The large galleries with paragenetic ceilings were formed in the entrance part of Škocjanske Jame (Mahorčičeva and Mariničeva Jama, Tominčeva Jama, Schmidlova dvorana and Tiha Jama).

The next phase of the cave evolution included important changes. Gradient increased and turned towards NW. This resulted in the entrenchment of the main stream passage. In the inner parts of the cave, in Hankejev Kanal, cutting resulted in an 80-m canyon, while in the entrance part of the cave, down cutting did not exceed 10 m. These changes can be connected with regional tectonic

activity, i.e. uplift and tilting of the whole Kras delayed by the time needed for adaptation of all caves in the Reka system.

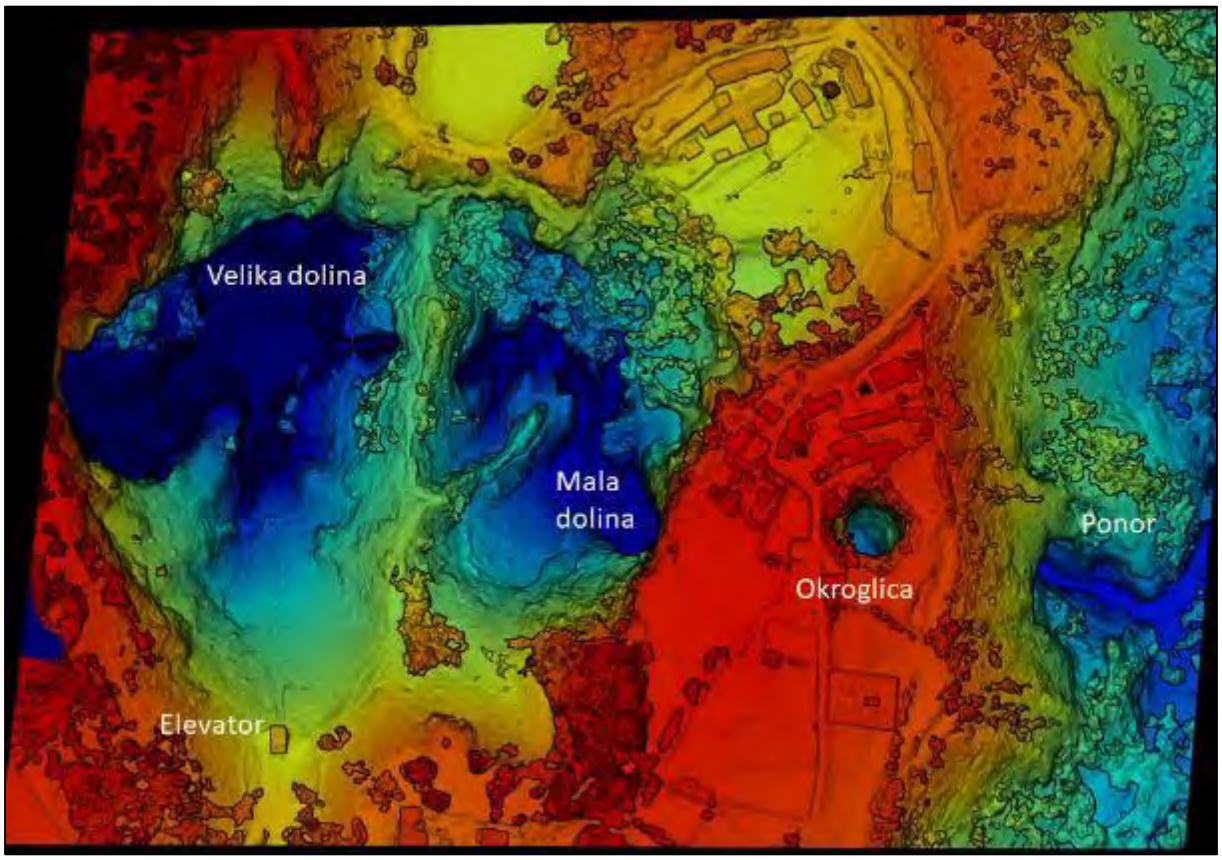

Fig. 3.15: DEM of ponor and collapse dolines from drone images (from Walters & Zupan Hajna 2020).

In collapse dolines above Škocjanske Jame and Divaški kras it can be observed that intense collapsing occurs only where caves cross tectonically fractured zones within the height of the zone of regular flooding (Mihevc 2001). In some cases, there are passages at different levels crossing the same fractured zone and in each case a collapse chamber developed. This shows that the collapsing is not a simple failure of fractured rock, but a special speleological process. Oscillation during floods enables intrusion of water and dissolution in the fractured zones. Enlarged fissures destabilize the rock and make collapsing possible. The process also removes the collapse material by dissolution and physical transport. If the collapse chamber is no longer within the zone of flood waters the process slows down, or even stops due to deposition of flowstone in fissures. The evolution of large collapse chambers and collapse dolines is a result of a combination of several factors and not just simple collapsing due to rock failure in the cave ceiling. The process can't be treated as the decay of caves only, but surely as a distinct speleogenetic and geomorphic process.

3.3) ROCK RELIEF

Rock forms and their connection to the rock relief are revealed as important evidence of the way the cave formed and developed. Today the central passage is primarily formed by the relatively rapid water flow which carves various types of scallops and potholes. The flow transports large amounts of sand and gravel and agitated afflux surfaces are mechanically smoothed or jarred. Scallops are found in those parts of the riverbed which transported material does not reach. Long, narrow and

open scallops (Fig. 3.16/1,2) indicate rapid and relatively small water flows acting on the rock with light pressure. Scallops distributed in traverse series are the consequence of forced whirling, determined by the form and size of the space through the water flows (Fig. 3.16/3).

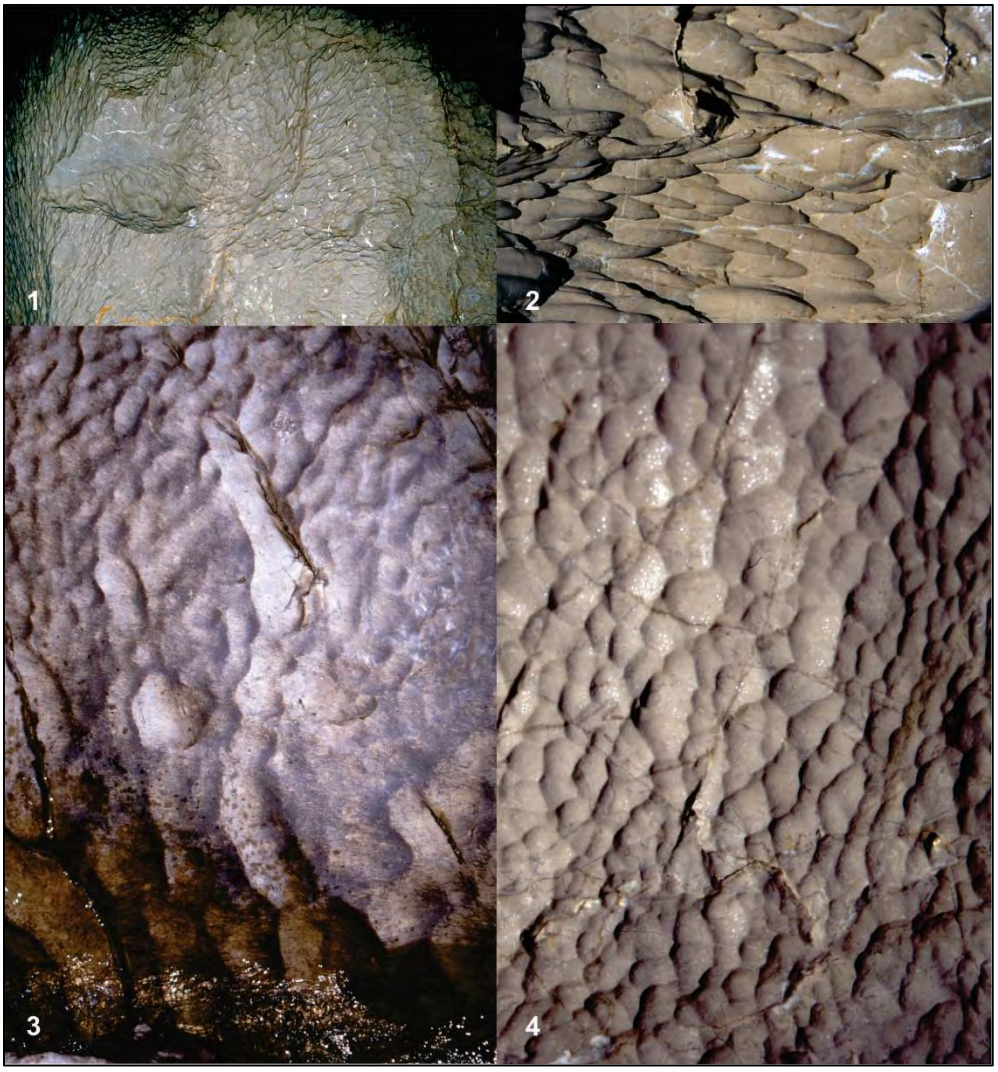

Fig. 3.16: Photos of long, narrow and open scallops (1, 2), scallops distributed in traverse series (3) and A mature scallop network forms (4) (photos T. Slabe).

A mature scallop network forms (Fig. 3.16/4) when the formation of the network and the size of the scallops is primarily affected by the whirling of fast water flows past diversely composed rock. For the most part the first group of scallops develops when the level of the water flow in the riverbed is low. A mature network of scallops develops higher on the walls; it is carved when the level of the water flow in the riverbed is higher. Form and size of the space in wider parts of a passage do not greatly affect water flow whirling. Parts of the riverbed protruding from the wall higher above the floor are covered by the first group of scallops. Behind an obstacle the water flow velocity increases. Generally, high water is of a short duration, which is why the distribution of various networks of scallops is preserved in a relatively small space. It is possible to explain the way the walls of narrower sections of the passage are eroded by rapid water flow from observation of particular flow scallops. Potholes of different sizes and forms (Fig. 3.17/5,6,7) reveal their development in the diversely formed passage.

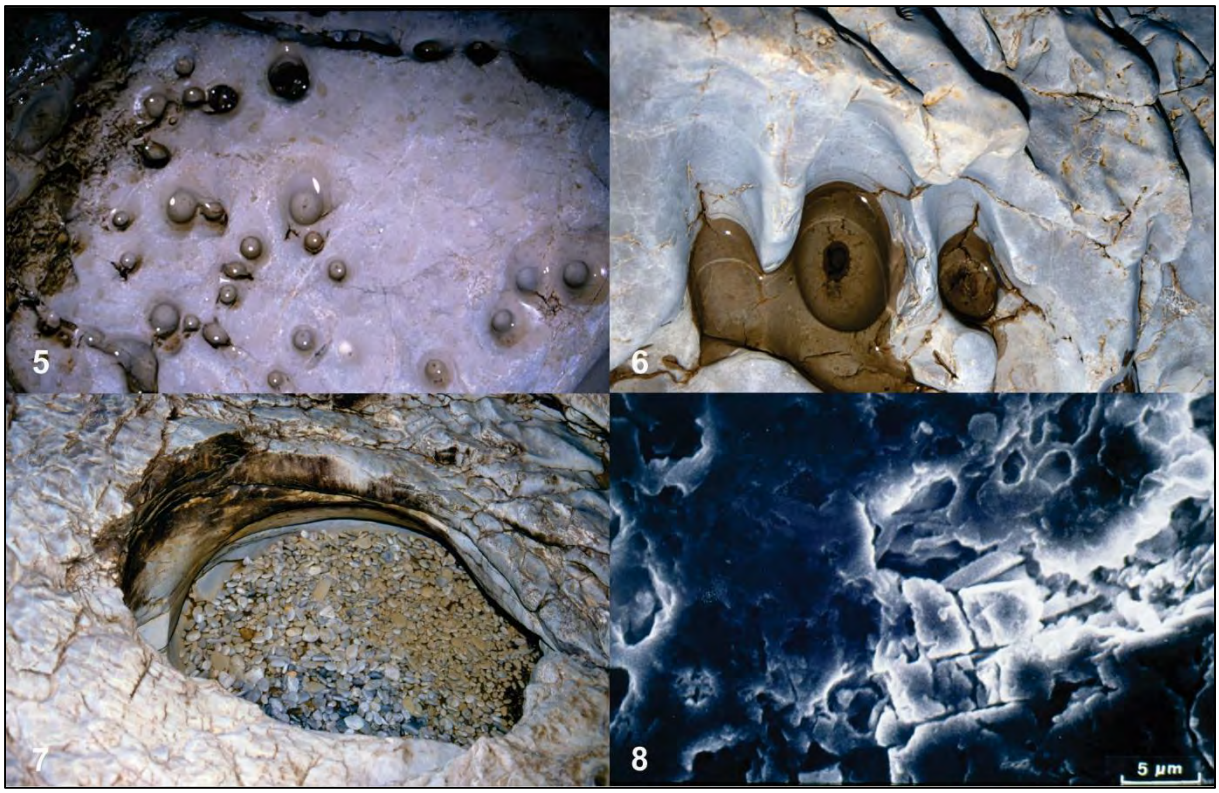

Fig. 3.17: Photos of potholes of different sizes and forms (5, 6, 7), and under a scanning electron microscope render variations in smoothness of the rock surface (8) (photos T. Slabe).

The surfaces of rock forms can frequently assist in explaining the process of their formation. Surfaces of scallops viewed with the naked eye seem relatively smooth, as are the surfaces of potholes, except for individual thin scratches. The jarred surface is jagged. Magnifications under an scanning electron microscope render variations in smoothness of the rock surface clearly visible (Fig. 3.18/8). The consequences of relatively rapid deepening of the riverbed are old potholes that are preserved on the walls. In »Rudolfova Dvorana« there is in the wall above the Reka riverbed a huge meander niche still reached by high waters. There are cups on its ceiling. Above the niche is a large pothole. The water carving the niche has reached the pothole. The new form is thus composed of two which have been left behind by two periods of passage development. The Reka's riverbed is deepening, which is also indicated by wall notches, which are the consequence of different levels of water flow. The present heights of water level fluctuation are variable. Reka's frequent water level fluctuations reveal below-sediment recesses. The bottom of the riverbed is covered with a thin layer of flowstone as a consequence of frequent, longer-lasting low water. The entire narrower part of the riverbed is deepened by a channel of over a metre in diameter (Fig. 3.18/9), we find a number of smaller channels in wider parts of the riverbed. Due to the dripping of unsaturated water from the ceiling on the edge of the rock riverbed, a channel forms (Fig. 3.18/10). A floor pit forms where water drips and from it water runs down the rock.

The initial periods of the development of the upper passages with water flow flooding the cave are revealed by ceiling cups. In some places on the upper parts of the walls, above-sediment channels are preserved. Above-sediment channels and anastomoses are evidence of flood periods when the passage was filled with fine grainy sediment and water ran only in smaller amounts below the ceiling.

Fig. 3.18: Small channels in riverbed (9, 10) (photos T. Slabe).

3.4) FLOODS IN ŠKOCJAN CAVES: OBSERVATIONS, ANALYSES, MODELLING

The aquifer of Kras is roughly a 40 km long, 13 km wide and several kilometres thick carbonate slab, extending in a SE-NW direction between Škocjanske Jame (Škocjan Caves), the Soča River, Vipava Valley and the Bay of Trieste (Fig. 3.19). It is surrounded by flysch areas, giving rise to magnificent contact karst features. The main allogenic input into the system is the Reka, with long-term (1952–2013) average discharge of about 8 m^3/s. The ratio between the highest and the lowest flow rate in the period 2005-2013 was 1700, with a maximum measured discharge of 305 m^3/s, and a minimum of 0.18 m^3/s.

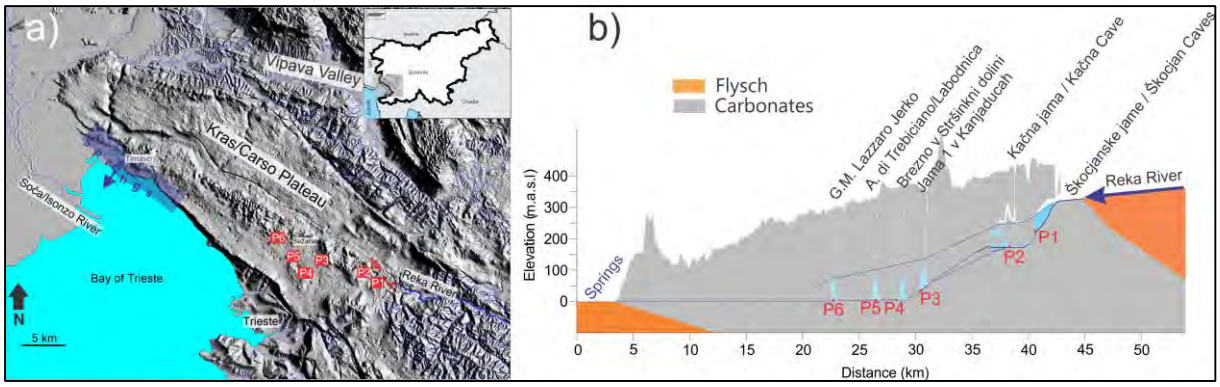

Fig. 3.19: DEM terrain visualization(a) and topographic profile (b) of the Kras/Carso Plateau with the position of some caves with access to groundwater flow. The dotted blue lines in the profile show base level and flood level at the observation points (from Gabrovšek et al. 2018).

The upper Reka-Timavo system: Škocjanske Jame and Kačna Jama

The Reka enters the aquifer at Škocjanske Jame. Its flow can be currently reached in 8 other caves between Škocjanske Jame and a series of springs between Aurisina and Duino at the NW coast of the Trieste Bay, with the Springs of Timavo being the most abundant (Fig. 3.19). The data, interpretation, and modelling are presented by Gabrovšek et al. (2018).

First part of the system comprises of Škocjanske Jame and Kačna Jama (Snake's Cave). The cross-section of this part is shown on Fig. 3.20.

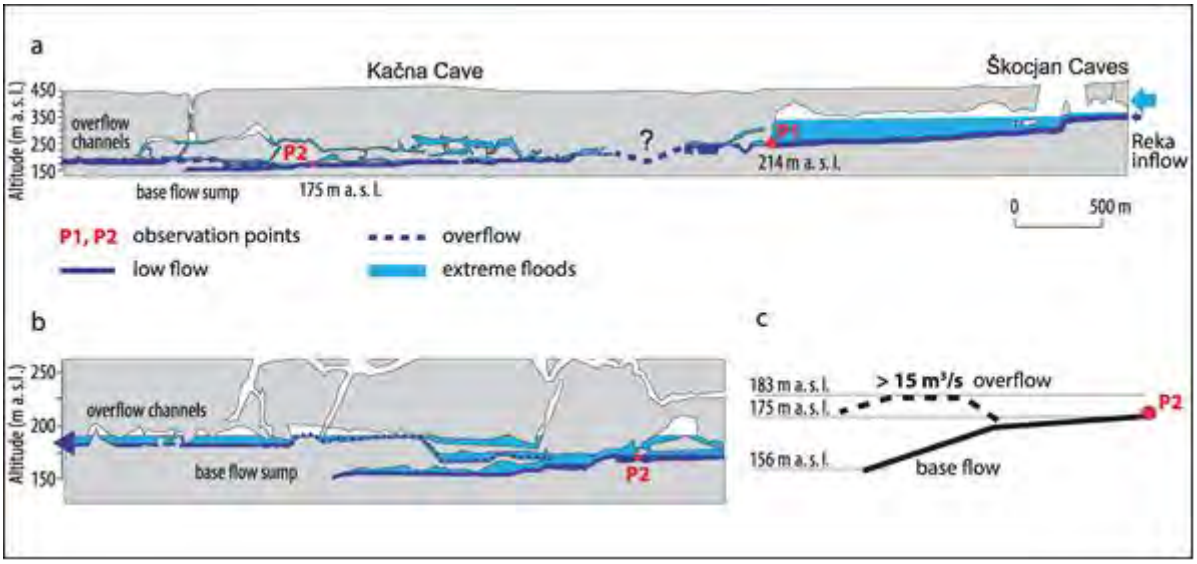

Fig. 3.20: a) Cross-section through Škocjanske Jame and Kačna Jama *with the position of observation points P1 and P2. Dark blue lines/regions indicate low flow water positions, and the pale blue shows the floodwater situation. b) Detailed view of the region of P2 in Kačna Cave. c) Flow routing at low flow (solid line) and high flow (dotted line) behind P2 (from Blatnik et al. 2020).*

The Reka reaches the flysch–limestone boundary about 7 km upstream from the Škocjanske Jame and initially flows through a canyon. At the entrance to the Škocjanske Jame, the canyon turns into an underground channel with a cross-section of 30 m by 40 m, which is after few hundred metres interrupted by collapse dolines from where the river continues along an underground canyon; 2.6 km long, 10 m to 60 m wide and 80 m to 145 m high. In Martelova dvorana, the channel is interrupted by a cross-Dinaric fault, and the cross-sectional area drops abruptly by roughly three orders of magnitude, to "only" several tens of square meters. Here, at 214 m a.s.l., is the position of the first observation station P1. From here, the flow follows a sequence of channels (with a cross-section of several tens of m2) and continues into a sump, which is still unexplored, but the connection to another sump 800 m NW in the Kačna Jama is certain. Kačna Jama can be entered from the surface through a 186 m-deep shaft that connects to a complex system of epiphreatic and vadose channels, distributed along at least two distinct levels. The cave is >13 km long and 280 m deep. The lower epiphreatic level is dominated by the flow of the Reka River, which mostly flows in an open channel during low to medium hydrological conditions, when water leaves the cave through the terminal sump at 156 m a.s.l. Observation station P2 in Kačna Cave is in the section called Brzice (= rapids), about 300 m upstream from the sump, at 175 m a.s.l. When the outflow capacity of the sump is exceeded, water flows along a system of overflow channels following the SE–NW (Dinaric) trend. More than 2 km of the overflow channels, interrupted by perched sumps, have been explored. Historical markings (organic debris) of floods in Kačna Cave are > 100 m above the base flow level (Fig. 3.20).

Flood response

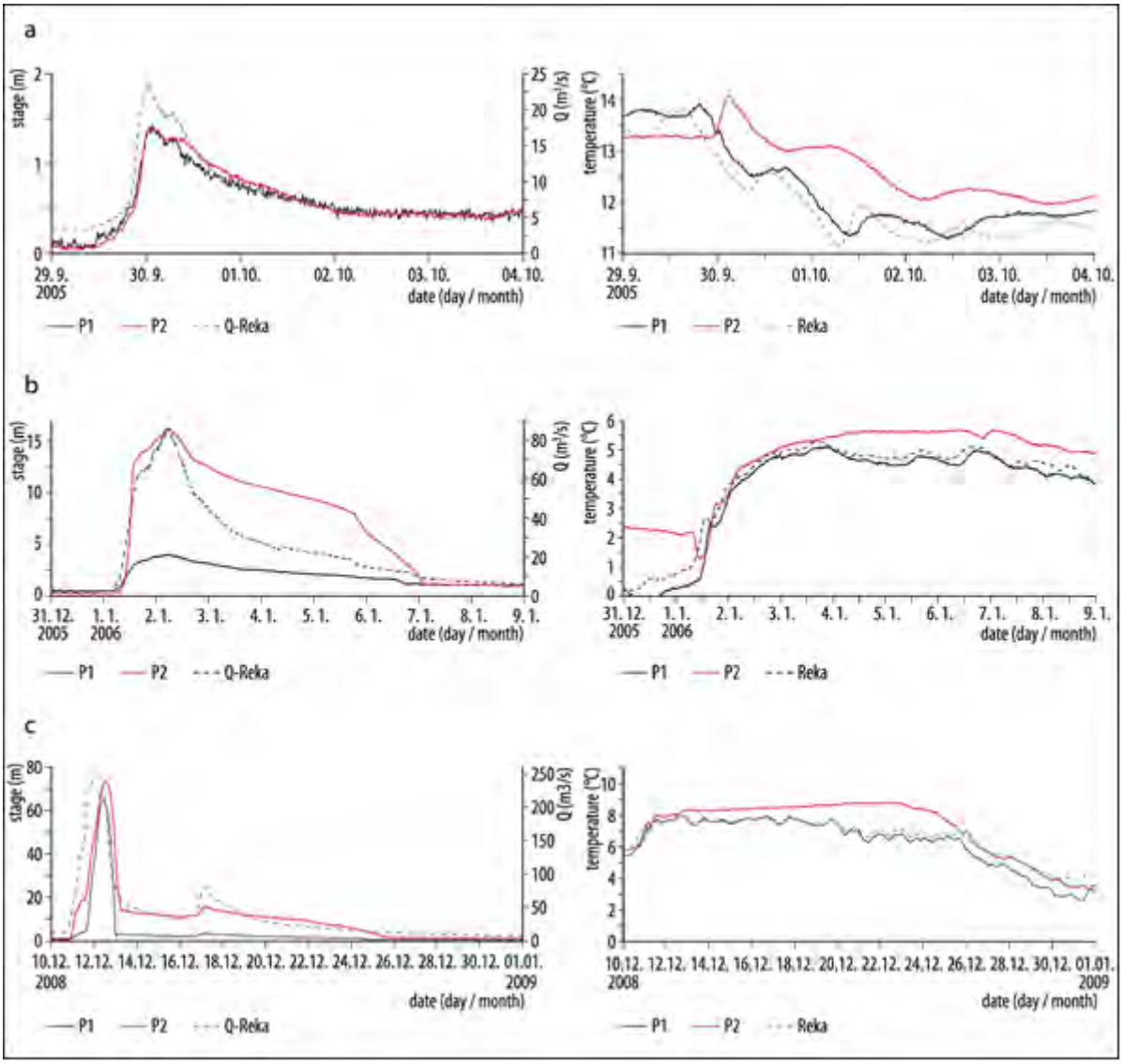

Fig. 3.21: Stage and temperature hydrographs at Škocjanske Jame (P1) and Kačna Jama *(P2) during small (a), medium (b) and large (c) flood events (from Blatnik et al. 2020). Note that the range of stage axis differs between the cases.*

Fig. 3.21 shows the response of the water level in Škocjanske Jame (P1) and Kačna Jama (P2) during three events with different peak flows. During a small event, comparable responses at both locations are recorded (Qmax = 23 m^3/s, Fig. 3.21a). In a medium event (Qmax = 85 m^3/s, Fig. 3.21/3b), the level at P1 rises to 4 m, while the level at P2 shows a steep rise to 15 m and slow recession (-2 m/day), as long as the flow rate is above 15 m^3/s. Finally, it recedes at the rate of about -4 m/day to the base level. During a large event (Qmax = 250 m^3/s, Fig. 3.21c) stage rises vigorously to 65 m at P1 and 73 m at P2, where it drops rapidly almost to the base level when the discharge drops below 100 m3/s, while at P2 stays elevated until Q> 15 m^3/s. During the rising stage of the medium and large events, inflection at about 13 m can be observed at P2, suggesting an overflow level.

The interpretation of the response and stage-discharge curves is based on the known geometry and base flow directions in Kačna Jama (see Fig. 3.20). There, the flow at low stage enters a narrow channel, which ends in a sump at 156 m a.s.l. The limited capacity of this outflow back-floods this part

of the cave and diverts water into large galleries positioned about 9 m above the instrument. This obvious overflow resolves the first inflection in Kačna Jama (Fig. 3.21b and c).

The situation is clearer in Fig. 3.22, which shows the level at P1 and P2 as a function of the Reka flow rate for the entire observation period. For Q<100 m^3/s, P1 stays below 4 m, while the level at P2 rises above 10 m for Q>20 m^3/s. When flow is higher than 130 m^3/s, a steep rise with similar characteristics at both locations is observed.

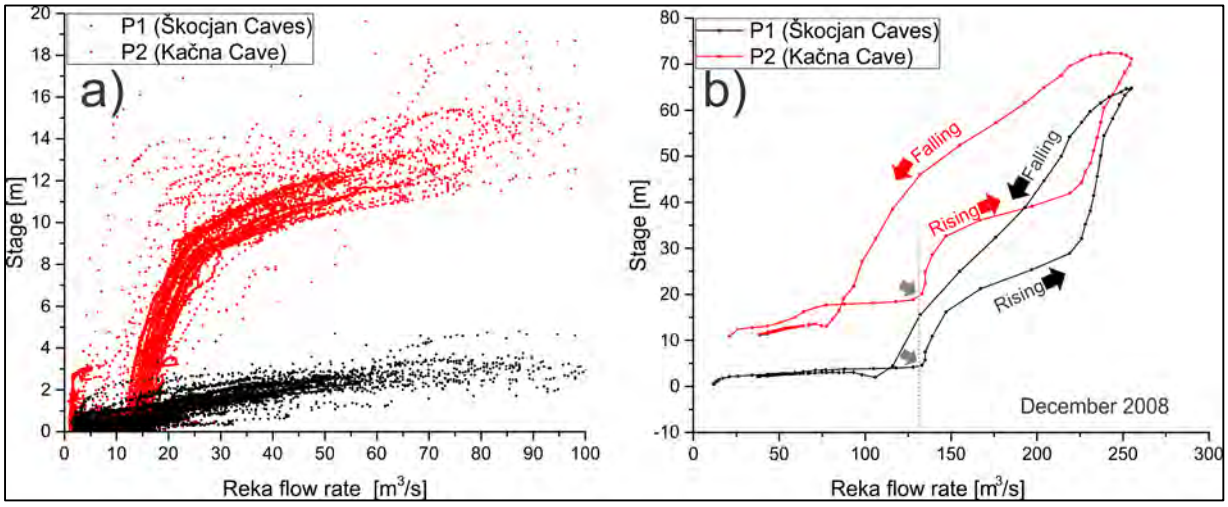

Fig. 3.22: Stage at P1 and P2 as a function of Reka flow rate (from Blatnik et al. 2020). a) Entire cloud of data points for Q<100 m^3/s. b) Situation at large flood event of December 2008. Note the common inflection towards steep rise at about 130 m^3/s, marked by grey arrows.

However, a more interesting question is what causes large floods in Kačna Jama and particularly in Škocjanske Jame, where the major inflection in the stage-discharge curve occurs at about 130 m^3/s (Fig. 3.22b). This inflection is always slightly preceded by a major inflection in Kačna Jama (grey arrows in Fig. 3.22b), which suggests that the back-flooding is triggered by the constriction behind the observation point in Kačna Jama.

Another insight is given by Fig. 3.23, which shows the relation between heads at both points. Two major floods from December 2008 and February 2009, deviate as large loops.

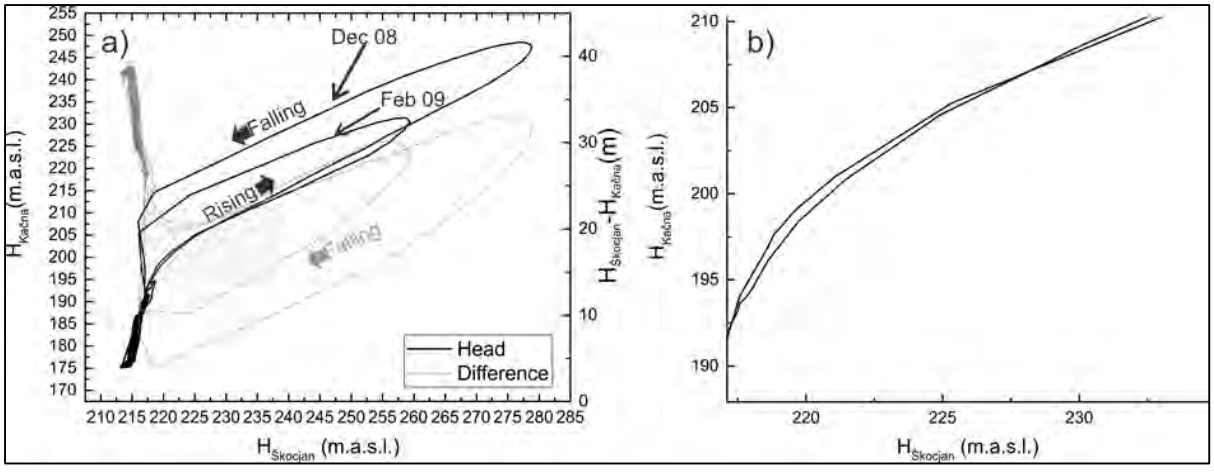

Fig. 3.23: a) Black curve: the relation between heads in Škocjanske Jame (P1) and head in Kačna Jama *(P2) (from Blatnik et al. 2020). The grey curve shows difference HŠkocjan-HKačna. b) Rising stage of the curve in the region marked by a rectangle in the figure a.*

During the rising stages of both flood events, the heads at both caves start to correlate, when the head in Kačna Jama rises above 190 m.a.s.l. Only a small deviation between both floods occurs during further increase (Fig. 3.23b). In general, the loops in such correlation plots are caused by time delay between response at the points and/or by the stored water between both points, which becomes the sole reason when both points are fully hydraulically connected. In this case the additional flow of the stored water results in slower recession at the downstream point, as compared to the upstream point. Larger floods may store more water between the points, which makes their hysteresis larger, as can be seen in Fig. 3.23a.

Note that the rate of head rise at P1 becomes higher compared to the rate at P2, when it is reached by back flooding. The reason for this is that there are several conduits between both points that become pressurised when back-flooded, resulting in a large head-drop along them.

SWMM model of the hydraulic response to high recharge events

We have modelled flood propagation through Škocjanske Jame and Kačna Jama with SWMM. The model is based on the one presented by Gabrovšek et al. (2018), but only the first part of the system, relevant for P1 and P2, is taken and optimised manually. The plan-view of the model is shown in Fig. 3.24a and the cross-section at different flood stages in Fig. 3.24c. Fig. 3.24b shows observed and modelled response at P1 and P2 during the period of the February 2009 flood. Despite the fact that the model's geometry is highly simplified and partially unknown, the model captures all characteristics of the observations. Four stages of the flood event are shown in Fig. 3.24c: 1) before the flood, when all the water is drained by the low water sump beyond P2, 2) when overflow is active and P2 is already back-flooded, but the response at P1 is still small, 3) at the peak, where all conduits are pressurised and, 4) when P1 has dropped almost to base level and P2 is still high.

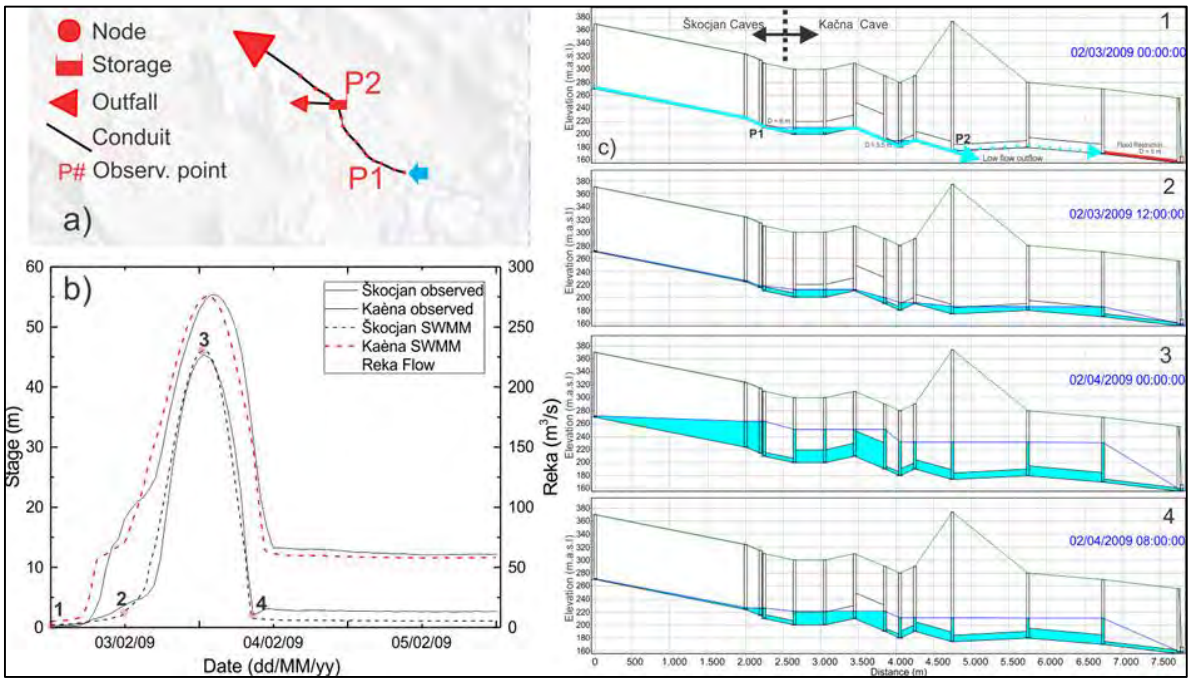

Fig. 3.24: a) Plan view of the SWMM model (from Blatnik et al. 2020). b) Modelled (dashed lines) and observed (full lines) responses at P1 and P2 during the flood event in February 2009. The recharge is shown by grey dotted line. Points 1-4 show four the positions of stages presented in the figure cc. c) Cross-section of the model at four stages during flood event. Pale blue regions denote the water level; dark blue lines show total had along the profile.

Flood event in February 2019

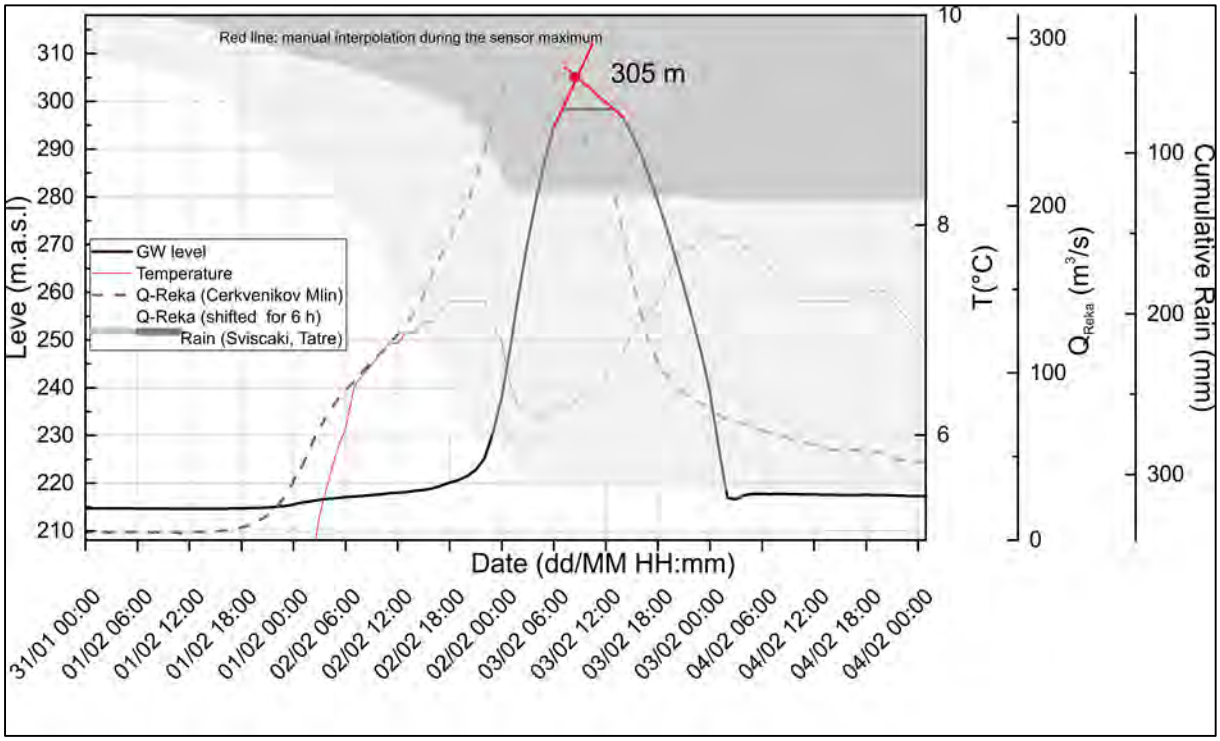

Fig. 3.25: The flood event of 2019: Cumulative rain at two stations, discharge of the Reka River and level and temperature in Martel's Chamber (from Blatnik et al. 2020). Dotted grey line shows discharge shifted for six hours, an estimated travel time from gaging station to Martel's Chamber.

Between January 27th and February 4th 2019, over 300 mm (almost 200 mm in the most intensive 30 h period) of rain fell in the mountainous region of Mt. Snežnik and about 150 mm in the area of Škocjan (2020). The discharge of the Reka River at the Cerkvenikov Mlin gaging station peaked at 300 m3/s. During the event 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. 3.25 and 3.26) 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; at some places the thickness of fresh deposits was above 50 cm (Fig. 3.27).

Fig. 3.26: A simplified extended elevation of Škocjan Caves with approximate maximal water level during the flood of February 2019 (from Blatnik et al. 2020).

Fig. 3.27: Photos of the 2019 flood. a) Velika Dolina collapse valley. 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)).

Gravity observations of floods

From July 2018, we also performed a time-lapse gravity observation with a gPhone gravimeter (herein referred as SK1) positioned on the surface above Škocjan Caves. The idea was to observe gravimetric response due to mass changes caused by flooding (Pivetta et al. 2021).

The gravimeter was installed in a building near the information centre, approximately 250 m from the Šumeča Jama (Rumoring Cave). The raw gravimetric have to be processed to remove signals of tidal and non-tidal origin and atmospheric signals in order to obtain the residual, i.e. the gravity variations caused solely by the flood event. Fig. 3.28a) and b) show map of Škocjan caves with elevation of bottom ceiling and flooded region at two different water levels. Fig. 3.28c to e show measured and modelled water level, gravimetric response and stored volume. The "whole model" version includes also water stored in collapse dolines and Reka Canyon prior to the ponor. Inclusion produced a much better fit to gravimetric data. The model used in this work also included an improved geometry of Škocjan Caves based on 25 cross-sections of the Reka Canyon made with laser profiler.

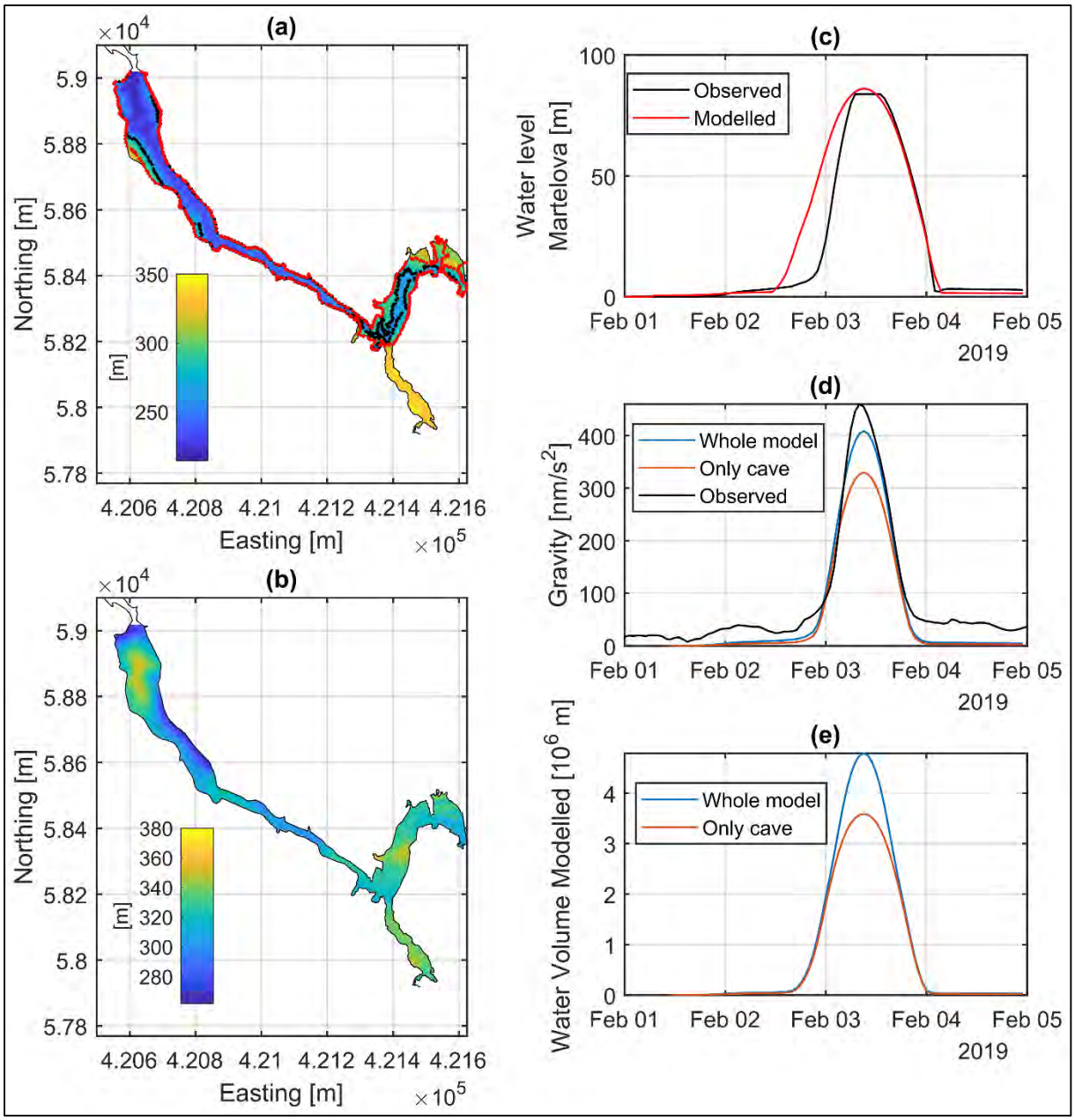

Fig. 3.28: Hydrological and gravitational response to flood event (from Pivetta et al. 2021). (a) Elevation of the strembed during low flow (m a.s.l.) where the Reka flows; the red and black outlines show the flooded area when the water level in P1 is respectively 86 and 50 m. (b) Elevation (m a.s.l) of the ceiling of the cave. (c) Observations (black) and modelling (red) of the water level time series at P1 (d) black: observed gravity residual; blue: modelled gravity transient for the whole model, which includes the flooded areas out of the cave; red: gravity effect of the solely masses inside the cave. (e) Stored water volume during the flood; the colour code as in (d).

3.5) MICROMETEOROLOGY OF ŠKOCJANSKE JAME

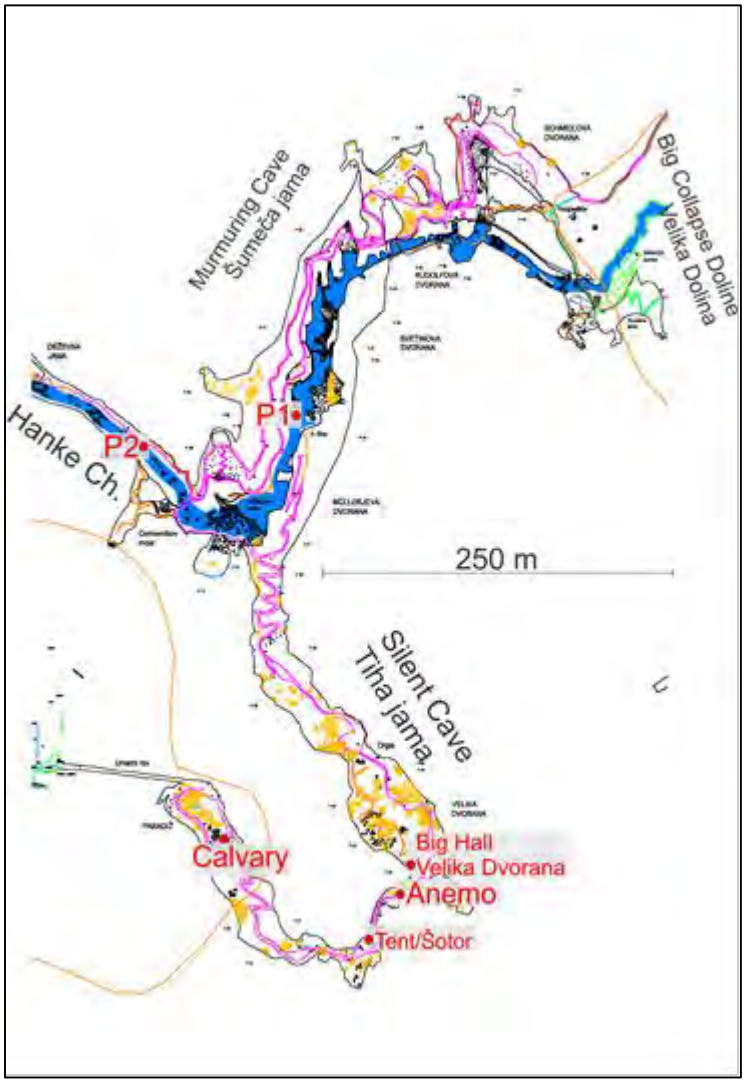

Fig. 3.29: Part of the Škocjan Caves with Murmuring Cave and Silent Caves, with locations of observation stations referred in this section (IZRK ZRC SAZU).

A convection cell in the Reka Canyon

The canyon of Reka is meteorologically the most dynamic part of Škocjanske Jame. 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. These observations suggest a convection cell in which cold outside air flows into the cave at the bottom of the canyon, is warmed by heat exchange with the massif, and then rises and flows under the ceiling to the exit (Fig. 3.30). Of course, convection in reality is probably even more complicated, but to get a more detailed picture, one would need more measurement points.

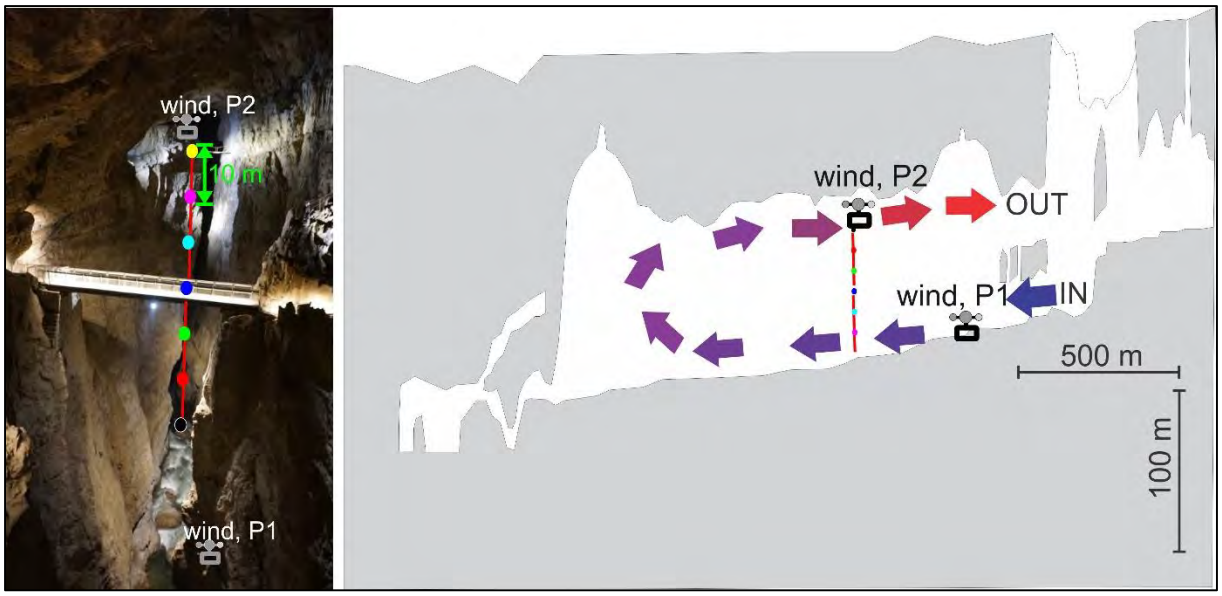

Fig. 3.30: Observations and concept of convection cell in the Reka Canyon in Škocjan Caves (F. Gabrovšek). Left: Picture of Šumeča Jama (Murmoring Cave) and Hanke Channel with position of anemometers (P1-6th Watefrall, P2-Novak Bridge) and line of temperature loggers below P2. Right: Profile of Reka Canyon with (so far) estimated convection cell. Arrows indicate temperature (blue->red = cold -> warm) and direction of airflow.

To evaluate this process in more detail, we installed ultrasonic anemometers just above the river level at the Sixth Waterfall in the Šumeča Jama (P1 in Fig. 3.30) and under the ceiling of the gorge above the Novak Bridge (also Felsen Brucke, P2 in Fig. 3.30) in the Hanke Channel.

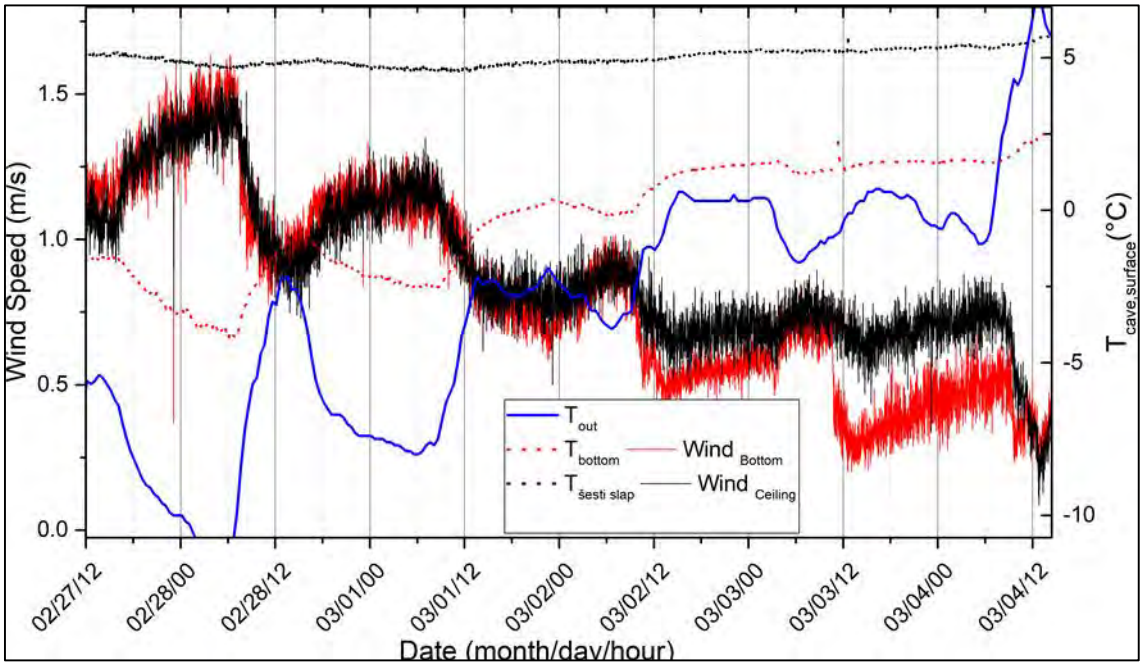

Fig. 3.31: Airflow velocity and temperature at bottom (red curves) and below the ceiling of the canyon (black curves) in winter 2018 (F. Gabrovšek). Blue curve shows the outside temperature.

Fig. 3.31 shows the airflow velocity at both anemometers, temperatures at the ground and under the ceiling, and outdoor temperatures at the end of February and beginning of March 2018. The temperature below the ceiling (P2) is constantly in the range of 5°C, and the temperature at the bottom

(P1) 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.

Transitional periods, when external temperatures drop or rise below or above the temperatures of the cave, are the most interesting from the viewpoint of cave meteorology. Fig. 3.32 shows the airflow velocity and temperatures during the transition from summer to autumn 2018, starting with a typical summer regime and entering into the first fall cooling. In the first part, before September 24th, when the outdoor temperature does not drop below 15°C, the air flows into the cave at both locations, with the airflow over the Novak Bridge (P2) being much faster and more responsive to changes in outdoor temperature than the airflow at the river bed (P1). During the cooling (shaded part of Fig.32), a convection cell as described above forms when the outdoor temperature drops below 5°C. The airflow speed at both locations are comparable. The change can also be seen in the temperature: The blue curve shows the value 40 m above the bottom of the canyon below P2. The relatively constant temperature drops when the convection cell forms and then follows the variations of inflow into the cave: the stronger the inflow of cold air, the lower the air temperature in the canyon.

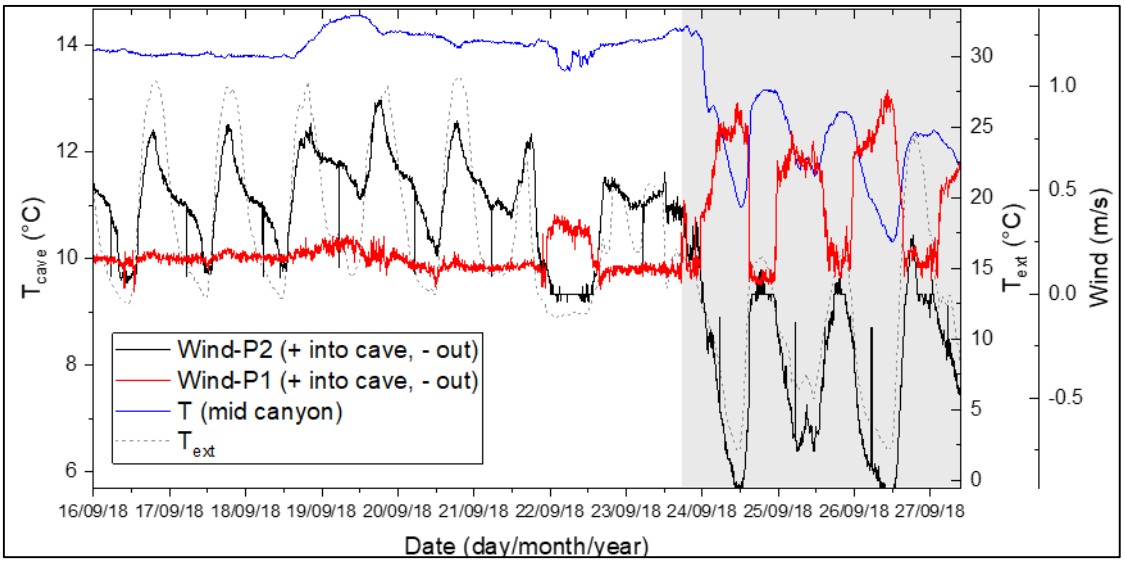

Fig. 3.32: Airflow speed at the Novak Bridge (P2, red) and at the 6th Waterfall (P1, black), external temperature (dotted) and temperature 30 m below the Novak Bridge (P2) (F. Gabrovšek).

Fig. 3.33 shows the airflow velocity and temperatures at different height above the river at P2 during the warm period in September 2018. The temperature is highest at the highest point, where the airflow is strongest. The airflow speed increases with the outside temperature.

When the outside temperature drops below 15°, the velocity decreases rapidly, and so does the temperature below the ceiling.

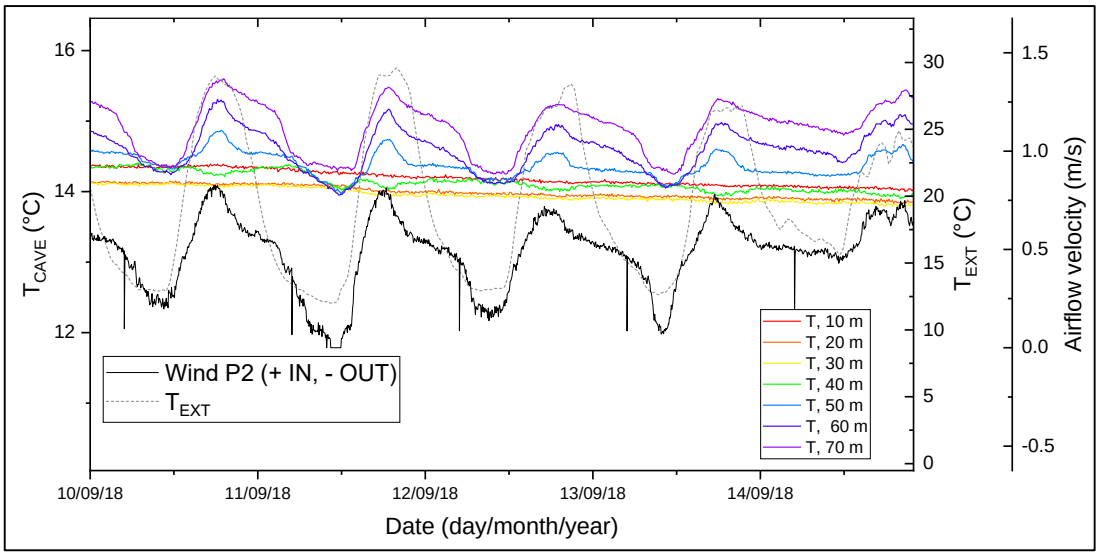

Fig. 3.33: Airflow velocity at Novak Bridge and temperatures at different heights above the bottom of the Canyon (F. Gabrovšek).

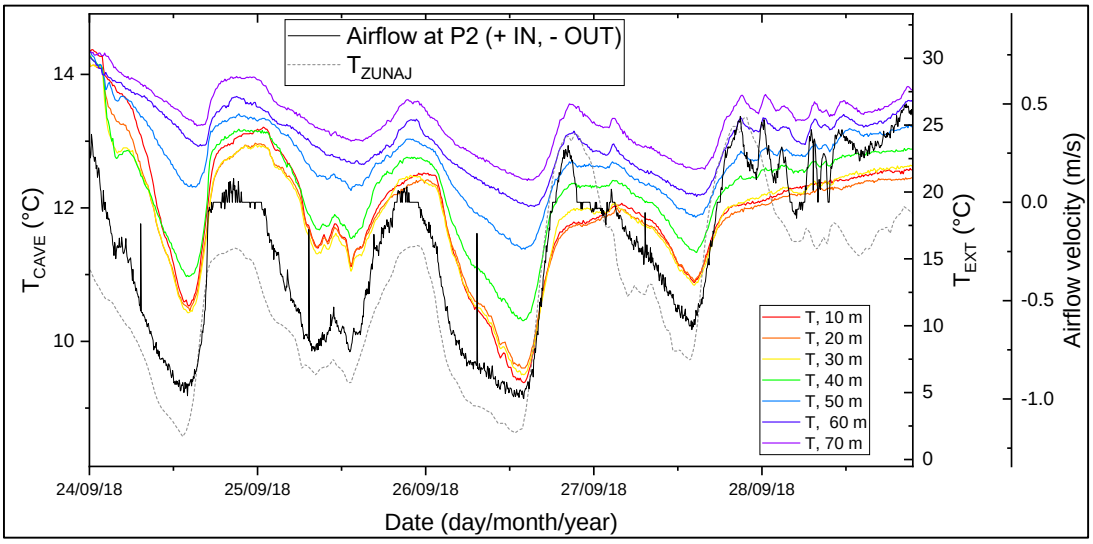

Fig. 3.34: Airflow velocity at Novak Bridge and temperatures at different heights above the bottom of the Canyon during the cold period in September 2018 (F. Gabrovšek).

During cooling, convection cell establishes. The temperature profile at P2 show a high vertical gradient.

Fig. 3.35 shows the airflow velocity at the ceiling as a function of external temperature. During the cold period, when the convection cell is active, the velocity shows (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. Such a relationship is typical of air flow under the influence of the "chimney effect".

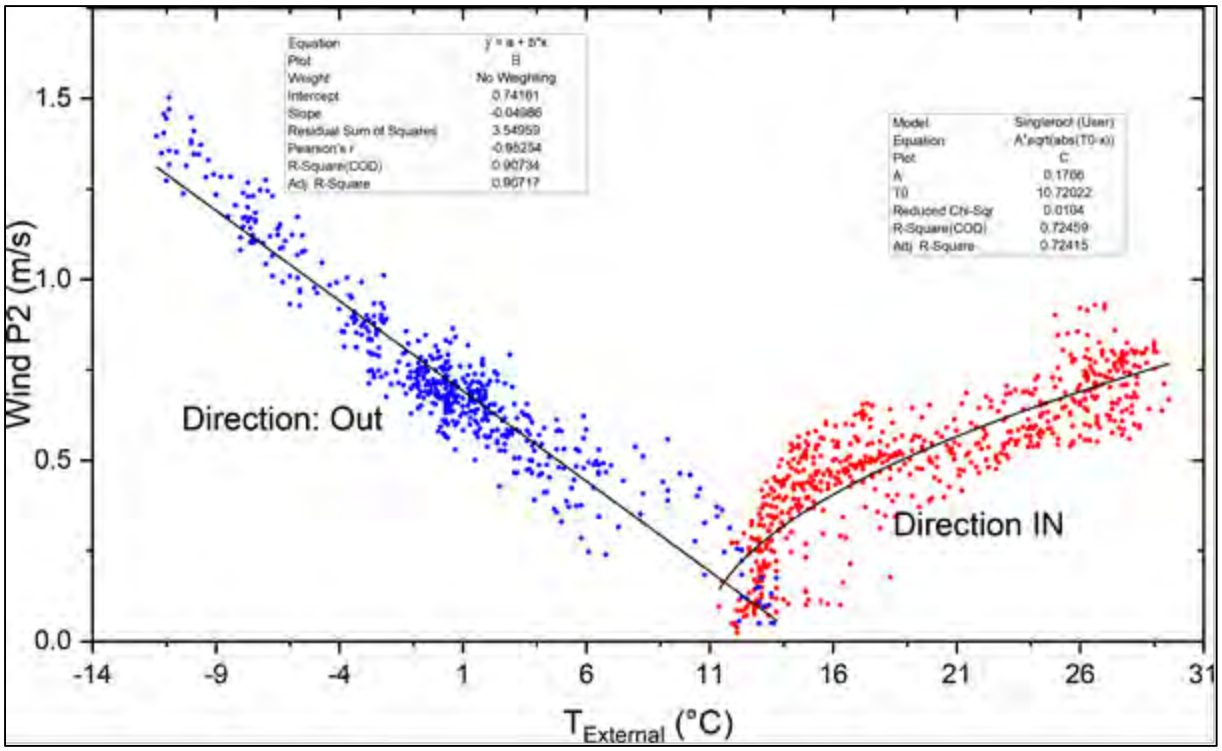

Fig. 3.35: Airflow velocity at Novak Bridge (P2) as a function of external temperature (F. Gabrovšek).

Climatic characteristics of the Tiha Jama

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/Murmoring Cave). The second "entrance" is an artificial tunnel from collapse doline Globočak, which is open only during the passage of tourists. In a sense, a silent cave can be considered a "blind tunnel", with no open access to the surface.

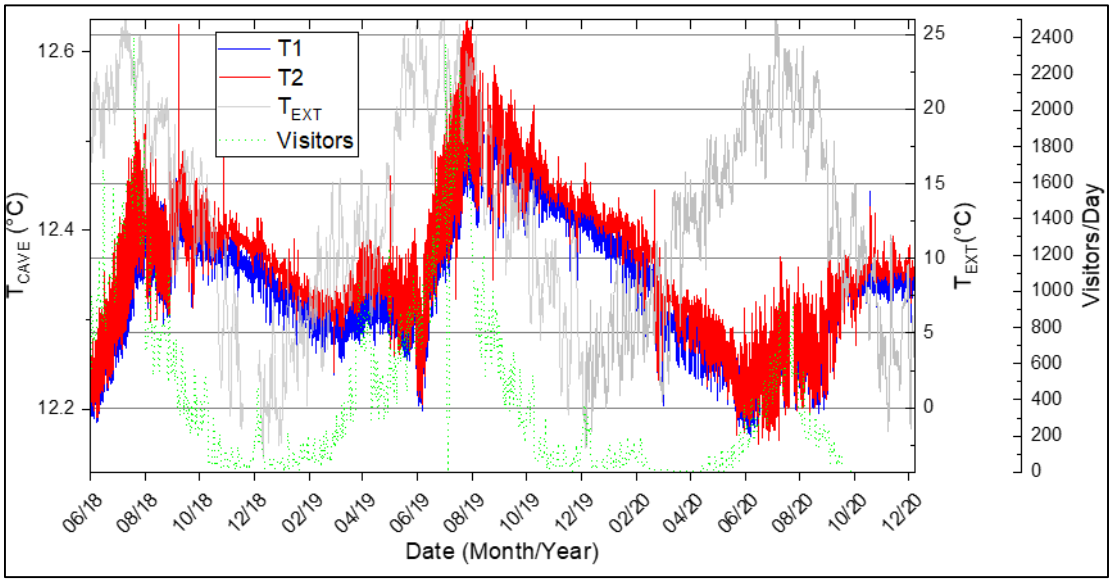

Fig. 3.36: Temperature in Velika Dvorana (Large Hall), external temperature and the number of visitors between June 2018 and December 2020 (F. Gabrovšek).

Fig. 3.36 shows the course of temperature in between June 2018 and December 2020. The temperature in the Velika Dvorana (Large Chamber) varies between 12.2°C and 12.6°C; the annual

maximum is in late August and the minimum in March. Even a brief comparison between the years 2018/19/20 shows that the main factor for the temperature increase is the number of visitors.

In 2020, following the closure due to Covid, the temperature decreased until the end of June, regardless of the increase in outdoor temperature. It is only with the increase in the number of visitors that the temperature rises. The peak temperature is also much lower than in 2019, when the number of visitors reached a record. Without the influence of attendance, the Great Hall would probably have a much more constant temperature; probably a little below 12°C.

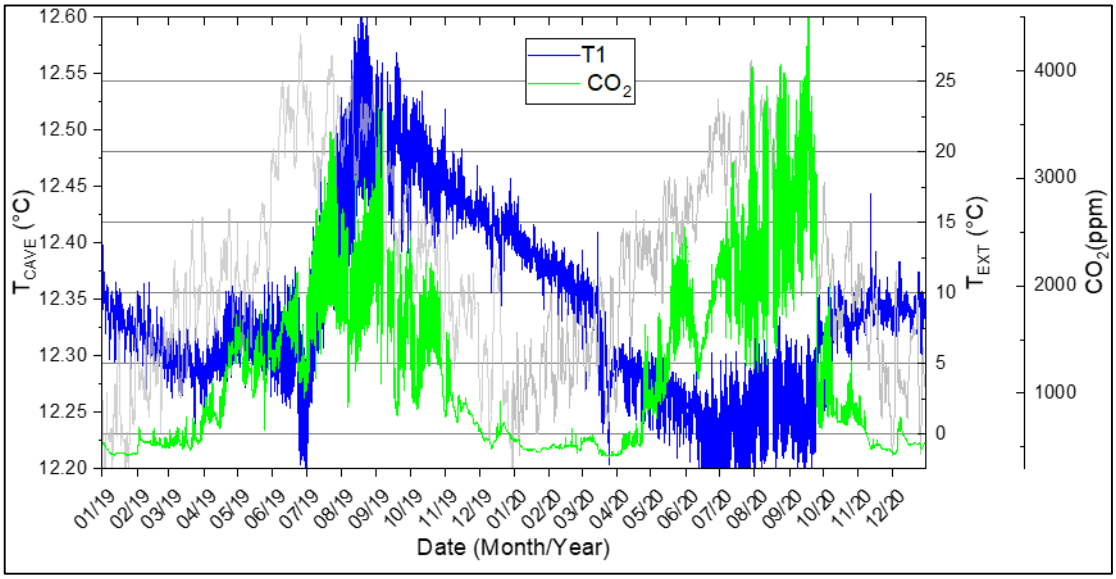

Fig. 3.37: Temperature and CO2 in Velika Dvorana (Large Hall) during 2019 in 2020 (F. Gabrovšek).

The CO_2 concentration is apparently contradicting, with higher values in 2020 (Fig. 3.37). In summer season the opening of the door for the tourists results in ventilation and reduction of CO_2 despite the input from the visitors. With less visits and ventilation caused by opening the door, as in 2020, the natural inflow of the CO_2-enriched air from the vadose zone becomes dominant.

During the cold season, the direction of natural ventilation leads from the Šumeča Jama through the Tiha Jama to the surface, which is why low CO_2 concentrations are also measured in the Tiha Jama.

Fig. 3.38 shows the CO_2 variation in Velika Dvorana, external temperature, and airflow at the passage to the Velika Dvorana in July 2019. The gray area (1) shows the part of the day with visits, between 9 a.m. and 5 p.m., and the area 2 shows the part of the day without visits. Opening the tunnel door causes an influx of outdoor air from the direction; CO_2 concentration fluctuates because of the dilution due to induced ventilation and accumulation due to natural inflow and contribution from the tourists. After the end of the visits, when the doors are closed, the CO_2 level increases until the early morning hours. The increase is caused by the natural ventilation (chimney effect), when the CO_2 enriched air from the vadose zone enters the hall predominantly through the system of fractures.

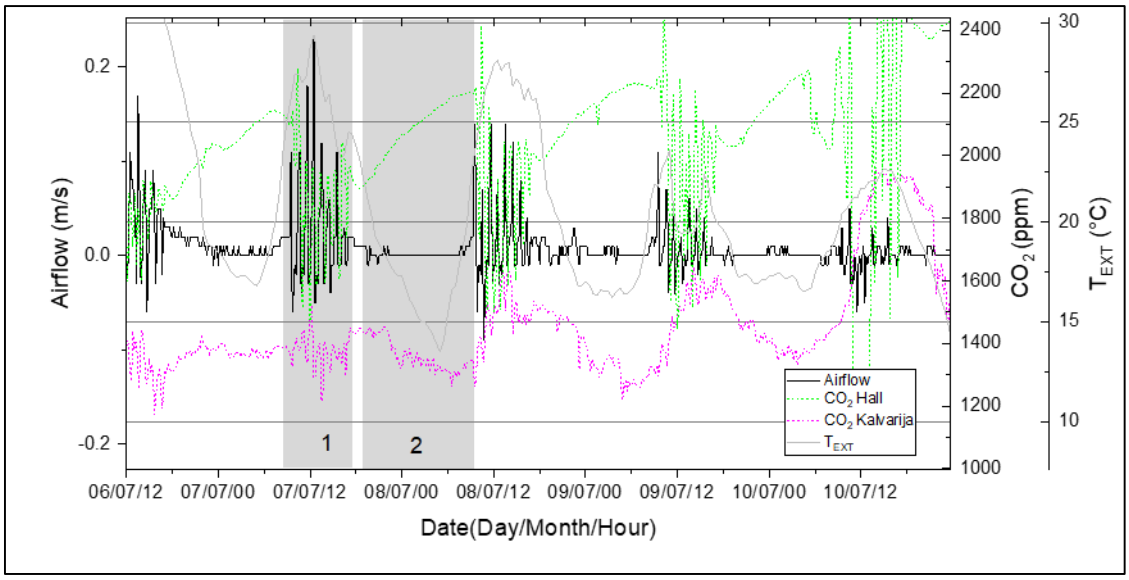

Fig. 3.38: Airflow velocity into Velika Dvorana, CO_2 concentration in Velika Dvorana and Kalvarija and external temperature in July 2019 (F. Gabrovšek).

During the Covid shutdown in 2020, we could observe the atmospheric dynamics undisturbed by the visits. Fig. 3.39 shows what happens in the Velika Dvorana (Hall), Šotor and Calvary sites in April when the outside temperature varies between 0°C and 20°C. CO_2 shows a characteristic set of accumulation and relaxation curves. It turns out (and this is also true in general) that it begins to rise when the outdoor temperature reaches about 17°C and starts to fall when the outdoor temperature drops below 12°C (see dotted lines in Fig. 3.38). The airflow is typically weak, just above the measurements limits and therefore just indicative. During CO_2 accumulation, the airflow is coming from the direction of Calvary. During relaxation, we do not record the airflow, although it is difficult to explain the decrease in CO_2 other than that the air flows in from the direction of Šumeča Jama. The CO_2 dynamics at the Šotor station are quite different from those at the Kalvarija station; further study would be required to understand them all.

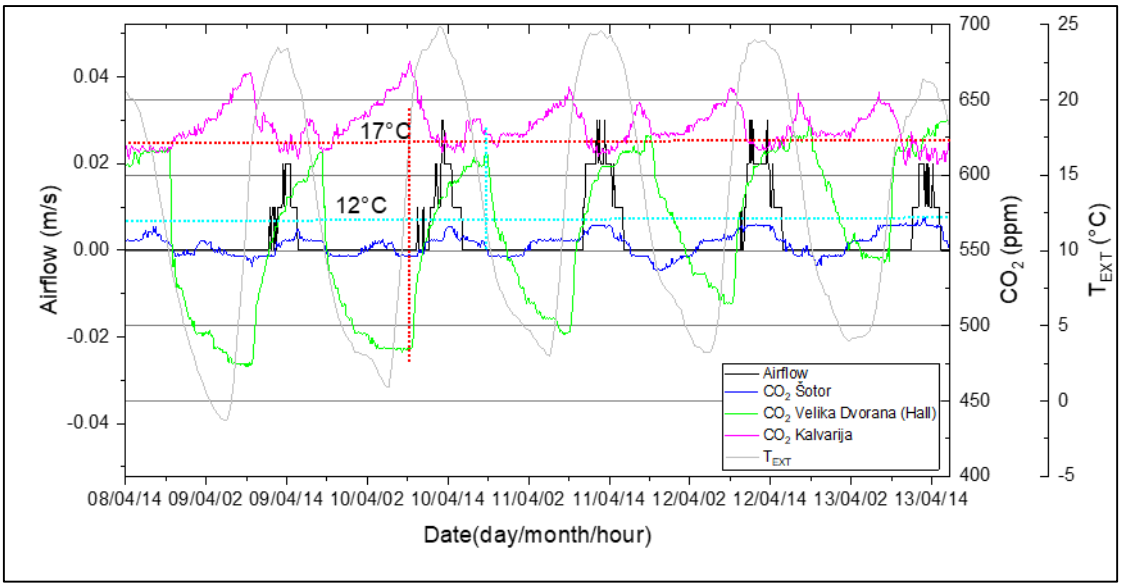

Fig. 3.39: CO_2 concentration, airflow and external temperature in transitional period of April 2020; during shutdown (F. Gabrovšek).

Although we detect only a stronger air flow due to the position of the anemometer in Tiha Jama, we have observed periods of increased flow that are not related to the opening of the door. It turns out that we can associate these periods with the time of stronger bora gusts at the surface. Wind driven cave ventilation has been observing in Postojna Cave and Kačna Jama, but apparently this mechanism also exists in Škocjanske Jame (Fig. 3.40).

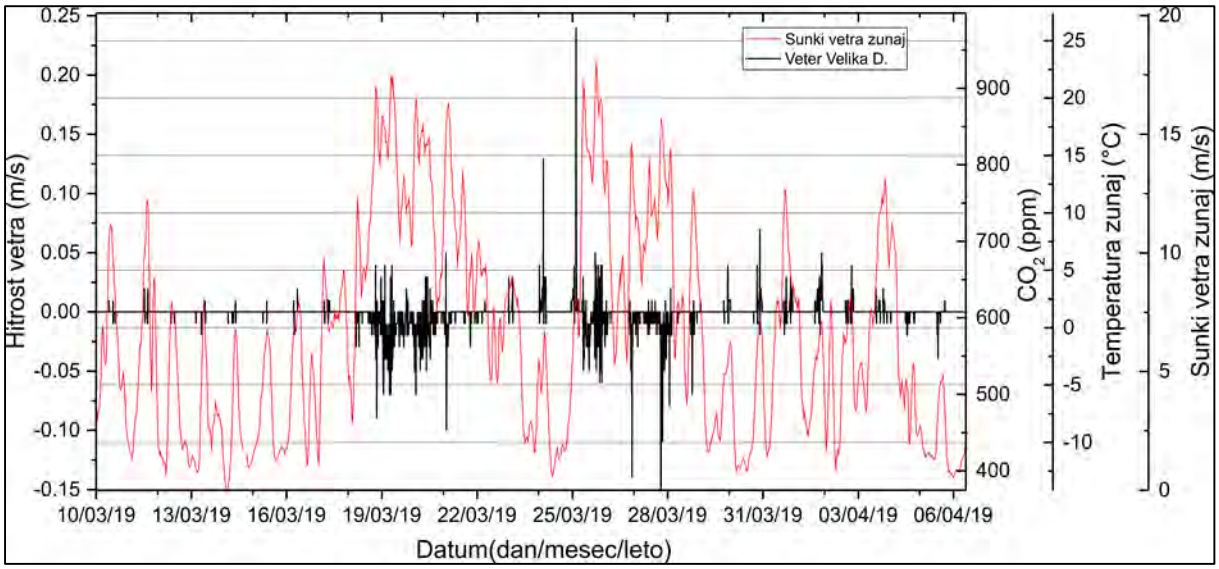

Fig. 3.40: Airflow in Tiha Jama (Silent Cave) driven by external wind gusts (F. Gabrovšek).

3.6) SPELEOBIOLOGIJA

Epikarst fauna in Škocjanske Jame

The epikarst is the boundary between soil and rock in the karst landscape, an ecotone between the surface and subterranean environment. Because the epikarst cannot be sampled directly, the epikarst fauna is best studied by collecting and filtering drip water that seeps down the walls or drips directly from the cave ceiling (Fig. 3.41/1). Drips exhibit considerable environmental and species diversity heterogeneity (Pipan, 2005; Pipan & Culver, 2022). Animals in drip water are those that have been flushed out of their primary habitat above the cave passage.

Fig. 3.41: On photo 1) Sampling of epikarst fauna (photo J. Hajna); and on 2) Male of stygobiotic copepod Speocyclops infernus (Cyclopoida) from percolating water in Škocjan Caves (photo T. Pipan).

Vertically percolating water from the epikarst collects in pools and streams and is often relatively rich in organic matter (Culver & Pipan, 2013). In addition, a significant number of terrestrial and aquatic organisms are flushed from the epikarst into pools and streams (Ravbar & Pipan, 2022). Although some of these animals, particularly copepods, are capable of colonizing the pools and

streams, others, such as *Collembola*, survive for short periods at most and are food sources for the cave inhabitants.

The aquatic fauna of the epikarst consists of various invertebrate species, with Copepoda (species in the Cyclopoida and Harpacticoida groups) being the most common representatives. Other groups, including Amphipoda, Ostracoda, Oligochaeta, and Gastropoda, are less common but frequently found in drips and pools filled with drip water (Culver & Pipan, 2014).

We collected 11 different taxa in drips and drip pools sampled in Škocjanske Jame. In addition to copepods, there were numerous specimens of Nematoda, Ostracoda, and Amphipoda, and few specimens of Isopoda, Oligochaeta, Gastropoda, Acarina, Collembola, Diptera, and Coleoptera. Special attention was paid to copepods (Table 3.01), of which 20 species were found, of which four species belong to Cyclopoida and 16 to the Harpacticoioda group. Among them were five species new to science: *Bryocamptus*, *Moraria*, *Parastenocaris* in cf. *Stygepactophanes*. Most of them are epikarst specialists, not found in any other subterranean aquatic habitat than epikarst.

Epikarst and epikarst fauna are highly vulnerable to environmental change, so successful conservation of epikarst communities should focus on protecting the surface landscape (Pipan et al., 2018).

Table 3.01: List of epikarst copepod species from percolating water in Škocjanske Jame. Stygobiotic species are highlighted with an asterisk (*).

	drips	pools
CYCLOPODA		
Diacyclops languidus (Sars, 1863)	+	+
Megacyclops viridis (Jurine, 1820)	+	+
Paracyclops fimbriatus (Fischer, 1853)	+	+
Speocyclops infernus (Kiefer, 1930)*	+	+
HARPACTICOIDA		
Attheyella crassa (Sars, 1862)	+	+
Bryocamptus pygmaeus (G. O. Sars, 1862)	+	
Bryocamptus typhlops (Mrazek, 1893)*	+	+
Bryocamptus zschokkei (Schmeil, 1893)	+	+
Bryocamptus n. sp.*	+	+
Canthocamptus staphylinus (Jurine, 1820)	+	
Elaphoidella cvetkae Petkovski, 1983*	+	
Elaphoidella slovenica Wells, 2007*	+	+
Moraria poppei (Mrazek, 1893)	+	+
Moraria stankovitchi Chappuis, 1924*	+	
Moraria n. sp.*	+	
Morariopsis scotenophila (Kiefer 1930)*	+	+
Parastenocaris nolli alpina (Kiefer, 1938)*	+	+
Parastenocaris n. sp.1*	+	
Parastenocaris n. sp.2*	+	+
cf. *Stygepactophanes* n. sp.*	+	

Terrestrial subterranean fauna in Škocjanske Jame

The Škocjanske Jame are one of the most famous and best researched karst phenomena in Slovenia. Despite the numerous speleological studies carried out in the past, the knowledge about subterranean fauna is still insufficient. Data on the fauna are still scattered over many scientific articles and species descriptions, many of which are in need of thorough taxonomic revision. The Škocjanske Jame are one of the oldest caves opened to tourism in Slovenia. Opening a cave to tourism inevitably involves disruption of the natural habitat, as it is accompanied by major physical changes in the cave, such as construction of walking surfaces, railways, widening of passages, and installation of lighting, which greatly affect the relatively stable (micro)climate (Groth et al., 1999, Gillieson, 2011). Changes introduced by the establishment of caves for tourism often have, at least potentially, strong negative impacts on subterranean biodiversity, as subterranean habitats are generally characterized by perpetual darkness and relatively constant environmental conditions (Culver & Pipan, 2019). Climatic conditions have profound effects on specialized subterranean species, as they are generally adapted to narrow temperature and humidity ranges (Rizzo et al., 2015; Kozel et al., 2019; Pallarés et al., 2019). Even small changes in microclimate can negatively affect specialized subterranean fauna. In some cases, tourist use can lead to declines in populations of certain troglobiotic species (Pacheco et al. 2020). However, some studies report that disturbance of cave habitats does not necessarily lead to declines in biodiversity when disturbance is limited in duration, intensity, and spatial extent (e.g., Faille et al. 2014). Interestingly, many tourist caves have also been shown to harbor highly diverse troglobiotic fauna (Culver et al., 2021). Potential negative impacts of tourism can only be assessed by long-term monitoring of subterranean fauna in relation to various environmental factors.

In recent years, we have conducted three preliminary surveys of the subterranean fauna in the Škocjanske Jame in order to determine the spatial distribution of the fauna and possibly supplement the existing faunal inventory. To this end, we established 16 sampling sites along the tourist path. We sampled different locations in the cave to cover as many different microhabitats as possible. Where possible, sampling sites were chosen near water puddles fed by percolation water. Our goal was also to check whether subterranean fauna near these puddles was more abundant and species-rich compared to other sites. Percolation water from the upper layers is often rich in organic material, making it one of the most important food sources in deep subterranean habitats. Our results could serve as a basis for long-term monitoring to assess potential changes in faunal composition over time and space due to tourism activities.

Altogether we recorded 1379 individuals belonging to 41 species (Table 3.01). Collembolans from the family Entomobryidae were most common, followed by cave crickets *Troglophilus neglectus*, mites from the family Opiidae, and dipterans from the family Phoridae. Of all recorded fauna, 11 species are recognized as specialized subterranean species, i.e., troglobionts. Troglobionts predominated in the first part of the cave, where microclimatic conditions were probably most favourable. Their abundance decreased inside the cave, which is consistent with some literature on the spatial distribution of troglobionts in caves (Tobin et al., 2013; Kozel et al., 2019). Compared to some other tourist caves in Slovenia (e.g. Postojnska jama, Cave under Predjama Castle, Križna Jama), the number of troglobionts was relatively low. However, we assume that the number of troglobionts will be larger after taxonomic revision of many unidentified species. Due to the presence of troglobionts along the entire tourist part and the increasing number of visitors to the Škocjanske Jame, and the related pressure on the fauna, a permanent monitoring of the fauna is strongly recommended. Because of the large amount of organic material washed into the cave by the Reka, some

nonspecialized species form permanent populations in certain places in the cave where they would not otherwise survive.

Table 3.02: List of species recorded along tourist path in Škocjanske Jame. Specialized subterranean species are highlighted with an asterisk (*).

PHYLUM	CLASS	ORDER	GENUS, SPECIES
Nematomorpha	Gordioida	Gordioidea	*Gordius* sp.
Mollusca	Gastropoda	unidentified	Gastropoda sp.
		Stylommatophora	*Oxychilus cellarius* (O.F.Müller, 1774)
Arthropoda	Arachnida	Araneae	**Stalita taenaria* Schiødte, 1847
			Nesticus eremita Simon, 1880
			Metellina merianae (Scopoli, 1763)
		Opiliones	*Leiobunum rupestre* (Herbst, 1799)
			Mitostoma chrysomelas (Hermann, 1804)
		Sarcoptiformes	Opiidae sp.
		Mesostigmata	Gamasidae sp.
	Chilopoda	Lithobiomorpha	*Lithobius validus* Meinert, 1872
	Diplura	Diplura	**Plusiocampa* sp.
	Malacostraca	Isopoda	*Armadillidium vulgare* Latreille, 1804
			Cylisticus convexus (De Geer, 1778)
			**Alpioniscus strasseri* (Verhoeff, 1927)
			**Androniscus stygius tschameri* Strouhal, 1935
			**Cyphoniscellus herzegowinensis* (Verhoeff, 1901)
			**Titanethes dahli* Verhoeff, 1926
	Entognatha	Collembola	*Entomobryidae sp.
			*Isotomidae sp.
			*Onychiuridae sp.
			Sminthuridae sp.
			Tomocerus sp.
	Insecta	Coleoptera	*Abax* sp.
			Laemostenus cavicola (Schaum, 1858)
			Laemostenus (*Antisphodrus*) *schreibersii* (Küster 1846)
			Carabidae sp.
			Bathyscia montana Schiødte, 1848
			**Bathysciotes khevenhuelleri* (L.Miller, 1852)
			Cholevinae sp.
		Diptera	*Dryomyza* sp.
			Heleomyzidae sp.
			Phoridae sp.
			Psychodidae sp.
			Trichocera regelationis (Linnaeus, 1758)
			Sciaridae sp.
			Atheta sp.
		Orthoptera	*Troglophilus neglectus* Krauss, 1879
		Psocoptera	Psocoptera sp.

Microbiota of Škocjanske Jame

Airborne cave microorganisms. The air in Škocjanske Jame is a very dynamic microbial habitat due to the cave characteristics, such as large underground spaces, underground river, presence of visitors. Several sampling campaigns were conducted along the tourist footpaths and the underground river canyon to determine the airborne microbiota (aerobiome). Bacteria that were not present during and immediately after tourist visits could be considered as natural airborne background, such as *Arthrobacter arilaitensis*, *Kocuria polaris*, *Paenibacillus amylolyticus*, *P. polymyxa*, *Pseudomonas antarctica*, *P. cedrina* ssp. *cedrina*, *P. jessenii*, *P. marginalis*, *Staphylococcus equorum*, *S. haemolyticus*, *S. pasteuri*, *S. warneri*, and *Streptomyces badius*. Interestingly, in the Tiha jama section, a statistically significant, strong positive correlation was found between the number of tourists and the increase in the concentration of airborne bacteria above the background level. Along the underground river canyon air is influenced by the Reka, and a very strong influence was observed especially during high water discharge. Aerosolized microorganisms from the Reka directly affect air quality (Mulec et al 2017).

Microorganisms in water habitats

The chemical state of the Reka in Škocjanske Jame reflects the conditions of surface flow before it sinks underground. Nitrate, sulphate, and ammonium levels indicative of pollution are generally within the typical range for surface waters. At low discharges and during the first wave after heavy rains, the quality of the Reka deteriorates, as indicated by elevated concentrations of microbiological indicators of faecal pollution such as *Escherichia* coli and enterococci.

Water condensates, known among speleologists as cave silver or cave gold because of their appearance, are common in Škocjanske Jame and are particularly dense on cave surfaces where cold and warm air mix, for example, in the transition zone between Tiha Jama and Šumeča Jama. These water droplets usually cover microbial mats of different colours. The mats have different colours: yellow, white, pink, light brown, blue and green (Fig. 3.42/1).

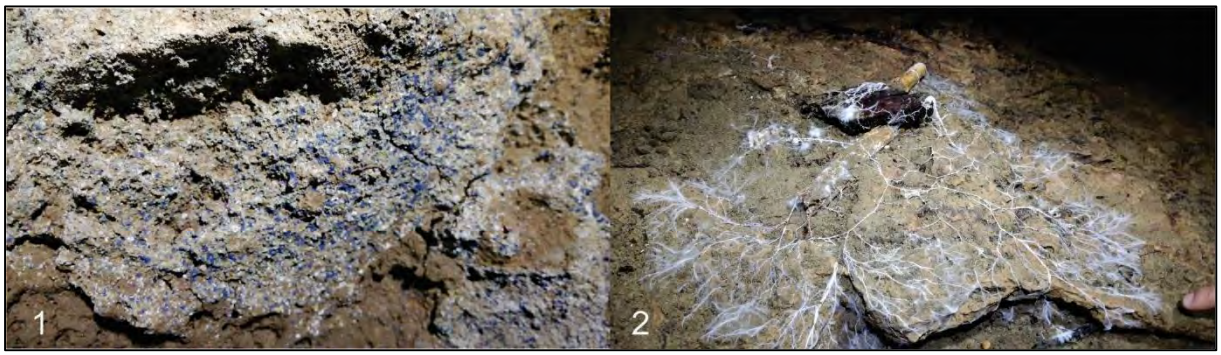

Fig. 3.42: 1) Microbial mat in Škocjanske Jame; and 2) fungal mycelium growing on river sediment and organic debris (photos J. Mulec).

Microorganisms enter the cave via percolation water. Many seeps are activated only during and shortly after precipitation. The total cell count sometimes exceeds 104 microbial cells in one millilitre of seepage water (Blatnik et al 2020). The chemical quality of percolation water varies slightly among sites, e.g., nitrate concentrations generally do not exceed 20 mg/l.

Microbial mats

Vertical black stripes on rocks named tintenstriche dominate the vertical walls in Velika Dolina. They extend for several metres and are clearly visible especially during wet periods and when seeps are active. The sunlit walls of the Schmidlova dvorana cave entrance are largely colonised by phototrophic microbial mats. Microscopic analysis revealed 80 different cyanobacterial and algal taxa. The most abundant cyanobacteria belonged to the genera: *Aphanocapsa*, *Aphanothece*, *Chroococcus*, *Gloeocapsa*, *Lyngbya*, *Phormidium* and *Scytonema*. Diatoms (Chrysophyta) were also common among eukaryotic algae, especially *Navicula* spp. and *Chlorella* sp., *Stichococcus bacillaris* and *Trentepohlia aurea* among green algae (Chlorophyta) (Mulec et al 2008).

Stromatolitic stalagmites are located in the illuminated part of Scmidlova Dvorana. The growth rate of these biogenic calcareous structures depends on the intensity of the incident light, the properties of the drip water and the growth of cyanobacteria. Most of these structures are in the initial stage of growth or grow slowly. Microscopic analysis of the scraped microbial mat from the surface of the stromatolitic stalagmite revealed 35 different taxa dominated by cyanobacteria (74%), while coccoid forms (23%) were less abundant. The filamentous cyanobacteria *Calothrix*, *Homoeothrix*, and *Schizothrix* contributed significantly to the volume of the mat. A small portion of the community consisted of eukaryotic algae (17% Chlorophyta and 9% Chrysophyta) (Mulec et al 2007).

In Schmidlova dvorana and Tominčeva Jama there are many curved, tufaceous stalactites, the end sections of which face the incident light. These structures are generally soft, and microscopic analyses revealed the dominance of cyanobacteria (86%), represented by the genera: *Aphanocapsa*, *Chondrocystis*, *Chroococcus*, *Gleoecapsa*, *Leptolyngbya* and *Oscillatoria* (Mulec et al 2007).

Microorganisms and bats

Škocjanske Jame host one of the largest population of Schreibers's long-fingered bats (*Miniopterus schreibersii*) with more than 8,000 individuals. In the surrounding park area (30 km^2) there is a very diverse bat population with so far 25 known species (out of 30 species living in Slovenia) from the genera: *Barbastella*, *Eptesicus*, *Hypsugo*, *Miniopterus*, *Myotis*, *Nyctalus*, *Pipistrellus*, *Plecotus*, and *Rhinolophus* (Blatnik et al 2020). Bat guano is a special terrestrial habitat for guanophillic organisms and an important source of nutrients for cave invertebrates. Thus, freshly deposited guano in the Šumeča Jama section had a high concentration of cultivable bacteria (1.19×108 CFU/g) and fungi (2.51×105 CFU/g) (Mulec et al., 2016).

Guano from Škocjanske Jame was tested for the presence of the fungal pathogen *Pseudogymnoascus destructans*, formerly *Geomyces destructans*. This fungus is the causative agent of white-nose syndrome in bats and is responsible for the high mortality rate of bats in North America. Molecular analysis of freshly deposited bat guano detected the presence of *P. destructans* (Mulec et al 2013), but to date no infected bats have been reported during regular monitoring of the bat population in Škocjanske Jame.

Microorganisms in cave sediments

The Reka River transports and deposits biota and organic and inorganic material along the cave passages in Škocjanske Jame (Fig. 3.42/2). Much of the originally deposited material is usually washed away during floods. The concentration of cultivable microorganisms in recently deposited river sediment was in the range of 107 CFU per gram (dry weight) of sediment. Preliminary metagenomics analysis of 16S rDNA sequences revealed diverse microbial communities with a large proportion of unaffiliated sequences. Commonly encountered genera in the sediments were *Aquincola*,

Bradyrhizobium, *Burkholderia*, *Dongia*, *Enhydrobacter*, *Flavobacterium*, *Frankia*, *Gaiella*, *Hyphomicrobium*, *Phenylobacterium*, *Paenibacillus*, *Pseudomonas*, *Pseudonocardia*, *Pseudoxanthomonas*, *Rhizobacter*, *Rhodoplanes*, *Rubrivivax*, *Sphingomonas*, *Tepidamorphus*, *Terrimonas* and *Thiobacillus* (Blatnik et al 2020).

The role of microorganisms and their influence on natural processes in Škocjanske Jame and other similar karst areas are far from being fully understood. This environment supports a variety of microorganisms and their interactions. Cave microbiologists not only discover new microbial diversity and metabolic pathways, but also find such places interesting for studying gene flow into or out of microbial populations.

3.7) TOURIST VISIT AND PROTECTION

Protection of the caves

The first activities to protect Škocjanske Jame began more than four decades ago. In 1980, the local district council, which managed the cave at that time, decided to preserve the karst environment and prevent any inappropriate tourist development in and around the caves. Since 1986, the caves have been on the UNESCO World Natural and Cultural Heritage List. The area is over 200 ha and includes the area above the cave, the river gorge and the surrounding collapse dolines.

The national Act on the Škocjan Caves Regional Park, adopted in 1996, gradually expanded the protected area. The act defines a central protection zone of 413 ha around the caves and a zone of influence of 45,000 ha in the Reka River watershed. In addition, in 1999 the caves were included in the Ramsar list of wetlands, and in 2004 the park was included in the World Network of Biosphere Reserves "Man and the Biosphere"; both are under the auspices of UNESCO. The Park is also a member of the Alpine Network of Protected Areas and the Europarc Federation, which is a professional network of European Protected Areas.

Since the park and the protected area have no buffer zone, the surface above the cave and the underground water flow suffer from the expansion of urban and industrial development. The entire Reka catchment area is protected to prevent pollution of the water flowing into the caves. However, not all regulations are strictly enforced. The catchment area is densely populated, and the regulation not to change the regime of the river or its quality is practically impossible to implement. In addition, there is no law protecting or regulating activities in the zone immediately outside the park boundaries. Therefore, the park is directly threatened or has been affected by the activities planned immediately outside the park boundaries, such as the development of industrial zones, transport routes, urbanization, etc. The realization of these plans already caused the destruction of the karst surface with its unique surface features, as well as the underground: destruction of caves, cave sediments and underground habitats, alteration of the water flow regime and/or water pollution, etc.

Lampenflora

Lampenflora is a group of organisms that develops around lamps in caves and is the cause of biological deterioration of surfaces and changes in the characteristics of the surfaces on which they grow, such as stalactites, sediments, prehistoric paintings and historical signatures. Lampenflora that spreads invasively on cave surfaces gives caves and other karst formations an unaesthetic and unnatural greenish appearance. The influence of lampenflora on cave fauna is indirect as it represents nutrients in a generally oligotrophic cave environment. Non-cave fauna feeding on lampenflora may even displace troglobiont species from such niches, impoverishing them in terms of species diversity and numbers (Mulec 2019).

The phototrophic part of the lampenflora consists mainly of three groups of microscopic phototrophs: prokaryotic cyanobacteria, eukaryotic Chlorophyta, and Chrysophyta (mainly diatoms). Microscopic analysis of lampenflora from Škocjanske Jame revealed 21 taxa of microscopic phototrophs, of which 57% belonged to Cyanobacteria, 29% to Chrysophyta and 14% to Chlorophyta. The most frequent green alga in Slovenian show caves, Trentepohlia aurea, was also common in Škocjanske Jame. The lampenflora mats are sometimes overgrown by mosses and ferns (Mulec et al 2008). From 2014 to 2016, cave management began coordinated actions to control the growth of lampenflora and remediate affected surfaces. These included removing lampenflora from cave surfaces, speleothems, and other affected cave infrastructure using hydrogen peroxide as a biocide, replacing heat-emitting halogen lamps with LED lamps, shortening lighting duration for individual lighting sectors, applying low illuminance levels to speleothems, and monitoring illuminated surfaces for colour development and microbial colonization.

Fig. 3.43: Lampenflora in Škocjanske Jame (photo S. Šturm)

Contact surfaces and walking footpaths

Tourists bring and spread a considerable amount of organic material in caves with their shoes. It was expected that the microbiological load on tourist footpaths in Škocjanske Jame would gradually decrease from the cave to the interior. Due to bat droppings inside the cave, the microbiological load is higher, especially the bacterial indicators of faecal contamination, e.g., *Escherichia coli* (Mulec 2014). To limit the entry of alien organic material into the cave, the cave manager installed a disinfection barrier (2021) at the entrance so that tourists can clean and disinfect the surface of their shoes before entering.

4) LIPOVE DOLINE UNROOFED CAVE AND SEDIMENTS

The river with its tributaries is a typical allogeneic sinking river that brings alluvium to Škocjanske Jame, where along the riverbed from the ponor to the siphon different types of clastic sediments are present. Flysch sandstone pebbles predominate while limestone pebbles dominate at the siphon (Kranjc 1989). The flood clays and silts consist mainly of quartz, plagioclase, and clay minerals (Zupan Hajna 1995). Fossil deposits of chert (Gospodarič 1984), flysch sandstone, and limestone pebbles are known in the Černigojeva Dvorana (334 m a.s.l.). Sediments from unroofed caves above Škocjanske Jame also have very similar mineral composition (Zupan Hajna *et al.* 2017).

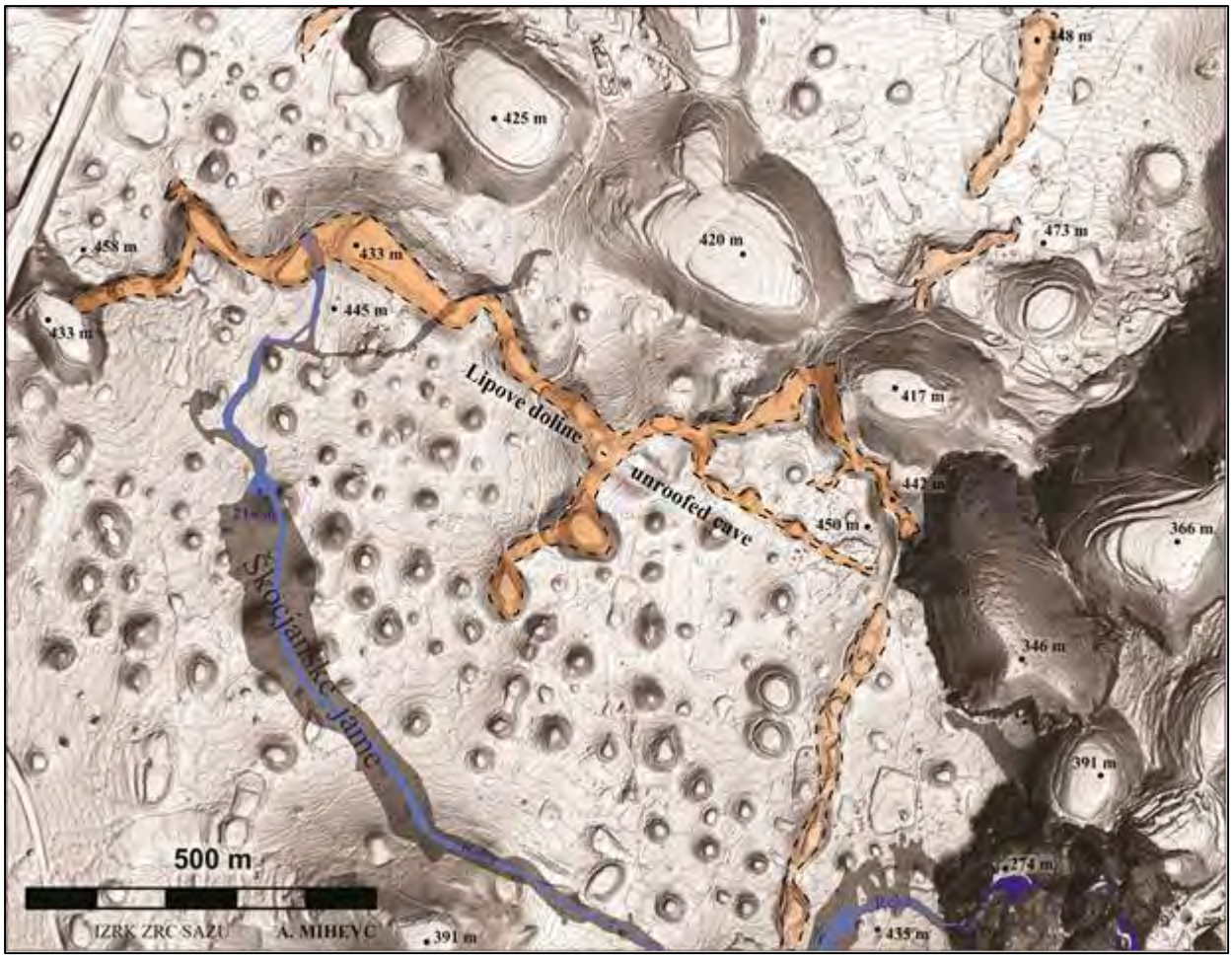

Fig. 3.44: Lipove doline (from A. Mihevc) and other small unroofed caves (brown) above Škocjanske Jame (grey) with underground flow of Reka (blue). Source of Lidar data: Geodetski oddelek ARSO.

Studied paleomagnetic properties of the sediments in the caves Divaška Jama, Trhlovca, Divača profile, Risnik Unroofed Caves, Škocjanske Jame (e.g. Zupan Hajna et al. 2008, 2020), gave results that the age of the alluvial sediments is most probably up to 5 Ma. Clastic fills of unroofed caves and extant caves of Divaški kras consist mainly of weathering products of Eocene flysch rocks eroded from the Reka catchment. In all cases relatively equal mineral composition prevailed, indicating the main source was from flysch sediments which were weathered in different degrees. The mineral composition of the Eocene flysch sandstones of Brkini SE of Divača, which is the catchment area of the Reka, varies more in the quantity of individual minerals than in the presence of different minerals.

The largest unroofed cave, 1.8 km long, is known in Lipove doline above Škocjanske Jame. The actual underground river bed in Škocjanske Jame is 230 m below those unroofed caves. Unroofed cave in Lipove doline is located on the surface northeast of Škocjanske Jame, named after group of dolines Lipove doline. In the western part of this roofless cave, quartz sand was extracted, during which a large amount of flowstone and a large stalactite were exposed. The mapping of the surface revealed that the unroofed cave is exposed in 1,800 m long series of dolines and elongated doline-like depressions in elevation about 450 m a.s.l. NE of Škocjanske Jame where the Reka flows at 214 m a.s.l. The bottoms of dolines are 5 m to 10 m below the level of the rest of the surface; the depressions are 20 m to 30 m wide. Siliciclastic fluvial deposits, sandy clays and massive flowstone fill the bottom of the dolines.

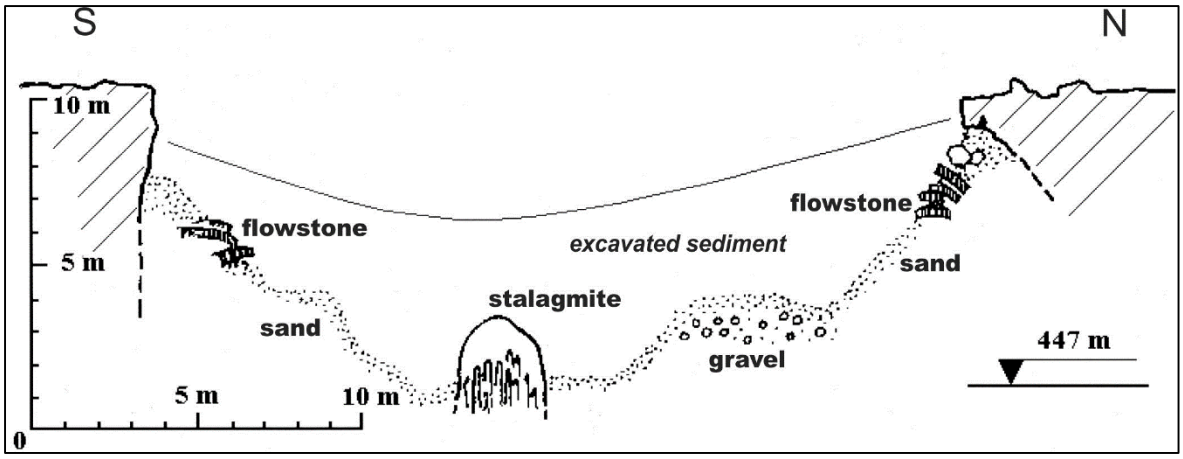

Fig. 3.45: Cross section of the unroofed cave with alluvial sediments and stalagmite at N part of Lipove doline (from Mihevc 2001).

The unroofed cave in Lipove doline is similar to Škocjanske Jame in its dimensions (Fig. 3.44), as the width of the passage was in some places likely to be more than 20 m. Concerning the massive stalagmites and flowstone, the ceiling was a least 100 m thick during the time flowstone was depositing in the cave. Flowstone deposited between phases of sedimentation of allogenic fluvial sediments (Fig. 3.45). Origin of the sediments is Eocene flysch, transported to the cave by a sinking river. A rough estimate would be that there are still approximately 45,000 m^3 of allogenic cave sediments preserved in the unroofed cave.

5) KOZINA – UPPER CRETACEOUS PALEOKARST

Last stop of the excursion is at paleokarstic pit cave with dinosaur remains (compiled from Debeljak et al., 1999, 2002; Košir et al., 2000; Otoničar, 2006, 2016a, b).

To define the term "paleokarst", Bosak et al. (1989) first defined the terms "karst period", "karst phase" and "karst event" They defined "karst phase" as a period during which a generation of karst features forms under relatively stable conditions (boundary conditions are more or less stable during an extended period). In the karst record, each phase represents distinct changes in boundary conditions, usually caused by geodynamic or major climatic changes. A karst period, comprising one or more karst phases, is defined as a long-lasting period of continental weathering and groundwater circulation terminated by a subsequent marine transgression over the karst surface. A karst event represents a brief, extended, potentially catastrophic event in the hydrogeologic system. In keeping with the terms defined above, Bosak et al. (1989) defined paleokarst as: "karst formed largely or entirely during past geologic periods".

Because in Australia the oldest relict caves, which were formed during the last still-ongoing karst period (see definition above) are Late Cretaceous in age and as such, despite of their age no paleokarstic, Osborne (2000) slightly redefined the paleokarst definition of Bosak et al. (1989) and proposed the following definition: "paleokarst refers to karst formed mostly or entirely during past karst periods". The latter definition is used here.

Fig. 3.46: a) The undulating paleokarst surface separates the Upper Santonian light grey shallow marine massive limestone of the Lipica Formation and the Maastrichtian dark grey plustrine limestone of the Liburnija Formation; highway cut near the village of Kozina. b, c) A paleokarst shaft filled with breccia, where remains of fossil vertebrates were found, i.e. teeth and crushed bones of dinosaurs and crocodiles (Maastrichtian) (from Košir et al. 1999).

In SW Slovenia and NW Croatia (Istria), a regional unconformity separates the passive margin shallow-marine carbonate successions of various Cretaceous formations from the Upper Cretaceous to Eocene palustrine and shallow-marine limestones of the synorogenic carbonate platform (Košir & Otoničar, 2001; Otoničar 2006, 2016). The unconformity is related to the non-synchronous uplift and subaerial exposure of most of the Adriatic carbonate platform in the Late Cretaceous and Early Paleogene at the periphery of the foreland basin. At Kozina, it separates the underlying sequence of shallow marine carbonates (Lipica Formation) from the overlying paralic carbonate complex of the Liburnian Formation. The unconformity is expressed in a paleokarst surface characterised by a series of pocket-like and gently undulating decimetre- and metre-scale depressions ("pothole paleokarst depressions" and "hummocky paleokarst depressions" in the sense of Vanestone 1998) (Fig. 3.46a) and larger, distinctly irregular depressions and shafts ranging in diameter and depth from several metres to tens of metres (Fig. 3.46b, c). A diverse assemblage of terrestrial vertebrates was discovered in a road cut near the village of Kozina (Figs. 3.46, 3.47). Numerous teeth and fragmented bone remains (Fig. 3.47) occur in the breccia filling a paleokarst pit cave within the Upper Cretaceous carbonate platform succession (Fig. 3.46b). This distinctive vertebrate assemblage consists of dinosaurs and crocodiles and, in trace amounts, indeterminate remains of fish, amphibians, and other reptiles (Debeljak et al. 1999, 2002).

The age of the vertebrate deposits has not been directly determined. According to regional geological data (Jurkovšek et al., 1996, 1997; Otoničar, 2006), the total stratigraphic gap expressed by the paleosurface and paleokarst deposits in Kozina could be from the Late Santonian to the Late Maastrichtian (Fig. 3.48). The depressions are filled/covered with paralic carbonates, while "ferruginous-bauxite-carbonate" sediments and karst breccias (Fig. 3.46) often directly overlie the paleokarst surface. Oscillatory transgression across the paleokarst surface is indicated by the sedimentary succession arranged in shallowing upwards cyclical parasequences (Fig. 3.48). The limestone is frequently interwoven with pseudo-microkarst voids (sensu Freytet & Plaziat 1982) which exhibit breccia-like and "pseudobreccia-like" textures.

Fig. 3.47: Mainly dinosaurian bone fragments and teeth in breccia that infills a paleokarstic pit cave; motorway road-cut near the village of Kozina (photo B. Otoničar).

The evolution of paleokarst features and paleokarst as a whole is discussed by Otoničar (2007, 2016a, b and 2021).

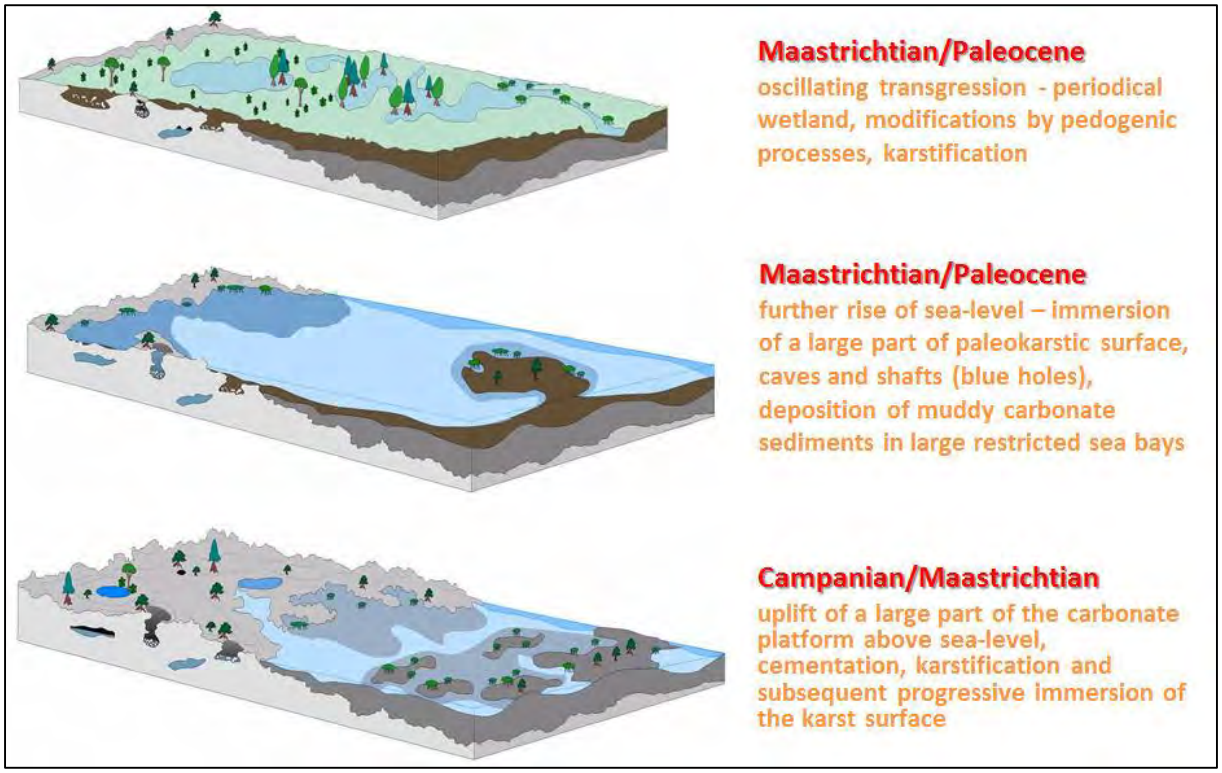

Fig. 3.48: Evolution of the paleoenvironment between the Campanian/Maastrichtian and the Paleocene in the wider area of present-day Kozina (Kras Plateau). The paleokarst surface that developed on the peripheral bulge is covered by palustrine carbonates of the synorogenic carbonate platform (from B. Otoničar 2016a).

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Whole-day field trip (D):

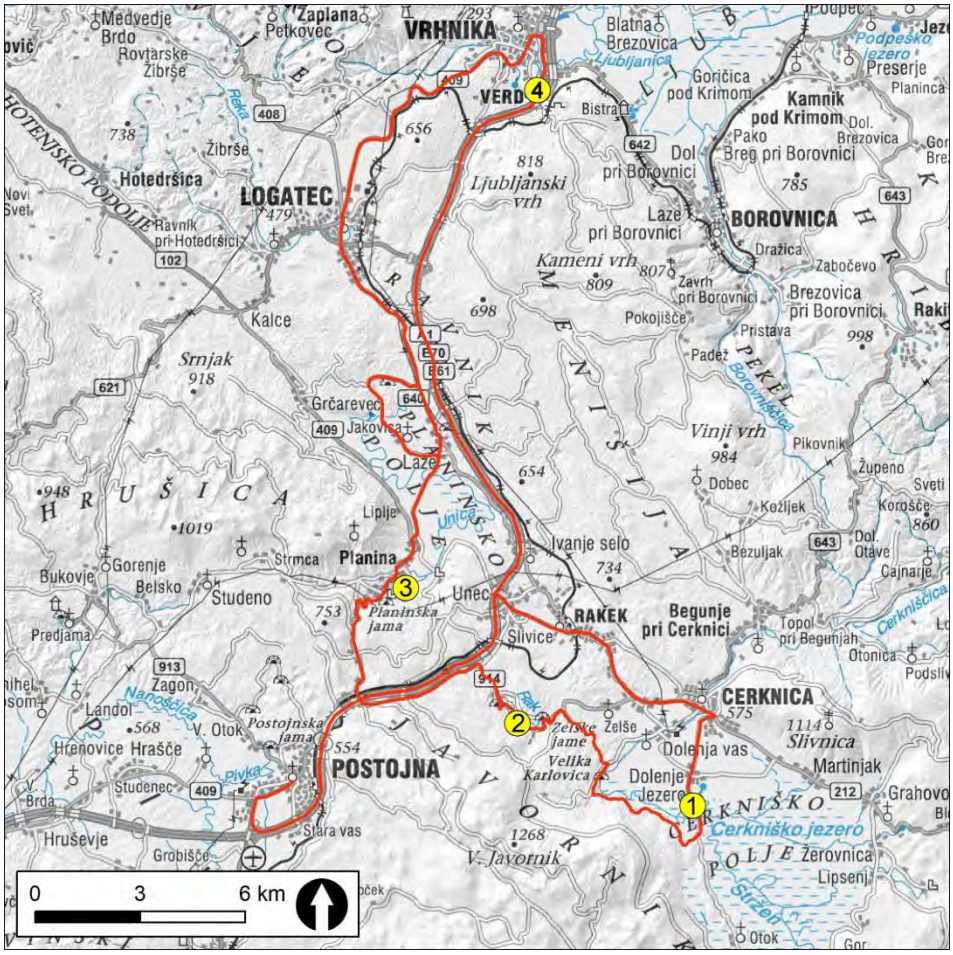
GROUNDWATER FLOW IN THE LJUBLJANICA RECHARGE AREA

Friday, 23rd June 2023, 9:00–17:00

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

Stops:

1 – Outflow zones of Cerkniško Polje
2 – Hydrology of the Rakov Škocjan karst valley
3 – Planinska Jama with underground confuence of rivers
4 – Collapse dolines and springs of Ljubljanica River near Vrhnika



Značilnosti podzemnega toka v zaledju Ljubljanice

Celodnevno terensko delo (D); petek, 23. junij 2023;

Za kraško zaledje izvirov Ljubljanice je značilno menjavanje kraških polj in kraških planot. Niz kraških polj s ponikalnicami ima dinarsko smer (SZ–JV), del voda pa se priključi z JZ, s Pivške kotline. V prvem delu ekskurzije predstavimo Cerkniško polje ter Rakov Škocjan z značilnimi kraškimi pojavi (kraški izviri, požiralniki, jame, vodotoki). Drugi del je posvečen izvirom Unice in Ljubljanice. Poudarek je na predstavitvi zadnjih raziskav, kjer smo raziskovali tok vode v Rakovem rokavu Planinske jame in določili prostorske in časovno spremenljivost vodnega toka. Prepoznali smo tudi prelivne kanale in potencialne geološke pregrade, ki lahko vplivajo na dinamiko pretakanja podzemne vode in poplavljanje na površju.

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. 4.1). 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 estimated total size of the Ljubljanica recharge area is almost 1800 km^2, of which about 1100 km^2 are karstified. The karst catchment area was delineated during an extensive tracing campaign in the 1970s (Gospodarič & Habič 1976).

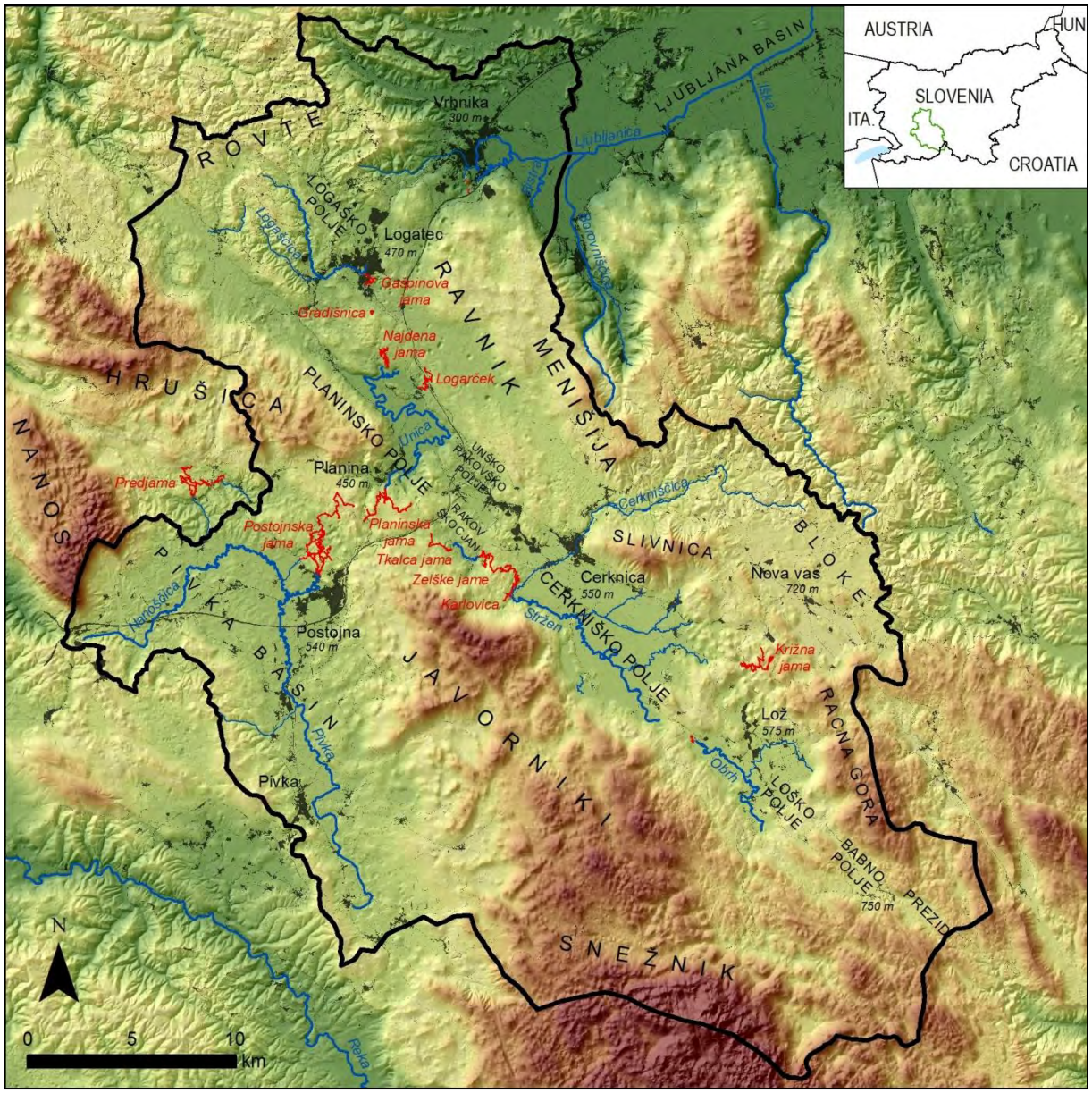


Fig. 4.1: Ljubljanica River recharge area with high karstic plateaus, karst poljes and surface rivers. The main caves are shown with red lines.

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 that allowed high rock purity, generally with less than 5%,

locally even only 0.1%, insoluble residues. 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. 4.2) (Vrabec 1994). The Idrija Fault Zone largely determines the direction of regional flow (Fig. 4.2). 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).

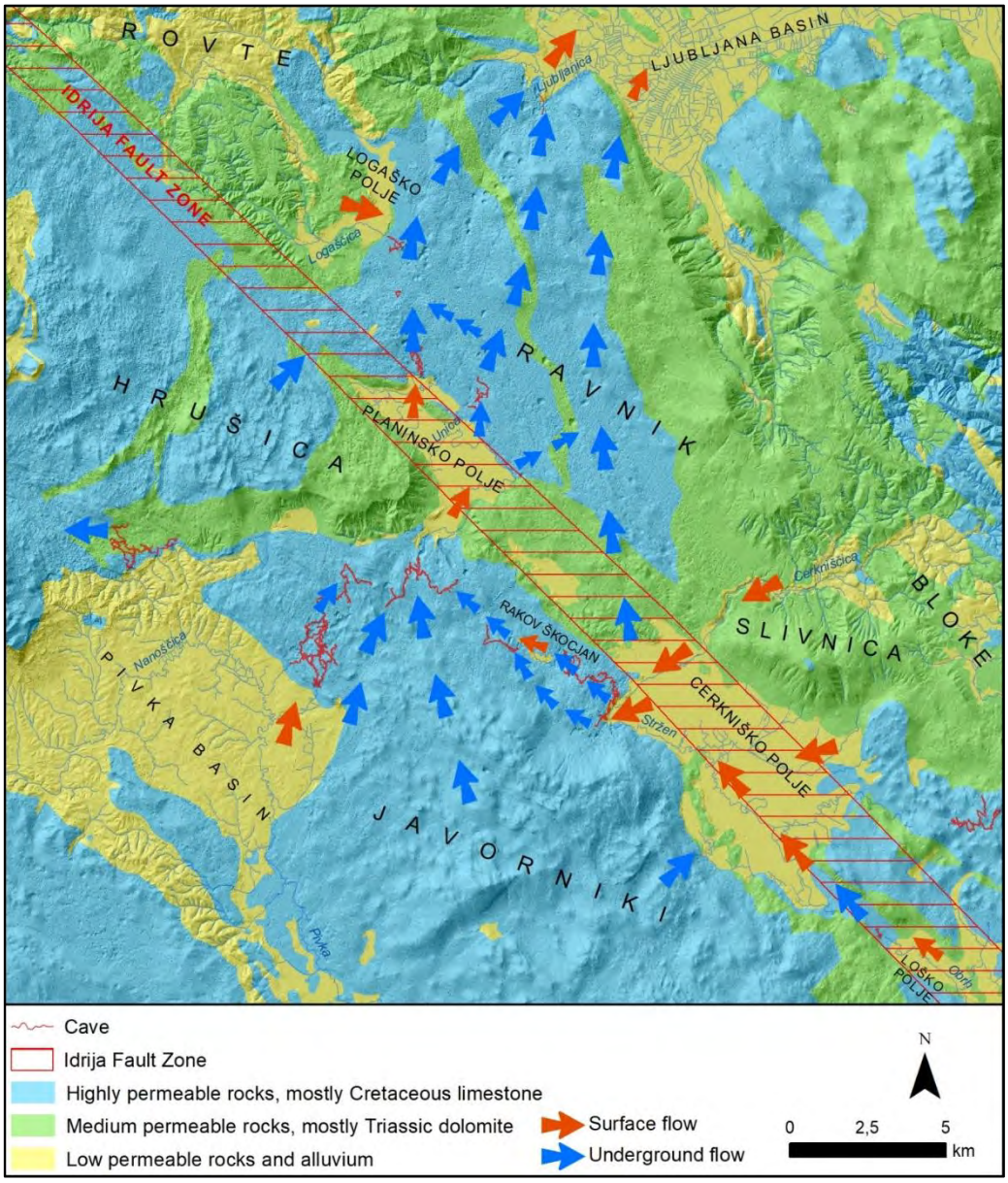


Fig. 4.2: Geology and hydrology of the Ljubljanica recharge area (adapted from Krivic et al. 1976).

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. 4.3). 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. The streams that flow through them have different names: Trbuhovica, Obrh, Stržen, Rak, Pivka and Unica. 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. Along its eastern and northern edges, the water sinks back underground and flows northwards to several large and many small springs aligned along the southern edge of the Ljubljana Basin, which is connected to the gradual tectonic subsidence of the area (Krivic et al. 1976; Gams 2004). The average annual discharge of the Ljubljanica springs is 38.6 m^3. An additional amount of water drains from the low- to medium-permeable Rovte plateau and contributes to the Ljubjanica springs by sinking into the ponors of Logaško Polje (Mihevc et al. 2010).

There are almost 1600 known caves located in the recharge area of the Ljubljanica River (Cave register 2019). Most of them are accessible fragments of a fossil underground drainage system (Habič 1973; Gospodarič 1981; Šušteršič 1999, 2002). The average cave length is 48 m and the depth 18 m. However, the largest cave systems are water-active and sum a total of about 80 km of epiphreatic channels (Fig. 4.3).

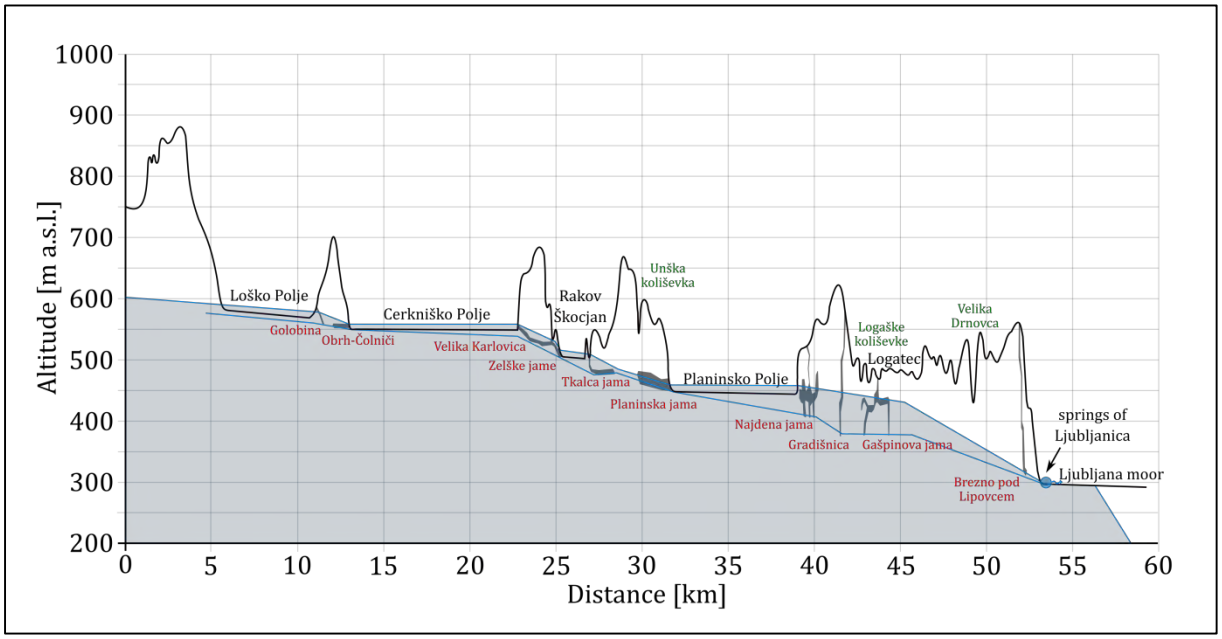


Fig. 4.3: Cross section of Ljubljanica River recharge area following an initially SE-NW trend along the Idrija Fault Zone between Loško and Planinsko Polje, and turning N from Planinsko Polje toward the Ljubljanica springs near Vrhnika. The major caves are indicated in red, large collapse dolines in 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. 4.4a). 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. 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. 4.2).

Fig. 4.4: (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. 4.4b), 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.

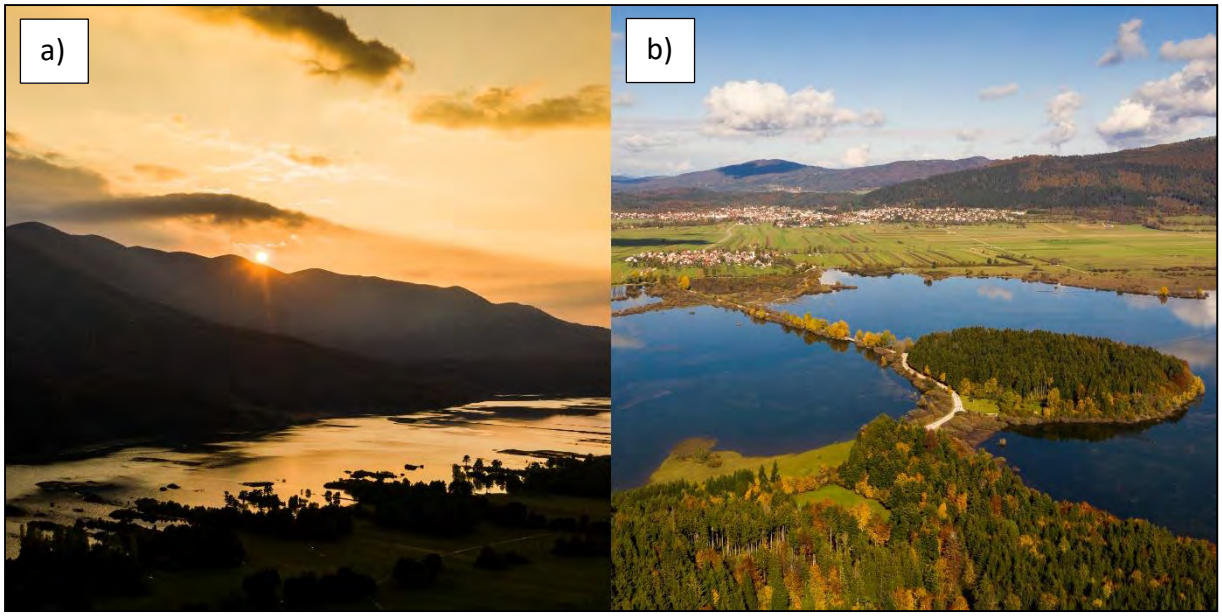


Fig. 4.5: Cerkniško Jezero. a) Lake and Javorniki Mountains at sunset. b) View toward the village of Dolenje jezero (Photos: M. Blatnik; RI-SI-EPOS).

In the last centuries, several plans were made to change the hydrological behaviour of the polje, but none was 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. 4.6). 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; Fig. 4.7a), where an impressive narrow arch, which was part of the former cave ceiling, crosses the collapse doline (Gams 2004).

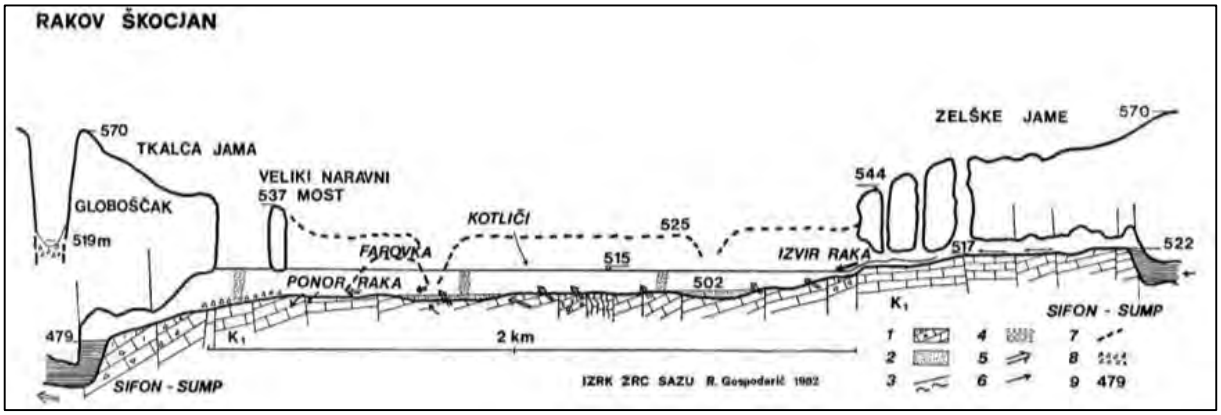


Figure 4.6: *Cross-section of the Rakov Škocjan karst valley between the Rak spring at Zelške Jame and the terminal ponor in Tkalca Jama. Legend: 1. rocky bottom; 2. alluvia; 3. fault zone; 4. flood level in 1982; 5. karst spring: 6. water flow directions; 7. terraces; 8. boulder rocks; 9. altitude.*

Downstream, the valley widens and several springs (Fig. 4.7b) 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; Fig. 4.8). The height of the bridge is comprised 9.5 and 17 m, its width is between 15 and 23 m and the length is of 56 m. The rocky arch is made of thick-bedded and anticline-folded Lower Cretaceous limestone.

Fig. 4.7: Rakov Škocjan karst valley. a) The arch of Mali Naravni Most. b) Kotliči spring at the beginning of a hydrological event (Photos: M. Blatnik).

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; Fig 4.8a). 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.

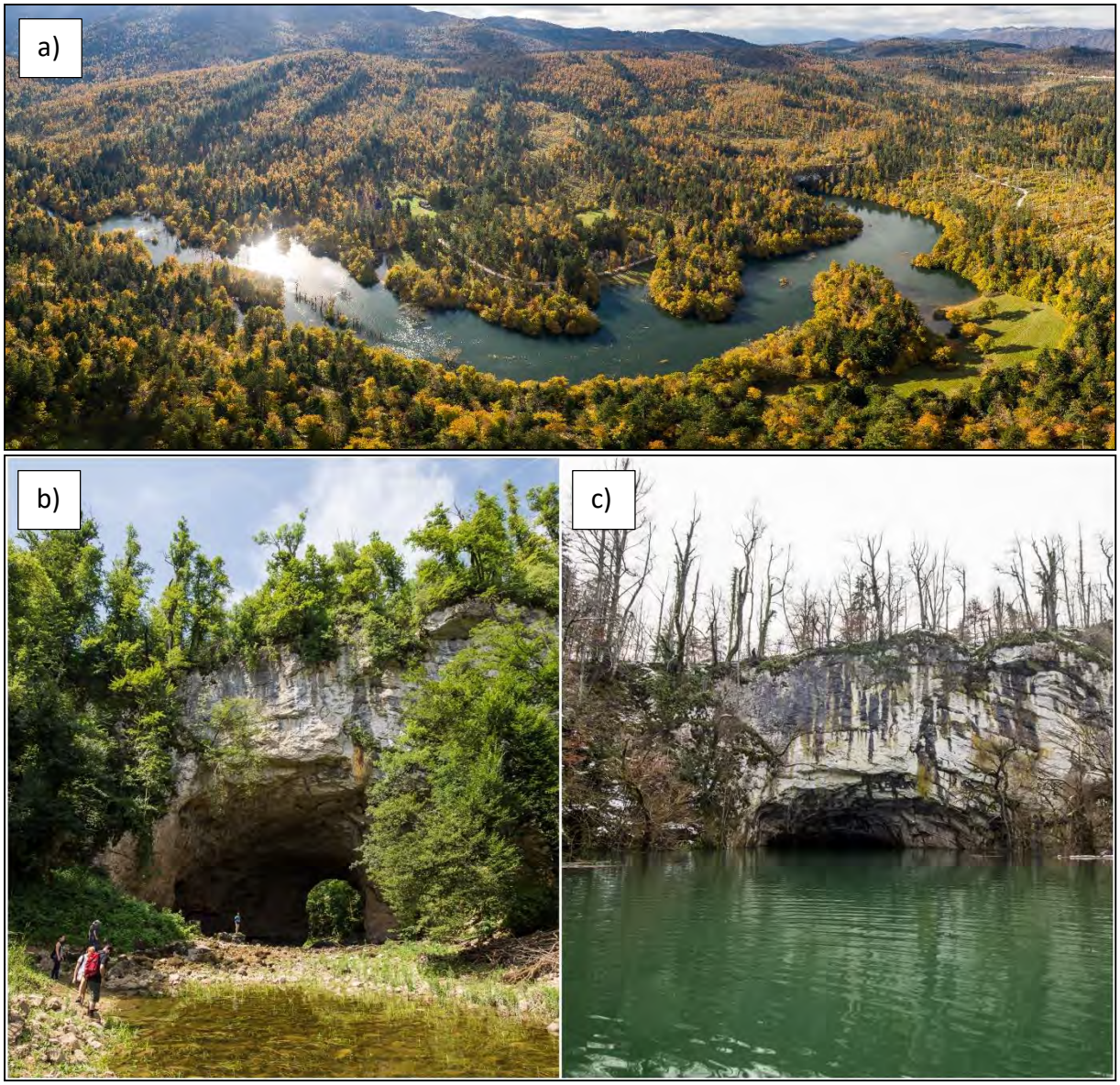


Fig. 4.8: a) Flooded Rakov Škocjan Karst Valley in October 2020, b) Veliki Naravni Most (Big Natural Bridge) during dry period in summer; and c) during high water event in winter (Photos: M. Blatnik; RI-SI-LifeWatch).

PLANINSKA JAMA – THE MYSTERIOUS LAKE

Planinska Jama (Planina Cave) is a large spring cave located on the southern edge of Planinsko Polje (Fig. 4.9a). The cave is about 6.6 km long and consists mostly of large active river passages with cross-sections often larger than 100 m^2 (Fig. 4.11 left). The cave is known to be the confluence of two important regional rivers (Fig. 4.9b; Fig. 4.10): the Pivka River, which drains a large allogenic catchment through the Postojnska Jama (Gabrovšek et al. 2010; Kaufmann et al. 2016, Kogovšek 2022) and reaches the confluence with the cave via the Pivka Branch, and the Rak River, which carries water from Rakov Škocjan and Cerkniško Polje via the Rak Branch. Finally, a large amount of water also flows into the Rak Branch via the siphon of the Javornik Current, which is located below the Mysterious Lake (Fig. 4.10) (Kaufmann et al. 2020). The water exits the cave under the common name Unica River with a discharge between 0.2 and 90 m^3/s (Kogovšek 2022).

The different parts of the aquifer that feed the Unica spring show considerable differences in water contribution (Savnik 1960, Kogovšek 2022). During high water conditions, there is a groundwater divide in the Javorniki Mountains. The water discharges through the western, eastern and northern edges of the massif. Then the nearby Malenščica spring (Fig. 4.10), which is mainly fed by the the autogenic Javorniki water and allogenic water from the Rakov Škocjan reaches a maximum discharge of 9-10 m3/s (Kogovšek 1999; Kovačič 2010, 2011). As the spring is damped, the Rak Branch is activated and acts as an overflow, while the Unica spring also receives water from the Pivka Branch. At low-flow, after the Cerkniško Jezero is drained, the outflow is solely directed towards the Malenščica spring, while the Unica spring is fed exclusively by the Pivka Branch (Kaufmann et al. 2020, Kogovšek 2022). The inversion of the flow direction between the Mysterious Lake and the Malenščica spring was numerically simulated with a pipe flow model (Kaufmann et al. 2020).

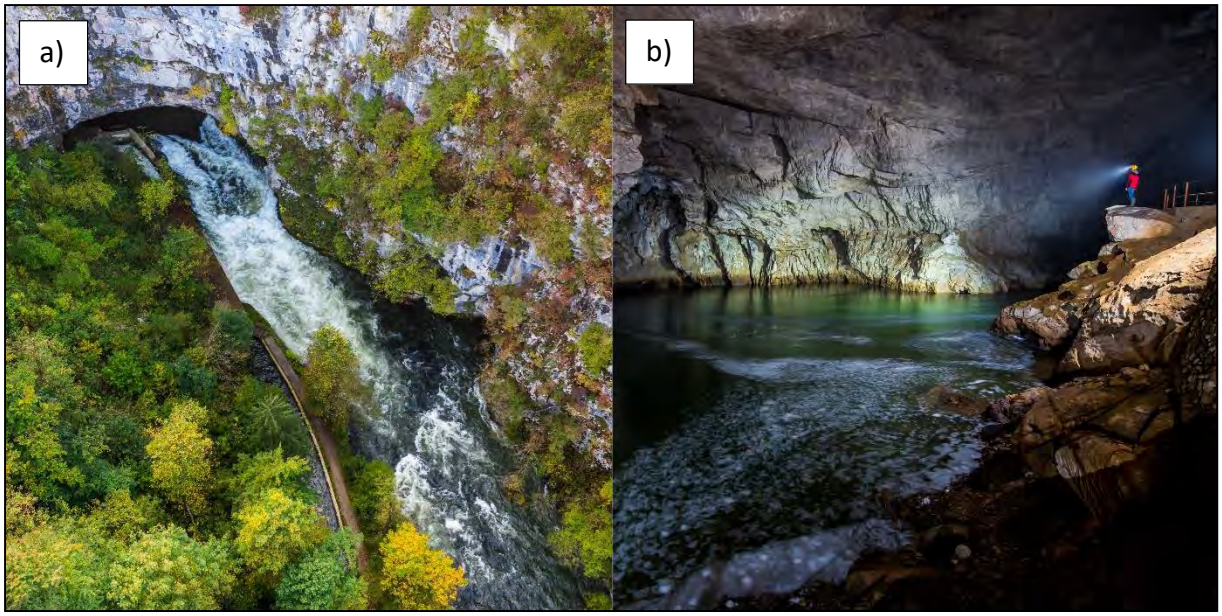


Fig. 4.9: Planinska Jama. a) Cave entrance. b) Confluence of the Pivka and Rak Branches (Photos: M. Blatnik; RI-SI-EPOS).

There are also differences in flow velocities between low and high flow conditions (Petrič et al. 2018). In general, the apparent dominant flow velocities in the karst aquifer are five times higher during high water (between 20 and 25 m/h) than during low water conditions (~ 4 m/h). In the well-developed conduit networks of Karlovica-Zelške Jame, Tkalca-Planinska Jama and Postojnska-

Planinska Jama, flow velocities were up to fifty or even ninety times higher during high water (between 170 and 1000 m/h) compared to the velocities observed during low water (~ 4-23 m/h) (Petrič et al. 2018).

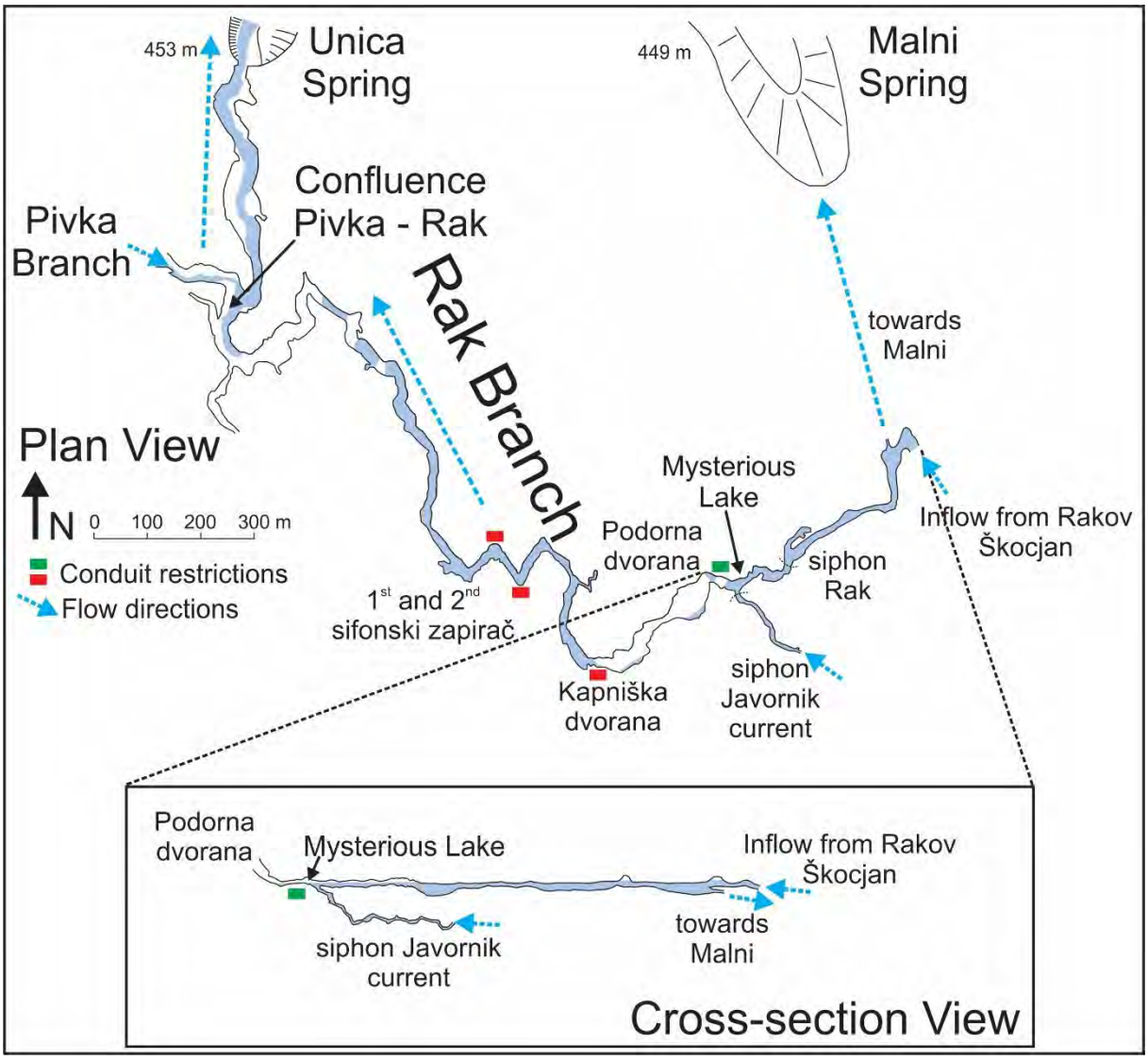


Fig. 4.10: Detailed view of the Rak Branch of Planinska Jama and cross-section of its terminal siphon in the Mysterious Lake (Gams 2004; Kaufmann et al. 2020).

The cave entrance is in Upper Cretaceous limestones and dolomites. The entrance part and the Rak Branch are developed in Lower Cretaceous bedded limestones, limestones with chert and limestone breccia. The Pivka Branch and the Rudolfov Rov (passage south of the Rak Branch), on the other hand, are formed in Upper Cretaceous massive limestone and breccia with Caprinidae and Chondrodontae (Habič 1984). Both parts of the cave end with siphons that have been dived but do not yet have a connection to the upstream systems. However, the recent dives in the final siphon of the Pivka Branch give justified hope that a connection to the Postojnska jama cave system could be established in the near future.

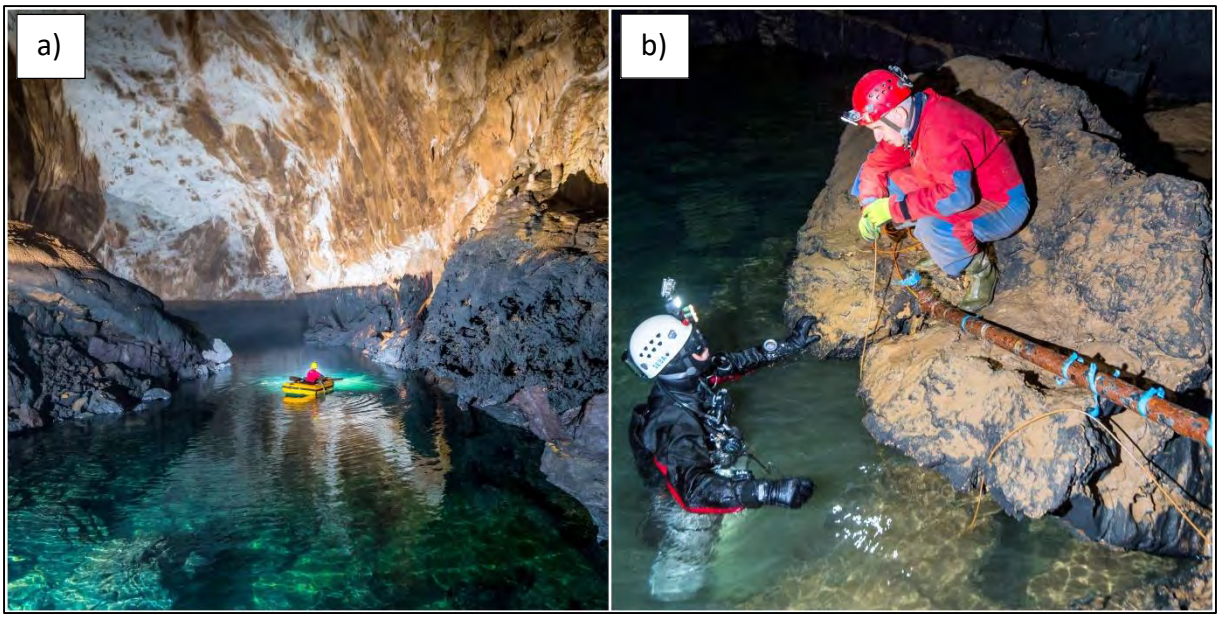


Fig. 4.11: Planinska Jama. a) example of typical large cave passage in the Rak Branch. b) recent diving exploration in the Mysterious Lake and Javornik Current (Photos: M. Blatnik).

The research conducted in Planinska Jama over the last three years focused mainly on studying the hydrological behaviour of the Javornik Current (Gabrovšek et al. 2019), a partially explored siphon that connects to the Rak Branch in the so-called Mysterious Lake (Figs. 4.10 & 4.11b). For this purpose, water pressure, electrical conductivity and water temperature were automatically recorded in both Mysterious Lake and the Javornik Current sump. The main objective was to find out whether the water coming out of the siphon is suitable for human consumption, to be used as a back-up reservoir for the municipalities of Postojna and Pivka (Gabrovšek et al. 2019).

While the discharge from the siphon is relatively constant, the origin of the water and its hydrogeological behaviour are more complicated. For many years, the siphon of the Javornik Current was assumed to be fed exclusively by autogenic waters infiltrating through the Javorniki and Snežnik Mountains (Petrič et al. 2018). However, recent observations recorded by the automatic data-loggers show much more complicated dynamics (Fig. 4.12). The measurements of temperature and EC indicate an obvious change of flow direction within the siphon of the Javorniki Current. This means that, depending on the hydrological situation, the direction of flow is from Mysterious Lake into the siphon or vice versa. In the first case, the water in the siphon is almost the same as in Mysterious Lake, dominated by the inflow from Rakov Škocjan. In the second case, the water in the siphon is the "real" Javornik Current. The exact mechanism and conditions have yet to be determined (Gabrovšek et al. 2019).

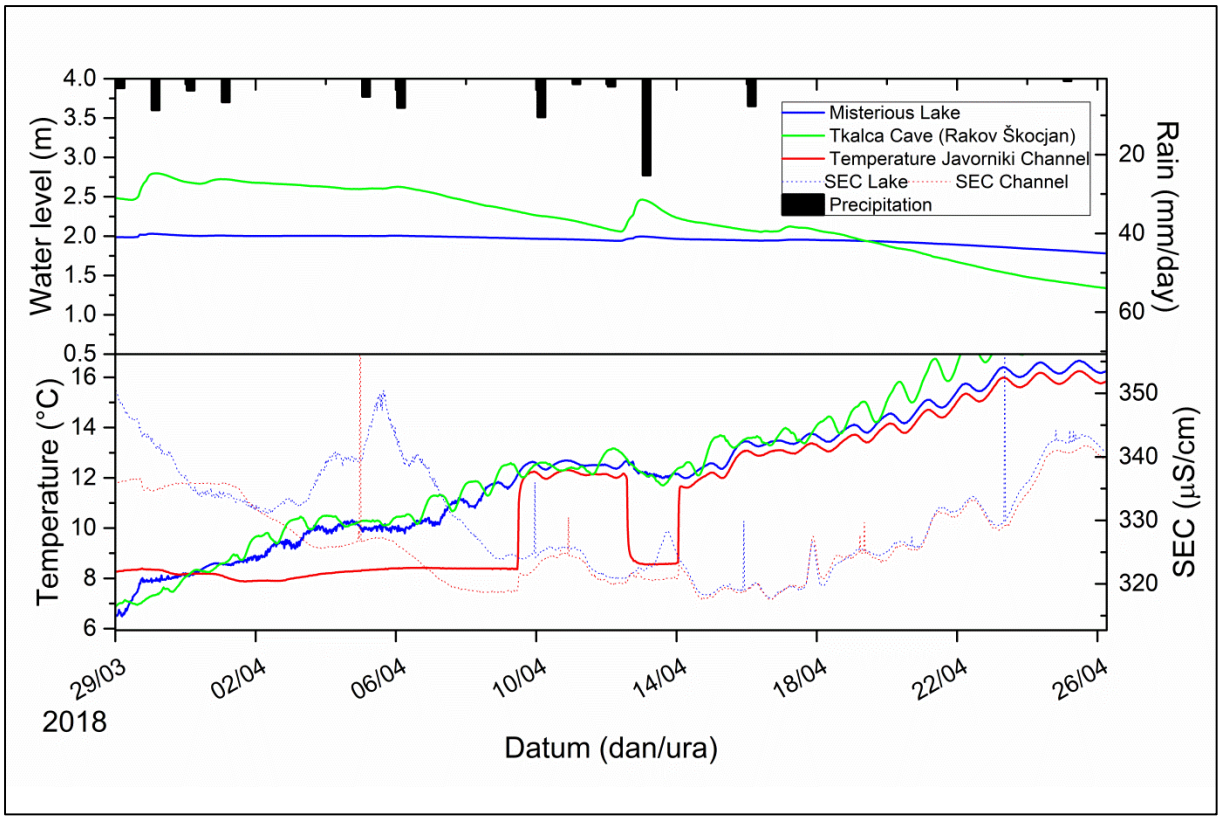


Fig. 4.12: Example of hydrological event showing a flow reversion in the siphon of the Javornik current.

COLLAPSE DOLINES IN THE HINTERLAND OF THE LJUBLJANICA SPRINGS

Collapse dolines are large closed depressions formed by subsidence and/or partial collapses of cave ceilings. Large collapse dolines form in the crushed/fractured zones above the main groundwater flow, where dissolutional yield is high due to high (rock surface)/(water volume) ratio (Gabrovšek & Stepišnik 2011).

Between Logatec and Vrhnika several large collapse dolines formed along the main drainage pathways of underground Ljubljanica River (Celarc *et al.* 2013). Table 4.1 lists the bottom elevations, and dimensions of the largest. Estimated volume of the biggest of them (Velika Drnovica) is around 1.6 million m^3.

Table 4.1: Some characteristics of collapse dolines along the main pathways of Ljubljanica River.

Name	Bottom elevation (m)	Radius (m)	Average depth (m)
Velika Drnovica	409.0	157	106
Velika jama	424.0	143	66
Mala Drnovica	520.0	101	60
Stranski dolec	457.0	90	69
Masletova koliševka	435.0	89	70
Srednja Lovrinova koliševka	443.0	96	57

Seven collapse dolines are located in the immediate hinterland of the main Ljubljanica spring (Tab. 4.2). The bottoms are relatively levelled and covered with over 30 m thick loamy sediment. The elevation of the bottoms of all these dolines are within 10 m of each other. Flooding has been

observed in Grogarjev dol recently. The estimated volume of Paukarjev dol is about 1 million m^3 (Gabrovšek & Stepišnik 2011).

Table 4.2: Some characteristics of collapse dolines located in the near hinterland of the Ljubljanica springs.

Name	Bottom elevation (m)	Radius (m)	Average depth (m)
Paukarjev dol	297.3	125	55
Meletova dolina	297.7	84	33
Grogarjev dol	294.0	80	35
Tomažetov dol	304.4	66	35
Babni dol	295.0	58	27
Susmanov dol	298.9	50	18
Nagodetov dol	300.8	38	18

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 spring generally follows the contact of Jurassic limestone and Quarternary sediments underlain by Triassic dolomite (Celarc *et al.* 2013) (Figs. 4.13). 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 springs have shown, that major springs show similar temperature dynamics, however, easternmost spring at Bistra differs quite substantially from the others (Fig. 4.14). The temperature lag is higher and the hydrograph lacks short-time disturbances. This 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) (Fig. 4.15).

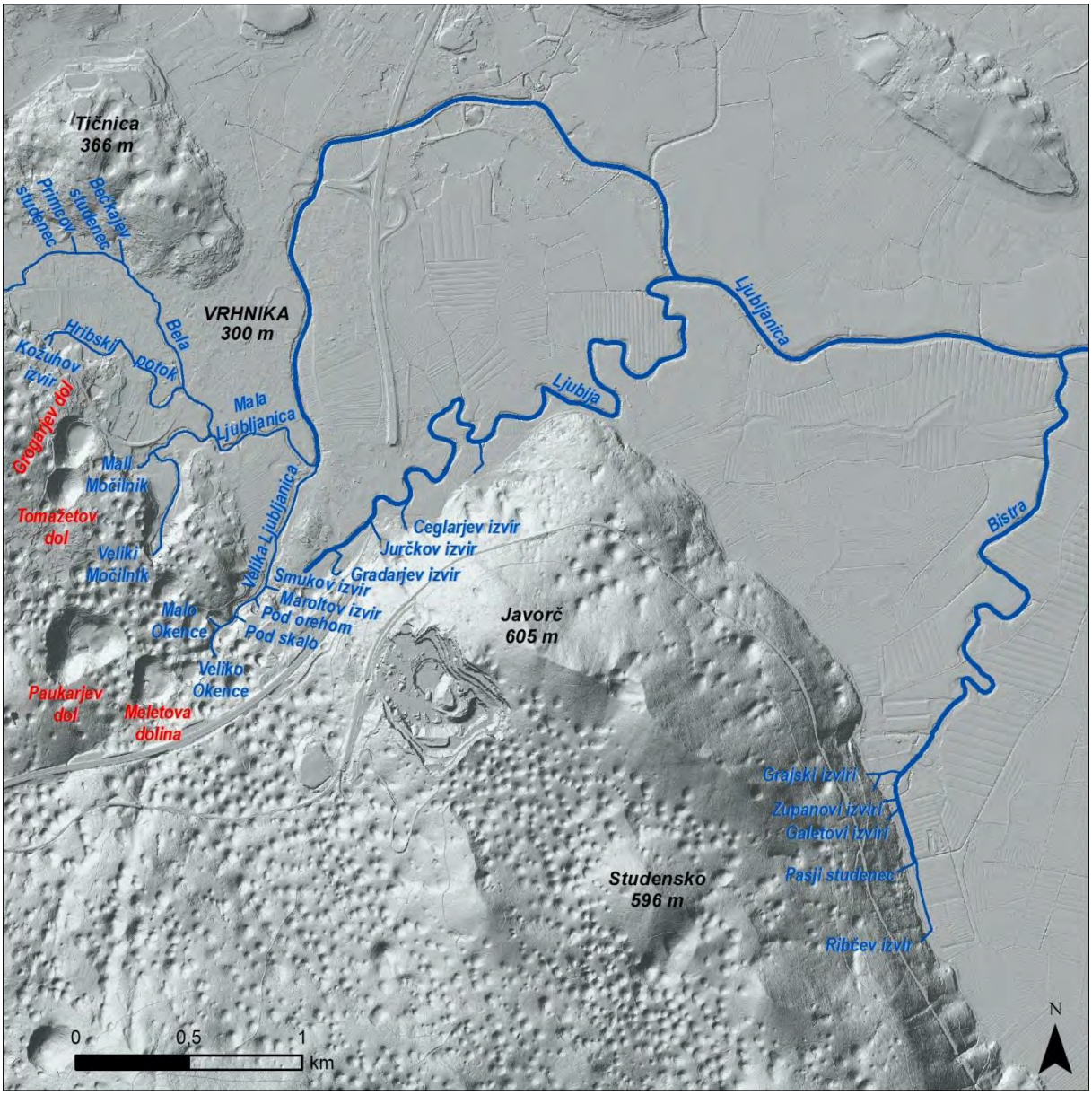


Fig. 4.13: Location of collapse dolines and Ljubljanica springs near Vrhnika.

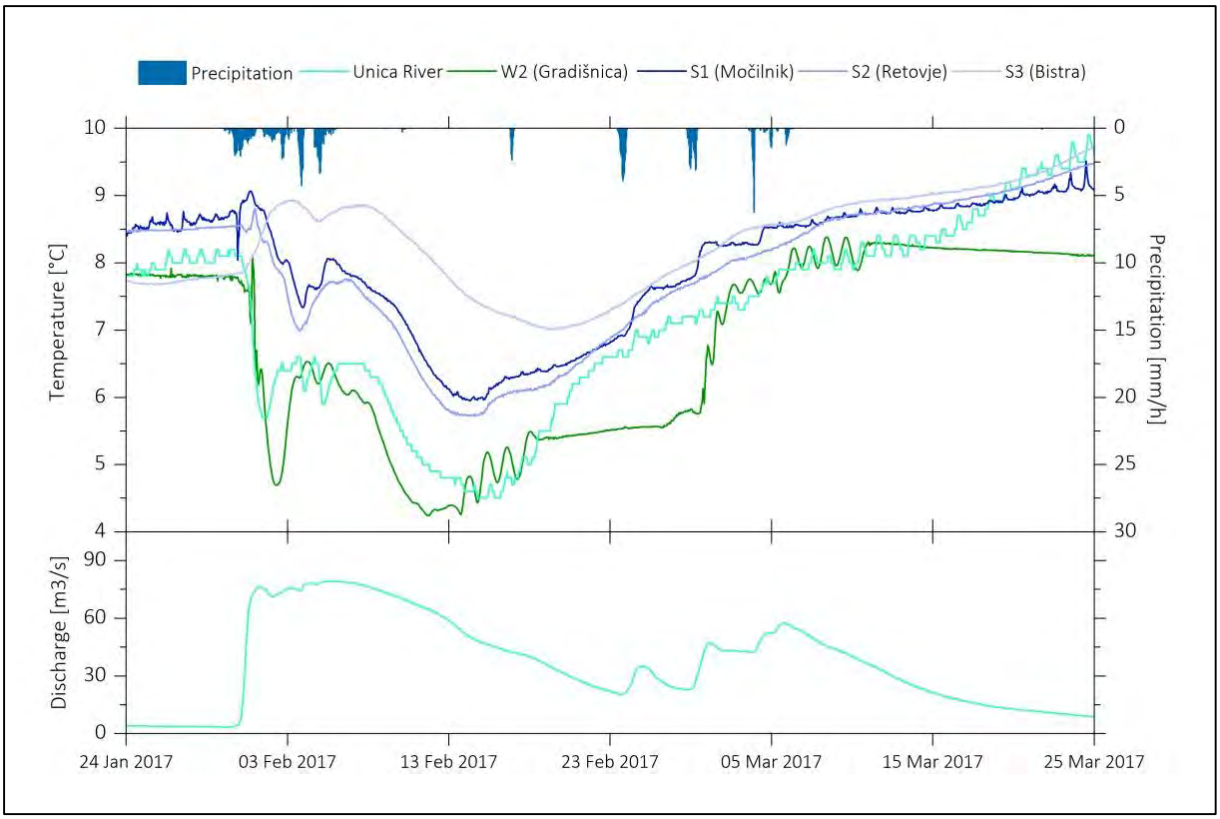


Fig. 4.14: Temperature hydrographs at springs of Ljubljanica compared to the cave Gradišnica and Unica River.

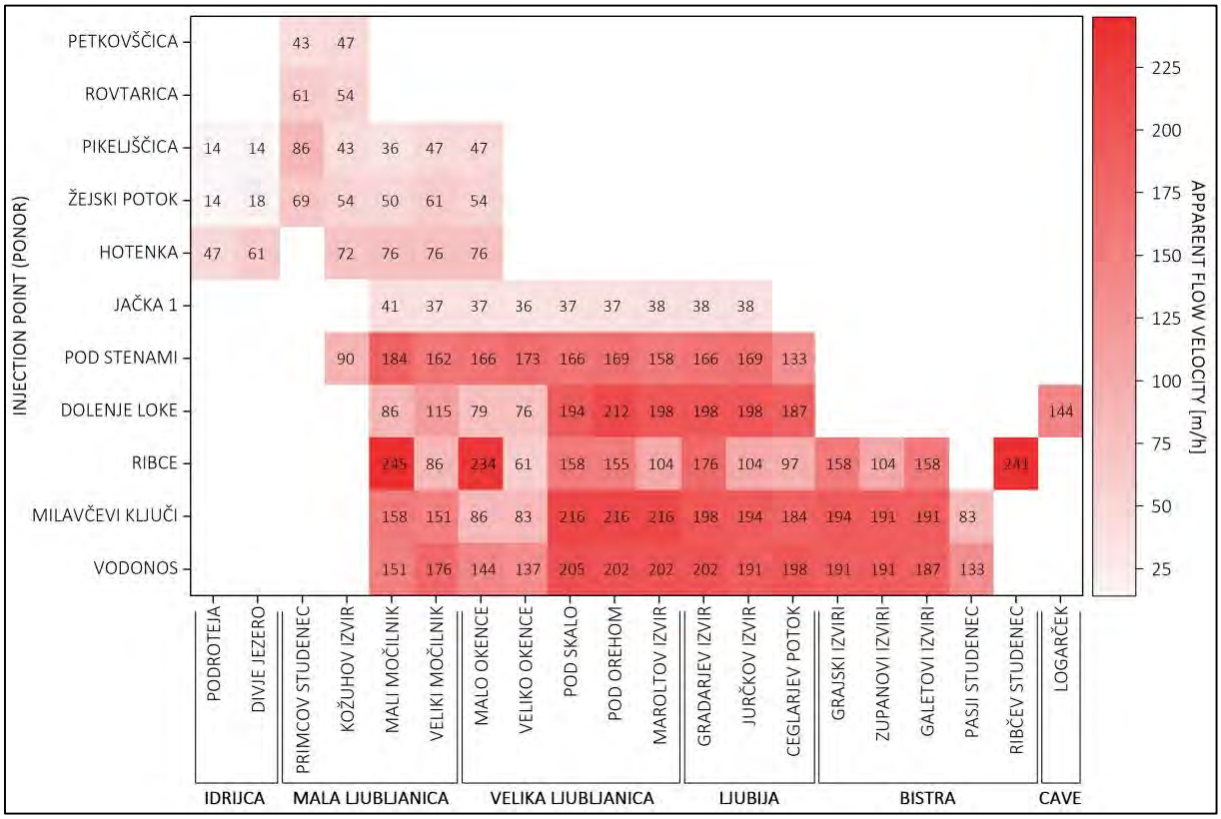


Fig. 4.15: Apparent flow velocities between the studied ponors and the springs obtained from the dye tracing campaign in 1975. On vertical axis injection points (ponors or surface streams) whereas on horizontal axis locations of sampling points (springs or caves) are listed.

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ABSTRACTS
IZVLEČKI

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

The Mescla Cave (Alpes-Maritimes, France). Overview of researches in a deep-phreatic cave

Jama Mescla (Alpes-Maritimes, Francija). Pregled dosedanjih raziskav globoke freatične jame

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The Mescla Cave (Alpes-Maritimes, France) is a thermo-mineral spring, whose passages have been explored by scuba diving to -267 m, one of the deepest in the world. The ongoing researches combine hydrological recordings at the outlet and analysis of samples and videos brought back by divers. U/Th dating of flooded speleothems identifies a base level rise by aggradation of the Var River around 1000 BCE. The passages which were accessible above the water table before this period contain a thanatocenosis of bats (*M. schreibersii, M. blythi, R. ferrumequinum*) as well as minerals from the decay of guano (fluorapatite, kaolinite). Sand cores taken 300 m from the entrance contain minerals characteristic of the Var River, introduced during floods causing a rise in the river level of several meters and flow inversions. These laminated allogenic sediments are interpreted as the record of extreme flood events associated with climatic degradation during the Little Ice Age (LIA) and contemporary intense cultivation in a mountainous watershed that is highly susceptible to soil erosion. A juniper branch introduced by these floods has been dated by 14C around 1300 BCE. Video analysis shows that the conduit oscillates mainly along the bedding planes, with little influence from fractures. The CTD data loggers located at the spring characterize the hydrodynamics (recharge type, recessions, snowmelt, mobilization of different water masses according to the types of events etc.). The Earth's tides appear during recessions. All these research topics are under development, to which is added a study of the recording of the neotectonic activity in the speleothems. The installation of integrative flow measurement by radar sensor at the spring is in progress. One of the objectives is to identify the flow inversions linked to the rises of the Var River level.

Keywords: *stratified aquifer, bats, thanatocenosis, speleogenesis, hydrodynamic, Earth tides*
Ključne besede: *stratificiran vodonosnik, netopirji, tanatacenoza, speleogeneza, hidrodinamičen, Zemljino plimovanje*

Kosovo Abysses (Vertical caves)

Kosovska brezna

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Karst terrains in Kosovo are built from karstified limestone of the Triassic and Cretaceous ages and of Paleozoic marble. These terrains include an area of 1423 km^2 or 13.1% of Kosovo's territory. Abysses are underground karst formations and are quite widespread in Kosovo, but only a small number of

them have been researched. Abysses or vertical caves (wells) are mainly found in: Mount Mokna, Bjeshkët e Nemuna, Mount Pashtrik, Mount Koretnik, Mount Akovan (Zatriq) and in the lower flow of the Mirusha River. These vertical channels, in some cases deep, continue into horizontal cave channels, through which there often flow permanent or temporary underground rivers. In some abysses, their bottom is covered with snow throughout the year, such as the Rodak abyss (about 80–100 tons), the Plenia e Madhe Abyss, and the Bad Abyss, etc. The most important abysses or vertical caves explored thus far in Kosovo are: the Twin Abysses or the Bottomless Abyss (−122 m), in Rrasa e Zogut, the Zgatari's Abyss (−103.5 m), in Opoja, the Bad Abyss (−68 m ,) in Bajshë / Mount Mokna, the White Queen's Abyss (−48 m), in Akovan / Zatriq, the Chaka Abyss (−45 m), in Pashtrik, the Gjins' Abyss, (−33 m) in Pashtrik, the Pigeons' Abyss (−26 m), in Akovan / Zatriq, the Twin Abyss (caves), (−22 m) in Mount Mokna, the Rodak Abyss (−49 m) in Mount Mokna / Kaliqan, the Abyss Plenia e Madhe (−42 m), in Mount Mokna, the Bad Abyss (−82 m), in Mount Mokna at the Kaliqani diary-farms. Based on the exploration of these abysses, it has been concluded that some of these abysses have great scientific value that should be explored in the future. In addition to scientific values, these abysses also present touristic values. Until now in Kosovo, only the Twin Abyss (cave) is prepared for tourism with "Via Ferrata" and is used by climbers and performers of extreme sports.

Keywords: *Kosovo, abyss, tourism, karst terrains*
Ključne besede: *Kosovo, brezno, turizem, kraške pokrajine*

Monitoring strategies in cave microclimate monitoring studies – Dos, Don'ts, Maybes

Pristopi pri opazovanju jamske mikroklime

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The planning of microclimatic measurements in caves depends on numerous factors. These include the known ones, such as adequate funding and available measurement equipment, their capabilities and limitations, and the creativity and improvisational skills of the researcher. In order to develop a strategy for continuous monitoring of microclimate and to study the fluctuations of CO_2 concentration under the conditions of limited financial resources and measuring devices, different measurement methods were applied in Samograd Cave and Barać Caves in Croatia: continuous measurements with loggers and spot measurements with hand-held measuring devices. We pursued the following objectives: representativeness (spatially and temporally, e.g., coverage of the entire year/seasons), comparability, and long-term measurements to collect data series over the years in an attempt to discover regularities. Each of the measurement methods used has its advantages and disadvantages, which we would like to present. With the previous financial support of the Public Institution Cave Park Grabovača and the Public Institution Barać Caves, a series of data on air temperature, relative humidity and CO_2 concentration on different time scales have been collected in this way in recent years. These data are useful for microclimate research, sustainable management of tourist caves and planning of further research. With the start of the CARDIKARST project, there are new opportunities for research work based on the above experience. This work is supported by the Slovenian Research Agency and the Croatian Science Foundation within the project Dynamics and distribution of CO2 in karst vadose and epiphreatic zone (CARDIKARST) IPS -2022-02-2260.

Keywords: *cave microclimate, CO_2, research methods*

Ključne besede: *jamska mikroklima, CO_2, raziskovalne metode*

Identification and assessment of karst processes for the studies and the conservation of caves and their heritage

Prepoznavanje in vrednotenje kraških procesov pri proučevanju in ohranjanju dediščine jam

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Karst and cave landscapes are the result of complex interactions of geological, environmental and biological factors. Their studies bring essential information in karstology, archaeology and geomorphology to understand the paleo-environmental evolution at different scales. Such knowledge permits the assessment of conditions for the installation of conservation measures and management of natural and cultural heritage that compose them. In the French Jura, a network of regional nature reserves created to preserve cave habitats for chiropterans is also involved in cave studies and education. With the implementation of the reserve's management plans, it appeared essential to identify the various heritages present in the caves and the biotopes characteristics for the chiropterans, in order to assess the possible evolution of the environments and the consequences that result from it. Various studies and the monitoring of these sites have been installed gathering karstologists, chiropterologists, archaeologists and speleologists to provide data and analyses. This presentation describes the methodology and the results obtained based on the examples of three of these reserves: the Chenecey cave, the Creux à Pépé and the Baume River. They contribute significantly to the orientation of management and conservation plans as well as to the knowledge of the Jura karst.

Keywords: *cave heritage, cave processes, environmental interactions*
Ključne besede: *jamska dediščina, jamski procesi, okoljske interakcije*

The value of satellite-driven snow cover data in the calibration of a karst hydrological model

Pomen satelitskih podatkov snežne odeje pri kalibracijah kraškega hidrološkega modela

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Snow cover is an important hydrological factor strongly affecting groundwater recharge in mountainous karst catchments. There is a need to develop a representative hydrological modeling concept that accounts for a representative simulation of the snow accumulation and snowmelt in the mountainous karst catchments. To achieve so, we improved the lumped conceptual hydrological model "VarKarst" with a satellite-data-driven snow routine to better simulate the spring discharge in snow-dominated mountainous karst catchments. To reveal the optimum contribution of the satellite-driven snow cover data on the model, we applied three different calibration strategies: (i) single-step single-variable calibration, (ii) single-step multi-variable calibration, and finally, (iii) two-step multi-variable calibration. To apply our methodology, we used the data from one of Austria's most important

mountainous karst springs, "Klaffer Spring" in the Hochschwab karst massif, one of the major drinking water resources of the city of Vienna. Our results confirmed that there are better methods than single-step multi-variable calibration to obtain the best simulations for discharge and snow storage simultaneously. Single-step single-variable calibration gives good discharge simulations, however, the increased number of calibrated model parameters increases the parameter uncertainty. The two-step multi-variable calibration method looks preferable, however, in this method the MODIS snow cover data can be used only to calibrate the snow parameters.

Keywords: *Mountainous karst, model calibration, VarKarst, satellite, snow*
Ključne besede: *Gorski kras, kalibracija modela, VarKarst, satelit, sneg*

How do radon dynamics differ within caves with different airflow mechanisms?

Kako se dinamika radona spreminja v jamah z različnimi režimi pretoka zraka?

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Cave air circulation provides an important control on cave environments by influencing gas, dust, and aerosol transport. Numerous airflow mechanisms drive cave air circulation including the chimney effect, circulating convective airflow, surface wind-driven airflow, and barometric airflow. Radon is a potential significant radiation exposure source to cavers and people who work inside of caves. Most previous studies of cave radon have been conducted in caves that are relatively well connected to the surface, consequently, airflow direction or rate of ventilation are the main controls on radon concentrations. Here, we will explore whether radon dynamics differ in caves that ventilate by different mechanisms. For example, can radon source hotspots be a greater factor than ventilation in the parts of caves that have a poor connection to the surface atmosphere? Speleoclimate stations will be placed in Mammoth Cave, which has chimney effect airflow, Jewel Cave, which has barometric airflow, and Carlsbad Caverns, which has circulating convective airflow, barometric airflow, and surface wind-driven airflow. These stations will measure radon levels, wind velocity, temperature, humidity, and barometric pressure to determine how different ventilation mechanisms influence gas transport and control radon dynamics.

Keywords: *radon, cave ventilation, gas transport*
Ključne besede: *radon, jamska prezračenost, plinski transport*

Do existing conceptual models of critical zone processes apply to karst?

Ali obstoječi modeli procesov kritične cone veljajo za kras?

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Substantial recent work has focused on understanding Earth's critical zone – which spans from the base of weathered bedrock up into the top of the tree canopy. Within the critical zone, interactions among geological, biological, climatological, chemical, and hydrological processes act to sculpt Earth's surface and provide a range of ecosystem services that humans rely on. A better understanding of the dynamics and structure of the critical zone is needed to predict future responses to climate change

and anthropogenic disturbance. Most of the work in critical zone science has focused on landscapes underlain by silicate rocks. Here, I review conceptual models developed for understanding the critical zone and explore their application to karst settings. I detail a variety of ways in which these models may fail, or require modification, when applied to karst, and examine important open questions in carbonate critical zone science.

Keywords: *critical zone, carbonates, conceptual models, weathering, landscape evolution*
Ključne besede: *kritična cona, karbonati, konceptualni modeli, preperevanje, razvoj pokrajine*

Sulfuric acid caves of the world: a review

Žveplene jame: svetovni pregled

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Most caves we can explore today are of epigenic origin, in which (surface) waters obtain their aggressiveness mainly from soil CO_2. In the last 30 years an increasing number of cave systems has been categorized as hypogenic, where (deep rising) fluids are undersaturated and create some of the largest cave systems in the world. For example, mixing of different saturated fluids or between salt and fresh waters, and cooling are the main processes that can cause the renewing of aggressiveness towards carbonates, but also acids can be involved in hypogenic karst. One type of hypogenic karst involves sulfuric acid, mainly produced by the oxidation of hydrogen sulfide rising from depth. Although this type of process has been described since the early 19th century, the first elaborated theories are rather recent, and a detailed model was proposed only in the mid-1970s. Only a few cave areas were known to host sulfuric acid caves, but studies were boosted with the discovery and understanding of a few active sulfuric acid speleogenesis (SAS) environments. Today over 80 areas in the world are known to contain sulfuric acid caves, offering a wide variety of situations and conditions, and an increasing number of active and inactive SAS caves are being discovered and explored every year. This review gives a historical overview of studies on these caves, explains the chemistry behind the formation of the dissolving fluids and their interaction with the carbonate host rock, and describes the chemical, mineralogical, geomorphological and microbiological signatures typical of sulfuric acid dissolution. The significance of SAS caves in landscape evolution and their possible role in deep karstification, and thus hydrocarbon reservoirs and deep hydrogeology, is also discussed.

Keywords: *hypogene speleogenesis, rising fluids, hydrogen sulfide, deep karst*
Ključne besede: *hipogena speleogeneza, dvigajoči fluidi, vodikov sulfid, globoki kras*

The CryoKarst Project: Academic research meets citizen science to study ice deposits within caves

Projekt CryoKarst: akademske raziskave srečajo skupnostno znanost pri preučevanju ledu v jamah

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Citizen science is a collaborative approach in which members of the public actively participate in scientific research with positive effects for both the scientific community and the citizens by generating new knowledge, enhancing scientific literacy, promoting community engagement, increasing public trust in science, and fostering more informed policy decisions. However, effective communication, rigorous data quality control, and ethical considerations regarding participant engagement are essential for the success of the project. The CryoKarst project (Cryosphere in the Karstic environments of Friuli Venezia Giulia) has been developed thanks to a scientific agreement between the Geological Survey of the Friuli Venezia Giulia Administrative Region (FVG; Italy) and the Polar Science Institute of the Italian National Research Council (CNR). Main purposes are: i) Revision and implementation of the regional inventory of caves (CSR), mainly looking at the underground environments characterized by the presence of permanent snow, firn and ice deposits; ii) development and testing of near-range remote sensing techniques for 3D surveying (SfM-MVS, LIDAR), aimed at the characterization of the hypogeal glacial environments and their spatio-temporal evolution; iii) monitoring and study of climate-cryosphere interactions in the underground glacial environments in connection with the external cryosphere. Given the high number of caves with ice deposits currently present in FVG, it would be necessary an extraordinary effort in terms of staff and days in the field to achieve a decent result. To provide surveyors with basic information to correctly and unambiguously characterize hypogeal ice deposits, a survey protocol was drafted and the volunteer cavers were trained. This joint effort represents an expression of citizen science and will make it possible to optimize the updating times of the RSC as well as provide important data for the planning of medium to long-term monitoring, eventually assessing the impacts of present climate change on groundwater resources.

Keywords: *ice caves, cryosphere, karst, citizen science, ice*
Ključne besede: *ledene jame, kriosfera, kras, skupnostna znanost, led*

Polygenic speleogenesis of Grotta dei Pipistrelli (Matera, southern Italy)

Večfazna speleogeneza jame Grotta dei Pipistrelli (Matera, južna Italija)

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Located a few kilometres south of the city of Matera (southern Italy), and with its entrances on the western side of a fluviokarst canyon (the deeply incised "Gravina di Matera"), Grotta dei Pipistrelli cave developed along the contact between the Plio-Pleistocene Calcarenite of Gravina and the underlying Upper Cretaceous Apulia carbonate units. With a total extension of 225 m in plan, this karst system consists of a primary sub-horizontal conduct with few secondary passages and a collapse doline on the roof. A multi-method approach including morphological, mineralogical, and geochemical investigation of cave rock-relief features and deposits, together with the structural and lithostratigraphic description

of the host rocks (inside and outside the cave), is ongoing to reveal the complex speleogenetic history of the Grotta dei Pipistrelli and thus being able to make possible karst morphogenetic inferences also on a regional scale. In the central portion of the primary conduct, the remains of a ~2-m-thick fine-grained siliciclastic succession related to previous Middle Palaeolithic to Bronze Age archaeological findings are the object of a detailed facies analysis. Several cave-rocky features were observed, including ceiling pockets and cupolas, condensation-corrosion channels, pendants, wall convection niches, smooth walls, and replacement pockets. Secondary cave minerals such as calcite, gypsum, quartz, arsenopyrite and brushite were found on the walls and floor of the cave. In addition, some negative 34SV-CDT values of gypsum indicated an origin linked to the oxidation of sulfur-bearing minerals within the host rocks. These preliminary data sustain a possible hypogenic inception of the Grotta dei Pipistrelli, as well as a late stage of epigenic overprinting testified by the presence of condensation-corrosion morphologies and by the allogenic waters' circulation that allowed the emplacement of an alluvial deposit inside the cave when it was finally connected to the surface, within the framework of a clear polygenic speleogenesis.

Keywords: *hypogenic speleogenesis, epigenic overprinting, cave-rocky features, secondary cave minerals, alluvial cave sediments*
Ključne besede: *hipogena speleogeneza, epigeneza, jamski skalne oblike sekundarni jamski minerali, aluvialni sedimenti*

Assessment of Hydrogeochemical characteristics of Karst Aquifer from a semi-arid region

Vrednotenje hidrogeokemičnih lastnosti kraškega vodonosnika v semi-aridnem območju

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Physico–chemical parameters of groundwater provide specific information about the karst aquifers and their heterogeneity. Spatial and temporal variability of karst water chemistry has also been studied worldwide to interpret structure, nature and location of chemical inputs, nature of different reactions and mixing processes occurring in the system etc. for the water resource management and protection of the karst aquifers. Proterozoic carbonate rocks are the main water source for irrigation and domestic use and they are also intensively quarried for cement production and building stones. It is therefore, of primary importance to assess to what extent these carbonate units are karstified, so as to provide recommendations for appropriate land and water resource management. The heterogeneous and anisotropic property of karst aquifers is a result of the dissolution and karstification of carbonate rocks. Agricultural activities cause an increase in the concentration of pollution-related ions (nitrates, sulphates, chlorides, etc.). The variability of water chemistry was discussed in terms of different processes like dilution and water–rock interactions, etc. The study reveals a pronounced seasonal hydrochemical variation in the limestone aquifer. Samples were collected both from spring and bore wells. Dissolution of carbonate minerals is the main source of major ions (Ca^{2+}, Mg^{2+} and HCO_3^-) in the water. Hydrogeochemical evolution and possible water–rock interaction is discussed to find variations in physico–chemical variables of groundwater.

Keywords: *karst water, hydrogeochemical property, hardnesss, semi-arid region*
Ključne besede: *kraška voda, hidrogeokemične lastnosti, trdota, semi-aridna območja*

Models of Speleogenesis: What have we learned so far?

Speleogenetski modeli: kaj smo se do sedaj naučili?

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When considerations on speleogenesis turned from observational explanations to a mechanistic approach, the problem of cave existence appeared. Namely, if dissolved by linear kinetics, the dissolution rate along a one-dimensional fracture drops exponentially. Several mechanisms were proposed to explain the existence of long conduits; a good example being mixing corrosion. The proposal of a kinetic trigger, supported by new results of experiments on calcite dissolution kinetics, in principle, solved the problem. When dissolution kinetics becomes nonlinear, the dissolution rates along a fracture drop by power law, and dissolution can progress deep into the fractures. Feedback between dissolution rates and flow rates results in an abrupt increase of growth after a long period of slow stagnation, called breakthrough. In the late 80s and early 90s, early models of 1D fractures and 2D fracture networks were presented, and speleogenesis was discussed in terms of different boundary conditions, lithology, mixing corrosion, etc. The breakthrough time was introduced as a measure of karstification intensity in certain settings. By considering fractures as more realistic 2D structures instead of 1D structures, the nonlinearity condition also vanishes; in a 2D fracture, a dissolution front is inherently unstable, which leads to fingering, flow focusing, and accelerated breakthrough. The complexity of natural settings and the multiphase origin of most cave systems are still too complex to produce their digital twins. Why modelling then? The models of speleogenesis are tools based on basic principles of flow, dissolution, and transport that give us insight into what mechanisms might, and almost surely do, happen in nature. Using these models, we have so far revised the role of mixing corrosion in early speleogenesis, evaluated the risks caused by hydraulic structures, such as dam sites in karst areas, shown how different boundary conditions and settings result in different cave geometries in confined and unconfined settings, simulated the growth of collapse dolines, discussed the speleogenetic role of deep flow, and the response of evolving karst systems to base level changes. These models have been used to produce the digital karst aquifers and study their transport properties, among many other things. The digital power and new modelling tools and approaches allow us to build more complex, almost realistic model. Although appealing, we want to stress the use of models to deepen our understanding of cave formation. In this sense, the increase of complexity is reasonable only when simpler settings are profoundly understood by the researcher. The space for further evolution, however, is huge. Many aspects of speleogenesis, such as evolution in vadose and epiphreatic settings and interaction with the vadose atmosphere, are now being approached by modelling, and many important topics are still waiting to be tackled.

Keywords: *speleogenesis, numerical modeling, dissolution kinetics*
Ključne besede: *speleogeneza, numerično modeliranje, kinetika raztapljanja*

The concept of the caves evaluation methodology in Slovakia

Princip vrednotenja jam na Slovaškem

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Cave evaluation is important for understanding, protecting, and managing cave systems. Different environments, the mentality of people from different parts of the world, and various perspectives on the caves around the world offer a spectrum of ideas on how to evaluate the significance of the caves. A standard methodology is missing, but there are many good examples of criteria that should be taken into account. From the scientific, natural, historical and cultural values, through perceptions of visitors, to potential for further use, research, or protection, caves are the subjects of assessment from the Geoheritage point of view, for the purposes of show cave management or also as a part of abiotic geosystem services, recently. In Slovakia, massive development activities, agriculture, logging, or intensive recreation in karst areas could be seen, resulting in possible pollution or contamination of the cave environment or its components. Consequently, there is a need for a uniform methodology for an evaluation that avoids subjectivity in decision-making process for authorization of such activities. The study presents the possible key for objective decisions, which should be based on objective criteria. Inspired by other studies and adding own levels or parameters specified for the Slovak caves, a concept of methodology is proposed. It includes an evaluation both on national and international scales in the field of geomorphology (morphology, morphometry, genesis), geology (lithology, structural geology, sediments, and other infills), hydrology, zoology, paleontology, history, and archeology. Although subjective criteria, such as aesthetic value, are problematic, they are still considered important, and therefore they are also discussed.

Keywords: *cave, evaluation, assessment, Slovakia*
Ključne besede: *jama, vrednotenje, ocenjevanje, Slovaška*

^{222}Rn as a natural tracer to investigate recharge and groundwater flow dynamics at three Mediterranean karst systems in Southern Spain

^{222}Rn kot naravno sledilo za raziskovanje napajanja in dinamike toka podzemne vode treh sredozemskih kraških sistemov južne Španije

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Comprehensive knowledge of groundwater origin and movement into karst aquifers is crucial to establish the adequate management practices. This is of special interest in areas strongly affected by the impact of climate change, such as the Mediterranean region. This work aims to better understand recharge processes determining groundwater flow in 3 mountainous carbonate aquifers in Southern Spain. To achieve this purpose, spring discharge and electrical conductivity data as well as ^{222}Rn activity were measured and interpreted in karst groundwater. Karst groundwater discharge at the investigated springs varies between 3 and 1400 L/s, while electrical conductivity (EC) values range between 227 and

1929 µS/cm. ^{222}Rn activity data are found between 31-3630 Bq/m^3. The temporal evolution of EC, water temperature and ^{222}Rn showed relatively constant values during dry periods in all examined karst springs but abrupt decreases after intense recharge events. A detailed –daily- control during high waters in the Sierra de Ubrique revealed slight increases in ^{222}Rn activity at the beginning of the rising limb of spring discharge. However, circulation of recently infiltrated rainwater through karst conduits (in turbulent flow regimes) and the mixing with old waters provokes a marked dropping in the measured parameters at karst springs. The combined -spatial and temporal- analysis of data from the three sites revealed that ^{222}Rn activity in groundwater is directly related to the characteristic mean residence time (and karstification degree) of each study area. Furthermore, the preliminary analysis indicates that the presence of some impervious lithologies, such as clays, might generate a higher contribution of ^{222}Rn activity in groundwater. Long residence times, groundwater–rock interaction or a combination of these processes are also responsible for the highest radon activity measured at in the karst springs. Moreover, the complexity of groundwater flow systems due to tectonical stetting of examined aquifers have direct implications in the transference of ^{222}Rn.

Keywords: *Radon 222, karst, recharge, Southern Spain*
Ključne besede: *radon 222, kras, napajanje, južna Španija*

And now for something completely different! - Morphology and deposition of the Main (sulfide) Ore in Proterozoic dolomites at Nanisivik Mine, Baffin Island, Canada

In sedaj, nekaj popolnoma drugačnega ... Morfologija in mineralizacija sulfidne rude Main v proterozojskih dolomitih. Rudišče Nanisivik, Otok Baffin, Kanada

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Nanisivik zinc/lead mine (Lat. 73°N, Baffin Island) is in dolomitized Proterozoic platform carbonates dipping ~150N and overlain by shale aquitards. The principal deposit, the Main Ore, is of zinc, lead and iron sulfides, plus gangue minerals (chiefly, secondary dolomite cement). It extends as a horizontal body along the strike for three km in a horst block and is terminated at both ends by modern valley entrenchments. The Ore body is consistently ~100 m wide and 5–7 m deep. It terminates upwards at a horizontal corrosion bevel across the dipping bedrock. Within the Main Ore two or more generations of sinuous, meandering, solution-residual dolomite fins extend into the ore-filled cavity. Sharp, horizontal corrosion notches 20–30 cm high also extend deep into the dolomite walls. They are filled with layered pyrites, some of which continue into the Main body to truncate earlier, dipping, sulfide deposits. Sedimentary textures suggest that the ore cavity formed by paragenesis in a channel-flow mode, with ore and gangue deposition on the floor taking place in tandem with dissolutional cavity extension upwards. Fluid inclusions indicate derivation of the metals from exchange reactions with underlying metalliferous shales, indicating low water/rock ratios and ore fluids similar to oilfield brines. S isotope fractionations indicate temperatures of 90–150 ± 40°C, suggesting that the Main Ore formed along a rising gas/brine or water/brine interface at least 1600 m below any open land surface. Latest studies suggest a Grenvillian age (~1.1 Ga) for the Main Ore. This is now a permafrost region. Wall temperatures in the mine are −11°C. Burial by glacial ice on one or more occasions during the Quaternary allowed the bedrock temperature to rise, permitting sub-glacial groundwaters to dissolve secondary dolomite along the south wall, reducing parts of the Ore body to breccias that are now firmly cemented by ground ice.

Keywords: *lead/zinc pyrites, dolostone, paragenesis, intrusive deposition*
Ključne besede: *svinčevo/cinkovi piriti, dolomit, parageneza, intruzivni nastanek*

Karst digital twin - evaluation of remote sensing spatiotemporal data for modelling the karst systems

Kraški digitalni dvojčki – vrednotenje daljinskega zaznavanja časovno-prostorskih podatkov pri modeliranju kraških sistemov

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With the rapid development of technology karstologists become able to perform research on karst systems based on large collections acquired by different data-loggers, measuring devices, remote sensing systems etc. Different data in high spatiotemporal resolution and different modelling software tools introduced the possibility of observing the karst systems as their "digital twins" – the spatiotemporal data representation of a karst system modelled with computer software. The aim of this study is to evaluate the possibility of using different spatiotemporal data to create karst system digital twin for the very first time to characterise groundwater recharge processes, known by our best knowledge. Data on different parameters have been collected by data-loggers inside caves of Notranjski kras (SW Slovenia) and on Mt. Miroč (E Serbia). Precipitation, evapotranspiration, and discharge data from the hydrometeorological authorities have been acquired (ARSO). Also, remotely sensed data on precipitation, soil moisture, snowmelt, and evapotranspiration from Copernicus CDS. The latter two resources have been correlated to evaluate the usability of remotely sensed data since not all karst areas are covered with monitoring networks of good density to cover the entire recharge area. For example, analysis showed that for precipitation events there is large correlation between ARSO and Copernicus CDS data, even in high temporal resolution, while the correlation on actual amount of precipitation there is good correlation when there are small amounts of precipitation, while on heavy precipitation the actual amounts acquired by Copernicus CDS are very large compared to ARSO. After evaluation, all the data have been modelled using modern software tools to create spatiotemporal digital twin, giving the opportunity to get better insight on how water travels through the karst systems. The results obtained are important to improve the understanding of infiltration rates and the modelling approaches of karst hydrological processes.

Keywords: *karst systems, karst digital twin, hydrology, spatiotemporal data*
Ključne besede: *kraški sistemi, kraški digitalni dvojček, hidrologija, prostorsko-časovni podatki*

Geological origin and value of karst spring in Jinan, North China

Geološki izvor in pomen kraških izvirov v Jinan-u, severna Kitajska

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Karst groundwater is widely distributed in northern China, which provides a large amount of groundwater resources for regional agriculture, industry and urban water supply. Karst springs not only have the value of water resources, but also have the significance of tourism and ecology. Jinan Spring Area is located in Jinan, Shandong Province, China including many springs in this city. For this reason, Jinan has the title of "The City of Thousands of Springs". The terrain in the area is high in the south and low in the north. The Cambrian and Ordovician strata, mainly carbonate rocks, cover the metamorphic rocks of the southern Taishan Group. The surface and underground karst fractures of

the carbonate strata are developed, providing a good channel for groundwater migration. In the process of runoff from south to north, karst groundwater meets the obstruction of intrusive rock mass in the north and flow out into spring water. Spring water is concentrated and exposed in the urban area of city, which improves the urban ecological environment and attracts lovers of natural landscape. It has good economic, social and ecological value to urban development and residents' quality of life.

Keywords: *North China, karst springs, geological origin, value*
Ključne besede: *severna Kitajska, kraški izviri, geološki izvor, pomen*

Geochemical and isotopic approaches in research on dedolomitization and speleogenesis processes

Uporaba geokemijskih in izotopskih analiz pri interpretaciji procesov dedolomitizacije in speleogeneze

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Dedolomitization is a process often described in the literature on the diagenesis of carbonate rocks, however, the direct relationship between dedolomitization processes and/or its products and speleogenesis is still not entirely clear. As part of a joint Polish-Slovenian project, interdisciplinary research is conducted in the Rovte region (central Slovenia), where phenomena related to speleogenesis in the dedolomite were described (e.g., Otoničar et al. 2016). According to the results of preliminary hydrogeochemical studies in this area, the dissolution of calcium sulphates and dedolomitization are still active processes. Thanks to this, this area is suitable for the study of direct relationships between the processes of gypsum dissolution, currently active dedolomitization and development of karst caves, and their products occurring in the form of sediments and secondary minerals on the walls of caves. The most important cave for our research is Mravljetovo brezno v Gošarjevih rupah, which wall rock is mostly composed of a yellowish to reddish-brown calcareous deposit in an otherwise Middle Triassic gray dolomite formation (Otoničar et al. 2016). In order to obtain the broadest possible spectrum of information on the processes accompanying the formation of individual minerals, both carbonate samples and sulfur minerals (such as, gypsum, epsomite, or pyrite) are examined. The preliminary results of our research will be presented, especially geochemical and isotopic studies of rock samples collected in Rovte region. The project is 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: *dedolomitization, speleogenesis, sulfur minerals, isotopes, Slovenia*
Ključne besede: *dedolomitizacija, speleogeneza, žveplovi minerali, izotopi, Slovenija*

Identification of karst depressions based on LIDAR - challenges from the Slovak karst region

Prepoznavanje kraških depresij na podlagi LIDAR tehnologije – izzivi s slovaških kraških regij

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The area of the Slovak Karst is the best-preserved plateau karst area in Slovakia. It was possible to identify about 1000 dolines in the topographic maps, but many of them were missing. The availability of LIDAR from the summer of 2022 allowed us to observe more closely even those that are not on the original topographic maps, but also to ask many questions. When working with LIDAR, we managed to automatically identify about 6000 depressions, but of different origin, not only dolines, but also anthropogenic lime pits, mining pits and pits after tree felling or biogenic origin. The main challenge was to distinguish these forms from each other and to try to get the largest number of dolines. In addition, in the automatic detection of depressions, they are merged and sometimes even very small depressions are not detected. Regarding the morphometric parameters of dolines and their statistical processing (area, volume), we asked ourselves what can be considered the circumference (edge) of a doline, since different approaches are used in the published researches, but they yield very different results. The dolines of the Slovak Karst are mainly situated in karst rocks (mainly Wetterstein limestone), less so in sediments. In terms of shape, character and size, clear regional differences can be seen between the west and east of the Slovak Karst, which indicate a different geomorphological development of the territory. The largest and most regular dolines were observed in the western part of the territory, on the other hand, the eastern ones are irregular with relatively difficult identification not only on LIDAR but also in geomorphological mapping. During our work, it was confirmed to us that automatic identification based on LIDAR is significantly easier, but it is necessary to subsequently confirm the results of field research.

Keywords: *Slovak karst, dolines, LIDAR, depressions detection*
Ključne besede: *slovaški kras, vrtače, LIDAR, detekcija depresij*

The Karst organic carbon sink process in a typical karst surface river, Lijiang, Guilin, China

Ponorni procesi organskega ogljika v tipični kraški površinski reki, Lijiang, Guilin, China

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Aquatic photosynthesis transforms inorganic carbon to organic carbon (OC), which contributes to autochthonous organic carbon (AOC) in sediment and particulate organic carbon in surface karst aquatic systems. Recalcitrant dissolved organic carbon (RDOC) resulting from microbial carbon pump (MCPs) holds promise as a relatively long-term natural carbon sink, but the origination division of microbial carbon and its formation mechanism remains unclear. Samples were collected seasonally from the upper to lower reaches of Lijiang to determine the dissolved organic carbon (DOC) composition and microbial-sourced DOC (MDOC) formation mechanism. Three CDOM components were calculated by parallel factor analysis (PARAFAC) from EEM spectra, which were allochthonous soil-sourced DOC (SDOC), autochthonous aquatic plant-sourced DOC (APDOC), and microbial-sourced DOC (MDOC). SDOC is induced by large amounts of precipitation causing soil erosion in summer. APDOC formation is encouraged by moderate water temperatures in spring and fall restricted by high

water turbidity in summer. DIC fertilization effect in karst aquatic systems directly promotes APDOC formation and indirectly promotes MDOC. RDOC concentration was determined by in situ bacteria incubation, which accounted for 67% to 93% of DOC concentrations. Sporichthyaceae accounted for 3.4%–22.6% in May and Novosphingobium accounted for 3.5%–34.0% in July. These were the critical bacteria species induced MDOC formation, which were confirmed by their abundances in KEGG pathway modules determined by PICRUAST2. Heterotrophic bacteria dominate autochthonous DOC and RDOC formation in the karst surface river, which is valuable for understanding organic carbon cycling in karstic aquatic systems.

Keywords: *karst aquatic system, carbon sink, organic carbon, heterotrophic bacteria, CDOM spectrum*
Ključne besede: *kraški vodni system, ponor ogljika, heterotrofične bakterije, CDOM spekter*

Building hydrogeological 3D conceptual models of karst aquifers with visual KARSYS

Ustvarjanje hidrogeoloških 3D konceptualnih modelov kraških vodonosnikov s programom "visual KARSYS"

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For the last 7 years, SISKA develops a webtool which allows the user to build a 3D geological model of a given karst massif and showing how groundwater can flow through the karstified layers. The approach is conceptual, applying geological and hydrogeological principles of the KARSYS approach. Visualkarsys.com is used for various applied projects and it has been adopted by a few universities for teaching. The use of visual KARSYS is free of charge and new functionalities and features are being added making visual KARSYS more efficient and useful. The last developments recently added refer to (i) the dynamic flow animation module (FAM) and (ii) the meta-project module. The FAM intends to visualize conceptual models of groundwater flow-systems in 3D in a dynamic way. It is designed for all types of hydrogeological settings, including karst and other high heterogeneous aquifers (e.g. volcanic, fissured...). The FAM aims to explicitly show the movement of groundwater flowing through the aquifer (including rainfall, surface runoff, allogenic vs. autogenic recharge, infiltration through unsaturated zone, flow-paths, etc.). It was designed for showing to non-hydrogeologists how groundwater flows through complex heterogeneous aquifer systems such as karst. The animation module can address different timescales (1 month, 10 years, 200 years) and different spatial scales. The meta-project module allows the user to combine geological and hydrogeological data and information from different projects in a new project which overlaps existing ones. Users can then save time and effort by reusing parts or the whole of existing projects in a new one which could be bigger or smaller. Information and data could then be updated from one project to another thus avoiding the multiplication of the same data which traceability can be kept. This is a first step in the direction of nested models at different scales sharing the same data.

Keywords: *karst, 3D model, conceptual model, flow, visual KARSYS*
Ključne besede: *kras, 3D model, konceptualni model, tok, visual KARSYS*

Physico-Chemical characteristics of Karst Water

Fizikalno kemijske lastnosti kraških voda

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The physical and chemical characteristics of karst water are not a sole function of flow path in the carbonatic rock mass. In this paper, parameters like the type of precipitation, soil cover, morphology of the exposed area, and the hydrochemistry of the infiltrating water into the karst is used to find the chemical characteristics of karst water. The temperature, conductivity, pH and DO variability was minor as indicated by small standard deviations of the measurements.

Keywords: *karst water, physical parameters, chemical parameters*
Ključne besede: *kraška voda, fizikalni parametri, kemični parametri*

Hydrogeochemical monitoring in the Rovte region (Slovenia) to assess the potential for dedolomitization

Hidrogeokemični monitoring na območju Rovt (Slovenija) za oceno potencialne dedolomitizacije

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Dedolomitization is an elusive process that converts dolomite into calcite, forming “dedolomite”. Dedolomite has been found in the Rovte region, western Slovenia, and notably, within the cave Mravljetovo Brezno v Gošarjevih rupah (MBGR). Our project aims to understand the role of dedolomitization in the formation of MBGR cave. One research avenue focuses on hydrogeochemistry of three artesian wells emerging from deep boreholes that cut Upper Permian and/or Lower Triassic Ca-sulphates, to assess whether these waters have the potential to cause dedolomitization. During dedolomitization, magnesium in the dolomite is replaced by calcium, and thus, requires a reaction-solution highly enriched in Ca. One theory that could explain the presence of Ca-rich waters is through the dissolution of gypsum and anhydrite ($CaSO_4$). This process would, therefore, result in waters rich in Ca, Mg and S with the requirement of being under-saturated with respect to gypsum and dolomite but over-saturated with calcite. Preliminary results from our nine-month monitoring campaign of these boreholes, and comparisons with five springs, show that the borehole (well) waters fit the criteria for dedolomitization. The average concentrations of Ca^{2+} in the wells (WEL-Z, WEL-R and WEL-B) are 260, 97 and 53 mg/L (respectively), while those of the springs are 51 mg/L. Concentrations of Mg^{2+} in wells are 59, 36 and 25 mg/L, while springs are 18 mg/L. Concentrations of SO_4^{2-} in wells are 882, 301 and 72 mg/L, while springs are just 4 mg/L. Continuation of our monitoring for a full year, in addition to isotopic analyses, will further improve our understanding of deep phreatic hydrogeochemical processes, the potential for dedolomitization and how this may affect speleogenesis. This work is funded by the Slovenian and Polish research agencies (ARRS and NCN) through the bilateral Polish-Slovenian research project CEUS (project code in Slovenia: N1-0226; project code in Poland: 2020/39/I/ST10/02357).

Keywords: *dedolomitization, hydrogeochemistry, speleogenesis, Rovte region, Slovenia*

Ključne besede: *dedolomitizacija, hidrogeokemija, speleogeneza, Rovte, Slovenija*

Groundwater exchange between the Izeh alluvial aquifer and the surrounding karstic aquifers in the northeast of Khuzestan province, Iran

Interakcija podzemnih voda med medzrnskim Izeh vodonosnikom in obdajajočim kraškim vodonosnikom, severovzhodna Khuzestan provinca, Iran

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The Izeh alluvial plain is an open polje surrounded by carbonate rocks and as a result of intensive tectonic activities carbonate rocks have been subjected to fracturing and weathering. The carbonate rocks eroded products along with the inflow of suspended solids through the flooding deposited into the polje producing relatively outstanding alluvium thickness reaches over 100 m. Though the interbedded alluvium consists of clay, silt, sand, and gravel, but in all well logs a mixture of these components is observed, and the silty-sand is predominant. Despite the existence of the karstified rocks in the command area, due to heavy demand the community suffers from a shortage of water for drinking and other purposes, furthermore, in some parts of the area the karstic aquifer is exposed to nitrate deterioration. In this investigation, an attempt has been made to determine water circulation among the water-bearing horizons including the Izeh alluvial aquifer, the Pion and the Chalkhoshk anticlines, and the Izeh alluvial aquifer, and the Naal-e- Asbi syncline. To reach the goal the geological structures, hydrogeological, hydrochemical (trace elements) and nitrate and stable isotope (^{2}H and ^{18}O), and secondary isotopes (d-excess) were taken into account. The results indicated that there is a connection between the Chalkhoshkak anticline and the alluvial aquifer but the alluvial aquifer recharges the Pion karstic aquifer, which in turn discharges a considerable amount of water from the area to the Karun River through progressed conduits in the north and northwest. On the other hand, the Izeh alluvial aquifer and a part of the Chalkhoshkak karstic aquifer recharge the Naal-e- Asbi karstic aquifer in the southeast. Thus, the Pion anticline plays an important role to discharge the area, and only a part of the Chalkhoshkak karstic aquifer contributes water to the demand area.

Keywords: *karstic aquifer, Izeh alluvial aquifer, discharge, recharge*
Ključne besede: *kraški vodonosnik, Izeh medzrnski vodonosnik, praznenje, polnenje*

Terrain uplift recorded by hypogenic karst features – the case of Peninsular Malaysia

Dvig ozemlja zapisan v hipogenih kraških oblikah na Malajskem polotoku

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Widespread features of hypogenic karst were identified in caves in the northern part of Peninsular Malaysia. Host rocks are Paleozoic to Triassic metamorphic limestone and marble. Cave fill is mostly Late Pliocene-Early Pleistocene Old Alluvium, Late Pleistocene fluvial sediments and soil, and

speleothems of various age. Based on morphology of the caverns and their infill a succession of their origin is proposed, interpreted in the framework of a gradually rising landscape throughout millions of years. 1) Phreatic zone (below karst water table), where the caverns were formed. Surface of the cavities displays an intricate pattern of scallops, pendants, keels, windows, discharge slots, rift conduits, etc. Minimum value of depth of formation equals to the height of karstified mountains, maximum value of formation depth can attain a few kilometres. Temperature and chemical composition of adjacent, aggressive, sulphurous thermal springs, geothermal gradient and tectonic regime of the region provide means to attribute 2–3 km minimum depth of the hydrothermal reservoir. 2) Epiphreatic zone (at karst water table): notches, ledges, lateral niches, corrosion tables and flat roofs. Altitude of this zone is determined by sea level around the peninsula: stable before the Quaternary, oscillating during Quaternary (low during glacials, high during interglacials). The Kinta Valley caves reached this level in the Late Pliocene – Early Pleistocene, as shown by various dates measured on the tin-bearing alluvial infill. 3) Vadose zone (above karst water table): ceiling niches, cupolas, formed by a heated, aggressive vapour environment. During further uplift rainwater percolating downwards produced various dissolution features on any of the older morphologies. Terrestrial infill and speleothem formation continues here up to modern times. This succession of formation from (1) to (3) is proven by successive overprinting of mesoscale solution features. Underground cavities are everywhere, where soluble host rock is available. When approaching the surface, they lose supporting water content, roof and walls are breached by erosion, and solution growth changes to precipitation infilling by speleothems. There is relatively minor effect of solution by rainwater, if compared to the volume of subsurface dissolution. Continuing uplift erodes the host rock containing the caves, leaving behind ruins of former caves, displaying one or more of the features listed above.

Keywords: *hypogenic karst, karst features, cave fill, Malaysia*
Ključne besede: *hipogeni kras, kraške oblike, jamska zapolnitev, Malezija*

Paleomagnetic and rock magnetic investigations of cave sediments in Lipiška Jama: insight into Classical Karst (SW Slovenia) evolution

Paleomagnetne in kamninske magnetne raziskave jamskih sedimentov v Lipiški jami: vpogled v razvoj Klasičnega Krasa (JZ Slovenija)

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The Lipiška jama Cave at the south edge of the Kras Plateau (Slovenia) is a 1,400 m long, inclined to the SSW. It is recently functioning in epiphreatic and vadose regimes. Three allogenic sedimentary sections, each 2 to 3 m thick, deposited in three different levels of the same cave passage (i.e. Kozinski rov), were sampled (bottom, middle, top). With the omission of the lowest level section, which was disturbed by slides and slumps, the other two sections were sampled using high-resolution method (described in Zupan Hajna et al., 2008). For magnetomineralogical characterization of the sediments rock magnetic methods such as acquisition of isothermal remanent magnetization (IRM), S-ratio, anisotropy of magnetic susceptibility (AMS), etc., were applied. Magnetic susceptibility shows a wide variation of values in all three sections. A low coercivity mineral (e. g. magnetite) is identified as the main carrier of magnetization. The AMS shows dominantly oblate fabric, which corresponds to fine-grain sedimentation. Alternating field (AF) demagnetization was applied to determine characteristic remanent magnetization (ChRM). Primary magnetization, and the presence of both normal (N) and reverse (R) polarity samples, were determined. The section in the bottom level of the cave passage,

which was extensively influenced by post-depositional features, displays a chaotic distribution of the ChRM components. The section in the middle level of the cave passage reveals R and N polarity zone within the allogenic sediment with a nearly antipodal position of their mean directions, as well as basal flowstone with R polarity. The highest positioned section reveals mainly R polarity and occasionally N polarity samples. Although the homogenous non-laminated clay forms this sedimentary sequence, AMS parameters suggest some samples suspected of slumps behaviour. The presence of R polarity zones in two studied sections in the Lipiška jama suggests an age at least within the Matuyama Chron. Correlation with other sections in the area will help the understanding the evolution of the Classical Karst. This research is supported by Mobility Plus Project (No. SAZU-22-08) and Research Plan of the Institute of Geology of the Czech Academy of Sciences (No. RVO67985831).

Keywords: *paleomagnetism, rock magnetism, cave sediments, Classical Karst, dating*
Ključne besede: *paleomagnetizem, kamninski magnetizem, jamski sedimenti, Klasični Kras, datiranje*

Karst rock reading and development models

Branje kraške skale in razvojni modeli

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A development model enables us to discover the overall development of the formation of the selected part of the rocky karst surface. The individual rock forms that have merged into the rock relief represent just one stage of development. Good knowledge of the overall development enables us to discern the development so far and predict future development. A number of development models can be discerned. The study of the formation and development of karst phenomena and their rock relief using laboratory plaster modeling has again proven useful and informative. One of the basic models reveals the manner of the rain-induced formation and development of horizontal and gently sloping carbonate rock strata into karren and stone forests, especially after the disintegration of the upper (thinner) rock strata and the denudation and shaping of the bottom strata. It reveals many characteristics of rock formation, from the sheet flow to the formation of rain flutes, their merging into rain channels and the development of funnel-like notches; that is, developmental transition of rock forms and rock relief in the overall development from the flat surface to its dissection into peaks. We continued the study of subsoil karren that forms under tight, poorly permeable contact with soil and of rain flutes formed by water at various temperatures. We determined the pattern of the reshaping of plaster tubes that are wider at the flow inlet than at the outlet end. The results are a significant contribution to explaining the formation of high ceiling niches and pockets in karst caves. The third experiment was carried out in phreatic conditions where water in a flume was forced to flow between layers of different composition. During the experiment, we observed the typical development of channels between pure plaster layers (uniform limestone beds), between plaster layers with added Portland cement reinforced fragments (breccia beds), siporex (slowly dissolving beds) and between three different layer types.

Keywords: *Karren, karst rock reading, laboratory plaster modeling, development models*
Ključne besede: *škraplje, branje kraške skale, laboratorijski poizkusi z mavcem, razvojni modeli*

Exploring the hydrological sensitivity of surface water and groundwater resources in the Boreal region of Estonia

Raziskovanje hidrološke občutljivosti površinskih in podzemnih voda v Borealni regiji Estonije

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This study explores the hydrological sensitivity of surface water and groundwater resources in the Boreal region of Estonia. The boreal region is known for its unique ecosystem and significant freshwater resources, which are vital for the economy and environment of the region. Emphasis is put on assessing the interconnectivity of surface water and groundwater resources and their sensitivity to changes in climate and land use. We aim to discover the areas affected the most by climate change, especially drought events. Through multivariate analysis of meteorological, hydrological, hydrogeological and spatial data, the parameters specific to sensitive water bodies are identified. The preliminary results of the study highlight the vulnerability of the boreal region's water resources to drought events and the importance of understanding the hydrological sensitivity of the region. Peculiarities are evident in the hydrological behavior of stream water bodies, which indicate the hydrogeological conditions in the watershed, such as karstification, distribution of peat soils or topographical articulation. The findings provide insight into the potential impacts of climate change and land use on the region's water resources during drought events and can provide input for future management strategies for sustainable use of water resources in the boreal region of Estonia.

Keywords: *hydrological sensitivity, climate change, surface water, groundwater, drought*
Ključne besede: *hirološka občutljivost, klimatske spremembe, površinske vode, podzemne vode, suša*

The volcanoclastic material in the deep cave sediments of the high karst area on Mt. Biokovo

Vulkanoklastičen izvor globokih jamskih sedimentov v visokem krasu Biokova

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Clastic sediments in karst areas can be considered one of the most exciting archives of past events. Preserved in specific karst traps, they can be used as a distinctive tool for reconstructing palaeoenvironmental variations, such as, tectonic, climate, and volcanic events. Mt. Biokovo in Croatia is one of the typical high mountains in the Dinaric Karst area. Strong karstification and diverse surface relief resulted in the lack of thick Quaternary deposits, and only occasionally sediments are preserved at the bottom of the sinkholes, glacial moraines, or as colluvial breccias on steep slopes of the mountain. However, a depositional trap for clastic sediments was discovered at the bottom of the vertical, nearly 1000 m deep Njemica Cave with an entrance near the mountain’s highest peaks. Detailed analysis of sediments from the Njemica Cave was performed using sedimentological, petrological, and mineralogical methods. The sediment is mostly silt with mineral assemblages determined using optical microscopy of heavy and light mineral fractions combined with major element composition analysis done with an electron microprobe (EPMA). Minerals found in the sediments are dominantly quartz, followed by idiomorphic sanidine in the light mineral fraction. The

heavy mineral fraction is dominanted by idiomorphic clinopyroxenes (diopside) and Fe, Ti-oxides (magnetite and ilmenite). Additionally, volcanic glass shards were found in the samples as well. A similar mineral assemblage was also determined in the soils from the sinkholes and the matrix of lithified Quaternary breccia from Mt. Biokovo. The homogeneity of the mineral composition among different sediment karst traps, combined with the idiomorphic morphology of mineral grains and several preserved volcanic glass particles, indicate that the provenance of the sediments was volcanic. Geochemical and mineralogical indicators propose that this volcanoclastic material is connected with fall deposits from explosive eruptions of south Italian volcanic provinces.

Keywords: *cave sediments, heavy and light minerals, major elements, volcanoclastic*
Ključne besede: *jamski sedimenti, težki in lahki minerali, glavni elementi, vulkanoklastičen*

Dynamics of Glacier Ice-Contact Speleogenesis and CO_2 sequestration: the pressure story

Dinamika kontaktne speleogeneze ledeniškega ledu in sekvestracije CO_2: zgodba o tlaku

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The terrain position of relict phreatic caves in formerly glaciated areas demands mechanisms for generating an elevated water-table in order to make them functional. This can be accommodated by filling the adjacent relief with rock or with ice. The two scenarios had different timing and duration, of which the glacier ice-contact alternative would be the most recent, and therefore probable. The formation of endokarst is an important carbon sink, where CO_2 is transferred into dissolved bicarbonate; the glacier environment is no exception. It is therefore of interest to investigate the dynamics between glaciers, water flow, sediment content and the kinetics of calcite dissolution. Basal and surface glacial waters have different chemistry, the former is close to saturation, whilst surface meltwater is in open-system equilibrium with atmospheric CO_2. *In vitro* experiments have demonstrated an inhibition effect on speleogenesis from suspended rock flour. This is basically due to the large specific surface of crushed mineral particles with a high free energy, compared to the relatively limited (and stationary) wall surface of a cave. Most of the dissolution potential is consumed before water can enter the karst. The pressure effects from ice burden is not well understood, and a new series of experiments investigate the pressure effect on dissolution rate and saturation capacity, corresponding to up to ca. 2 km thick ice-sheet cover. This was done in a modified Büchi stainless steel autoclave. The autoclave was totally filled (no gas space) with water that had been equilibrated with N_2/CO_2- mixtures at standard (20°C), closed, pressurised and temperated. Pressure was set and maintained with a HPLC piston pump. An accurately weighed amount (1 gm) standard calcite sample (Glomdal marble) was added after pressurisation and thermostating through a specially designed sample injector that did not disturb the pressure. The calcite had been ground to a limited grain size range and had a calibrated specific surface area. Concentration/time was logged at 1 sec intervals using electric conductivity as concentration proxy. Each experiment was run for about 48 h to approximate equilibrium. After pressure release, the water was immediately filtered (10 µm), titrated with EDTA and EGTA and control measured for pH and conductivity. Conversion to concentration and subsequent time-differentiation was done in tailored code (Delphi Embarcadero) for calculation of initial rate and other parameters. Arrhenius parameters are similar at atmospheric pressure and at 180 bar, allowing extrapolation to near-freezing temperatures. Both dissolution rate (mMoles cm^{-2} sec^{-1}) and capacity (mMol L^{-1}) increases positively with pressure, but the pressure-acceleration of rate display a significant break of slope at about 60 bar. This is tentatively interpreted as a compression effect (barrier) of the

hydrated species in the CO_2-H_2O-$CaCO_3$ system. The results have complex consequences for glacier ice-contact speleogenesis as decreasing penetration distance, etc. Also, in the case of subglacial (read ice marginal) speleothem deposition, increased pressures will attain equilibrium faster and at a higher capacity, providing higher supersaturation potential at the depressuration site in aerated caves at atmospheric pressure. The results may also affect our further understanding the dynamics of ice age speleogenesis, glacial CO_2 sesquestration, subglacial carbonate precipitates and possibly the formation of ikaite in cold environments.

Keywords: *glacier environment, calcite dissolution, pressure effect, ice-contact speleogenesis, CO_2, sesquestration*
Ključne besede: *ledeniško okolje, razstapljanje kalcita, efekt pritiska, ledno-kontaktna speleogeneza, CO_2 seskvestracija*

Multivariate analysis of environmental and metagenomic data of two Karst water sources

Multivariatne analize okoljskih in metagenomskih podatkov iz dveh kraških vodnih virov

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Groundwaters represent about ninety-five percent of global liquid freshwater and provide an important source of drinking water all around the world. At the same time, karst aquifers are sensitive systems where, due to their characteristics, contamination can have a rapid and direct impact on water quality. Microbiological monitoring has so far been limited to standard culture methods that do not guarantee microbiological safety. In order to protect pristine groundwater reservoirs and maintain their safety, the understanding of composition, functioning and dynamics of native microbial communities is essential. Complex multivariate analysis was used to determine which environmental factors best explain variation in metagenomic profiles of microbial communities and their functional potential in pristine Karst aquifers. Metagenomes were obtained from two sampling sites with minimal human impact. The results will help us understand their natural state and determine which environmental factors contribute the most to their changes. DNA from water (sample 100 l) was obtained using filters 3 different sizes (>5 µm, >0.45 µm and >0.1 µm) in different times of the year to detect seasonal fluctuations. Environmental factors (n=25) were measured monthly and additional publicly accessible data was also used to determine association. Data analysis showed some significant differences in microbial communities between the two sampling sites and between different size fractions. Changes in microbiomes (bacterial and archaeal communities, functional profiles) are correlated with different environmental factors. Furthermore, we provide basis for massive assemblies of available cave shotgun sequencing to metagenome assembled genomes in the future. Last but not least, additional samples are being taken in order to evaluate the extent of microplastic in the effluents from the two streams.

Keywords: *karst aquifers, multivariate analysis, environmental factors, metagenomics*
Ključne besede: *kraški vodonosnik, multivariatne analize, okoljski faktorji, metagenomika*

A discovery and study of limestone depositional form on the Nullarbor Plain, Australia

Raziskave apnenčeve tvorbe na ravnici Nullarbor, Avstralija

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The Nullarbor Plain in southern Australia is an extensive, flat, karst surface covering approximately 200,000 km^2. It is composed mainly of Cenozoic shallow-water limestones that were uplifted during the Miocene. This remarkable landscape provides a rich archive of Earth surface processes from the middle Miocene to present in the form of etched imprints of ancient linear dune systems, remnant fluvial channels, and very early formation of caves, which are indicated by the presence of speleothems dating more than 8 million years. Recently, the 0.4 arc sec TanDEM-X Digital Elevation Model has opened up the potential to explore previously unresolvable fine-scale landforms on the Nullarbor Plain. Using this new dataset, an enigmatic landform with a circular outer ring and a central dome was discovered on the central part of the plain. The circular ring measures approximately 1250 m in diameter and rises up to 7 m above the surrounding plain, while the central dome is approximately 500 m in diameter and rises up to 10 m high relative to the surrounding plain. What makes this landform particularly intriguing is that it is distinct from other known landforms observed on the plain and cannot be readily explained by any of the known geomorphic processes, such as fluvial, aeolian, karst, tectonic or extra-terrestrial impact processes. In addition, the formation of dayas on the top of the landform indicate that the landform predates the karst features that have been previously documented on the plain. One of the limestone samples taken from the landform exhibits microbial boundstone facies, which suggests that the topographical expression of the annular landform may originate from the time of limestone deposition. In other words, it might be a topographical expression of a denuded bioherm.

Keywords: *Nullarbor, bioherm, carbonate platform, Miocene, topography*
Ključne besede: *Nullabor, bioherma, karbonatna platforma, Miocene, topografija*

When karst hydrology models were young – the concepts of karst water flow in the works of Alberto Fortis (1741–1803)

Ko so bili kraški hidrološki modeli mladi – koncepti kraškega vodnega toka v delih Alberta Fortisa (1741–1803)

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Alberto Fortis (1741–1803) was Italian naturalist with a wide range of scientific interests covering both social and natural sciences, such as geography, geology, biology and hydrology. He is best known for his book Viaggio in Dalmazia (Voyage into Dalmatia, 1774) that was the result of several of Fortis' voyages along the Dalmatian coast and its hinterland. In his works, Fortis demonstrated profound understanding about the evolution of karst landscape. Particularly interesting are his remarks about the water flow in karst, both over and underground. In some cases, his ideas about water flow in karst were so elaborate that they can be considered as early models of karst hydrology. Furthermore, some of Fortis's concepts about groundwater flow were confirmed by the results of studies carried out over

past few decades in the areas studied by Fortis. Fortis was particularly interested in the origin of water in rivers and lakes, and he noticed that a significant part of water circulation in karst occurs underground. For example, in the case of Cetina River he concluded that the river is too rich in water in comparison with its immediate waterless surroundings and that the river springs are remnants of former larger underground water flow. In the accounts about rivers Lika and Gacka (typical karst rivers) Fortis correctly understands that these sinking rivers provide water for the submarine springs (vruljas) on the nearby Adriatic coast. He also studied the origin of water in the Vransko jezero Lake on Cres Island and he concluded that the water in the lake comes from the surrounding hills and this local origin of lake water was confirmed during the modern studies. Much of Fortis' success in understanding karst hydro(geo)logy comes from his strong belief in fieldwork and from his reluctance to write about topics with which he was unacquainted.

Keywords: *karst hydrology, Alberto Fortis, Dinaric karst, Croatia*
Ključne besede: *kraška hidrologija, Alberto Fortis, dinarski kras, Hrvaška*

Fe-oxyhydroxide crusts on carbonates

Fe-oksihidroksidne skorje na karbonatih

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Fe-oxyhydroxides occur in various oxic surfaces and near-surface environments, such as soils, waters, stratified deposits (ferricrete) and karst caves. Depending on environmental conditions they occur as minerals ferrihydrite, goethite and lepidocrocite with hematite and maghemite as intermediate or end oxide phases. In the conditions of Dinarc karst, Fe-oxyhydroxides could be found also on the karst surface, namely in the form of several mm to several cm thick, partially degraded crusts that cover limestone or carbonate breccia. The detailed SEM/EDS analysis of the Fe-oxyhydroxide crust on limestone revealed a gradual transition between the Fe-oxyhydroxides and pure carbonate rock. Based on their specific characteristics, the internal, intermediate and external zone could be distinguished. The manner in which the Fe-oxyhydroxide crust occurs on the limestone, as well as relations between Fe-oxyhydroxides and calcite grains or clasts indicate weathered, tectonized and porous limestone surface before or simultaneously with impregnation and precipitation of the crust. Fe-rich and low-pH solutions penetrated the interior of the limestone and filled pores and spaces between calcite grains and crystals. In contact with calcite grains and crystals, Fe-oxyhydroxides began to precipitate. Identified Fe-oxyhydroxides contain minor levels of Si, Ca and Al, which indicates that water or solutions from which they formed, contained dissolved Si, Al and Ca.

Keywords: *karst, Fe-oxyhydroxide, precipitate, Dinaric karst*
Ključne besede: *kras, Fe-oksihidroksid, precipitat, dinarski kras*

To what extent reactivated faults are (not) responsible for karst process: example from Serbian Carpatho-Balkanides?

Kakšno vlogo igrajo reaktivirani prelomi pri procesih zakrasevanja: primer iz Karpato-Balkanidov, Srbija

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Carpatho-Balkanides represent part of the complex Dinaric – Carpatho – Balkan orogenic system, that geomorphologically dominates the central part of the Balkan Peninsula. The existence of this orogenic system is a result of closure of the Neotethys ocean and subsequent convergence of the Adriatic microplate and the Eurasian continent, that has been still active in the recent times. Such geodynamic characteristics conditioned complex tectonic structures, multiply reactivated during Late Cretaceous and Cenozoic times. The main aim of this work is to determine impact of these reactivated faults on the formation and evolution of karst process in the area of the East Serbian Carpatho-Balkanides. This was done by studying relationship of the evolution of karst caves or their specific conduits and mapped tectonic structures. For that purpose, three key areas have been chosen. The northernmost area, Dževrinska greda, is situated in the part of the orogen dominated by dextral strike-slip tectonics, related to the activity of the Poreč – Cerna-Jiu Fault during Oligocene to recent times. The central part of the investigated area, around the Mala Bizdanja Cave, is situated in the area in which tectonic regime is defined as transpressional, with regionally important structures multiply activated during Late Cretaceous and Miocene – recent times. The southeasternmost area is located in the Vidlič thrust zone, where compressional events were active during Cretaceous and Miocene times. Preliminary results from several karst caves show that proto-conduits are mainly formed along regionally important fault structures, occasionally assisted with mechanical erosion in areas of fault-related rocks.

Keywords: *Carpatho-Balkanides, karst caves, reactivated faults, transpressional tectonics*
Ključne besede: *Karpato-Balkanidi, kraške jame, reaktivirani prelomi, transpresivna tektonika*

Student geological mapping of the Black Olms habitat and its catchment area in Bela krajina

Študentsko geološko kartiranje habitata črnega močerila v Beli krajini

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The Black Olm (Proteus anguinus parkelj) is an endemic species, that lives in a very limited (10 km^2 only) karstic hydrogeological system west of Črnomelj (Bela krajina, SE Slovenia). Researchers have observed a steady decline in the population over the past few decades due to various environmental factors. Six Geology students from the Faculty of Natural Science and Engineering (University of Ljubljana) set out to map the hinterland of the karst springs in which the Black Olm was found so far. The main goal was to define the geological structures, which limit the habitat of this endemite. The mapped area is paleogeographically located on the northeastern part of the Adriatic carbonate platform, and structurally belongs to the External Dinarides. Prior to fieldwork, the alignments of dolines were observed with Lidar to determine structural blocks, that were later verified in the field.

The determination of lithostratigraphic units has been up to now done only at the macroscopic scale. Preliminary results show three distinct trends in doline alignment: 1) N–S orientation, 2) NW–SE orientation, and 3) NE–SW orientation. The lithostratigraphic units of the Upper Jurassic succession could not be macroscopically distinguished due to a lack of index fossils, but the Lower Cretaceous succession was divided based on lithofacies groups. The succession begins with an exchange of limestone and dolomite beds, followed by light grey mudstones, thin bedded black bituminous limestones, thick bedded oncolithic limestones that laterally transition into rudist limestones. The carbonate succession is followed by polilithic breccias, bioclastic calcarenites (still Lower Cretaceous) and black foraminiferous limestones of the Cenomanian age (Upper Cretaceous). NW–SE doline orientation shows the Dinaric fault system orientation and the NE–SW follows the Mid-Hungarian system. The N–S lines of dolines could not be assigned to any of the main known regional tectonic fault system. Large differences can be observed when comparing the nevely gathered data with previous geological maps. Further work is needed to characterise the stratigraphical succession and determine the structural model. So far, we can say with certainty, that the black olms habitat and its catchment area is limited with two faults in NW–SE direction. The authors would like to thank the HaČloRi project for co-financing the costs of field work.

Keywords: *Proteus anguinus parkelj, Adriatic carbonate platform, geological mapping, stratigraphy*
Ključne besede: *Proteus anguinus parkelj, Jadranska karbonatna platforma, geološko kartiranje, stratigrafija*

Multidisciplinary metadata portal at the Karst Research Institute ZRC SAZU

Multidisciplinarni metapodatkovni portal na Inštitutu za raziskovanje krasa ZRC SAZU

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The IZRK Metadata Portal (https://metadata.izrk.zrc-sazu.si) was created at the Karst Research Institute ZRC SAZU Data Centre utilizing the GeoNetwork platform to create a system administration and user interface for interdisciplinary environmental data mining and data product access. The new metadata portal adheres to FAIR data principles and the data lifecycle, and it collects and maps diverse datasets, databases, research locations and equipment, virtual laboratories, processes, and codes. The portal also provides data for the multidisciplinary KARST database as well as multidisciplinary research covering all areas and functionalities of a karst environment. Furthermore, as part of three major initiatives, the portal is intended to create a temporal and spatial link between specific locations and their data: RI-SI-LifeWatch (2019–2021); RI-SI-EPOS (2019–2021); and eLTER RI (2020–2025). The portal provides end users with standardized metadata and datasets for multidisciplinary research areas (e.g., bio-geo-chemical data, time series, geospatial data), as well as a free local cloud repository for secure data storage. The metadata portal is open to all members of the Slovenian Research Infrastructure communities (LifeWatch, EPOS and eLTER) as well as their stakeholders and collaborators from Slovenia and abroad.

Keywords: *data portal, GeoNetwork, FAIR, LifeWatch Slovenia, EPOS Slovenia, LTER Slovenia*
Ključne besede: *podatkovni portal, GeoNetwork, FAIR, LifeWatch Slovenija, EPOS Slovenija, LTER Slovenija*

Hydrogeology of Quri Qaleh cave, Kermanshah Province, Iran

Hidrogeologija jame Quri Qaleh, provinca Kermanshah, Iran

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Quri Qaleh cave is located in the southern slopes of Shaho mountain, which is part of the Zagros mountain range in Hewraman. This cave is part of the Bisotun karst aquifer in the northwest of Kermanshah province. The cave entrance is located at 34°53'58.2"N 46°30'07.8"E. The Quri Qaleh cave has been formed within Bisotun stone Formation (Early Triassic-Late Cretaceous) with a 300 m thickness. At the beginning of the study, in order to identify underground water resources in the region, the hydrology of Bisotun karstic aquifer and its surrounding areas was investigated. Then, a water balance method was used in the environment of ArcGIS10 to estimate the inlet and outlet water of Bisotun karstic aquifer, with Quri Qaleh being one of its drains. The results indicated that the aquifer is only fed by rainfall, which was 162.4 MCM for the period Oct 2007–Oct 2008. Assuming that conditions would be stable, changes in reservoir of the balance of Bistoun karstic aquifer was considered to be zero. Thus, the error of estimation in the balance equation was +10.1 MCM. Quri Qaleh spring has an annual discharge of 8.2 MCM, hence discharging about 5% of the water that enters the aquifer. In order to geomorphologically study Quri Qaleh cave, its constituent components and speleothems were examined hydrograph analysis of Quri Qaleh spring showed that its reservoir stone has good karstification. This spring is fed through open ducts and canals.

Keywords: *Quri Qaleh Cave, Bisotun karst aquifer, water balance, geomorphology*
Ključne besede: *jama Quri Qaleh, kraški vodonosnik Bisotun, vodna bilanca, geomorfologija*

Assessing environmental health through monitoring of microbiological parameters and time-series analysis of oxygen in diversity hotspot river ecosystems

Ocenjevanje zdravja okolja s spremljanjem mikrobioloških parametrov in analizo časovnih vrst kisika v rečnih ekosistemih vročih točk diverzitete

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The Pivka River in SW Slovenia receives water discharge from agricultural activities, settlements, and the major Postojna wastewater treatment plant (WWTP), designed for 21000 population equivalent (PE). The discharge from the WWTP significantly impacts the water quality, as reflected in physical, chemical, and microbiological parameters of the river. Elevated levels of fecal contamination indicators, such as Escherichia coli and enterococci, were consistently observed during monitoring campaigns and often accompanied by low levels of dissolved oxygen (DO). The Pivka River ends in the karst cave Postojnska jama, which is home to one of the world's richest subterranean faunas. A monitoring site was established to collect data on DO before the water sinks underground. Regression analyses, univariate and multivariate time-series analyses using autoregressive methods were performed to investigate oxygen conditions. Anomalous variations in DO occurred when values dropped below 3 mg/L and became more pronounced until the ecosystem became fully anoxic. These

fluctuations were due to environmental conditions, organic load, and resident biota. Predictions for future DO value anomalies showed that the model could provide a reliable estimate for a short period, such as one day. This example showcases an analysis pipeline based on specific and established DO threshold values, which is crucial for ecosystems with diversity hotspots where prolonged low DO values pose a threat to their biota.

Keywords: *aquatic ecosystems, dissolved oxygen, modelling, prediction*
Ključne besede: *vodni ekosistemi, raztopljeni kisik, modeliranje, napoved*

Revisiting contaminant mixing and transport modeling approaches in karst systems: Model limitations and new prospective

Repriza: modeli mešanja onasneževal in transporta v kraških sistemih: meje modelov in nove perspektive

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Due to the contamination risk of groundwater in karst regions, particular attention needs to be devoted to the requirements for a successful modeling practice to simulate karst mixing and transport processes. Certainly, modeling mixing and transport processes in karst systems is a challenging task due to the substantial limitations on data collection, system's perceptual understanding, and model conceptualization. The limitations are even further multiplied by the application of mathematical models, especially for model parametrization, parameter identification, and uncertainty quantification. This presentation systematically and critically reviews the current state of knowledge on modeling mixing and transport processes in karst groundwater resources while mainly focusing on the requirements to succeed in contaminant mixing and transport modeling. By drawing the lessons from the current literature on modeling mixing and transport processes in karst systems (over 2800 published peer-reviewed papers), we articulate the necessity for the development of karst-dedicated mixing and transport models to properly resemble the system's hydrochemical functioning. To address the knowledge gap, we applied a new process-based transport modeling approach to one of the largest drinking water resources (Wasseralm spring) in Austria to simulate the isotopic compositions ($\delta^{18}O$) of spring discharge. According to research findings, the applied transport model can be of benefit to assessing the karst aquifer vulnerability while revealing the critical functioning of the fast-flow component under global change (e.g., climate change, land cover-land use changes, overpopulation). Therefore, the modeling results could be used to sustainably manage and protect karst groundwater resources by representing and predicting the spatiotemporal behavior of the contamination plume through the karst systems.

Keywords: *contaminant transport, isotope, karst, karst modelling, water quality*
Ključne besede: *prenos onesnaževal, izotopi, kras, modeliranje krasa, kakovost vode*

Some examples of microclimate research in the Dinaric Karst in the context of climate change

Primeri mikroklimatskih raziskav na Dinarskem krasu v luči klimatskih sprememb

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Caves are a relevant source of information about events on the Earth's surface. Caves are more stable and clearly defined systems compared to surface ones. Through several examples from the Dinaric karst, we will consider how microclimate and other measurements in caves, continuous or spot, can be an important source of information about local and global climate processes on Earth. The focus of our research is carbon dioxide that plays a central part in the weathering of carbonates, giving karst aquifers a potential role of a net global CO_2 sink. This work has been supported by the Slovenian Research Agency and Croatian Science Foundation under the project Dynamics and distribution of CO_2 in karst vadose and epiphreatic zone (CARDIKARST) IPS-2022-02-2260.

Keywords: *cave microclimate, physical processes, carbon dioxide, karst, climate change, CARDIKARST*
Ključne besede: *jamska mikroklima, fizikalni procesi, ogljikov dioksid, kras, klimatske spremembe, CARDIKARST*

Dispersal of aquatic organisms in karst landscapes

Disperzija vodnih organizmov v kraških pokrajinah

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In the project *Dispersal of aquatic organisms in karst landscapes* we investigate colonization patterns of aquatic organisms in the Balkan Peninsula. Karst represents a special environment for the resident organisms, which are highly influenced by the unstable aquatic conditions. Previous studies on dispersal routes of aquatic organisms in the Dinaric karst came to opposing findings. While some concluded that karst landscapes act as isolating factors, others found evidence of subterranean migration through underground water links. However, all the findings were a kind of by-product of studies, actually investigating population genetics or biogeographical questions – not one aimed especially at resolving the hypothesis of underground migration. In this project, the migration in karst landscapes is assessed using different methods, such as next generation sequencing-based population analysis. We aim to resolve the population structure of three very different groups of aquatic organisms (fishes, cave olm and isopod crustacean) and to compare it with the hydrological literature in order to draw some conclusions on the dispersion routes of these organisms – including a possibility of underground migration. An interesting aspect of the project is also evaluation of using biological tracers for water tracing in karst, whereby the information might also contain a time component - previous hydrological connection seen through current population structure of the investigated

organisms. Thus, in addition to biological findings, this study is also relevant for research areas such as karstology, hydrology and water management.

Keywords: *karst, dispersal of aquatic organisms, underground migrations*
Ključne besede: *kras, disperzija vodnih organizmov, podzemne migracije*

Advances in karst science since the founding of the Karst School in Slovenia

Napredki v krasoslovju od ustanovitve Mednarodne krasoslovne šole v Sloveniji

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In 1972 we were warmly invited to Slovenia by Dr. Ivan Gams and his family to experience what we considered to be the "real" karst. Establishment of the Karst School still lay 20 years in the future, but karst science was already growing rapidly. It was clearly recognized that the greatest need was for physical and chemical measurements to understand the origin of karst and how it behaves. Toward that goal, Dr. Gams and his colleagues had already established a program of collecting and analyzing data from the local karst. Cave mapping and hydrologic projects were providing a basic understanding of karst and cave systems, and how they respond to environmental conditions. Analysis of water samples from local dolines, caves, and karst springs were clarifying the hydrology and origin of karst features. This knowledge was growing rapidly as new analytical techniques developed. Computer technology was then becoming widely available, allowing easier and more accurate interpretation of field data. Techniques for precise dating of geologic and geomorphic events helped to clarify the relation of caves to their surrounding landscapes. An understanding of biological activity in caves began to reveal processes and features that had previously been understood mainly from their physical and chemical nature. Researchers in karst science have increased in number, as well as in technical skills. Collaboration with scientists throughout the world – for example by this conference – has greatly helped to broaden everyone's views. Since our first visit, we have returned to Slovenia and its neighboring countries more than nine times, to share ideas and memories, while watching how the understanding of karst has grown. Comparison with past records and literature show how significant the advances in karst have become during this time, in Slovenia and throughout the world.

Keywords: *Karst science, Karst School, Slovenia*
Ključne besede: *krasoslovje, Krasoslovna šola, Slovenija*

Investigation of the intensity of surface carbonate corrosion process using rock tablet method in "Northern Velebit" NP (Croatia)

Raziskave intenzitete procesov raztapljanja površinskih karbonatov z uporabo metode kamninskih tablet na Severnem Velebitu (Hrvaška)

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In order to better understand the formation of karst landscape, different methods measuring the intensity of carbonate corrosion process can be applied. Rock tablet method has been one of the most widely used due to its relatively simple principle, easy and versatile application, and affordability. The area of the “Northern Velebit” NP is almost entirely built of chemically "pure" carbonate rocks: limestones, dolomites and carbonate breccias (Jelar deposits). The intensity of carbonate corrosion depends on a whole series of factors: lithology, structure, relief, climate, hydrology, soil, vegetation, and more recently also anthropogenic impact. Thus, the measurements were made at eight locations ranging in altitude from 950 to 1600 m above sea level. Here, the average annual air temperature varies from 12.0°C to 3.0°C, while the amount of precipitation varies from 1200 to 2600 mm per year. There is as well, considerable zonation of vegetation, from the sub-Mediterranean (plant community Ostryo-Quercetum pubescentis) to the high-mountain forest community of Mountain Pine and Honeysuckle (Lonicero-Pinetum mugi). The measurements were done using “standard” rock tablets and those of local lithologies. “Standard” rock tablets are made of Upper Cretaceous (Senonian) limestone from a quarry near Lipica (Slovenia) having 97.9–98.7% $CaCO_3$. Those rock tablets are 42 mm in diameter, 3–4 mm thick and have been used worldwide, providing relative weathering rate, and allowing comparison of results with other locations or climates. In order to obtain absolute weathering rates, we used rock tablets made of local lithologies. Rock tablets were set on the surface, but as well buried in the soil and if possible, set on the soil/rock contact. The depth of rock tablets setting depended on the depth of the soil profile and the amount of carbonate skelet present in the profile.

Keywords: *carbonate rocks, intensity of carbonate corrosion, denudation, rock tablets*
Ključne besede: *karbonatne kamnine, intenzivnost karbonatne korozije, denudacija, kamninske tablete*

What do we know about the 'karst water table'? – Insights from caves in the Eastern Alps

Kaj vemo o “gladini kraškega vodonosnika”? – Dognanja iz jam Vzhodnih Alp

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Karst hydrological systems are highly heterogeneous, with numerous small pores with slow flow interacting with relatively few large, fast-flowing tubes. Although karst systems behave very differently from pore aquifers and there is no classical groundwater table, the term 'karst water table' is often used for simplicity. However, little is known about the nature of these enigmatic features. The Northern Calcareous Alps, as part of the Eastern Alps, are an ideal place to gain insights into the 'karst water table'. They are characterised by large karst plateaus built up from kilometer-thick layers of carbonate rock, and many deep caves reach basal sumps. In addition to insights into palaeo-water tables derived from morphological observations, caves from ten karst massifs were studied for this review. Water levels in the sumps, time series from pressure loggers, and tracer tests were compared. In addition to the fact that some of the ponds have large variations of 200 m and more, observations during low flow conditions give the following picture. In some of the karst massifs, the sump levels are caused by dolomite layers beneath the limestone. In most of the massifs there seem to be extensive zones (up to a few kilometers) with similar phreatic levels. It seems that, especially in former glaciated areas, they drop dramatically (about 100 m) at the edge of the plateaus, whereas in areas less affected by Pleistocene glaciation, these levels are closer to the base level. Only in one karst area, under certain hydrological conditions, is the water table completely horizontal for at least 3 km. Of particular note is the 156 km-long Schönberg cave system, where opposite flow directions have been observed depending on hydrological conditions.

Keywords: *karst hydrology, karst water table, Eastern Alps, deep caves, sumps*

Ključne besede: *kraška hidrologija, gladina kraškega vodonosnika, Vzhodne Alpe, globoke jame, sifoni*

Application of iPhone 13 PRO device for measuring scallops in Mylna Cave in Tatra Mountains using LiDAR and SfM techniques

Uporaba iPhone 13 PRO za merjenje faset v jami Mylna v Tatrah s tehniko LiDAR in SfM

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The study tested the capabilities of the Apple iPhone 13 PRO device using two measurement techniques, LiDAR (Light Detection and Ranging) and SfM (Structure from Motion), in a cave environment by measuring scallops in Mylna Cave in the Western Tatra Mountains. The tested device provides an interesting and inexpensive alternative for cave research using TLS (Terrestrial Land Scanner) type scanners or more expensive MLS (Mobile Laser Scanning) type scanners. The study used a dedicated "3d scanner app" application to create two terrain models: LiDAR and SfM. A comparative analysis of the techniques used shows that the SfM model is characterized by greater detail. The results obtained for this model indicate that the scallops measured in the Great Corridor of Mylna Cave belong to at least two different generations of forms. In the case of the LiDAR method, the resolution of the models obtained was not precise enough to identify small (<3 cm) scallops. For three LiDAR models, the average length of scallops was 10,32 cm and for three SfM models 5,16 cm. They were determined the length of scallops allowed for calculating paleoflow velocity. The average value for LiDAR models was 28,98 cm/s and for SfM models - 48,10 cm/s. Based on the asymmetry of scallops, the paleoflow direction was determined. It is consistent with the current direction of the flow of the Kościeliski Stream. The spatial imaging techniques used with iPhone 13 PRO differ regarding the DEM creation method and model details. This is influenced by parameters related to lighting, distance, scanned surface character and microclimatic conditions of the cave.

Keywords: *light detection and ranging (LiDAR), structure from motion (SfM), cloud points, scallops, paleoflow*
Ključne besede: *svetlobno zaznavanje in merjenje (LiDAR), večslikovna fotogrametrija (SfM), oblak točk, fasete, paleo-tok*

Studies on the cave animal DNA molecules can help us understand the formation and genesis of karst areas

Raziskave molekul DNA jamskih živali nam lahko pomagajo razumeti nastanek in razvoj kraških območij

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The evolutional history of plant and animal species, and their present geographical distribution, essentially depends on the geographical and geological units. The subterranean (cave) animals, due to their significant isolation and limited dispersal in space and time, show an extraordinarily great extent of endemism. So far, speleologists have relied mainly on geographical and geological knowledge to explain taxa distributional patterns. Nowadays, biologists apply modern phylogenetic approaches, studying DNA molecules of animals and plants, to understand taxa phylogenetic history. In recent

decades, researchers applied standard molecular phylogenetic PCR methods to analyze selected DNA genes of different subterranean animals. The molecular data showed that gene flow among the populations of subterranean animals was limited among the geographical karst units for extended periods than believed. The results are sometimes surprising and partly in contradiction with accepted traditional geographical units. In our recent study, we molecularly analyzed samples of the subterranean Leptodirini beetles as representatives of the subterranean terrestrial animal group. We found that the evolution of the Palearctic group started in the Balkan region in the early Tertiary period and was followed by a relatively fast spreading of ancestor lineages throughout Europe. Due to the early Eocene climatic changes, the ancestors of the lineages separately occupied various suitable exposed subterranean habitats. During the orogenesis and exposure of the isolated karstic massifs, evolutionary radiations lead to morphologically distinctly different yet genetically related species. Within the Dinaric Karst boundaries, live and partly overlap representatives of different phylogenetic clades. With the help of the geolocation of taxa known localities and cartographic distribution display of the genera from the North Dinaric and South Dinaric clades, now we can precisely determine, at least in zoogeographical respect, the external boundaries of the Dinaric Karst area.

Keywords: *cave animals, phylogeny, PCR, Dinaric Karst boundaries*
Ključne besede: *jamske živali, filogenija, PCR, meje Dinarskega krasa*

Geomorphology of the alluvial fans in selected Dinaric Karst poljes in Croatia

Geomorfologija aluvialnih vršajev z izbranih dinarskih kraških polj na Hrvaškem

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Karst poljes are one of the most significant landforms of the Dinaric Karst. As relief depressions they represent zones of accumulation of various sediments. Among other things, alluvial fans often appear at their edges, covering their bottom to some extent. The aim of this work is a geomorphological analysis of alluvial fans in selected poljes of the Dinaric Karst in Croatia. The analysis was carried out on the basis of digital elevation models 5 x 5 m, topographic maps 1:25000 and basic geological maps 1:100000. In the first phase, the visual detecting, mapping and digitization of the alluvial fans was carried out. This was followed by morphometric processing and morphogenetic analysis of their catchment area. This study was conducted in 12 karst poljes in Croatia. In these poljes 38 alluvial fans with associated 42 drainage basins were registered. The largest mapped alluvial fan has an area of 24.35 km^2, and the average area of all fans in the whole studied area is 2.2 km^2. According to the number of drainage basins that supply a one alluvial fan, single (30.79%), double (3.8%) and triple (5.13%) basins were recorded. The largest drainage basin has an area of 23.42 km^2, and the average area of all 42 drainage basins is 3.78 km^2. Drainage basins are mainly formed on impermeable and less permeable rocks (clastic and dolomite). Large poljes have a small percentage of the surface covered by alluvial fans (e.g., Ličko polje, 1.7%), while this percentage can be substantial in small poljes (e.g., Velikopopinsko polje, 46.9%). This study has shown that in a landscape dominated by karst denudation, erosion at the sides of karst poljes and accumulation of material in alluvial fans play an important role in the development of relief.

Keywords: geomorphology, polje, alluvial fan, Dinaric Karst, Croatia
Ključne besede: *geomorfologija, polje, aluvialni vršaj, dinarski kras, Hrvaška*

Reniferowa Cave – a new research site on the map of Polish caves

Jama Reniferowa – nova raziskovalna točka na karti Poljskih jam

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In 2020, speleologists from Polish speleoclub Tarnowski Klub Taternictwa Jaskiniowego (TKTJ) discovered a karst fissure leading to the new cave situated in the northern exposition of Biedruniowa Skała rock complex (Suliszowice, Silesian Voivodeship). The cave was formed within the Upper Jurassic limestone of the Kraków-Silesian Homocline. The newly discovered cave was named Reniferowa (Reindeer Cave). Performed cave survey revealed ~12.5 m in length and denivelation of 3.5 m. The cave represents a karstic void developed horizontally, which morphology relates to the system of vertical and horizontal joints. In the cave's ceiling plunge pools and flute casts were recognized, which may indicate its origin in phreatic zone. In 2022, the preliminary interdisciplinary research of the Reniferowa Cave was performed. The aim was to establish an excavation and to conduct cave sediments analyses. At this stage, exploration was carried out within two square meters of the cave bottom to a depth of ca. 80 cm. At the bottom of this profile there was recognized a silt layer, the top part of which (ca. 70 cm) consisted of chaotic, brecciated material with inserts of clay sediments. Below, a horizon of a fine-grained sands of cream to brown colour was found, with a large share of the silty fraction. In the alluvium archaeological artefacts were found - two Swiderian points, dated to the late Palaeolithic (Younger Dryas). Animal remains have also been discovered, such as, a Late Pleistocene reindeer talus, Holocene phalanges and teeth of a brown bear, as well as a least weasel mandible and a wildcat scapula. As part of comprehensive sediment research, samples were collected for geological (sedimentological and geochemical), palynological and radiocarbon analyses. The Biedruniowa Skała rock complex, unlike other regions of the Kraków-Częstochowa Upland, was not of interest to researchers. The discovery of the Reniferowa Cave has opened up new possibilities for analysing this area.

Keywords: *Reniferowa Cave, Late Pleistocene, late Palaeolithic, mammal remains*
Ključne besede: *jama Reniferowa, pozni pleistocen, pozni paleolitik, ostanki sesalcev*

Contribution of paleokarsts in the understanding of Monts de Vaucluse (France) geological calendar

Doprinos paleokrasa pri razumevanju geološkega zapisa gorovja Monts de Vaucluse (Francija)

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The Monts de Vaucluse are located in south-eastern France and correspond to a geological entity characterised by the presence of a thick carbonate series deposited between the Upper Barremian and the Lower Aptian: the Urgonian of Provence. Since this period, the area has been subjected to a succession of several major geodynamic phases, resulting in significant gaps in the sedimentary record. These gaps, which can sometimes extend over several tens of millions of years, make it difficult to understand the geological calendar of the Monts de Vaucluse (i.e., all the geological events that have affected the area). The presence of particular geological objects, the palaeokarsts, offers a means of better characterising these gaps by providing information preserved locally in their fillings. For this work, more than 180 karstic objects spread over several sectors of the Monts de Vaucluse were described and sampled. Among the various analyses carried out in the laboratory, an innovative dating methodology was applied to the carbonate fillings taken from these paleokarst objects. This work has allowed the identification of three phases of karstification: a first one between the Upper Aptian and the Lower Albian, a second one in the Lower Eocene during the Ypresian and a last one in the Oligocene. Coupled with the precise characterisation of the palaeokarsts, these dates provide information on the structuring of the reservoir with respect to eustatic, tectonic and palaeoenvironmental parameters.

Keywords: *Monts de Vaucluse, Urgonian, paleokarst, geological calendar*
Ključne besede: *Monts de Vaucluse, Urgonij, paleokras, geološki zapis*

The enigma of the oldest allogenic sediments of the Unroofed Cave Loza - preliminary results (Slavinski ravnik, W Slovenia)

Enigma najstarejših alogenih sedimentov Brezstrope jame v Lozi – preliminarni rezultati (Slavinski ravnik, Z Slovenija)

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The studied Unroofed Cave Loza is located in the karst plain of Slavinski ravnik, which is south of the Postojna Basin, where ponor contact karst developed more than 6 Ma ago. The studied sites are dislocated NW from the main cave area and probably belong to the same or even to an older unroofed cave. The latter seems very likely, as the present Rakuliščica stream carries eroded flysch sediments in the form of sandstone pebbles, sand, silt and silty clay material, which can be observed in blind valleys,

active and relict ponor caves and in the 4.3 km long main channel of the Unroofed Cave Loza. In contrast, the allogenic sediments of the studied sites consist exclusively of siliceous pebbles. After macroscopic crosschecking, we selected different pebble lithotypes for further petrologic and biostratigraphic studies. We distinguished five main facies groups: A) quartz sandstone, B) postdeformation chert participates, C) replacement chert, D) silicified pelitic tuffs, and E) radiolarites. The latter were subjected to biostratigraphic analysis, which yielded five different ages for these pebbles: Ladinian to Carnian, Bajocian, Bathonian-Callovian, Kimmeridgian (possibly Lower Tithonian), and Late Tithonian to Berriasian. Provenance for some lithotypes can be assessed: quartz sandstone pebbles (A) most probably originate from the Carboniferous to Early Permian clastic successions known from the Dinarides and the Southern Alps. Silicified pelitic tuffs (D) and part of the radiolarites (E) originate from Ladinian basinal successions with a similar occurrence to the first group. Most of the radiolarites (E) are from the Middle and Upper Jurassic deep marine Tolmin and Biancone limestone formations, known only from the Southern Alps. A similar provenance is most possible also for the part of the replacement chert (C). Provenance analysis indicates that the source area of allogenic sediments studied was quite distant, since at least part of the pebbles originated from the Southern Alps. This suggests that the sediments were delivered to the Postojna area through an ancient and as yet undescribed hydrological system, different from the present one, which is supported by the dating results obtained in an allogenic succession within the unroofed cave further south. The preliminary results indicate that the investigated cave remnant represents the oldest known epiphreatic speleogenetic phase in Slovenia.

Keywords: *unroofed cave, biostratigraphy, epiphreatic speleogenesis, Slavinski ravnik, Slovenia*
Ključne besede: *brezstropa jama, biostratigrafija, epifreatična speleogeneza, Slavinski ravnik, Slovenija*

Laboratory and numerical simulations of infiltration processes and solute transport in karst vadose zone

Laboratorijske in numerične simulacije infiltracijskih procesov in disolucijskega transporta v vadozni coni

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Groundwater in karst systems is a vital resource, which is often highly vulnerable to contaminants that infiltrate through the vadose zone. Understanding the processes of water and contaminant infiltration in the vadose zone is extremely important for protecting and managing karst water resources. Previous studies utilized hydrodynamic and hydrochemical data collection in karst caves and hydrogeophysical prospecting to investigate infiltration processes. However, these methods cannot quantitatively characterize the influence of the internal structure on the infiltration process and solute transport in the karst vadose zone under controlled conditions. To overcome limitations of previous research, a laboratory-scale physical model of the karst vadose zone (extension 1 × 1 × 1.5 m^3, including soil layer, epikarst, and transfer zone) was constructed, and a corresponding lumped parameter model (including soil reservoir, fast reservoir, and slow reservoir) was developed to investigate the effects of rainfall intensity and intrinsic structure of the karst vadose zone on infiltration processes and solute transport. Five factors were considered in laboratory experiments: (1) the rainfall intensity, (2) the slope of the surface, (3) the degree of karstification, (4) the thickness of the transfer zone, and (5) the existence of epikarst. The lab experiments result in a number of recession- and breakthrough curves. The variation of these results in response to changes of the various factors was analyzed. To further analyze and investigate the water and solute infiltration processes in the laboratory-scale physical model,

numerical computations were subsequently conducted to simulate the laboratory experiments, and to analyze the solute mass and water volume in the respective reservoirs.

Keywords: *karst vadose zones, laboratory experiments, numerical simulation, rainfall percolation, solute transport*
Ključne besede: *kraška vadozna cona, laboratorijski poiskusi, numerične simulacije, perkolacija dežja, transport raztopljenih snovi*

Role of geologic history and basic factors in karst models

Vloga geološke zgodovine in temeljnih dejavnikov v kraških modelih

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Geoscientists build (or envision) models, representations of natural systems, to understand how those systems work, or to predict impacts when changes are being considered. For example, groundwater modelling can help answer questions about flow directions, velocities, and effects of pumping withdrawals. Karst modelling may encompass flow/storage analysis and can also include things such as aqueous geochemistry/reactive flow, speleogenesis, and landscape evolution. The utility and quality of any model ultimately depends upon veracity; how well it represents the natural system. The foundation of a model relies upon basic factors such as boundary conditions, material properties, and proper conception of the dominant processes acting in the system (for example conduit vs. diffuse flow). Each of these is a direct consequence of the geologic history of the system, and deep consideration of history provides critical insight for construction of an accurate model. Efficiency and accuracy in model conceptualization and realization can be increased by a) consideration of the geomorphological paradigm of "structure-process-time", and b) categorization of terranes. Structure-process-time evaluation examines the involved materials and their conditions, and then the processes/durations that have acted on them. Categorization of terranes involves grouping landscapes, whether contiguous or not, according to their underlying general character (e.g., Heath, 1984 Groundwater Regions; DRASTIC vulnerability mapping, etc.). These approaches have not been regularly undertaken when developing conceptual or other models for karst systems. But, they can be critical in even seemingly "simple" settings. As an example, a very subtle low-relief karst is present in north-central Ohio, USA. Many dolines are found, but caves are nearly absent. Initial hypotheses considered that the karst may have been erased or obscured by glacial processes. Comprehensive evaluation revealed that an underlying evaporite unit, and multiple reversals of groundwater flow on order of 10-100 ka timescales resulted in a polygenetic karst with stacked flow systems.

Keywords: *geology, models, Ohio, groundwater*
Ključne besede: *geologija, modeli, Ohio, podzemna voda*

Planetary caves: expanding our knowledge about karst and speleogenesis from Earth to the Solar System

Jame na drugih planetih: širjenje znanja o krasu in speleogenezi od Zemlje do Sončnega sistema

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While the surfaces of terrestrial planets of our solar system have been documented with high resolution, multispectral cameras, and even by rover missions, very little is known about the subsurface and the potential presence of underground voids. Early in the seventies, planetary geologists had already identified peculiar collapse sinkhole-like morphologies in several volcanic areas of Mars and in the lunar Maria. These “sinkholes” are often referred to as “collapse” or “pit” chains when they are aligned. Since these features lack the elevated crater rim and ejecta deposits that are typically associated with impact craters, they have been thought to represent collapses of underground cavities. Because most of these features are found on lava flows or along the sides of volcanic edifices, they were very early associated to the putative presence of “lava tubes”, also known as “pyroducts”. Currently, more than 300 of these potential cave entrances have been identified on the Moon and more than 1000 on Mars. Several potential cave accesses on Mars have been identified in association with karstic surface morphologies in highly-soluble geological terrains like salt domes and extensive sulphate deposits. The exploration and mapping of planetary caves could open a new era of planetary exploration. Robotic technologies could allow examining stratigraphic sections of lava flows from skylights allowing to collect new data on the formation of flood basalts on the Moon and shield volcanoes on Mars. Intact, open segments of lava tubes could provide stable shelters for human habitats shielded by cosmic radiation and micrometeorite impacts on the Moon. Karstic caves on Mars could host important proxies of the planet’s environmental conditions in the past and potential subsurface extant life. Because of these scientific opportunities planetary caves should be considered main targets for the exploration of the Solar System and for the search of past and present extra-terrestrial life.

Keywords: *planets, Moon, Mars, astrobiology, space missions*
Ključne besede: *planeti, Luna, Mars, astrobiologija, vesoljske odprave*

Traces of ancient glaciations in karst environment - a case study in the Venetian Prealps

Sledovi starih poledenitev v kraških okoljih – primer iz Benečije

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To understand the ancient glaciations of a mountainous area, it is necessary to consider together the forms of erosion and those of accumulation in their topographic context, aiming to model the relative glacial systems, which can be reconstructed on the basis of the interrelationships between the various forms. In the karst areas, the forms of glacial erosion are often easily recognizable, given that the geomorphological dynamic favors their conservation. The very ancient deposition forms, on the other hand, are hardly recognizable or absent, given that chemical erosion contributes to the decrease in

volume of the moraines until their total disappearance. As a case example, the ancient glacial system of Valon del Malera, developed in Jurassic limestones and main dolomite, partly preserved in the Lessini Mountains (Prealpi Venete, NE Italy) and partly in the nearby Carega massif (Piccole Dolomiti), is illustrated. The forms of erosion document the dismantling of some valley segments due to accelerated erosion phenomena attributable to active tectonics along an important fault system. Other segments are, however, very well preserved. On the other hand, forms resulting from the "over-imprinting" of some ancient morainic ridges are recognizable, due to the fact that in favourable cases the morainic cover has reduced the rate of lowering of the cover-rock interface of the underlying limestone, in comparison with the surrounding rocky surfaces not covered by till deposits, causing the formation of rocky ridges. However, the temporary aquifer hanging within the moraine has favored the development of a grike type covered Karren in the limestone, with isolated spikes or pillars of rock. Ridges mainly or totally formed by rock in place are described, which, according to all evidence, are the result of the "over-imprinting" by ancient moraine ridges mostly or totally eroded.

Keywords: *Relict glacial forms in karst areas, Morainic ridges, over-imprinting, karst solution*
Ključne besede: *reliktne ledeniške oblike v kraških pokrajinah, morenski hrbti, kraško raztapljanje*

Nerochytical Speleogenesis (NERO): mobile CO2 as driving force for karstification. A new thesis

Nerocitična speleogeneza (NERO): mobilni CO_2 kot sila, ki poganja zakrasevanje. Nova teza

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The Greek word nerochytis (sink) is pointing to the main aspect of this new theory of speleogenesis, which says that CO_2 has its own vertically oriented mobility, independent of the hydrological cycle. The NERO thesis presupposes the encounter of a mobile gas phase with a (temporary) stagnant or close-to-stagnant aqueous phase at the karst water table. On the one hand, karstic ground water is in equilibrium with CO_2 and dissolved lime, where the karst water is following the hydrological cycle. On the other hand, seasonal CO_2 peaks in the vadose zone and in cave air are following underground ventilation patterns including effects of density differences. When both phases come together at the karst water level, peaks of cave-air CO_2 are dissolved into the karst water, sinks down and remains trapped. As a result, new, additional lime solution is created, exactly where caves form and grow: at the karst water-level. NERO speleogenesis is a CO_2-controlled process; thus, NERO research has potential to be relevant for climate geoengineering. This contribution will explain the stations of gaseous mobile CO_2 in the green karst: outside atmospheric air, soil, vadose zone, phreatic zone, and the karst spring. In a cooperation between the University of Stuttgart and the Laichingen Caving Club, several fundamental experiments were carried out both in the laboratory and in the Laichinger Tiefenhöhle (Germany). They will be explained and their results summarized. The results clearly show that under natural conditions in caves, CO_2 migrates from the cave air into the karst water, where it is trapped in greater water depths. The main physical process is density-driven convectively enhanced dissolution. The amount of mobile CO_2 is relevant to karstification. Numerical simulations complement all experiments. The Working Group NERO is interested in extending interdisciplinary cooperation.
https://www.iws.uni-stuttgart.de/en/lh2/research/projects/AK-NERO/

Keywords: *speleogenesis, CO_2 dynamics in karst systems, density driven dissolution*
Ključne besede: *speleogeneza, dinamika CO_2 v kraškem sistemu, raztapljanje, ki ga poganja gostota*

Signal examples from different aquifer source areas in the flood events of Davorjevo brezno

Raziskave različnih izvornih območij voda na podlagi signalov poplavnih dogodkov Davorjevega brezna

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A particular phenomenon was observed between the 5th and 6th of December 2020. On December 6, h 07:00 (at I W: Q 10.3 L/s, EC 492 µS/cm, Tw 10.37°) a rainfall event started up to December 7, h 01:00 with a total of 77 mm of rain (at I W: Q 95 L/s, EC 364 µS/cm, Tw 9.95°). The flood peak at I Weir was reached on December 6, h 20:15 with Q 279.0 L/s, EC 304 µS/cm, Tw 9.42°. The peculiarity of this event is that on December 5, h 04:50 (one day before the rain flood event) an EC peak of 796 µS/cm (Q 1.78 L/s) was recorded, together with an insignificant amount of rainfall (1.8 mm). Even considering a long period before, the amount of local rainfall has been scarce (only 6.6 mm from November 16 to December 5). In contrast, precipitations mainly affected the upper part of the Reka's catchment (weather stations of Ilirska Bistrica and Klana respectively 20 and 35 km from Škocjan). As a first hypothesis, the increase of the EC value may be explained by looking the Reka increase of average discharge from 2.2 m^3/s to at h 08:30 >3 m^3/s to h 09:30 >6 m^3/s (Cerkvenikov mlin station). Indeed, the hydraulic load of the karst aquifer in upstream area could cause an ejection of highly mineralized waters (piston flow) stored in the reservoirs. The afore mentioned Reka flood event reached its peak on December 6, at h 20:00, with 232 m^3/s (hydrometric height 527 cm). In this event, the II Weir shows a similar behavior, especially in the EC curve.

Keywords: *classical Karst, flood, acquifer, hydrogeology, electrical conductivity, flow rate*
Ključne besede: *Kras, poplave, vodonosnik, hidrogeologija, elektroprevodnost, pretok*

Is the thermal signal a reliable proxy to decipher flow conditions in karst aquifers?

Ali so temperaturni signali zanesljiv proxi pri razumevanju pretoka skozi kraški vodonosnik?

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Karst aquifers are often studied through spring hydrographs, thermographs and chemographs. However, accessible caves offer a unique opportunity to investigate how cave conditions influence the thermal signal. Here, we examine how cave conditions in the 10 km long river cave of Maaras in northern Greece transformed the temperature signal. The cave stream flows on a sandy streambed in a large conduit; previous studies have shown that the sediment accumulations are up to 45 m thick. The main branch is recharged by a polje; conditions shift seasonally between concentrated and diffuse infiltration. Temperature fluctuations occur on seasonal, event-based and daily time scales. Our results show how the thermal signal is transmitted and transformed along the cave stream and contrast this to the thermal pattern in the inlet of the main branch and the submerged side branch. Heat exchange between the cave stream and the porous aquifer in the clastic deposits strongly influence the water

temperature. The interplay between the in-cave porous aquifer and the cave stream raises the water temperature and dampens the temperature fluctuations in the spring.

Keywords: *thermographs, karst aquifer, cave river, Greece*
Ključne besede: *temperaturni grafi, kraški vodonosnik, jamska reka, Grčija*

Reddish Paleokarst Multiphase Infillings in the Megalodontid Bivalves and Solution Voids in the Julian Alps

Rdeče paleokraške multifazne zapolnitve Megalodontidnih školjk in korozijskih por v Julijskih Alpah

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At a nature-preserve protected site in the Julian Alps (NW Slovenia), in the Pod Peski valley, red fillings of megalodontid bivalves occur within the Upper Triassic Dachstein limestone. Based on optical and cathodoluminescent microscopy and X-ray fluorescence (XRF) analysis, four generations of shell fillings were recognized, some of which contain both cement and sediment subgenerations. Logging and sampling of the limestone sequence a few meters below and above the "main" layer containing the megalodontids mentioned above revealed that the limestone is characterized by solution cavities voids similar to the megalodontids. Namely, these voids are also filled with reddish multigeneration sediment with alternating calcite cement. Adjacent neptunian dykes were studied to clarify their influence on the last generation fillings. Two of them, located directly on the "main" layer with red-filled megalodontids, contain planktonic foraminifera, indicating Middle Jurassic or younger age. The next two neptunian dykes are located directly above the "main" layer, and one contains clasts with calpionellis characteristic of the Late Jurassic/Early Cretaceous. The last dyke explored is located a few tens of meters from the "main" layer and is several hundred meters long. In a few sample from this dyke Early Cretaceous planktonic foraminifera were identified. Microscopic analysis revealed that the reddish sedimentary fillings are part of a complex paleokarst system that produced the first three generations of fillings, and in the last (fourth) generation we noted similarities between the megalodontid fillings and neptunian dykes on the "main" bedding plane. In addition, a Santonian - Maastrichtian sedimentary fill with globotruncanid foraminifers were discovered in the upper part of the succession in one of the solution voids.

Keywords: *Southern Alps, Krn Nappe, Upper Triassic, Jurassic, megalodontid bivalves, paleokarst infills, neptunian dykes*
Ključne besede: *Južne Alpe, krnski pokrov, zgronji trias, jura, megalodontidne školjke, paleokraške zapolnitve, neptunski dajki*

Morphogenetic interpretation of shallow karst depressions of Upper Pivka, Slovenia

Morfogenetska interpretacija plitvih kraških depresij zgornje Pivke, Slovenija

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The Upper Pivka region lies in the catchment area of the Ljubljanica River. The area is known for its shallow karst and a number of intermittent lakes. Our study focused on the systematic geomorphological analysis and morphogenetic interpretation of depressions where these intermittent lakes occur. Morphographic mapping, sediment analysis and electrical resistivity tomography were used for this purpose. During our systematic morphographic study of selected features, we identified equifinality within all intermittent karst depressions of Upper Pivka – namely, although they exhibit similar morphology, they differ in their morphogenesis. We have found that the large karst depressions of Upper Pivka can be divided into two distinct morphogenetic types. The first type of depressions are areas of lowered relief between the surrounding conical hills. This type of depressions are located in the northern part of Upper Pivka. They are irregularly shaped, with gentle and balanced slopes and with a thin sediment cover in their bottom. We have interpreted them morphogenetically as periodically inundated uvalas. The second type are circular to semi-circular depressions with steep and regularly rocky slopes, and the flood loam deposits in their floor are up to several tens of meters thick. Based on their morphographic and morphometric characteristics, and according to the sedimentary bodies in their bottoms, we can define them as collapse dolines from a morphogenetic point of view. This study was carried out in the framework of the programme P1-0011, Regional Geology, funded by the Slovenian Research Agency (ARRS).

Keywords: *geomorphology, collapse doline, uvala, resistivity tomography (ERT), karst, Slovenia*
Ključne besede: *geomorfologija, udornice, uvala, upornostna tomografija, kras, Slovenija*

Multiphase Development of Ponor-Type Contact Karst on the Zrenj Plateau, Istria, Croatia

Večfazni razvoj ponornega tipa kontaktnega krasa na Zrenjski planoti, Istra, Hrvaška

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The Zrenj Plateau, located in northern Istria, Croatia, is a corrosion plain characterized by a widespread ponor-type contact karst on its northern and southern borders. Streams originating from Eocene clastic rocks infiltrate karstified carbonate rocks, predominantly of Cretaceous age. A comprehensive geomorphological examination of the region reveals that the contact karst's development transpired through at least three distinct stages. Initially, the plateau served as a shallow karst area where watercourses from non-karstified bedrock in the north flowed across the plain toward Dragonja, Potok, and Mirna. Concurrently, southern streams likely drained into Potok and Mirna at the lithological contact. In the second stage, a drop in the water table caused surface streams to incise into the karst plain, carving canyons. The third stage involved a further decrease in the water table, resulting in the disintegration of the surface river network and watercourses' subsequent submergence into the underground. This ongoing process gives rise to the ponor-type contact karst that characterizes the Zrenj Plateau today.

Keywords: *geomorphology, karst, contact karst, Istria, Croatia*
Ključne besede: *geomorfologija, kras, kontaktni kras, Istra, Hrvaška*

What controls short-term variations in CO_2 and ^{222}Rn concentrations in Modrič Cave atmosphere?

Kaj kontrolira kratkoročne spremembe koncentracij CO_2 in ^{222}Rn v jami Modrič?

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Radon (^{222}Rn), as a naturally occurring radioactive geogenic gas, presents potential health hazard in confined, poorly ventilated areas such as caves. Thus, in order to ensure safe work environment for the guides and cave scientists, it is necessary to determine precise temporal and spatial variations of radon concentrations. In Modrič Cave (littoral Croatia), small (829 m) two-branch horizontal show cave, we conducted 6.5-years and 5-years monthly measurements of CO_2 and Rn concentrations, respectively, which revealed basic ventilation pattern; it is seasonal density-driven air circulation controlled by the difference between outside and cave air temperature on which cave morphology and bedrock architecture are superimposed. Aiming to decipher short-term variation with respect to meteorological conditions (precipitation, wind), additional continuous measurements of cave-air concentration of Rn and CO_2 began in 6/2020 and 10/2021, respectively. Bearing in mind that the highest gas concentrations (~24,000 Bq/m^3 and ~12,000 ppm) were recorded in summer during the peak tourist season, sudden gases concentration increase/decrease governed by intensive precipitation/bora wind should be respected in terms of cave management. Since the radon underground pathways could be affected by the phenomena that precede or accompany the earthquakes we considered 13 earthquakes – 8 nearby (7–56 km) with magnitude M 2.1–4.7 and 5 distant earthquakes (115–175 km) with greater magnitude M 4.8–6.2, but no significant radon flux has been recorded. However, it could have been masked by other environmental features, especially during the warm periods when both radon and CO_2 as its carrier gas, are intensively produced in the soil horizon by plant respiration, microbial activity and limestone dissolution that enhances radon release.

Keywords: *CO_2, radon, cave monitoring, Croatia*
Ključne besede: *CO_2, radon, jamski monitoring, Hrvaška*

Sediments in a hypogenic underwater cave - an indication of high flow periods in the past

Sedimenti v hipogeni podvodni jami – znaki preteklih obdobij višjih pretokov

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The Molnár János Cave is the youngest member of the Buda Thermal Karst located under the capital city of Hungary. It is almost completely submerged; corrosion processes are still active in the mixing zones of the cave. The cave is thought to be of hypogenic origin, isolated from large scale interference from the surface. The isolation protects the huge amount of potable water filling the cave passages. Since the discovery of the cave natural sediment transport was not observed: flow velocities did not

exceed the threshold of motion. Sediment samples collected from the floor of the cave, however, indicate completely different conditions in the past: a rich layer structure with large differences in the particle size distribution can be observed in the silt covering the cave floors. With the help of cave divers sediment depth was mapped in the largest passages of the cave. Sediment cores were also taken using techniques adapted to cave diving. The layer structure of the core samples, chemical composition and particle size distribution of the individual layers were also determined. Cluster analysis was applied to the collected data to assign layers at the different sampling sites, allowing us to draw conclusions not only on past flow velocities but also on the direction of flows and the possible sites of water entering the cave in high flow events in the past.

Keywords: *hypogene karst, flow velocity, sediment layer structure, cave diving*
Ključne besede: *hipogeni kras, hitrost pretoka, sedimentne teksture, jamsko potapljanje*

Lithological characteristics of the dedolomite complex in Mravljetovo brezno v Gošarjevih rupah cave, central Slovenia

Litološke značilnosti dedolomitnega kompleksa v jami Mravljetovo brezno v Gošarjevih rupah, osrednja Slovenija

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The Mravljetovo brezno v Gošarjevih rupah is a cave located in an isolated karst area in central Slovenia and was formed in Middle Triassic dolostone (Anisian), which is part of a mixed carbonate-siliclastic succession that extends from the Middle Permian to the Middle Triassic. The regional structural setting, including N–S directed faults and 30°S dipping bedding combined with multiphase speleogenetic processes, which resulted in a complex, maze-like cave morphology. In addition to common morphological wall rock features, such as ceiling channels, cupolas, solution pockets, pendants, and anastomoses, some condensation corrosion features are also present, as well as siliciclastic sediments and speleothems. Among the most distinctive cave features are the yellow and red lithologies that cover much of the cave walls and fill some cave spaces. Yellow lithologies are usually found on the floor in the center of cave rooms or forming bridges that connect opposite walls of cave channels. They appear stratified, and some of them have laminitic textures with alternating dark and light laminae. Microscopically, they are composed mainly of microsparite with a small amount of quartz and clay minerals. The red lithology is in direct contact with the cave wall rock. Microscopically, it consists of calcite crystals in the form of relatively coarse grained xenotopic to locally hypidiotopic mosaic calcite, pseudospherulitic fibrous calcite, cone-like fibrous calcite, fibrous palisade calcite and brownish micritic calcite with or without a mesh of needle-fibre crystals, etched patches, or individual crystals of coarser grained calcite mosaic. The yellow and red color derives from the presence of intercrystalline iron hydrooxides. At the contact between red lithotype and dolostone wall rock, cavities with calcite box-work and spar calcite are formed. The few outer centimeters of the dolostone wall rock has a bleached appearance that under the microscope consists of a mosaic of calcite crystals with rhombic dolomite relics. Although the exact relationship between the different lithologies and the dolostone are still unclear, it is evident that these textures were caused by dedolomitization. The source of this material and the possible causes of dedolomitization are still being investigated. This work is funded by the Slovenian and Polish research agencies (ARRS and NCN)

through the bilateral Polish-Slovenian research project CEUS (project code in Slovenia: N1-0226; project code in Poland: 2020/39/I/ST10/02357).

Keywords: *dedolomite, cave sediments, speleogenesis, Slovenia*
Ključne besede: *dedolomit, jamski sedimenti, speleogeneza, Slovenija*

Managing lampenflora growth in Škocjan Caves, a World Heritage Site in Slovenia: a practical approach for show cave conservation

Nadziranje rasti lampenflore v svetovni dediščini Škocjanskih jam v Sloveniji: praktičen pristop za ohranjanje turističnih jam

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Škocjan Caves is one of the most significant karst phenomena not only in Slovenia's Classical Karst region but also worldwide. The site is on the UNESCO World Heritage List and is recognized as an underground karst wetland under the Ramsar Wetland Classification. Škocjan Caves attracted tourists as early as the 19th century. Since the introduction of electric lighting in the tourist section in 1957, the number of visitors has steadily increased from the initial 8,330 to 67,105 in 2002. In 2008, the number of tourists exceeded 100,000 for the first time. From 2016 to 2019, the number of visitors further increased from 150,000 to 200,000. During the COVID-19 pandemic in 2020 and 2021, Škocjan Caves were significantly less visited. However, since 2022, the cave has again been visited by more tourists, though still less than before the pandemic. During tourist visitation, the cave is exposed to artificial lighting. Almost all lighted surfaces in the cave had been gradually colonized by lampenflora, which became encrusted within the flowstone at some sites. From 2014 to 2016, the cave management started coordinated activities to control lampenflora growth and to remediate the affected surfaces, including (1) removal of lampenflora from cave surfaces, speleothems, and other affected cave infrastructure using hydrogen peroxide as a biocide agent, (2) replacement of heat-emitting halogen lamps with LED lamps, (3) shortening of the lighting period for individual lighting sectors, and (4) applying low illuminance on speleothems. These actions are supported by regular spectrophotometric measurements of illuminated surfaces and monitoring of microbial biomass to ascertain the trend of lampenflora growth and the most susceptible parts of the cave for its colonization, which receive additional attention and treatment. Monitoring shows that the trend of surface load with microbial colonization, after the initial increase in some places, no longer increases and remains at the same level. Since lampenflora is already present in the Škocjan Caves, measures to limit it must be implemented regularly, as it can quickly regrow.

Keywords: *cave management, conservation, monitoring, lampenflora*
Ključne besede: *upravljanje jam, ohranjanje, monitoring, lampenflora*

Submerged Izola karst: Investigating submarine sulphur springs

Izolski potopljeni kras: raziskovanje podmorskih žveplenih izvirov

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The limestones of the Izola anticline (SW Slovenia) are a geological particularity of the Slovenian coast, which otherwise consists of flysch. In addition, the Izola karst is also distinctive for its submarine sulfur springs, terrestrial sulfur springs, shafts and caves with hydrothermal characteristics. The warm and sulfurous water from the Sv. Peter Shaft and the Izola Shaft was used for spa in the 19th century, and the Antronček cave is suspected to be of hydrothermal origin. Hydrogeochemical and isotopic investigations of terrestrial and submarine sulfur springs were carried out to study the origin of the water and to better understand the interactions in the aquifer. Submarine sulfur springs occur in funnel-shaped depressions, also named pockmarks, where water springs from the unconsolidated marine sediment. Intense mixing with seawater is present in the upper layers of sediment. The isotopic composition of H and O suggests that the freshwater component in the sulfur springs originates from infiltration of local meteoric water. Regional groundwater flow is suggested to originate from the limestone formation either to the northeast (Classical Karst) or to the south (near the Dragonja river), and moving beneath the flysch formation under artesian pressure. As the water circulates through the deeper parts of the formation, it is heated before eventually emerging as springs through the fracture zone in the Izola limestones. Carbon isotopes indicate that the spring water is also in contact with organic matter, possibly coal in the Liburnia Formation beneath the alveolinic-nummulitic limestones in the Izola area. Higher iron and manganese concentrations point to reducing conditions that support bacterial reduction of marine or organic sulfate and production of hydrogen sulfide. The Izola karst is unique among Slovenian karst areas for its submarine sulfur springs. Ongoing research is shedding light on the origin of the hydrothermal sulfurous groundwater and the Izola karst environment.

Keywords: *karst, sulfur springs, hydrogeochemistry, stable isotopes, Izola*
Ključne besede: *kras, žvepleni izviri, hidrogeokemija, stabilni izotopi, Izola*

Complex evaluation of caves in the Krkonoše Mountains (northern Bohemia, Czechia)

Zapletena evalvacija jam v gorovju Krkonoše (severna Bohemija, Češka)

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The speleogenesis in the Krkonoše Mountains took part in substantial depths under the surface without any link to the present morphology. Phreatic speleogenesis was connected with the oldest flat and slightly undulated peneplain and with the first stage of shallow valley incision. Caves were disconnected from original hydrology and hydrogeology regimes and their function in recent systems is negligible, they are relic or rejuvenated. Present near-surface position of most of caves reflects the denudation during younger cyclic tectonic movements and river incision. Caves were much later re-

shaped in epiphreatic and vadose conditions. Inclined phreatic channels dominate in original cave morphologies with ceiling half-channels, scallops, and ceiling cupolas, and flat ceilings. Channels served as routes for ascending bathy- and deep phreatic waters and follow regional faults and overthrusts. The role of thermal waters was not proved. Intensive rock fissuration led to opening of vadose routes during tectonic uplift and to infiltration loaded by surface clastics. Older caves were filled. Coarse-grained particles were sieved in fissure porosity. The primary source of clastic sediments was in weathering products of crystalline rocks. Any allogenic deposits were detected. Intensive drip from open fissures contributed to local re-distribution of sediments within caves. Speleothem dating indicates polycyclic fill and exhumation of caves. Internal cyclic/rhythmic textures prove changing paleoenvironments on surface. Normal polarization of samples corresponds to age <773 kyr (Bruhnes Chron). Speleothems date clastic sediments to >400 kyr. Speleothems crystallized mostly during interglacials (namely MIS 5a to MIS 7e), but also in cold and extremely cold periods (glacials, like MIS 2, MIS 6c to 6a, MIS 8b, MIS 10c to 11a). Tectonic and near-surface marble fissuration and corrosion along fissures and cleavage substantially contributed to repeated re-shaping of originated cave spaces by rock falls or congelifraction. Speleothems were also damaged (fractures, opening of isotopic equilibria by corrosion). Funding: EU Operation Programme: Environment, Priority axis 4.1 no. CZ.05.4.27/0.0/0.0/15_009/0004533 & RVO67985831

Keywords: *paleokarst, infiltration cave sediments, speleothems, Th-U dating, paleomagnetism, sedimentology, speleogenesis*
Ključne besede: *paleokras, infilracijski jamski sedimenti, siga, datiranje Th-U, paleomagnetizem, sedimentologija, speleogeneza*

Evaluation of water Resources in the City of Bandundu

Ocena vodnih virov mesta Bandudu

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The City of Bandundu has considerable potential for water resources and aquatic ecosystems whose management, protection and enhancement are dependent on new challenges imposed by sustainable development, poverty reduction and climate change. Unfortunately, the relative weakness of the hydrogeological studies so for carried out in the country means that only very limited data are available to assess the hydrodynamic and chemical characterization of the rivers of Bandundu City. This study aims to provide decision-makers, researchers and donors with scientific information on the characteristics of the water of the Kasaï River. Thus, the characterization of the water resources of the Kasaï River has been carried out using isotopic tools and conventional hydrogeological techniques. The physical-chemical paramètres (pH, electrical conductivity, temperature, turbidity, major ions) have been measured. The Kasaï river was characterized by values of: pH 9.09, conductivity 28.4, temperature 29°C, O_2 4.53(60.5%), NO_3 4.5 mg/L, NO_2 0 021 mg/L, PO_4 0.36 mg/L, SO_4 1.6 mg/L, TDS 7.5 mg/L, CO_2 16.5*2 mg/L, turbidity 45 cm. This research must continue for all rivers of Democratic Republic of Congo with the support of partners and donors.

Keywords: *Hydrogeological, isotope, Kasaï, Bandundu, characterization, hydrodynamic*
Ključne besede: *hidrogeološko, izotopi, Kasaï, Bandundu, karakterizacija, hidrodinamsko*

Hydrogeochemical research of the Klariči water source catchment area – preliminary results

Hidrogeokemične raziskave v zaledju vodnega vira Klariči – predhodni rezultati

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Klariči water source covers the drinking water needs of five municipalities on the Kras plateau and represents an alternative source of water for the Slovenian Coast, thus accurate characterization of its aquifer is of essential importance. Previous studies have shown that water at Klariči shows different behavior during low flow conditions compared to high flow conditions, when there is an increase of certain parameters (e.g., Cl^-, Na^+). In previous studies this increase has been attributed to be either from an anthropogenic source or due to contribution from fossil marine waters present in the deeper carbonate units, and outflow at the Monfalcone thermal springs. To better characterize this groundwater system and its source components we have undertaken a detailed geochemical study, for which we sampled several locations in the Klariči catchment area (Soča and Vipava rivers, boreholes B-4 and B-9), including other locations on and near the Kras plateau (Sabliči, Jama pri Komarjih, the upstream part of Reka River, Monfalcone thermal groundwater) as well as Sea water. Samples were collected for various geochemical analyses, including water chemistry, stable isotopes of water, dissolved inorganic carbon, sulfate and strontium, as well as radiocarbon, tritium and noble gases. ^3H-^3He dating and ^{14}C data clearly separates the younger karst waters, from the older thermal waters, that is also reflected by their stable isotope data. The thermal waters have similar major ion and isotopic composition to the sea water. Noble gas data shows dominantly atmospheric helium at the young karst waters, crustal helium at the thermal waters, and surprisingly deep derived (mostly crustal) helium with up to ~5% mantle helium contribution at Klariči. A deep-sourced (thermal) contribution at Klariči is also indicated by the isotopic composition of the dissolved sulfate. Our preliminary results confirm a deep-derived contribution at Klariči, likely connected to thermal waters related by along a deep fault structure.

Keywords: *Klariči, Kras, groundwater, geochemistry*
Ključne besede: *Klariči, Kras, podzemna voda, geokemija*

Sinkholes in the South Franconian Alb (Germany): distribution and relations to geology and geomorphology

Udornice v severni Frankonijski Juri (Nemčija): porazdelitev in odnosi med geologijo in geomorfologijo

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As a well-known karst area in Southern Germany the South Franconian Alb shows mainly a slightly inclined plateau intersected by rivers and numerous dry valleys. Main rocks are limestones and

dolomites of Jurassic Age covered by post-Jurassic loamy deposits up to a few meters. Numerous sinkholes occur within the area. Unfortunately, till now the data collection is incomplete. Nevertheless, to gain insights into the background of sinkhole distribution and the related geologic, geomorphic and land use conditions the available data were compiled to an internal cadastre. Different local archives, the available geologic and topographic maps of the South Franconian Alb were searched for sinkhole information, on the other hand digital elevation models from selected areas were detected for hollow shapes or depressions to estimate the maximum quantity of possible dolines. For all detected objects both verified sinkholes and unclassified depressions the geomorphological environment, cover deposit, host rock, rock facies, stratigraphy and land use were listed. Currently, the amount comprises more than 30000 listed objects. About 45% are verified sinkholes, the rest remains unclassified until field confirmation or falsification. Great discrepancies for the sinkhole distribution related to land use are indicated. More than 90% of the detected objects are located within forests although forested areas cover only 30–50% of the South Franconian Alb. Thus, most of former sinkholes were destroyed by agricultural or other activities. Furthermore, historic mining activities (stone-age chert mining, historic mining pit areas for iron mining, small local quarries) have also changed the sinkhole distribution. Due to such anthropogenic overprinting of the landscape an automatic detection of dolines from digital elevation models requires a very critical assessment. Most of the verified sinkholes occur on the elevated and inclined plateau of the South Franconian Alb (80%), dry valleys show about 18%. Related to the regional geology ⅔ were detected in areas with loamy cover. About 1⁄10 were found within Cretaceous rocks or Miocene sediments as well resting upon the karstified carbonate rocks. Areas with Jurassic bedrock occurring at the surface show solely 16–17% of the detected sinkholes.

Keywords: *sinkholes, geology, geomorphology*
Ključne besede: *udornice, geologija, geomorfologija*

Marginal plains on Border Karst Poljes

Robne uravnave na pritočnih kraških poljih

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This research aims to provide a morphogenetic and morphodynamic interpretation of the formation of marginal plains on border karst poljes. The research objectives were achieved through morphographic, morphometric, and morphostructural analyses of border karst poljes. Petrological and geophysical analyses were conducted on sediment samples, which aided in providing a morphogenetic and morphodynamic interpretation of the formation of marginal plains. Qualitative descriptions of geomorphic forms were carried out using GIS tools and fieldwork. Relief analyses were performed on a digital elevation model to conduct morphometric analyses, while morphostructural analyses were conducted using geological maps and their interpreters. Petrological analysis involved the grain size analysis to determine processes which contributed to sediment depositon. Geophysical analyses were conducted using measurements of Electrical resistivity tomography to gain insight into current geomorphic processes under the sediment.

Keywords: *border polje, marginal plain, fluvio karst*
Ključne besede: *pritočno polje, robne uravnave, fluvio kras*

The clastic sediments origin of the Głęboka Cave (Kraków-Częstochowa Upland, Poland) in the light of heavy minerals analysis

Izvor klastičnih sedimentov v jami Głęboka (Krakovsko-čenstohovsko višavje, Poljska) na podlagi analize težkih mineralov

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The study aims to determine the origin of clastic sediments of the Głęboka Cave using heavy minerals analysis supplementing previously made granulometric, lithological, petrographic and mineralogical analyses. The cave is located in the central part of the Kraków-Częstochowa Upland (Poland), and the sediments were excavated during the arrangement of the tourist trail. Clastic sediments (unconsolidated or cemented by calcite) fill the Głęboka Cave almost to the ceiling and are partly covered by thick flowstone. U-series dating supported by the oxygen isotope stratigraphy allowed us to estimate the crystallization age of the flowstone in a range of 975–470 ka BP (Błaszczyk et al., 2018). The composition of heavy minerals in analyzed samples is mainly: kyanite, tourmaline, rutile, anatase/brookite, staurolite and zircon. These minerals are chemically and mechanically resistant. There is no garnet, epidotes, amphiboles or pyroxene in the samples. Based on the composition of heavy minerals in the Głęboka Cave, Cretaceous formations can be considered the source material. It can be stated that the source of the cave sediments was sandstone weathering debris and residual karst sediments from the surface. The higher content of kyanite and tourmaline in relation to zircon indicates a similarity to the composition of heavy minerals in the so-called moulding sands, and thus a greater similarity to the earlier studied cave sediments and weathering covers of the northern than southern part of the Kraków-Częstochowa Upland. The average value of the ZTR index (38–61%), mineral composition, and quartz grains coating and matting indicate short distance high energy flows from surface to the cavity. The conducted analyzes of heavy minerals allow us to exclude the Pleistocene, fluvioglacial and glacial origin of the sediments filling the Głęboka Cave.

Keywords: *clastic sediments, heavy minerals, Głęboka Cave, Kraków-Częstochowa Upland, Poland*
Ključne besede: *klastični sedimneti, težki minerali, jama Głęboka, Krakovsko-čenstohovsko višavje, Poljska*

Hypogene speleogenesis and the origin of collapse dolines in travertines of the Central Andes – interdisciplinary approach

Hipogena speleoeneza in izvor udornic v travertinih centralnih Andov, interdisciplinarni pristop

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The studied caves and collapse dolines in travertines, locally known as the Mulapampa travertines, are located in the Western Cordillera of the Central Andes (Peru). Travertines form a thick (up to > 100 m) and large area (11 km^2) cover filling the central section of the Huambo River valley (a tributary of the Colca River). The whole system occurs in the altitude range from 2970 to approx. 4000 m a.s.l. They

are of hydrothermal origin. The surface manifestation of the karst of the discussed area is large collapse dolines located in the southern part of the entire complex of travertines. They bear the local name *hutco*, which in the Quechua language means a hole. These forms reach from 10 to over 130 m in diameter and from a dozen to over 40 m in depth. The collapse dolines have regular shapes, often overhanging walls. They are arranged in several groups at different height levels, referring to the structure of the entire travertine cover. Three caves have been explored in the bottom of collapse dolines. Their general size and explored depth (36 to 87 m) make them among the world's largest caves in travertines. Based on the complex geochemical, mineralogical, speleological and geomorphological studies carried out so far in three discovered caves, it can be concluded that the caves and collapse dolines in the Mulapampa travertines are of hypogenic origin. The development of caves initiating the formation of collapse can be associated with speleogenesis in the presence of sulfuric acid, which results from hydrogen sulphide oxidation close to the groundwater table (sulphuric acid speleogenesis - SAS). Although SAS processes occurred in the period of increased volcanic activity in the region in the past, various sulphate deposits and minerals are still common at the bottom of one of the caves. This research was funded by National Science Centre (Poland), grant No 2020/39/B/ST10/00042.

Keywords: *sulphuric acid speleogenesis, collapse dolines, travertines, Central Andes, Peru*
Ključne besede: *speleogeneza žveplove kisline, udornice, travertine, centralni Andi, Peru*

Sedimentological and geochemical conditions along the inception horizons influencing the formation of the cave Pečina v Zjatih

Sedimentološki in geokemični pogoji vzdolž inicialnih kanalov, ki so pogojevali razvoje jame Pečina v Zjatih

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Pečina v Zjatih is one of the numerous caves in the Matarsko podolje region, a karstic plateau in SW Slovenia. The cave formed under phreatic, epiphreatic and finally vadose conditions in slightly bituminous Albian-Cenomanian limestone and is currently in the decay phase. Investigations focused on the inception horizons, along which several phreatic channels developed and influenced the formation of the cave. Rocks directly above and below the inception horizons were examined for their microfacies. 107 rock samples were collected from 86 layers, of which 43 samples were examined in detail for their sedimentological and geochemical properties (X-ray fluorescence and Loss on Ignition). Five inception horizons were identified in the cave. The results show that the geochemical properties of the beds immediately below and above the inception horizons differ in terms of elemental and organic matter content, and that the microfacies changes significantly along these contacts. Most of the succession is defined by open-marine lagoonal facies: peloidal grainstone with large bioclasts and intraclasts (MF1), ooid bioclastic grainstone (MF2), and partially washed peloidal packstone with bioclasts (MF3). In contrast, in the vicinity of the two inception horizons (IH4 and IH5), two microfacies characteristic of the restricted lagoonal environment are observed: bioclastic wackestone (MF4) and mudstone-wackestone facies with bioclasts (MF5). The organic matter in both microfacies types is much higher than in other microfacies types and therefore had a crucial influence on the formation of these horizons and consequently the cave channels. During oxidation, the organic matter caused the formation of aggressive acids that could dissolve the rock faster than carbonic acid. Apart from the organic matter, elevated Sr, Ba and S levels were also found in both microfacies, although no possible correlation with the inception horizons was found, and the terigene content was also higher than in other beds.

Keywords: *speleogenesis, inception horizon, cave, Pečina v Zjatih*
Ključne besede: *speleogeneza, inicialni kanali, jama, Pečina v Zjatih*

Arthur Marble Aquifer and Te Waikoropupu Springs, New Zealand: modelling flow contributions and nitrate sources

Vodonosnik Artur Marble in izviri Te Waikoropupu, Nova Zelandija: modeliranje tokovnih doprinosov in izvorov nitratov

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This paper presents a mass balance model of a karst groundwater system that supports a major karst spring with the prime purpose of investigating early signs of nitrate pollution and identifying its input sources. Te Waikoropupu Springs are the largest springs in New Zealand and amongst the largest in the Southern Hemisphere with a mean outflow of 13.4 m^3/s. They discharge the clearest water ever measured at a karst spring, but early warning of water quality deterioration is signalled by increasing nitrate concentrations. The springs discharge water from a partly artesian reservoir of 2.85 km^3 volume in karstified Ordovician marble with a transmission time averaging 7.9 years. Reservoir porosity is unusually high for a crystalline carbonate rock, estimated as 6%. Water emerging at Main Spring and adjacent Fish Creek Springs is a mix of recharge from four main sources. The paper investigates by means of mass balance modelling the proportions of water coming from each source, the origins of nitrate contamination and the contribution of nitrification. Water losses into the bed of the upper Takaka River, about 17 km from the Springs, provide 20% of mean flow at Main Spring, 36% of flow at Fish Creek Springs, and 67% of the volume discharged at submarine springs. Rain falling over farmed land in the central valley is estimated to supply 9% of total outflow at Main Spring and Fish Creek Springs but to contribute 82% of the NO_3-N output discharged at the springs. A 34% reduction of leachate concentration in the central valley would be required to bring NO_3-N values at Main Spring back to levels recorded in the 1970s.

Keywords: *karst aquifer, mass balance modelling, stable isotopes, nitrate, artesian, New Zealand*
Ključne besede: *kraški vodonosnik, masna bilanca, stabilni izotopi, nitrati, arteški, Nova Zelandija*

The Value of Stable Water Isotopes for Improving Karst Groundwater Models

Pomen stabilnih vodnih izotopov pri izboljšavah kraških modelov podzemnih voda

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Karst landscapes evolve from highly soluble rocks with dissolution features and serves as a significant source of drinking water, satisfying the demands of up to 50% of the population in some European countries. Process-based hydrological simulations play a vital role in delineating and understanding karst aquifer structures and their hydraulic dynamics. However, oversimplification in lumped models often result in poor representations of the complexity of karst systems. Therefore, it is crucial to establish more realistic model structures and obtain auxiliary information for their parameterization to improve the accuracy, applicability, and prediction skills of karst models. Previous studies in non-karstic terrains have shown that stable water isotopes as environmental tracers associated with

hydrodynamic information performed well in further calibrating and validating hydrological models. However, only a few studies have been conducted in karst by where auxiliary data has been used as compensate for disinformation to improve the modelling. The aim of this PhD project is to systematically explore the usefulness of stable water isotopes in karst spring discharge for improving karst model calibration and reducing production uncertainty. In particular, (1) I will prepare the available datasets for 119 springs and select one site with the best dataset for the development of a new model. (2) I will set up and evaluate karst models with different model structures that include the simulation of stable water isotopes transport by different ways. (3) I will assess the transferability and application of new local models to the larger sample of karst springs with stable isotopes that I previously prepared. (4) I will exploit the impact of simulation time scale and data resolution on transport simulation of isotopes. With my work, I hope to contribute the new conceptual modelling approaches for simulating the stable water isotope dynamics in karst systems in a more realistic way.

Keywords: *karst system, hydrological modelling, stable water isotopes, water management*
Ključne besede: *kraški sistem, hidrološko modelrianje, staviln vodni izotopi, upravljanje voda*

Natural and Anthropogenic Driving Forces of Carbonate Weathering and the Related Carbon Sink Flux

Naravne in antropogene gonilne sile preperevanja karbonatov in povezan ogljikov ponor

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Rocks weathering processes control global climate in geological short-term and long-term scale. The chemical weathering of carbonate rock is driven by environmental factors such as temperature, moisture, and CO_2 concentration, which can have natural (climate) or anthropogenic (land-use) origins. The better understanding of how carbonate weathering and related carbon sink flux dynamics under global climate and land use change is significant for tackling the global climate crisis in the future. In this lecture, we will introduce the weathering behavior of carbonate rock in different typical karst catchments with varying geological and environmetal backgrounds. Meanwhile, the results of a modelling comparative study will be presented to show how natural (climate) or anthropogenic (land-use) factors intertwined in shaping global carbonate weathering intensity and relevant carbon sink flux patterns. Furthermore, the responses of carbonate weathering and related carbon sink flux from the past to the future will also discussed.

Keywords: *carbonate weathering, climate, land use, carbon cycle*
Ključne besede: *preperevanje karbonatov, klima, raba tal, ogljikov cikel*

Atypical cave sediments from the Grofova jama (Kras Plateau) and their connection with the eruption of the Smrekovec stratovolcano

Netipični jamski sedimenti iz Grofove jame (Kras) in njihova povezava z izbruhom Smrekovškega stratovulkana

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The large amount of montmorillonite clay found in the relict karst cave on the hill above the flattened karst plain on the NE edge of the Gulf of Trieste is not comparable to the allogenic sediments from the caves of the Classic Karst, where the montmorillonite content is negligible. XRD analyzes indicate a very pure montmorillonite clay composition with rare admixtures of quartz grains and heavy minerals. Based on geochemical analyzes and comparisons with the composition of pyroclastic rocks from volcanic centers in the broader region, we consider that the montmorillonite clay in terms of geochemical characteristics related to the REE distribution, the LRRE-enriched samples, the LaN/YbN ratio and the significantly negative Eu/Eu* ratio, represents weathering pyroclastic ash from the Miocene eruptions of the Smrekovec Volcanic Complex (SVC) transported to the depocenter by NE winds. AFT the dating of the apatite grains gave 22 Ma ± 7 Ma, the K-Ar dating of the clay 23.4 ± 1.7 Ma. Thus, both determined ages can be related to the activity of the SVK, which is dated to 28-23 Ma. The presence of weathered volcanic ash in the studied cave indicates considerable explosive activity of the stratovolcano and the deposition of ash on the existing Oligocene karst surface.

Keywords: *montmorillonite clay, tephra, dating, Oligocene karst landscape, SW Slovenia*
Ključne besede: *montmorilionitna glina, tefra, datiranje, oligocenska kraška pokrajina, JZ Slovenija*


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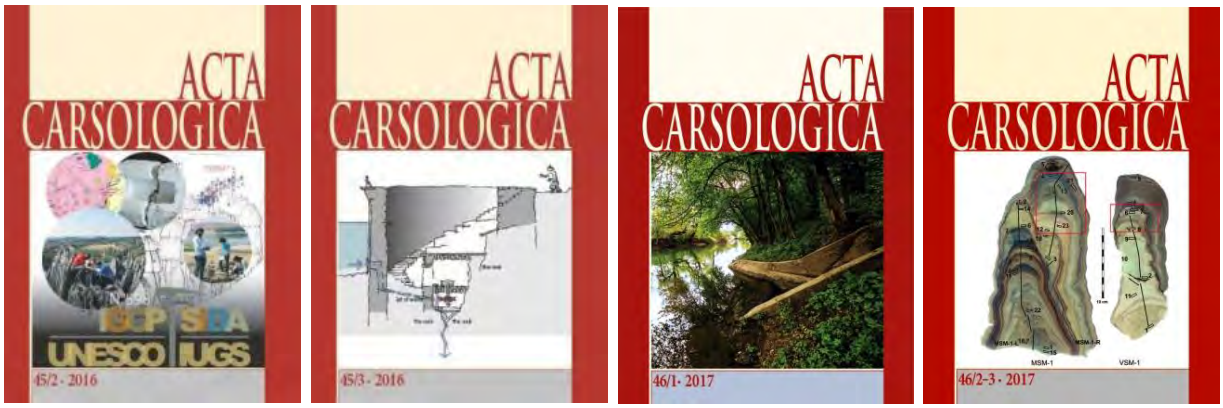

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