29th INTERNATIONAL KARSTOLOGICAL SCHOOL
"Classical Karst"

29. MEDNARODNA KRASOSLOVNA ŠOLA "KLASIČNI KRAS"

SPELEOLOGY
* within International Year of Caves and Karst

SPELEOLOGIJA
*ob Mednarnodnem letu jam in krasa

ABSTRACTS & GUIDE BOOK
POVZETKI & VODNIK

29th INTERNATIONAL KARSTOLOGICAL SCHOOL
"CLASSICAL KARST"

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Postojna
2022

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Thursday, June 16th, 2021 **Četrtek, 16. junij 2021**		
09:00–17:00	**Whole-day field trip (C)** / **Celodnevno terensko delo (C)** Postojna cave system. Walk from Institute to the ponor of Pivka River, Postojnska gmajna, Otoška jama, Risovec blind valley, entrance to the Magdalena jama, through Pivka jama, Črna jama, and Postojnska jama to its entrance. Postojnski jamski sistem. Pohod od Inštituta do ponora reke Pivke, preko Postojnske gmajne, Otoške jame, slepe doline Risovec, vhoda do Magdalene jame, skozi Pivko jamo, Črno jamo in Postojnsko jamo do njenega vhoda.	
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LIST OF POSTER PRESENTATIONS

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1	Ardetti Igor	Listening to the Davorjevo abyss
2	Brun Clarissa	Hydrocarbon pollution in the karst system: first monitoring and bioremediation approach
3	Iepure Sandra	The response of aquatic fauna to environmental conditions variability in Ghețarul de la Vartop cave (Apuseni Natural Park, Romania)
4	Knez Martin	Planning of the new railway line from the top of the Classical Karst plateau to the Port in Koper has ended, construction has begun
5	Lončar Nina	Phreatic overgrowths on speleothems (POS) as indicators of relative sea-level change along the eastern Adriatic coast
6	Lončarić Robert	Changes in CO2 and 222Rn concentrations in cave environment – Modrič Cave (Croatia) case study
7	Matoušková Šárka	Geochemical tracing of coin counterfeiting during Middle Ages in Koněprusy caves
8	Mulec Janez	Monitoring anthropogenic influences from spring to the ponor of the Pivka River, Slovenia
9	Năpăruş-Aljančič Magdalena	Karst groundwater biodiversity and habitats. Building in-situ virtual laboratories to assess the ecology of Proteus anguinus and its subterranean habitat throughout data platforms
10	Năpăruş-Aljančič Magdalena	Implementation of RI-SI-EPOS project - SLO KARST NFO
11	Oberender Pauline	Comparison of optical methods to generate 3-D models in order to quantify processes in a frost weathering cave
12	Plan Lukas	Analysis of black deposits from Austroalpine caves
13	Rehamnia Baraa	Biotechnological potentialities of spore-forming bacteria isolated from deep cave ecosystems in North Africa
14	Singer Autumn	Enhancing Scholarship in Karst Hydrogeology through Cultural Exchange
15	Surić Maša	Holocene environmental records from Croatian speleothems
16	Szieberth Dénes	Cave sediment analysis of Molnár János Cave – Hungary
17	Šarc Filip	Cave in the Mežica mine

18	Šegina Ela	Uncovering the subsoil karst surface morphology
19	Tičar Jure	Cave Jama v Dovčku: through speleogenesis towards climate reconstructions
20	Wildfong Emily	Drawing [with / as / by] Karst
21	Zupančič Maša	Cyanobacteria in underexplored karst and other extreme environments

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 20 min (15 min for talk and 5 min for discussion). Invited lecturers have 40 min for the lecture.

Posters

- Poster size: suggested max. format is A0 – 841 x 1189 mm (portrait layout).
- Poster presentation and display will be held at the Karst Research Institute.
- 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 13th, 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.
- 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

- Registration for each field trip will be possible only on Monday, 17th June 2019 at the registration desk. Since the places are limited, please, hurry up with the registration. Pre-announcement to the organizers is possible.
- 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. On Thursday a 10–12 km walk is expected.
- Insect repellents are recommended as we will be walking in the 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.

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 20 minut (15 minut za govor in 5 minut za razpravo). Vabljena predavanja so omejena na 30 minut.

Posterji

- Velikost posterjev: 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 minute 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, 13. junija, do odmora za kosilo.
- Med ogledom posterjev stojte poleg svojega posterja.

Obroki

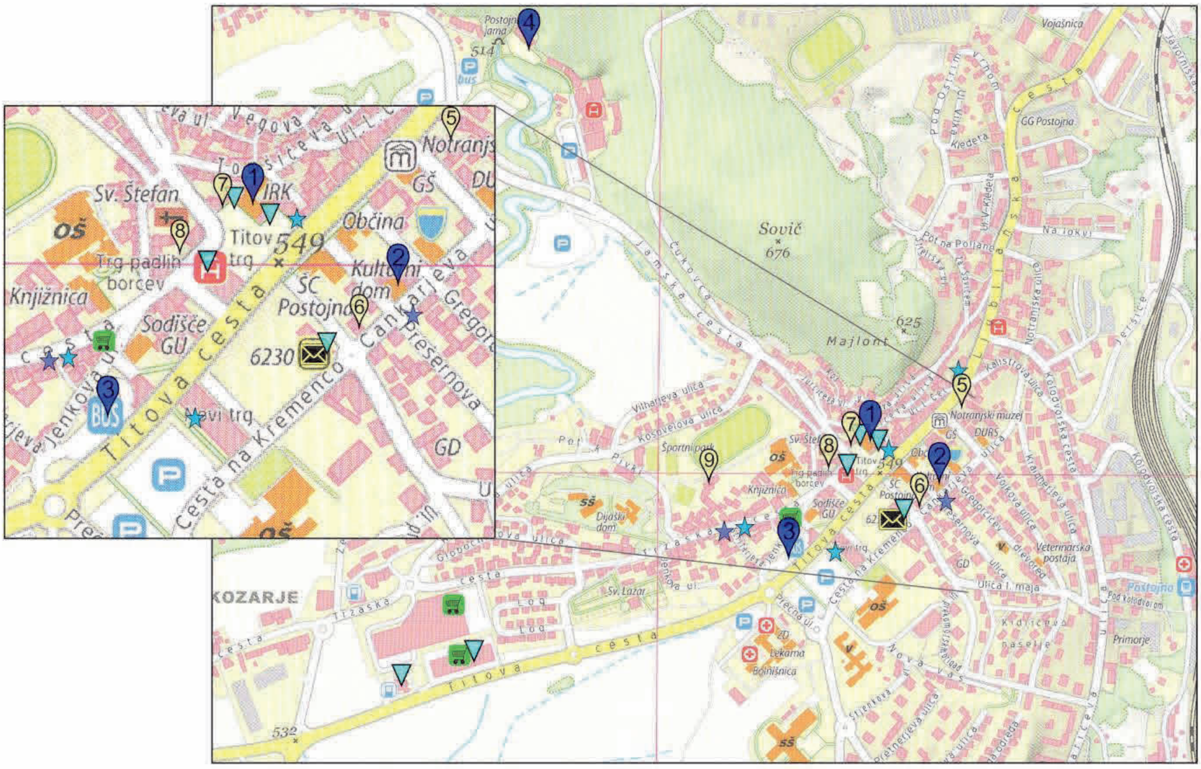
- Kosilo med predavanji in popoldanskim terenskim delom (torek in sreda) ni organizirano.
- Med celodnevnim terenskim delom (četrtek in petek) organiziramo enostavne obroke.
- Odmori za kosilo so v času predavanj (ponedeljek, torek in sreda) vključeni v program.
- V četrtek je v večernem delu programa planirana pogostitev in glasba v živo.

Terensko delo

- Prijave za terensko delo bodo mogoče le v ponedeljek, 13. 6. 2022 pri mizi za prijavo udeležencev. Pohitite s prijavo, saj so mesta omejena. Možna je predhodna najava organizatorjem.
- 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. V četrtek se pričakuje, da bomo prehodili 10–12 km.
- 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



Karst Research Institute ZRC SAZU / Inštitut za raziskovanje krasa ZRC SAZU

Cultural Center of Postojna / Kulturni dom Postojna

Postojna bus station / Avtobusna postaja Postojna

Entrance to cave Postojnska jama / Vhod v Postojnsko jamo

Places to eat: / Možnost prehrane:

Pizzeria and restaurant „Minutka“ / Picerija in restavracija „Minutka“

Bistro „Štorja pod stopnicami“ / Bistro „Štorja pod stopnicami“

Restaurant „Proteus“ / Restavracija „Proteus“

Bistro „Bar Bor“ / Bistro „Bar Bor“

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: UNRESOLVED MYSTERIES OF KARST

(Monday, 13th June, 2022)

This year's school will be as always a great opportunity as a 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, and it was quite successful, in that some answers could be found, and others are actively investigated at the moment.
Usually talks in schools and congresses deal with progress of ongoing research and with their results. This session, however, has the aim to present the still-unresolved problems and to promote and stimulate research! In opposition to many other scientific branches, karstologists most often try to collaborate in order to resolve problems. This session should therefore promote further the world-wide collaboration.
Because there are no results, talks usually are short, but because questions are formulated, discussion should be longer. Therefore, talks are limited to max. 5 minutes, while discussions may last 10–15 minutes.

You are all invited to contribute to the session. Please send a brief problem outline and description to praezis@speleo.ch.

With best regards,
Philipp Häuselmann (moderator)

POVABILO NA POSEBNO SEKCIJO: NERAZREŠENE SKRIVNOSTI KRASA

(ponedeljek, 13. junija 2022)

Kot je že v navadi, tudi letošnja Krasoslovna šola predstavlja odlično priložnost za srečanje tako uveljavljenih kot tistih manj uveljavljenih raziskovalcev krasa iz različnih predelov sveta.
V zadnjih letih, ko prirejamo posebno sekcijo, t.i. "Nerazrešene skrivnosti krasa", se je izkazalo, da je tovrsten način sodelovanja med raziskovalci zelo učinkovit, saj je bila tekom let razrešena marsikatera raziskovalna dilema, z mnogimi izmed njih pa se raziskovalci trenutno še aktivno ukvarjajo.
Običajno predstavitve na izobraževanjih, delavnicah in kongresih podajajo informacije o poteku raziskovanja ter končne rezultate raziskav. Pristop te sekcije pa je drugačen, saj je njen namen predstavitev še nerešenih raziskovalnih problemov ter spodbujanje raziskovalnega dela. V nasprotju z mnogimi drugimi panogami je pri reševanju krasoslovnih raziskovalnih vprašanj pogosto vzpostavljeno sodelovanje strokovnjakov z različnih področij, kar v širšem mednarodnem okviru spodbuja tudi ta sekcija.
Predstavitve naj bodo kratke, največ 5 minut; predstavljeni naj ne bodo rezultati raziskav, temveč raziskovalna vprašanja. Diskusija pa je lahko daljša, od 10 do 15 minut.

Vabim vas, da se aktivno udeležite sekcije. Prosim vas, da krajši povzetek raziskovalnega problema in njegov opis pošljete na e-mail *praezis@speleo.ch*.

S spoštovanjem,
Philipp Häuselmann (moderator)

INVITATION TO THE ONLINE COURSE »KARSYS«

(Monday and Tuesday, 20th – 21th June, 2022)

You can read more information about the KARSYS online course organized by our colleagues from the Swiss Institute for Speleology and Karst Studies:
https://www.visualkarsys.com/courses .

2022

20 Jun -
21 Jun

Visual KARSYS Course N14 / co-organized with the 29th IKS and the Eurokarst Conference 2022

From 1 PM to 4 PM (GMT +00)

Online

Public

Employees 150 €, students 100 € (+ discount 50€)

info@visualkarsys.com

This workshop is dedicated to the learning of the KARSYS approach through an application on a pilot site by using the Visual KARSYS web-tool (www.visualkarsys.com). Participants will be introduced in theoretical aspects of the approach and in the practical process of its application. Participants to the 29th International Karst School or ot the Eurokarst Conference 2022 (Malaga) will receive a €50 discount on the course price.

Download program

POVABILO NA SPLETNI TEČAJ »KARSYS«

(ponedeljek in torek, 20. – 21. junija 2022)

Na spodnji povezavi si lahko preberete več informacij o spletnem tečaju KARSYS, ki ga organizirajo kolegi iz Švicarskega speleološkega in krasoslovnega inštituta:
https://www.visualkarsys.com/courses

PILEUS, OKOLJSKE REŠITVE

(from Monday to Wednesday, 13th – 15th June, 2022)

“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, 13. – 15. junija 2022)

“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!

FIELD TRIPS

FIELD TRIPS

Afternoon field trip (A):

CAVES IN PODGRAJSKO PODOLJE CONTACT KARST

Tuesday, 14. 6. 2022, 14:00–19:30

Nadja Zupan Hajna, Astrid Švara, Blaž Kogovšek, Janez Mulec

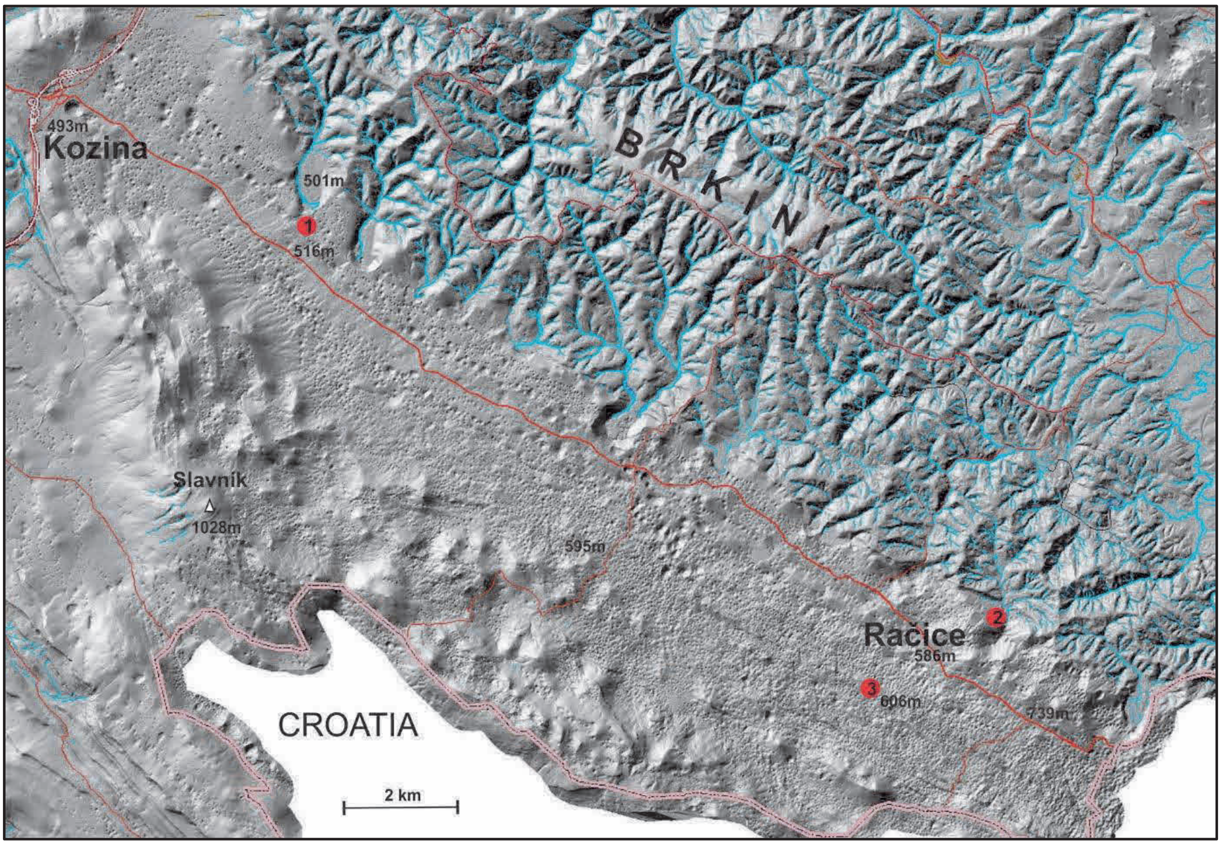


Fig. 1.01: Field trip stops in Podgrajsko Podolje; 1 – blind valley Brezovica, 2 – blind valley Račiška Dana, 3 – Račiška Pečina (cave).

CONTACT KARST

The contact karst of Podgrajsko Podolje (Figs. 1.01, 1.02) at the foot of Brkini hills was in past explained within the frame of cyclic and later climatic geomorphologic theory. Now we understand the contact karst features (e.g. Gams 1974, 2003; Mihevc 1991) as interaction of two systems of drainage, fluvial and karstic, which has distinctive geomorphic expression. Term contact karst describes karst that developed under the influence of the allogenic rivers, especially because of large quantity of water and sediment inflow. The term grows familiar in Dinaric karst where there are several such areas, which sharply contrast the karst without such influence. The allogenic discharge into the karst is responsible for the creation of several large blind valleys and large caves filled with allogenic sediments.

PODGRAJSKO PODOLJE BLIND VALLEYS

The Podgrajsko Podolje is a 20 km long and 2–5 km wide flat valley-like karst surface between mountain Slavnik and the Brkini hills (Figs. 1.01, 1.02). The hills, composed of Eocene flysch rocks (marls, quartz sandstone, and conglomerates) dissected by the fluvial relief are in the contact with the Cretaceous and Paleocene limestones (Fig. 1.01). The longitudinal section shows that the surface gently rises from about 490 m a.s.l. at Kozina village (in the northwest) to 650 m a.s.l. on the south-eastern end. The lowered surface continues towards SE but from the highest point near the blind valley Račiška Dana blind valley it lowers on the distance of 2 km for 200 m towards SE to surface of Brgudsko Podolje. This bend is most likely result of neotectonic movements.

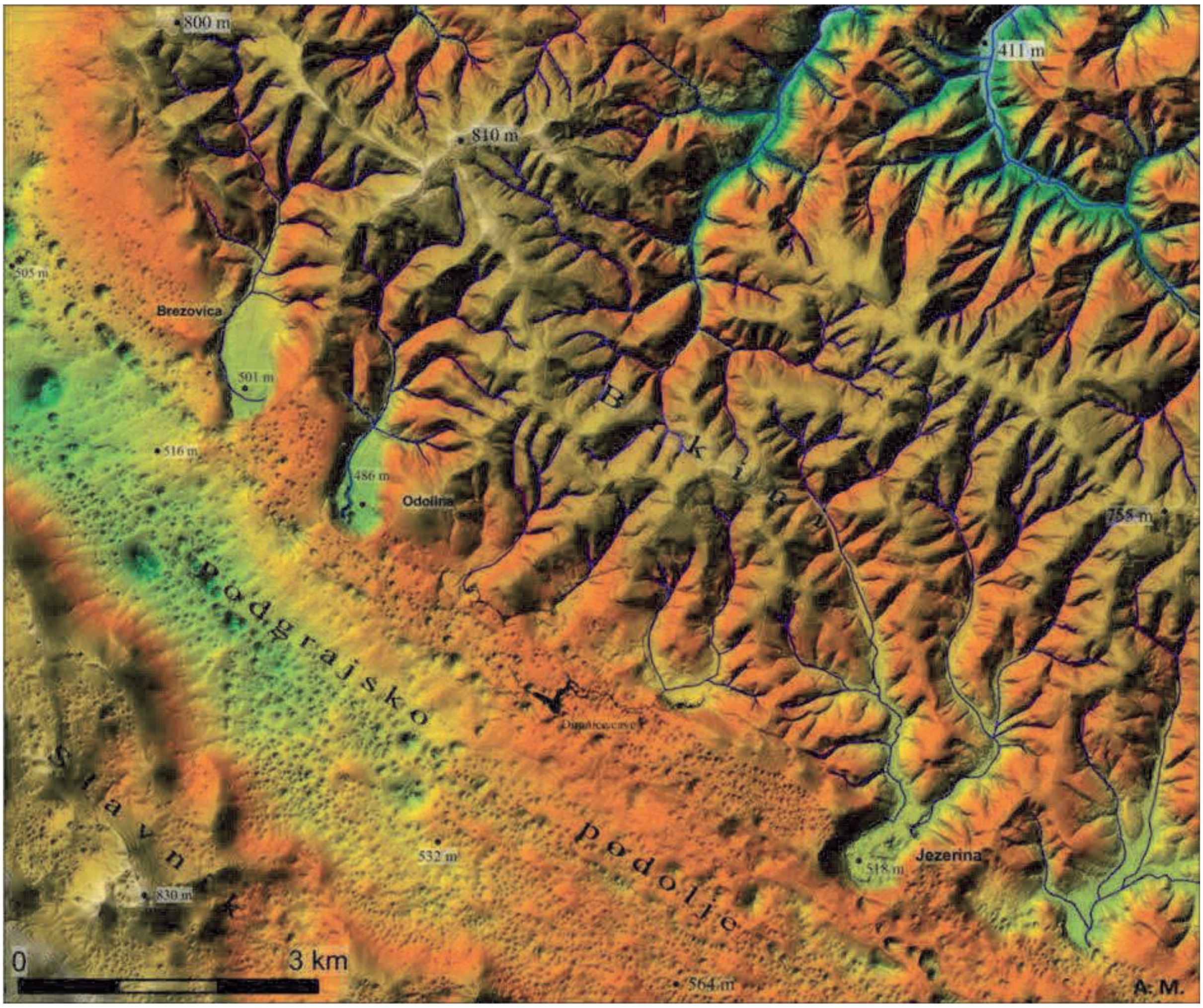


Fig. 1.02: Morphologically contact karst (center) is clearly seen as a row of blind valleys that are fed by surface streams flowing from fluvial relief (top). On lower part of the relief karst morphology surface was sculptured by precipitations only. Note solution dolines and larger collapse dolines. DEM (A. Mihevc) is made of 1 m grid Lidar data, Geodetski oddelek ARSO.

Surface of the Podgrajsko Podolje probably developed as a base-levelled plain, later it was dissected by the dolines and blind valleys. The blind valleys started to cut into the corrosion plain with small transverse and longitudinal gradient as in the contrary case the fluvial valleys should develop in them. They should be preserved on karst as dry valleys. Bad permeability (low gradient?) of the karst caused the deposition of the sediments on the edge of the karst in front of ponors and the deposits affected the planation and dissolution of the bottom of the blind valleys. In actual conditions the karst water table stays deep under the altitude of the blind valley bottoms (Mihevc 2001, 2007).

From the southern side of the Brkini hills water sinks in 18 separate streams into the karst of Podgrajsko Podolje (Figs. 1.01, 1.02, 1.03). A low gradient in the karst caused the deposition of the allogenic fluvial sediments on the edge of the karst in front of ponors. The sedimentation was caused because of a fast drop of transporting capacity of rivers which were losing water in karst in many separated small swallow holes and by the limited capacity of the ponors which caused back flooding and sedimentation. The floodwater and especially sediments enhance the dissolution of limestone below sediments, so blind valleys start by cutting down by corrosion into the previous base leveled surface.

Most of the brooks developed blind valleys bottom widened by corrosion. Blind valleys are deepened into border limestone for 250 m and its bottom lies 120 m below the surface of the Podolje. The bottoms of these valleys are situated between 490 to 510 m. As the blind valleys are incised in the border of the karst, uplifted towards SE, the blind valleys lying more to the south are deeper. The first, Brezovica blind valley is cut for 50 m only while the deepest is the last Račiška and Brdanska blind valleys. Possible sequence of the morphological events and dominant factors which were decisive for the formation of the actual relief forms were as follows: 1) The former shape along the contact with impermeable hills was levelled karst corrosion plain. The water flowing on it had modest gradient in karst and was capable of the planation of the surface only; 2) Tectonic uplift and lowering of the piezometric level enabled formation of deeper drainage and deepening of the blind valleys at the edge of Podgrajsko Podolje. Alogenic rivers no longer affected surface; 3) Surface has been lowered since for several hundred meters and is now cutting through many old caves. This has created unroofed caves or new entrances to caves. In some such a features old sediments are preserved.

Streams sink at 490 to 510 m a.s.l.; some can be followed in the accessible caves down to terminal sumps at 370 to 430 m a.s.l. The deepest cave is 150 m in-depth, and the longest is more than 6 km. More than a hundred vadose caves are known in the karst plain. A great oscillation of karst groundwater was observed. At the contact between Brkini and Podgrajsko Podolje, there are several caves in the blind valleys with access to groundwater, several of which end in syphons (Mihevc 1991). Continuous measurements of water levels are carried out in three caves: Dimnice, Odolinske ponikve and Hrušiške ponikve. During high water, the water level in Dimnice rises only up to 1.5 m, while in Odolinske and Hrušiške ponikve it is at least 40 m.

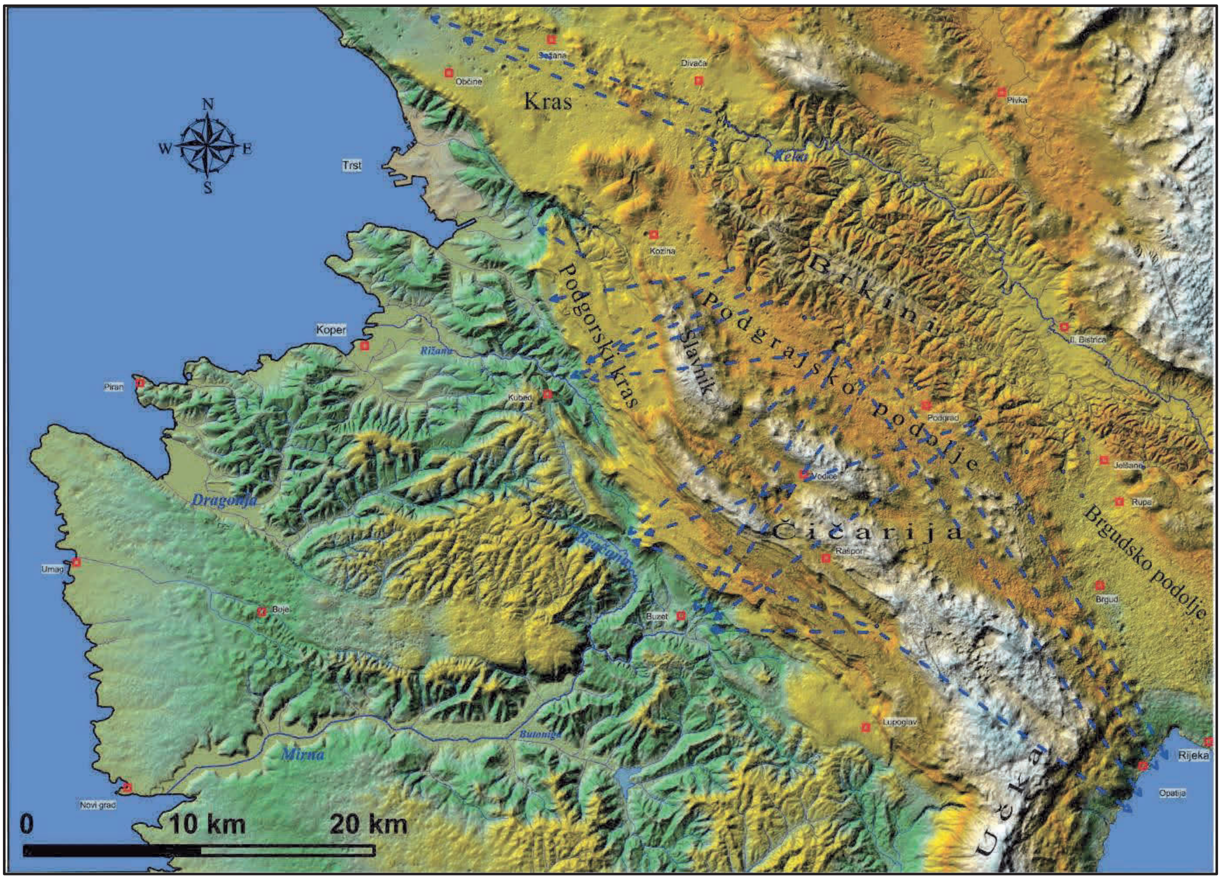


Fig. 1.03: Sinking streams of Podgrajsko Podolje and theirs underground water flows towards karst springs (modified from Zupan Hajna et al. 2015).

Water tracing showed that the sinking streams flow to three groups of springs: submarine springs along the coast in the Kvarner Bay, springs in Istria, and the Rižana springs (Fig. 1.03; Krivic *et al.* 1987, 1989; Prestor *et al.* 2015; Zupan Hajna *et al.* 2015). Continuous measurements of water levels were also carried out on surface streams in the blind valleys of Brezovica, Odolina and Jezerina. At low water, some disappear before reaching the ponors, and at high water, discharges can reach several m^3/s.

ACTIVE CAVE RAČIŠKE PONIKVE

Several streams flow from the Eocene flysch in this part of Podgrajsko Podolje, forming several active and fossil blind valleys, including the Račiška Dana blind valley (Fig. 1.04). The Račiška Dana blind valley was formed in Cretaceous and Paleocene limestones, in which there are also several ponors. The stream, which sinks into the ponor cave has a catchment area of about 3 km^2. The gradient of the tributaries is large. The brook flows from flysch to limestone about 400 m before it sinks in a cave Račiške Ponikve (Fig. 1.04, 1.05). Along the stream, an alluvial plain up to 40 m wide is formed at an altitude of about 475 m. At ponor, the steep slope turns into a wall up to 30 m high above the cave. At the present time, at an altitude of 470 m, the stream sinks into a short ponor steephead valley below its former, now fossil-blind valley (Mihevc 1991, 2007). A large fossil blind valley with a bottom at an elevation between 500 and 525 m has its edge at an elevation up to 750 m. In the bottom of this fossil blind valley some dolines have already been formed.

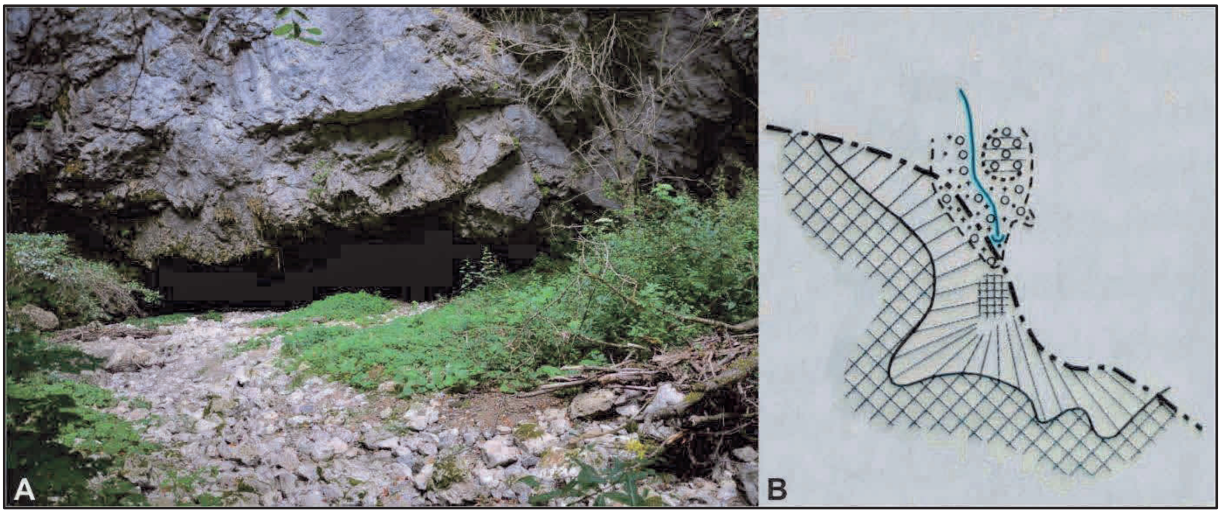


Fig. 1.04: A – entrance to the cave Račiške Ponikve in dry season; B – sketch of Račiška Dana blinde valley with ponor steephead (from Gams 2003).

Račiške ponikve is an epiphreatic cave with over 600 m long and 58 m deep intermittent stream at the bottom of the blind valley Račiška Dana. The cave consists of two passages, the lower one has a constant flow of water, but the upper one, slightly higher, is watered only occasionally. The main part of the cave is 300 m long and 9 m deep and ends in a hall with a large breakdown. It shows a paragenetic development, since the cave ceiling is completely levelled. Speleothems grow in several places in this passage. The alogenic sediments have their origin in weathered flysch rocks (main components: quartz, feldspar, chlorite, clay minerals). The dating of the stalagmite (60 cm long and 15 cm thick), which is occasionally flooded, failed because of the strong contamination of the speleothem layers with flood clay (Mihevc 2001).

In the entrance parts of Račiške ponikve on the cave walls a rich microbial mat has developed. The phototrophic mats were sampled at various distances from the cave entrance. In four macroscopically distinctive samples, 42 cyanobacterial and algal taxa were identified. Cyanobacteria dominated the aerophytic community, and more coccoid cyanobacteria were present in the community with increasing distance from the cave entrance. Although the cave walls of Račiške ponikve represent a typical aerophytic habitat, algae typical of aquatic and soil habitats were also present at all sampling sites (Mulec & Kosi 2008)

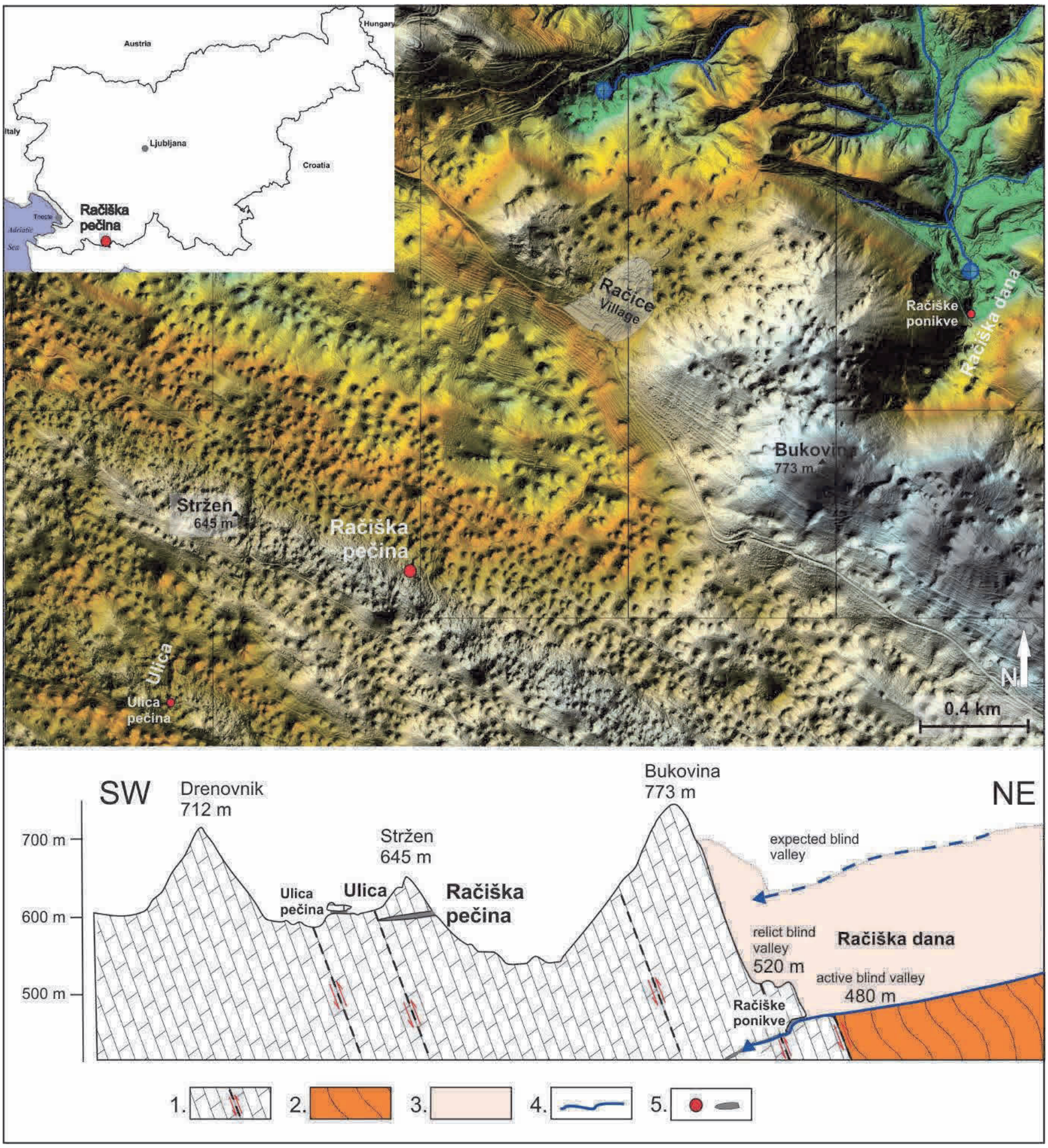


Fig. 1.05: Location of the cave Račiška pečina. DEM of the contact karst area (RS Lidar data, Geodetski oddelek ARSO) with studied cave position and schematic cross-section of the area. Legend: 1– carbonates (limestones and dolomites from the Cretaceous to the Paleocene) dissected by faults, 2– Eocene flysch rocks, 3– schematic outline of the relief from the time when Račiška pečina was an active water passage, 4– sinking streams in blind valleys, 5– cave entrances and caves (from Zupan Hajna et al. 2021).

RELICT CAVE RAČIŠKA PEČINA

The sedimentological record in the Račiška pečina cave sediment sequence is one of the best-preserved cave records of palaeoenvironmental changes for the last 3.4 Ma. However, as it is typical for cave terrestrial records, it contains many hiatuses in sedimentation. The section study helped to change the state of knowledge and understanding of the long-lasting deposition characteristics in the caves and provided enormous data on environmental changes over time.

Regarding the characteristics of karst areas where landscapes are exposed to chemical denudation, cave sediments from different environments and hydrological zones are often the only sediments representing the terrestrial phase of landscape evolution (e.g. Zupan Hajna et al. 2020). The Račiška pečina sediment section represents over 3 Ma of speleothem accumulation occasionally interrupted by infiltrated sedimentary deposits with palaeontological remains (Horáček et al. 2007; Zupan Hajna et al. 2008, 2010, 2020, 2021; Pruner et al. 2010; Moldovan et al. 2011; Miko et al. 2012). In about twenty years of research of this section, multiproxy approach was used: palaeomagnetism and magnetostratigraphy, mineralogy, geochemistry, sedimentology, petrology, stable isotopes, paleontology, and dating. The main focus of our work was on the palaeomagnetic research of the sediments, while numerical dating methods were used to improve the correlation of the obtained palaeomagnetic results with GPTS (Cande & Kent 1995; Grandstein et al. 2012; Cohen & Gibbard 2019), and paleontological finds further contributed to the chronological classification of the sediments.

Cave settings and speleogenesis

The Račiška pečina (Reg. No. 935; 45°30´12,10˝N; 14°09´00,83˝E; 609 m a. s. l.) is located in the south-western corner of Slovenia (Fig. 1.05), which geographically belongs to the NW edge of the Dinaric karst. Regarding climate conditions, the cave is located in the transitional Mediterranean climate zone with an average annual temperature of about 10.4°C and average annual precipitation of about 1,356 mm (http://meteo.arso.gov.si/).

From a geological point of view, the study area is located in the northwestern part of the Dinarides, in the collision zone between the Adria microplate and Eurasia. The tectonic evolution was largely controlled by the rotations of Adria (e.g. Handy *et al.* 2010), consequently, the formation of the present relief was under influence of its CCW rotations during the last 6 Ma. The northeastern microplate corner is bounded by the E–W-striking South-Alpine and NW–SE-striking Dinaric thrust belts and cut by dextral strike-slip faults (Vrabec & Fodor 2006). The cave is formed in thick-bedded limestones and dolomite with limestone breccias of the Lower Cretaceous, the beds dipping towards the north-east at an angle of up to 30° (Šikič *et al.* 1972). From the cave towards the blind valleys there is a succession of Lower Cretaceous limestones, dolomites, and their breccias through Upper Cretaceous limestones and dolomites to Paleocene and Eocene limestones, all deposited under different environments of the Adriatic Carbonate Platform. The marine carbonate sedimentation ended with an onlap of Eocene flysch deposition. The wider region has the character of an anticlinorium (Placer 1981), cut by numerous faults, reflect the multiphase kinematic evolution since Cretaceous (Jurkovšek et al., 1996). Based on the regional geology and the morphology of the cave passage, it can be assumed that the carbonate layers were already folded when the cave and its associated passages (channels) were active.

The entrance to the 304-meter-long cave passages is open to the north/northeast (Fig. 1.06). The cave consists of a simple horizontal, N–S-directed passage that is a relic of an old cave system partially opened to the surface. The passage is mostly over 10 m wide and 5–10 m high. On the southern side, the passage ends with the breakdown material. Skeletal remains (teeth, bones) and footprints were found on the cave floor, and scratch marks of the extinct *Ursus spelaeus* sp. were found on the cave walls and speleothems (Mihevc 2003). In the first half of the 20th century, the cave was used as a military magazine. The sediments in the floor of the cave were disturbed and mostly relocated. The cave floor was levelled and some large trenches were made in old massive speleothem domes. Our studied section is located in one of the trenches about 200 m from the cave entrance (fig. 6). Prior to military use of the cave, biologists visited the cave and discovered cave beetles (Verhoeff 1933). Although the cave was remodeled and used as a military object for decades, it is still quite rich in subterranean fauna (e.g. *Polak et al.* 2012).

The cave genesis has been associated with the evolution of local contact karst characteristics (Mihevc 2001, 2007). The cave is part of a relict cave system formed by allogenic streams flowing from the Eocene Flysch with ponors at about 630 m a.s.l. (Fig. 1.05). The cave functioned as part of a channels network, which included the now unroofed cave Ulica and the connected cave Ulica pečina (Zupan Hajna *et al*. 2008), that transferred water flow towards the springs. The gradient in the karst was low and the cave was at one time filled with fluvial sediments and shaped by paragenesis. The cave was deep below the karst surface during this time. Traces of phreatic (large cupolas and scallops), paragenetic and epiphreatic speleogenesis are still preserved in the cave. Allogenic material present in some places consists of weathered flysch remains (Zupan Hajna *et al.* 2008; e.g. quartz, muscovite/illite, chlorite, kaolinite, and feldspars). The transition to the vadose zone resulted in the exhumation and internal redistribution of the allogeneic cave fill and the beginning of the growth of massive speleothems (large domes and stalagmites) on allogeneic deposits. Signs of corrosion and erosion are visible on some of the oldest speleothems, possibly due to exposure to floodwaters, but no allogenic sediments were found between the flowstone layers. However, infiltrated clay- and silt-sized material is present between flowstone and other speleothem layers, containing very similar minerals to the allogenic sediments, but enriched in calcite, derived from weathered limestone and speleothem debris.

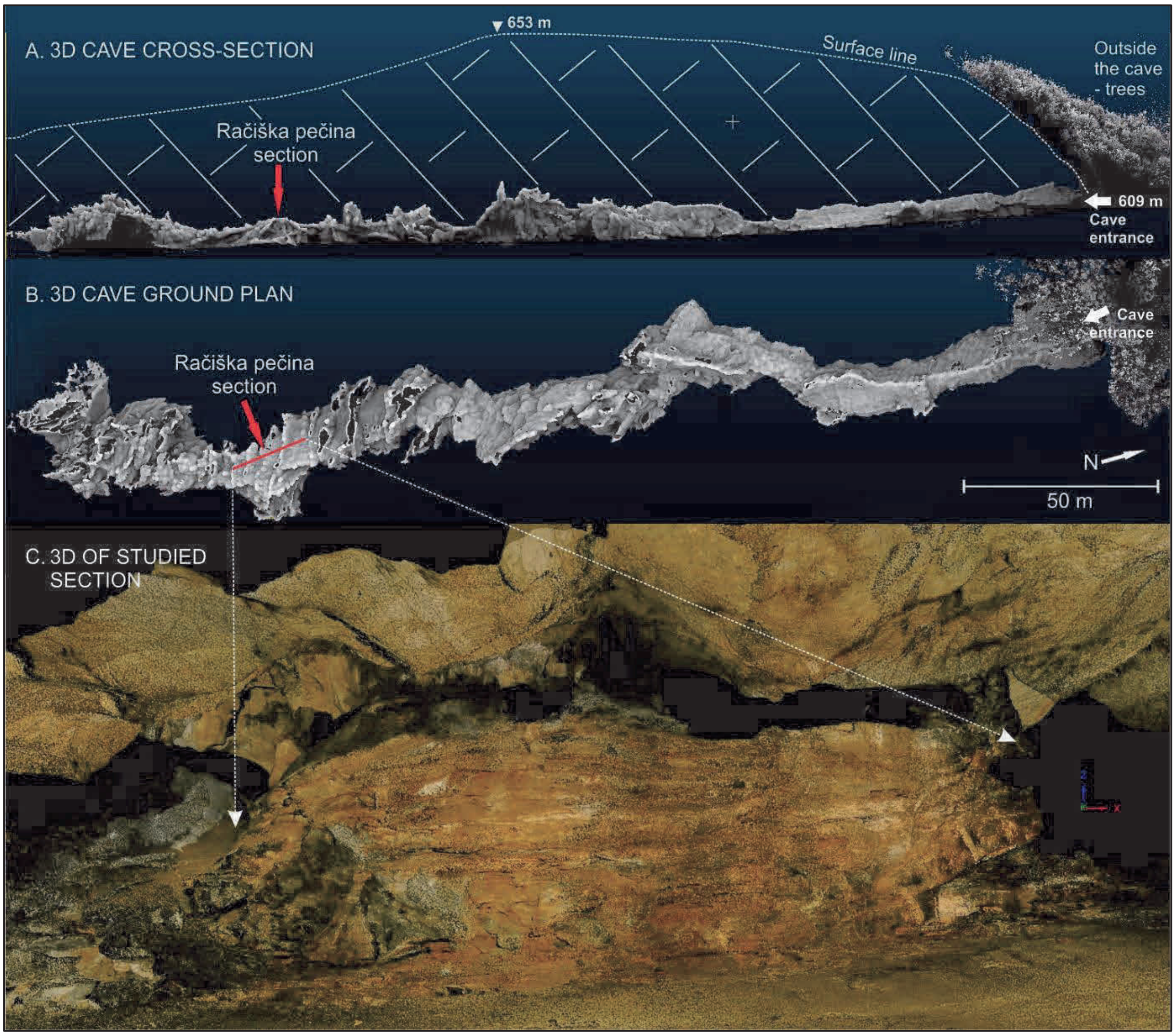


Fig. 1.06: The 3D cave image (cross-section and ground plan) of Račiška Pečina scanned by R. Walters and studied section (from Zupan Hajna et al. 2021). The section location and schematic thickness of the cave roof and the position of the surface position are given. The scale belongs to figures A and B.

Before the studied speleothem dome began to grow under vadose zone conditions, the cave was already disconnected from its hydrological function due to regional tectonic uplift (Mihevc 2007), and allogenic sediments were mostly eroded, but the cave remained closed to direct ventilation. The cave was later opened by chemical denudation of the overlying host-rocks and retreat of slopes towards the surface; with an average karst denudation rate of 20–60 m/Ma (Mihevc 2001) in the region, this occurred in the last 0.5 Ma. After the opening of the present entrance, cave bears began to enter the cave.

The recent ponors conveying water from the flysch through the subsurface to the springs are located at an elevation of about 500 m a.s.l.; the underground water connections to the springs at the Adriatic Sea (Fig. 1.03) were confirmed by tracer test (Krivic *et al.* 1989). The phreatic conduits are located now about 150 m below Račiška pečina. Two of the sinking streams are currently located only 2.5 km north and northeast of the cave (Fig. 1.05). The largest flows into the blind valley Račiška dana and sinks in the cave Račiške ponikve at about 480 m a.s.l. and continues towards the springs.

Sedimentary section study and results

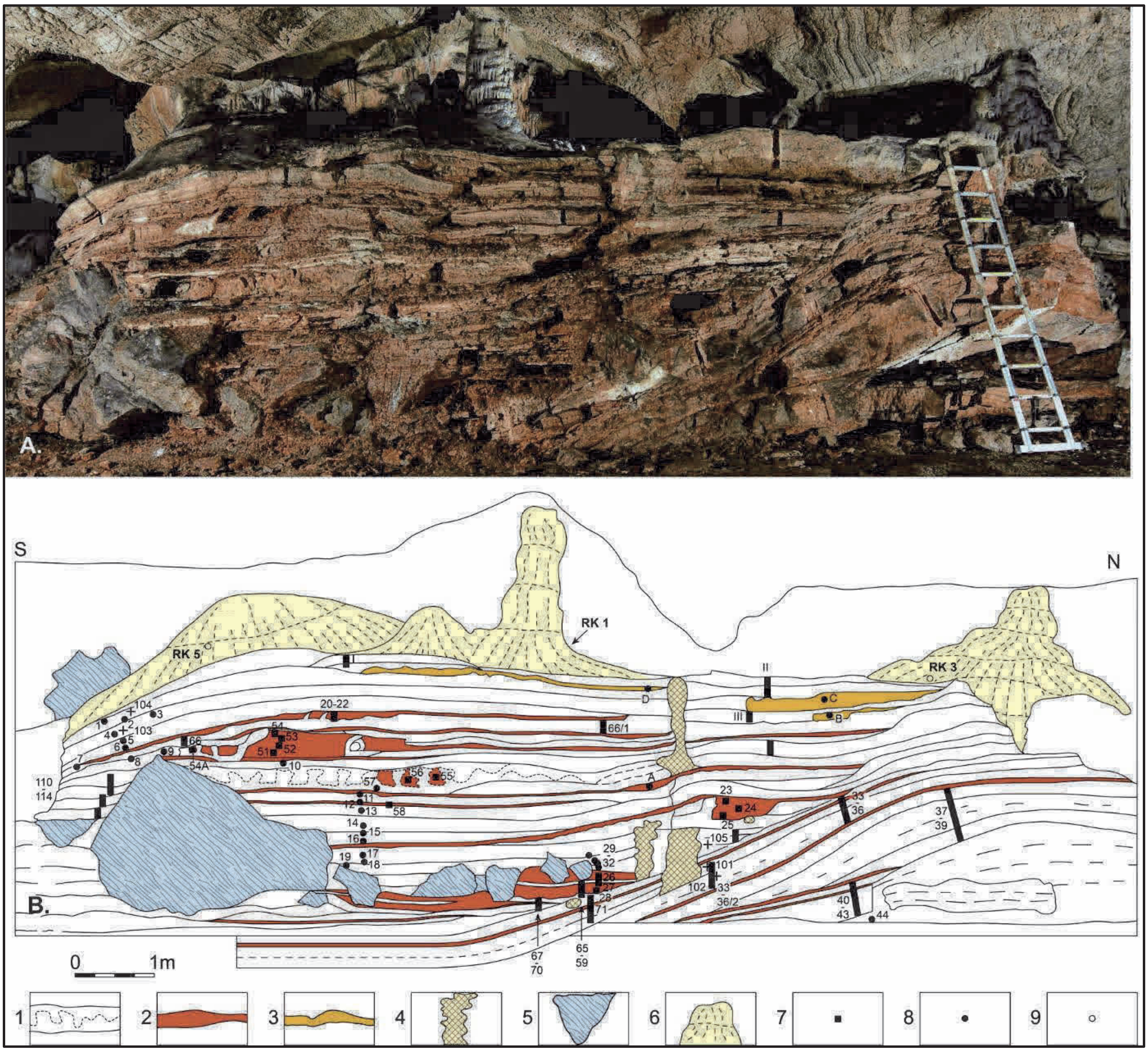


Fig. 1.07: Studied Račiška pečina sedimentary section with paleomagnetic samples positions and their numbers (from Zupan Hajna et al. 2021). 1 – rimstone pools, 2 – red clay layers, 3 – yellow clay layers, 4 – stalagmites, 5 – breakdown blocks of limestone, 6 – youngest speleothems, 7 – slices of speleothem layers for paleomagnetic analyses, 8 – cubes, RK – locations of drilled cores.

The research covered a sedimentary section about 13 m long and 3 m high (Fig. 1.07), consisting of flowstone layers intercalated by clay layers, in which paleontological material was also present. The section was hewed out in speleothem sometime after 1933. The section (Fig. 1.07) consists vertically of three main segments, and the thickness of the composite sample was 6.34 m (Zupan Hajna et al., 2008, 2020, 2021). The lowest section segment, located in the N part (colored light brown in Fig. 1.07), is up to 180 cm high and represents the growth stages of a large stalagmite dome. It consists of brown and reddish-brown, massive, porous speleothem layers with interlayers of red clay sediments (mostly 1–2 cm thick). Its accessible lowermost part ends with a distinct unconformity. The lowest layers of the section could not be accessed due to the presence of concrete installations in the cave floor. The middle segment (colored white in Fig. 1.07) of the section is up to 368 cm high in the central and S parts of the section, while it is up to 180 cm high in the N part. This segment consists of laminated porous flowstone, densely interbedded with red clays (1 mm to 10 cm thick). At the base of this segment are huge blocks of breakdown material and faunal remains in the deposited silty clay. The most upper segment (up to 96 cm high; colored light green in Fig. 1.07) is represented by light-colored, massive, laminated speleothem layers with two intercalations of greyish-brown/yellow clays with cave bear bones.

Horizontally, at the bottom of the N part of the section huge speleothem dome is present. This lowest dome stops growing at the end of the Pliocene/Pleistocene transition (Zupan Hajna *et al.* 2008; Sierpień *et al.* 2021). Above this dome, the section is divided into two parts by the stalagmite growing on the red clay layer, which represents the palaeomagnetic sample A (Fig. 1.07B). Above this layer, the two parts of the section had a different evolution. The S part represents the flowstone layers and rimstone pools above the breakdown material, and the N part represents the layers with large bones in yellow clay at the top of the section. The difference between these two parts is due to the different water sources that provided the water for the growth of the flowstone layer. The S part had a more constant and larger water inflow than the N part, which can be concluded from the presence of three layers of rimstone pools which are filled with red clay, and from the higher number of flowstone layers.

The whole section is covered by younger speleothems: two stalagmite domes and a column in the S part and a large stalagmite dome in the N part. On the section surface, above the top of the dome is a 1.5 m high opening to the cave ceiling, parts of the broken pottery were found by our team. The pottery still lies on micro and mezzo calcite gours which are now dry. It appears that the gours are dry for a long time because the pottery is loose and not attached by calcite in them. The pottery seems to date from the Bronze Age or later, but younger than Roman (Jamnik 2001; Skorupan 2003). Some of the upper flowstone layers (Fig. 1.07A) contain black laminae enriched in organic carbon (soot), which can be attributed to repeated human visitors to the cave. These layers have been dated to ~11 ka, ~9 ka, and ~3 ka. Although no archaeological excavations have been conducted, the location of the cave in close proximity to the natural pass between Adriatic Basin and inland may indicate that occasional visitors stopped here during their migrations from the very beginning of the Holocene (11.7 ka according to Cohen & Gibbard 2019) up to ~9 ka. The 3 ka old soot layer corresponds to the beginning of the Bronze Age in Europe (e.g. Langgut *et al.* 2015). In recent years, many studies deal with ancient human migrations (e.g. Palmisano *et al.* 2021) influenced by past climatic fluctuations detected also in stalagmites (e.g. Finné *et al.* 2017). The upper part of our studied section also contains evidence of such variability.

Multiproxy studies were used to identify the alternation of N- and R-polarized magnetozones and short-term excursions of the magnetic field, the palaeomagnetic log was calibrated by palaeontological data and U-series dating to obtain the time of deposition of the section, and stable isotopes were recorded to detect changing climate conditions during the last 3.2 Ma (Zupan Hajna *et al.* 2021). In the sequence are by **magnetostratigraphy** well recorded Pliocene/Pleistocene transition at 2.59 Ma, the Matuyama/Brunhes boundary at 0.773 Ma, and the presence of Olduvai subchron between 1.78–1.925 Ma.

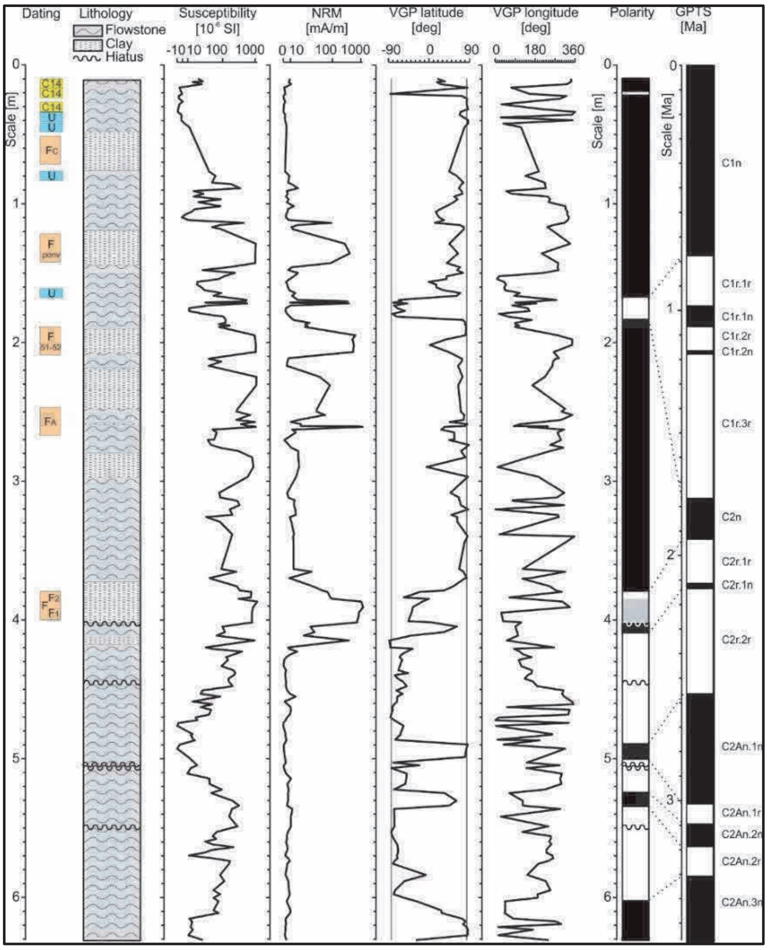


Fig. 1.08: The new magnetostratigraphic profile was correlated with GPTS (Cande and Kent, 1995; Gradstein et al., 2012; Cohen and Gibbard, 2019) and calibrated with paleontological data (Horáček et al. 2007; from Zupan Hajna et al. 2021). Polarity log: black – normal polarity, white – reverse polarity, grey – transitional polarity.

The finds of **small mammals** in sample F (Figs. 1.07, 1.09) of the section (Horáček *et al.* 2007; Pruner *et al.* 2009, 2010; Zupan Hajna *et al.* 2020) suggested dating to the mid-late MN17 mammalian biozone – the upper boundary of MN17 well-marked by FAD *Microtus* (*Allophaiomys*) *pliocaenicus* (see Horáček *et al.* 2007 for details) and related radical rearrangements in the structure of mammalian communities is correlated with the onset of the Olduvai event (Moldovan *et al.* 2011) found the fossil invertebrates of oribatid mites belonging to the same ecological group of forest inhabitants in their sample R4 (Fig. 1.09); this fauna was also determined as MN17–Q2 fauna.

Records of small mammals from the lower part of the section (a molar of *Apodemus* cf. *atavus* and dental fragments of *Borsodia* sp., and *Pliomys* sp.) suggest MN17 age, *Clethrionomys* cf. *glareolus* from the upper part suggests the Late Early or Middle Pleistocene age. Small mammals were found also in three of seven clay samples PONV, RD1 and F2 (Zupan Hajna *et al.* 2021). The best-preserved finds determined as *Clethrionomys glareolus* are from the site PONV. The same genus was also determined in the sample RD1. *Clethrionomys* is present from MN17– to recent, from the late Early Pleistocene (Q2 sensu Horáček & Ložek 1988) it represents the most common member of small ground mammal communities of Europe. The enamel fragment from F2 belongs to *Pliomys*, the genus which major radiation took place during the earliest Pleistocene (MN17–Q1).

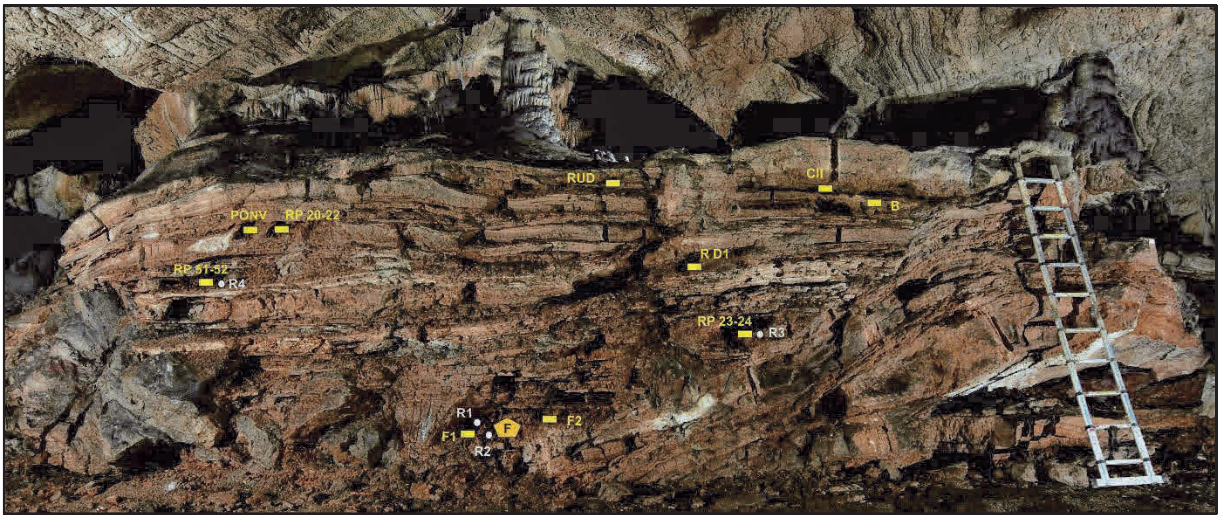


Fig. 1.09: Locations of the paleontological samples. Sample F (Horáček et al. 2007), samples R1–4 (Moldovan et al. 2011) and yellow boxes with their names represent novel results (from Zupan Hajna et al. 2021).

In the upper part of the section ***Ursus* ex gr. *spelaeus*** was confirmed (in sample CII) in the yellow clay layer older than ~72 ka (Zupan Hajna *et al.* 2021). Unfortunately, only two bones and a tooth fragment obtained during the last sampling could be used for taxonomic evaluation (Fig. 1.09). However, we prefer to assign all ursid specimens to the same taxon regarding their characteristic, to large cave bears (*Ursus* ex gr. *spelaeus*). They are typical representatives of European Late Pleistocene faunas which disappeared around 26,100–24,300 cal. BP.

Also worth mentioning are records of gastropod shells (Zupan Hajna *et al.* 2021) *Aegopinella* sp. and a troglobiont snail *Zospeum* sp. (Bole 1974). The most impressive of the last fauna finds were specimens, fragments, and imprints (partly petrified) of the **troglobiotic snail *Zospeum* sp**. in three samples PONV, RP 51–51, F2 of different ages (Fig. 1.07). According to the findings of fossil subterranean snails (samples F2, RP51–52, RP20–22) in clay layers dated by other methods, we can predict that they inhabited the cave at least since 2 Ma ago (Zupan Hajna *et al.* 2021). With the regard to DNA studies and molecular delimitation modelling (Weigand *et al.* 2013), the *Zospeum* belongs to subterranean evolutionary lineages which diversification is characterized by rare, long-range colonization events with *in situ* radiation into several lineages occupying isolated cave systems. With the respect to geographic distribution and evolutionary history of the group, these studies also assumed that European *Zospeum* originated no earlier than the beginning of the Early Cenozoic (approximately 65 Ma) with the start of Alpine orogeny. However, in our case, where the studied cave is located in the NW part of the Dinarides, the flysch was deposited over older carbonate rocks during Eocene. Here the maximum theoretical age can be set to the Eocene/Oligocene transition (approximately 40 Ma; Drobne *et al.* 2009). The findings of fossil subterranean snails (Zupan Hajna *et al.* 2021) presented here are the first palaeontological discoveries in general and can thus contribute to the knowledge of the maximum age and evolutionary history of this group. The only other true subterranean animal found so far in cave sediments was *Marifugia cavatica* (Annelida: Serpulidae) from Črnotiče unroofed cave (Mihevc 2000; Bosák *et al.* 2004).

A **detailed chronology** of the Račiška pečina section based on magnetostratigraphy and isotopic oxygen stratigraphy was created and correlated with palaeontological, U-series, and radiocarbon results (Zupan Hajna *et al.* 2021; Fig. 1.10). The Račiška pečina section deposited from ca 3.4 Ma to ca 80 ka (MIS Km3 to MIS 5). The section was divided in terms of stable isotope studies into two segments separated by principal disconformity (hiatus). The palaeoenvironmental changes associated with these disconformities were well expressed by the changing values of stable isotopes (Zupan Hajna *et al.* 2021; Sierpień *et al.* 2021). The lower segment correlates better with the regional Medi curve (Wang *et al.* 2010), while the upper segment – with the global LR04 curve (Lisiecki & Raymo 2005). This indicates changes in the main factors controlling environmental conditions in the area. From about 2.6–2.5 Ma climatic conditions were mainly controlled by global Atlantic Ocean factors. The Brunhes/Matuyama boundary occurred at MIS 19, at about 773 ka. Changes in the C and O isotopic records reflect the interglacial climate with the increase in temperature and decrease in humidity at this time and also the opening of the cave to the surface sometime between 500 ka and 350 ka ago. Since that time, large mammals, such as cave bears, have been able to enter the cave.

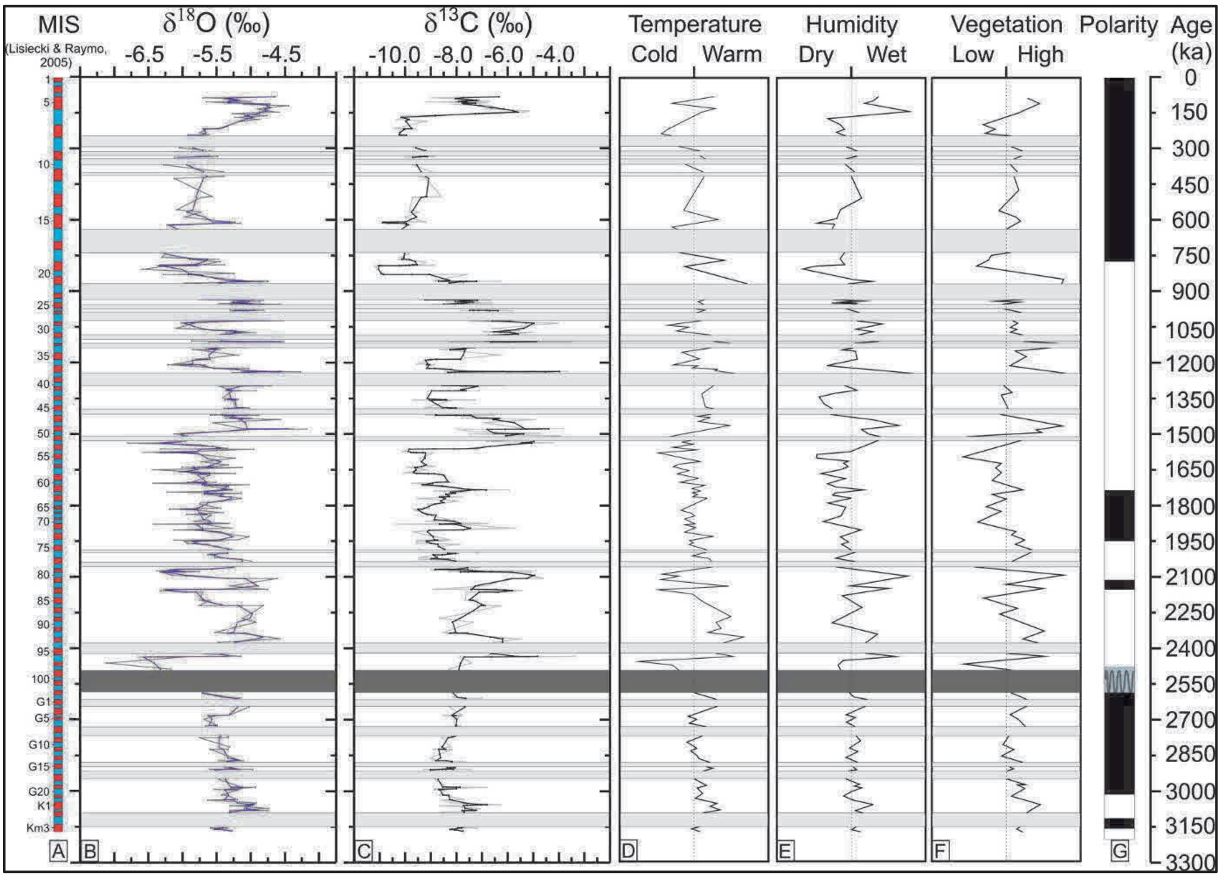


Fig. 1.10: Interpretation of oxygen and carbon record in the age scale(from Zupan Hajna et al. 2021). Legend: A – the scale of Marine Isotope Stages (MIS; warm – red; clod – blue; Lisiecki & Raymo, 2005); B – the record of oxygen stable isotope (smoothed data –blue; raw data – grey); C – the isotopes record of carbon stable isotopes (smoothed data – black; raw data – grey); D – the temperature curve; E – the humidity curve; F – the vegetation curve (low – the negligible presence of plants around the cave; the high – significant presence of plants around the cave); G – magnetostratigraphy log according to Pruner et al. (2009); black – normal polarity, white – reverse polarity, grey – transitional polarity, wavy line – the main disconformity; grey boxes – hiatuses; dark grey box – the main disconformity.

The Olduvai section is worth of interest (Zupan Hajna *et al.* 2021). With its thickness of ~200 cm (after clay/silt compaction) lasted for ~150 ka (1.78–1.925 Ma after Cohen & Gibbard 2019). The OIS model of the Olduvai section detected any longer hiatus (Fig. 1.10). It could be interpreted as continued deposition without substantial interruptions even during clay/silt deposition. The calculated average deposition rate of the Olduvai section was about 1.2 cm/ka, if taking into account eventual erosion of the clay/silt intercalations and corrosion of the speleothem calcite, we can speculate on a depositional rate up to 2 cm/ka. There are 6 thicker clay/silt layers and ~12 principal bedding planes in flowstones within the Olduvai section. If we speculate that the clay/silt and flowstone layers reflect changes in palaeoenvironmental conditions at the surface. The periodicity of principal bedding planes in the flowstones and clay/silt interbeds could, with all uncertainties, indicate the periodicity of the principal changes in periods with durations of ~15 ka and ~30 ka, respectively, i.e. very close to 11 and 40 ka long Milankovitch cycles (Milankovitch 1941) or 13-17 ka and 21-23 ka cyclicity of mean sea-level changes (Chapanov *et al.* 2015). The number of very thin clay/silt intercalations allows us to speculate more on finer palaeoclimatic oscillations outside the cave (needs further research), and their influence on depositional processes and history in the cave interior facies, deep within the cave.

With the latest research, we have found that the **history of dome deposition** is even more complicated (Zupan Hajna *et al.* 2021) than we thought in the first studies (e.g. Horáček et al., 2007; Zupan Hajna et al., 2008). With the new results from fauna, radiocarbon, and U-series dating, we were able to show that the N and S parts of the section have a different history of flowstone deposition and that the section actually consists of at least three overgrown speleothem domes (Zupan Hajna *et al.* 2021). But regarding the Račiška pečina section complicated structure (Fig. 1.11), there are still parts of it that have not been studied or dated.

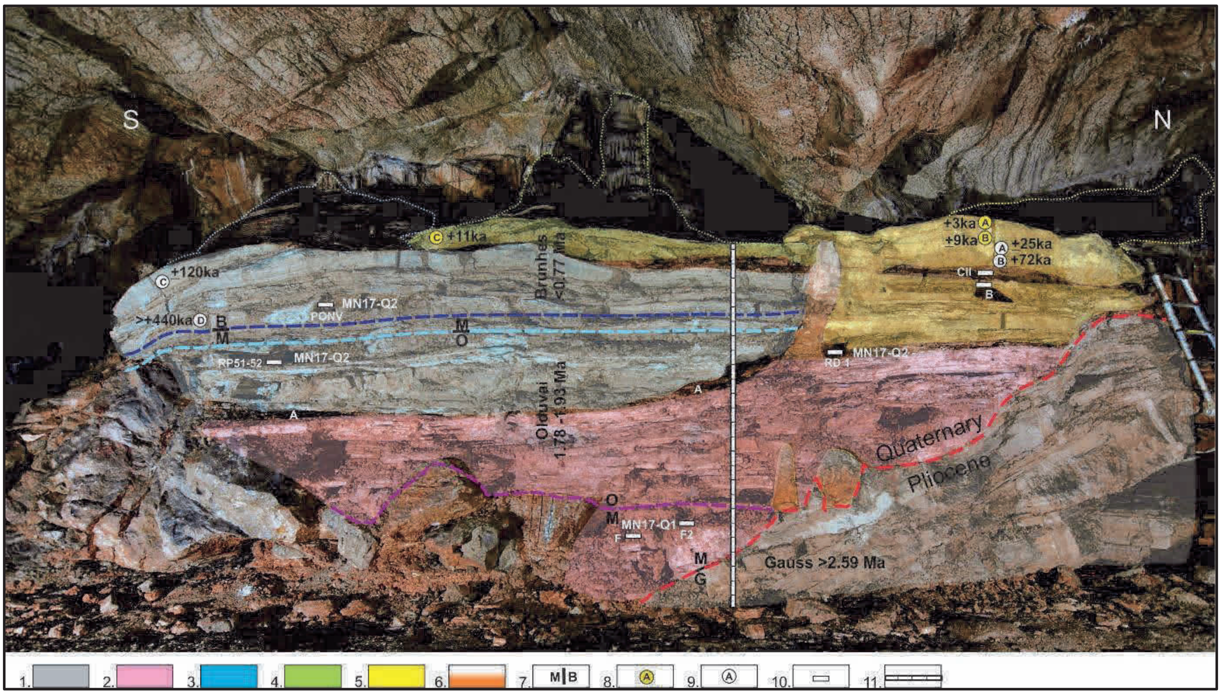


Fig. 1.11: Račiška pečina section with speleothem domes growth relations, dating results, and detected chron and subchron boundaries (from Zupan Hajna et al. 2021). Legend: 1 – N oldest dome, 2 – N middle dome, 3 – S dome, 4 – central top dome, 5 – N youngest dome, 6 – central stalagmites, 7 –chron and subchron boundaries, 8 – radiocarbon results, 9 – U-series results, 10 – paleontological samples with results, 11 – schematic location of stable isotopes log.

On the N side of the section (Fig. 1.12), the oldest speleothem dome (grey in Fig. 1.12) grew during Late Pliocene and its deposition terminated at the Pliocene/Quaternary transition. After that, two stalagmites were deposited from dripping water. For the middle speleothem dome (pink in Fig. 1.12) we do not know where it was fed from, but it grew during the Early Pleistocene and part of the Olduvai subchron. From time to time infiltrated silty clays were deposited between the speleothem layers, containing remains of fauna and broken soda straws. The deposition of this middle dome was significantly interrupted by a red clay layer (sample A) that was traced across the entire section. The palaeontological sample (RD1) from this layer already contains Late Pleistocene fauna (see Table 4). Stalagmite was deposited above this clay layer, which overlaid all the older calcite layers, and the section was divided horizontally into two parts. From there, the N and S sides of the section have different evolution and flowstone layers deposited by different water sources. The S speleothem dome (blue in Fig. 1.12) grew over the red clay layer A and contains the well-recorded Matuyama/Brunhes boundary. The only layer recorded in both upper parts is yellow clay, containing remains of *Ursus spelaeus*. At the top of the middle part of the section, the central upper dome (green in Fig. 1.12) has grown. The Račiška pečina section, like similar sediment types from other karst caves, does not allow continuous isotope records as in stalagmites but contains information about an extremely long depositional period.

Importance of speleothem dome

From results by Zupan Hajna *et al.* (2021) can be concluded that under the drier conditions no speleothem deposition occurred, which is reflected in short and long-lasting hiatuses in the studied section. It is also obvious that during a period of stronger rainfall events (higher water energy) the deposition of infiltrated clay material occurred over the existing speleothems. During the same events, existing fauna remains were washed and deposited in the currently active clay layer of the section. All clay layers were then covered with overlying flowstone layers, making them inaccessible from the surface and at the same time protecting them from younger erosion. With such an order of sedimentation, the fauna present in the respective layers represents the approximate sedimentation time. The Račiška pečina section is so fat a really important source of climate information for the last 3 Ma including the Pliocene/Quaternary and Matuyama/Brunhes transitions. We can conclude that the records from the Račiška pečina section have added to the knowledge of regional tectonic and climatic conditions, as well as palaeoclimatic transitions during the enclosed time in general.

The sedimentation in the cave reflected the evolution of the surrounding landscape, i.e. the regional uplift and climatic changes from the Late Pliocene to the Holocene. When the cave acted as a conduit between ponors at blind valleys and springs on the Adriatic Coast, allogenic sediments were deposited. After the cave was detached from its hydrological function due to the regional uplift (Mihevc 2007), speleothems started to deposit in the vadose zone. Clay sediments were deposited on existing speleothems only from infiltration waters.

The research of this section has also shown that speleothem domes contain a lot of different data that cannot be recorded in a single borehole or a single stalagmite.

REFERENCES:

- Bole, J., 1974: Die Gattung Zospeum Bourguignat 1856 (Gastropoda, Ellobiidae) in Jugoslawien. Razprave Slov. Akad. Znan. Umetn. 17, 249–282.
- Bosák, P., Mihevc, A., Pruner, P., 2004: Geomorphological evolution of the Podgorski Karst, SW Slovenia: Contribution of magnetostratigraphic research of the Črnotiče II site with Marifugia sp. Acta Carsol. 33(1), 175–204. https://doi.org/10.3986/ac.v33i1.323.
- Cande, S.C., Kent, D.V., 1995: Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. J. Geophys. Res. 100(B4), 6093–6095. https://doi.org/10.1029/94JB03098/.
- Chapanov, Y., Ron, C. and Vondrák, J., 2015: Millennialcycles of mean sea level excited by Earth´s orbitalvariations. Acta Geodyn.Geomater., 12, 3 (179), 259–266. https://doi.org/10.13168/AGG.2015.0028
- Cohen, K., Gibbard, P., 2019: Global chronostratigraphical correlation table for the last 2.7 million years QI 500. Quat. Int. 500, 20–31. https://doi.org/10.1016/j.quaint.2019.03.009.
- Drobne, K., Ogorelec, B., Pavšič, J., Pavlovec, R., 2009 : Paleocene and Eocene in south-western Slovenia, in: Pleničar, M., Ogorelec, B., Novak, M. (Eds.), The Geology of Slovenia. Chapter 6.2, 311–372.
- Finné, M., Holmgren, K., Shen, C.C., 2017: Late Bronze Age climate change and the destruction of the Mycenaean Palace of Nestor at Pylos. PLoS ONE 12(12): e0189447. https://doi.org/10.1371/journal.pone.0189447.
- Gams I., 1974: Kras. Slovenska matica, 359 pp.
- Gams I., 2003: Kras v Sloveniji v prostoru in času. ZRC Publishing, ZRC SAZU, 516 pp.
- *Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M. (Eds.), 2012: The geologic time scale 2012. Elsevier 1.* https://doi.org/10.1016/C2011-1-08249-8.
- Handy, M.R., Schmid, S.M., Bousquet, R., Kissling, E., Bernoulli, D., 2010: Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological–geophysical record of spreading and

subduction in the Alps. Earth Sci. Rev. 102(3–4), 121–158. https://doi.org/10.1016/j.earscirev.2010.06.002

- Horáček, I., Ložek, V., 1988: Palaeozoology and the Mid-European Quaternary past: Scope of the approach and selected results. Rozpravy ČSAV, řada matematických a přírodních věd, 98(4), 1–106.
- *Horáček, I., Mihevc, A., Zupan Hajna, N., Pruner, P., Bosák, P., 2007: Fossil vertebrates and paleomagnetism update one of the earlier stages of cave evolution in the Classical Karst, Slovenia: Pliocene of Črnotiče II site and Račiška pečina. Acta carsologica, 37(3), 451–466.* https://doi.org/10.3986/ac.v36i3.179.
- Jamnik, P., 2001: Račiška pečina. Varstvo spomenikov 38, 107.
- Jurkovšek, B., Toman, M., Ogorelec, B., Šribar, L., Drobne, K., Poljak, M., Šribar Lj., 1996: Geological map of the southern part of the Trieste-Komen Plateau 1:50.000: Cretaceous and Paleogene carbonate rocks. Inštitut za geologijo, geotehniko in geofiziko.
- Krivic, P., Bricelj, M., Trišić, N. & M. Zupan, 1987: Sledenje podzemnih vod v zaledju izvira Rižane (Slovenija, NW Jugoslavija). Acta carsologica, 16, 83–104.
- Krivic, P., Bricelj, M., Zupan, M., 1989: Underground water connections in Čičarija region and in Middle Istria (Slovenia, Croatia, NW Yugoslavia). Acta carsologica, 18, 265–284.
- *Langgut, D., Finkelstein, I., Litt, T., Neumann, F.H., Stein, M., 2015: Vegetation and Climate Changes during the Bronze and Iron Ages (3600–600 BCE) in the Southern Levant Based on Palynological Records. Radiocarbon 57(2), 217 – 235. https://doi.org/10.2458/azu_rc.57.18555.*
- *Lisiecki, L.E., Raymo, M.E., 2005: A Pliocene-Pleistocene stack of 57 globally distributed benthic δ18O records. Paleoceanography and Paleoclimatology 20(1) PA1003. hppts://doi.org/10.1029/2004pa001071.*
- Mihevc, A., 1991: Morfološke značilnosti ponornega kontaktnega krasa v Sloveniji.- Geografski vestnik, 63, 41–50.
- Mihevc, A., 2000: The fossilized tubes from the roofless cave – probably the oldest known remains of the cave worm Marifugia (Annelida: Polychaeta). Acta Carsol. 29(2), 261–270. https://doi.org/10.3986/ac.v29i2.465.
- Mihevc, A., 2001: Speleogeneza Divaškega krasa. ZRC Publishing, Ljubljana.
- Mihevc, A. 2003: Sledovi jamskega medveda v Račiški pečini. Naše jame 45, 48–55.
- Mihevc, A., 2007: The age of karst relief in West Slovenia. Acta Carsol. 36(1), 35–44. https://doi.org/10.3986/ac.v36i1.206.
- Miko, L., Mourek, J., Meleg, I.N., Moldovan, O.T., 2012: Oribatid mite fossils from Quaternary and pre-Quaternary sediments in Slovenian caves I. Two new genera and two new species of the family Oppiidae from the Early Pleistocene. Acta Mus. Nat. Pragae, Ser. B, Hist. Nat. 68(1–2), 23–34.
- Milankovitch, M., 1941. Kanon der erdbestrahlung und seine anwendung auf das eiszeitproblem. Akad. Royale Serbe 133.
- Moldovan, O., Mihevc, A., Miko, L., Constantin, S., Meleg, I., Petculescu A., Bosák, P., 2011: Invertebrate fossils from cave sediments: a new proxy for pre-Quaternary paleoenvironments. Biogeosciences 8(7), 1825–1837. https://doi.org/10.5194/bg-8-1825-2011.
- Mulec, J., Kosi, G., 2008: Algae in the aerophytic habitat of Račiške ponikve cave (Slovenia). Natura Sloveniae, 10, 39-49.
- Palmisano, A., Lawrence, D., de Gruchy, M.W., Bevan, A., Shennan, S., 2021: Holocene regional population dynamics and climatic trends in the Near East: A first comparison using archaeo-demographic proxies. Quat. Sci. Rev 252, 106739. https://doi.org/10.1016/j.quascirev.2020.106739.
- Placer, L., 1981: Geologic structure of southwestern Slovenia. Geologija 24(1), 27–60.
- Polak, S., Bedek, J., Ozimec, R., 2012: Subterranean Fauna Of Twelve Istrian Caves. Annales, Ser. hist. nat. 22(1), 7–24.
- Prestor, J., Pekaš, Ž., Kuhta, M., Koželj, A., Janža, M., Brkić, Ž., Celarc, B., Larva, O., Meglič, P., Dolić, M., Urbanc, J., Simić, B., Tot, I., Podboj, M., Maldini, K., Levičnik, L., Matić, N., Ferjan Stanič, T., Brun, C., Šram, D., Mrmolja, N., Mavc, M. & S. Pestotnik, 2015: Projekt ISTRA-HIDRO. Trajnostno upravljanje s čezmejnimi podzemnimi vodami med Tržaškim in Kvarnerskim zalivom / Održivo

upravljanje prekograničnim podzemnim vodama između Tršćanskog i Kvarnerskog zaljeva. Rezultati projekta.- Evropsko teritorialno sodelovanje SI – HR / Europska teritorijalna suradnja SI – HR. 182 str., 10 prilog. Ljubljana, Zagreb, Koper. Medmrežje: http://www.istra-hidro.eu/images/Produkti/novo/Vodilna_mapa_Vodeća_mapa_projekta_ISTRA_HIDRO_8i_KM_e.pdf

- Pruner, P., Bosák, P., Zupan Hajna, N., Mihevc, A., 2009. Cave sediments in Slovenia: results of 10 years of palaeomagnetic research. Slovenský kras (Acta Carsol. Slovaka) 47(2), 173–186.
- Pruner, P., Zupan Hajna, N., Mihevc, A., Bosák, P., Venhodová, D., Schnabl, P., 2010: Magnetostratigraphy and fold test from Računa pečina and Pečina v Borštu caves (Classical Karst, Slovenia). Stud. Geophys. Geod. 54(1), 27–48. https://doi.org/10.1007/s11200-010-0002-1.
- *Sierpień, P., Bosák, P., Hercman, H., Pawlak, J., Pruner, P., Zupan Hajna, N., Mihevc, A. 2021: The paleoclimate reconstruction of 3.2 Ma history in flowstones from the cave Račiška pečina (SW Slovenia): stable isotopes and isotopic oxygen stratigraphy (correlated by magnetostratigraphy). Geochronometria, 48, 31–45.*
- Šikić, D., Pleničar, M., Šparica, M., 1972. Osnovna geološka karta SFRJ, list Ilirska Bistrica, 1 : 100 000. Zvezni geološki zavod Beograd, Beograd.
- *Skorupan, J., 2003: Koščena igla iz Račiške pečine. Naše jame 45, 145–146.*
- Verhoeff, K.W., 1933: Arthropoden aus sudostalpinen Höhlen, gesammelt von Karl Strasser. Mitteilungen über Höhlen- und karstforschung 4, 1–21.
- *Vrabec, M., Fodor, L., 2006: Late Cenozoic Tectonics of Slovenia: Structural Styles At the Northeastern Corner of the Adriatic Microplate. In: Pinter, N. (Ed.), The Adria Microplate: GPS Geodesy, Tectonics and Hazards. Springer, 151–168.*
- Wang, P., Tian, J., Lourens, L.J., 2010: Stack of stable carbon and oxygen isotope record for Mediterranean Sea sediments. Earth Planet. Sci. Letters 290(3–4), 319–330. https://doi.org/10.1594/PANGAEA.790006.
- Weigand, A.M., Jochum, A., Slapnik, R., Schnitzler, J., Zarza, E., Klussmann-Kolb, A., 2013: Evolution of microgastropods (Ellobioidea, Carychiidae): integrating taxonomic, phylogenetic and evolutionary hypotheses. BMC Evolutionary Biology 13(18), 1–23. http://doi.org/ 10.1186/1471-2148-13-18
- Zupan Hajna N., Ravbar N., Rubinić J., Petrič M. (Eds.), 2015: Life and water on karst: monitoring of transboundary water resources of Northern Istria. ZRC Publishing, Ljubljana, 151 pp.
- Zupan Hajna, N., Bosák, P., Pruner, P., Mihevc, A., Hercman, H., Horáček, I., 2020. Karst sediments in Slovenia: Plio-Quaternary multi-proxy records. Quat. Int. 546, 4–19. https://doi.org/10.1016/j.quaint.2019.11.010.
- *Zupan Hajna, N., Mihevc, A., Pruner, P., Bosák, P., 2008: Paleomagnetism and magnetostratigraphy of karst sediments in Slovenia. ZRC Publishing, Ljubljana-Postojna.*
- *Zupan Hajna, N., Mihevc, A., Pruner, P., Bosák, P., 2010. Paleomagnetic research on karst sediments in Slovenia. Int. J. Speleol. 39(2), 47–60.* https://doi.org/10.5038/1827-806X.39.2.1.
- Zupan Hajna, N., Mihevc, A., Bosák, P., Pruner, P., Hercman, H., Horáček, I., Wagner, J., Čermák, S., Pawlak, J., Sierpień, P., Kdýr, Š, Juřičková, L., Švara, A., 2021: Pliocene to Holocene chronostratigraphy and paleoenvironmental records from cave sediments: Račiška pečina section (SW Slovenia).- Quaternary International, 605–606, 5–24. https://doi.org/10.1016/j.quaint.2021.02.035

Afternoon field trip (B):

CAVES OF THE NORTHERN BORDER OF PLANINA POLJE

Wednesday, 15th June, 2022, 14:00–19:30

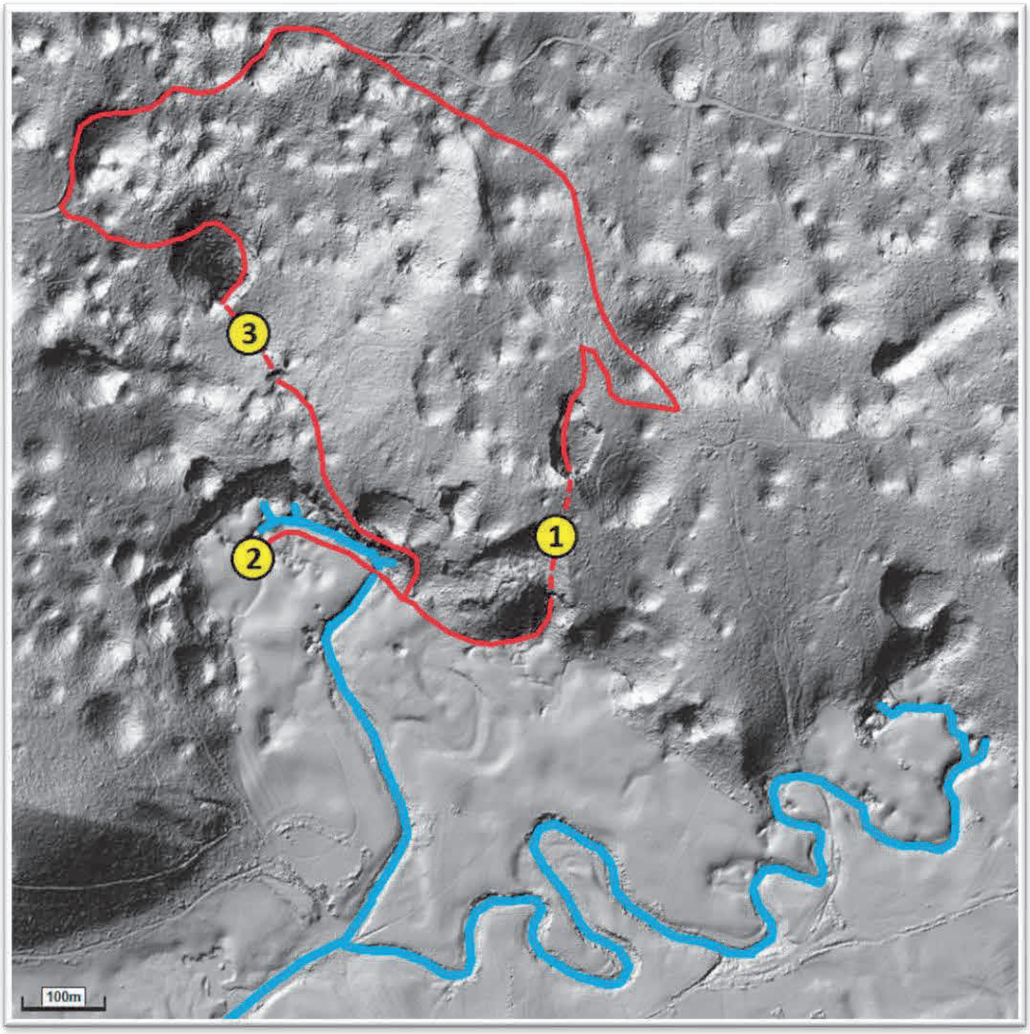
Matej Blatnik, Franci Gabrovšek, Andrej Mihevc

Stops:

1 – Vranja Jama – Mrzla Jama

2 – Northern ponors of Planinsko Polje

3 – Skednena Jama



Jame severnega roba Planinskega polja (t.j. Vranja jama, Skednena jama)

Popoldansko terensko delo (B); sreda, 15. junij 2022;

Poudarek ekskurzije je stik med severnim robom Planinskega polja in nizko kraško planoto Ravnik, ki se nahajata v jugozahodnem delu Slovenije, znotraj porečja Ljubljanice. Območje predstavlja enega ponornih območij občasno poplavljenega Planinskega polja. Tam voda ponika skozi številne požiralnike, na primer skozi ti. Putickove štirne, nato pa teče skozi vodno aktivno Vranjo jamo in Najdeno jamo. Na tem območju se nahaja tudi veliko jam, ki niso več vodno aktivne, med katerimi je med pomembnejšimi Skednena jama z vhodom na robu prostorne udornice in z manjšim predelom s periglacialnimi pojavi – sortiranimi krogi.

GENERAL DESCRIPTION

The focus of the field trip is the contact area between the northern part of Planinsko Polje and low karst plateau Ravnik, which are located in southwestern part of Slovenia, within the recharge area of the Ljubljanica River. The area presents one of ponor zones of periodically flooded Planinsko polje. There the water is sinking into numerous swallow holes, such as Putick's wells and afterwards flows through water active caves Vranja Jama and Najdena Jama. There are also some caves, which are no longer water active, among which Skednena Jama with an impressive collapse and section with periglacial formations (sorted circles) is of larger importance (Fig. 2.01).

Planinsko Polje is 10 km^2 large karst polje levelled at 450 m a.s.l., which receives water from about 1200 km^2 large recharge area (Gospodarič & Habič 1976). It receives water from the Pivka Basin on southwest and from set of karst poljes of Notranjsko podolje region on southeast. Both branches of the water flow join together underground in cave Planinska Jama and springs out as the Unica River on south of Planinsko Polje (Gams 2004). Another important spring on the southern part of polje is Malenščica, used also for a water supply (Frantar 2008, Petrič *et al.* 2018). On the western (below the mountain Planinska gora) and southern rim of polje there are many other perennial and temporary springs, on northwest near village Grčarevec also estavelles (Fig. 2.01). There are two main ponor zones on the polje, The first is located at its eastern border after about 7 km of meandering flow of the unica river, whereas terminal ponors are reached about 17 km of flow at poljes northern border (Fig. 2.01). Total outflow capacity of ponors is assessed at about 60 m^3/s (Šušteršič 2002) and when it is surpassed, polje gets flooded. Floods usually last between 1 and 2 months per year (Ravbar *et al.* 2018, Blatnik *et al.* 2019).

The plateau Ravnik is a well-karstified plateau with elevated rims encircled by the Planinsko polje on south, Logaško polje on west, plateau Menišija on east and and Ljubljana Basin on the north (Fig. 2.01). The elevation is from 500 to about 800 m a.s.l. The area has a very high density of dolines, an average of about 100 per km^2 (Breg Valjavec 2013). Besides numerous dolines, unroofed caves and collapse dolines are also common (Šušteršič 2002). Ravnik has one of the highest densities of caves in Slovenia with more than 800 caves discovered in an area of about 130 km^2. Currently, about 10 caves have known access to the groundwater flow, which is connecting Planinsko and Logaško Polje to the springs of the Ljubljanica River. Besides the position of the water caves, the distribution of collapse dolines and unroofed caves also indicate the possible direction of the groundwater flow (Šušteršič 2002).

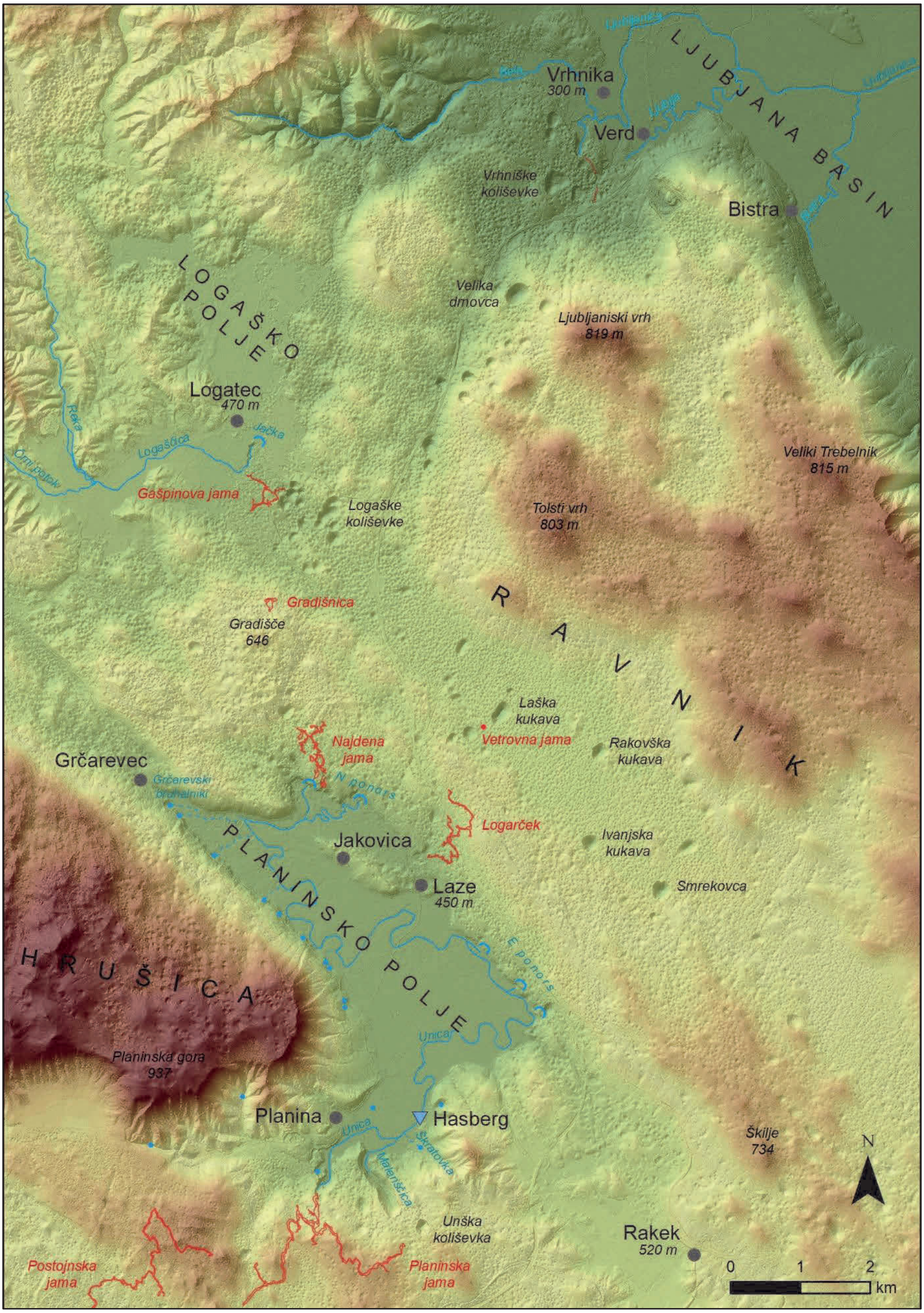


Fig. 2.01: Relief map of the area between the Planinsko Polje, Logaško Polje, and springs of the Ljubljanica River including the main surface waters and some of the large cave systems (DEM data from ARSO 2022; Cave data from Cave Register 2022).

VRANJA JAMA – MRZLA JAMA

Vranja Jama is a cave system with two entrances. The bigger one is located on north in a collapse doline called Vranja Jama (510 m a.s.l.) (Fig. 2.03), whereas the smaller one is called Mrzla Jama, located on south and lower elevation (463 m a.s.l.). The whole cave is 510 m long and 90 m depth (Fig. 2.02). After the collapse, the cave continues towards the southeast with a spacious inclined passage with large collapsed rocks on the floor (Gams 1963, Mihevc 2016). After the chamber with a relatively flat bottom, the cave continues in three directions: 1) horizontally for about 150 m through spacious passage covered by rocks and flowstone; 2) downwards over silty and muddy slope towards permanent syphon; 3) slightly down through narrow passage and then upwards through the second entrance Mrzla Jama (Fig. 2.02).

The cave is hydrologically well connected to Planinsko polje on south (Fig. 2.03) and about 6 km long cave Najdena Jama on north. The lowest part of the cave is permanently filled with water at the altitude about 420 m a.s.l. during the lowest stage. When polje is flooded, water level can increase for more than 20 m, so it can fill the lowest part of the entrance chamber (Fig. 2.04) and also part of the passage towards the entrance Mrzla Jama. There are no detailed measurements of the water level dynamics in cave Vranja Jama, but its location in the neighborhood of the cave Najdena Jama suggests that it might be recharged from the ponor zone Škofov Lom about 400 m on the southeast (Blatnik *et al.* 2019) (Fig. 2.08).

Cave geometry with multiple entrances is favorable for a dynamic airflow circulation, which is the most pronounced at the narrowest part of the cave, close to the entrance Mrzla Jama (in English Cold Cave) with a meaningful name. There during the warm part of the year relatively cold air from the cave blows out (Mihevc 2016). During winters airflow circulation is reversed - relatively warmer and lighter cave air is slowly blowing out through larger entrance at higher position and therefore cold outside air is sucked from lower positioned smaller entrance Mrzla jama (Mihevc 2016).

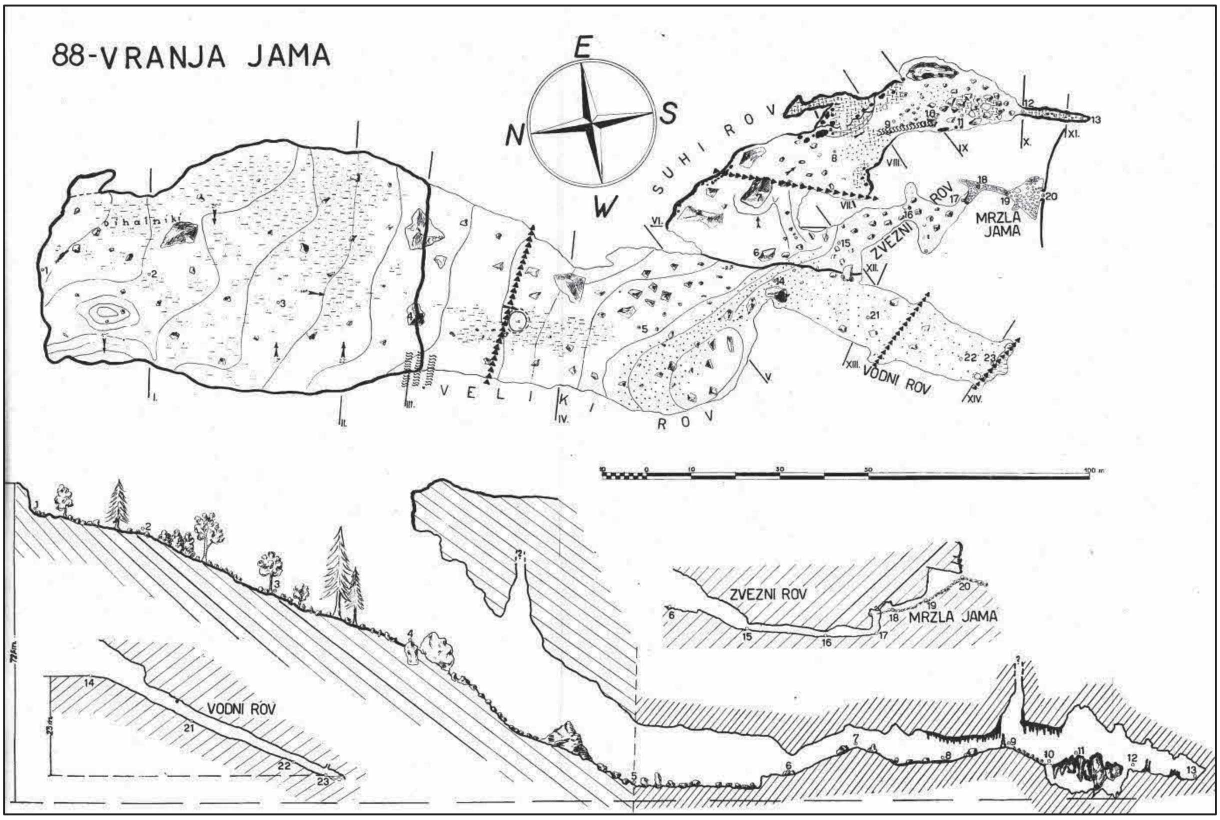


Fig. 2.02: Cross section through Vranja Jama and Mrzla Jama (after Gams 1963).

Fig. 2.03: Aerial picture of the entrance of Vranja Jama in front and northern rim of Planinsko polje with swallow holes in back (Photo: M. Blatnik; RI-SI-EPOS).

Fig. 2.04: Flooded entrance chamber in Vranja Jama in December 2017 (Photo: M. Blatnik).

NORTHERN PONORS OF PLANINSKO POLJE

Geologically, the area of Planinsko polje is composed of Cretaceous, Jurassic and Triassic limestones and dolomites and crossed with several structures, such as nappes and faults (Čar 1982; Placer 2008). The most important is Idrija Fault Zone with an orientation NW-SE, within which several karst polje (also Planinsko Polje) developed and which is also controlling the position of springs, ponors and direction of the ground water flow (Vrabec 1994; Placer 2008).

Planinsko polje (450 m a.s.l.) is positioned between Pivka Basin and Cerkniško Polje (Both 550 m a.sl.) on south and Ljubljana Basin (300 m a.s.l.) on north (Fig 2.01). Its area is about 10 km^2 and during floods almost the whole bottom can be flooded (Ravbar *et al.* 2021). Therefore, the floor is almost completely covered with grasslands, whereas fields and settlements are positioned on its rim (Fig. 2.01). The main water flow is the Unica River, which has two important springs from Planinska jama and Malni on south, whereas other smaller springs are positioned aso on its western border. Planinsko polje also has three important ponor zones, distributed at different areas:

1) Eastern ponors are located southeast from the village Laze after about 7 km of meandering flow of the Unica River. The zone is about 2 km long and total outflow capacity is about 18 m^3/s (Blatnik *et al.* 2017). When the discharge of the Unica River is higher, its flow is prolonged towards terminal ponors on north.

2) Northern ponors (Fig. 2.08) are also the terminal ponors of the polje. Most of the year they are dry, but when the discharge of the Unica River surpasses the outflow capacity of eastern ponors, water reaches this region. Ponors are distributed in two regions called Pod stenami (Fig. 2.06) and Škofov Lom (Fig. 2.05). Their outflow capacity is assessed to between 40 and 60 m^3/s (Šušteršič 2002).

3) Estavelles near Grčarevec are located at the northwestern edge of the Planinsko polje. Most of the year they are dry, but after some intensive rainfall, they first activate as springs, but as ponors only during the recession of the floods (Blatnik *et al.* 2020). Their discharge as springs or outflow capacity as ponors is not well known, but assessed at about 10 m^3/s (Savnik 1960).

After sinking through different ponor zones, water continues its flow underground through karstified plateau Ravnik (Gospodarič 1981; Habič 1984). There about 800 caves have been discovered and about 10 of them have an access to the groundwater. After about 12 km of the straight-line distance water springs through numerous springs of the Ljubljanica distributed near the town Vrhnika (Fig 2.01). At the most important ponors, water active caves and springs of the Ljubljanica river, water level has been observed and findings are described in the following paragraphs (Blatnik *et al.* 2019).

Fig. 2.05: Aerial picture of ponor zone Škofov Lom. (Photo: M. Blatnik; RI-SI-EPOS).

Fig. 2.06: In 1889 reinforced swallow holes Putick's wells (Putickove Štirne) while ponor zone Pod Stenami are functioning - (Photo: M. Blatnik).

Water level and temperature have been monitored in all active caves between Planinsko Polje and Ljubljana basin in years from 2006 to 2009 and from 2015 to 2020 (Turk 2010; Gabrovšek & Turk 2010; Blatnik *et al.* 2019; Mayaud 2019; Blatnik *et al.* 2020). Data loggers were installed in 8 caves (Logarček, Vetrovna Jama, Najdena Jama, Gradišnica, Gašpinova Jama, Brezno pod Lipovcem, Andrejevo Brezno 1, Veliko Brezno v Grudnovi Dolini) and three ponors on the rim of Planinsko Polje (Velike Loke, Pod Stenami, Škofov Lom). Figure 2.07 presents the recorded dynamics of underground water in March and April 2018, which are explaining different flooding dynamics in outflow zones Pod Stenami and Škofov Lom and downstream located cavec.

Water level measurements showed complex dynamics in water level variations, which can be up to 60 m (Fig. 2.07), and different rate of changes of groundwater level (from several hours during increase to several weeks during decrease). During all high water events there is a different temporal response in water level increase (Blatnik *et al.* 2019; Mayaud 2019; Blatnik *et al.* 2020). When the discharge of the Unica River is increasing, water first reaches eastern ponors and then northern ponors (first among them ponor zone Pod stenami), resulting in shifted temporal response in downstream located caves (Figs. 2.07). This dynamic explains late response in cave Najdena Jama in comparison to nearby located ponor zone Pod Stenami. Obviously, water from po neighbouring ponor zone Pod Stenami bypasses cave Najdena Jama, which is recharged through more apparent ponor zone Škofov Lom (Fig. 2.07 & 2.08). Considering the geological structure with less permeable parts in Idrija Fault Zone, this explanation is plausible (Blatnik *et al.* 2019). Water level hydrographs also show inflection points, presenting temporal slower increase/decrease of the water level. This dynamic indicates the presence of overflow passages at certain levels. Temperature and EC hydrographs have been interpreted for the travel time estimation between successive observation points, which varies from about 150 to 300 m/h during high water events (Blatnik *et al.* 2019; Blatnik *et al.* 2020).

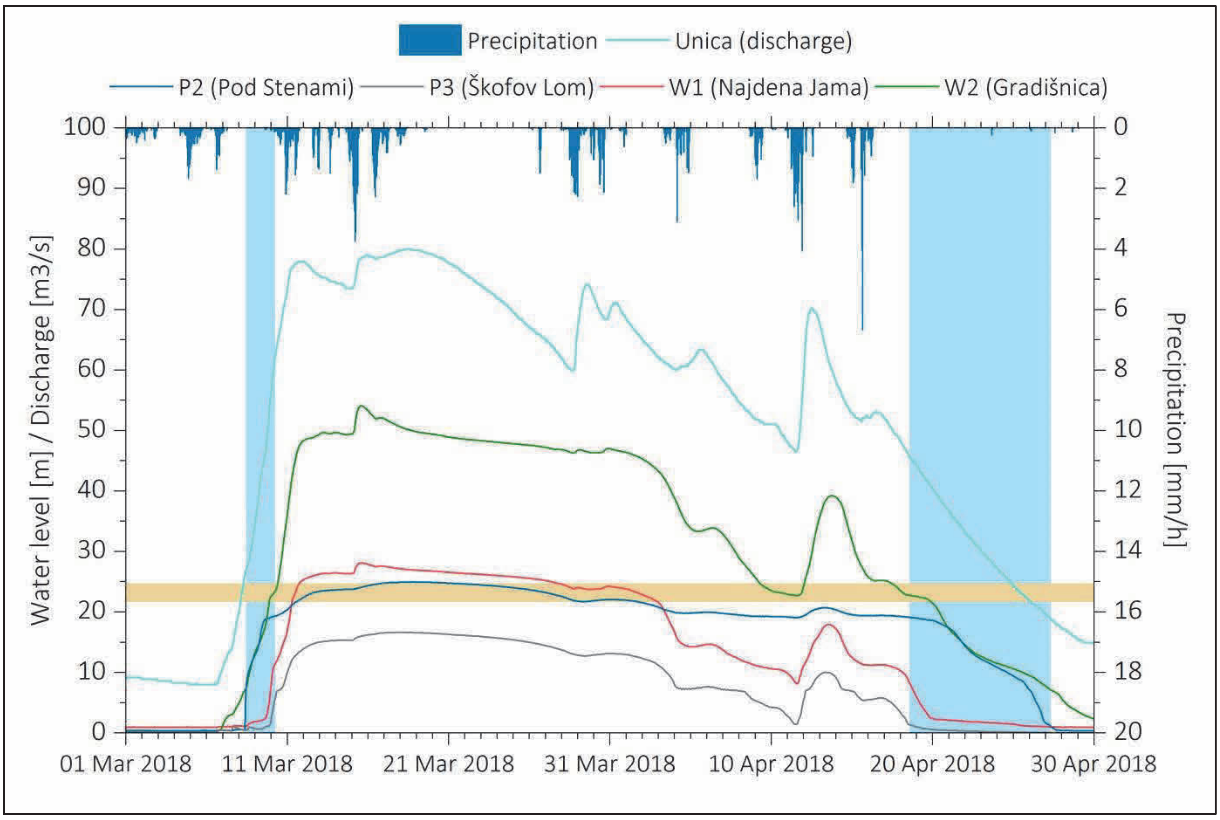


Fig. 2.07: Water level dynamic in selected caves between Planinsko Polje and Ljubljanica springs during high water event in March and April 2018. Blue areas denote different response of water level change, orange area denotes temporal slower increase/decrease of water level in cave Gradišnica.

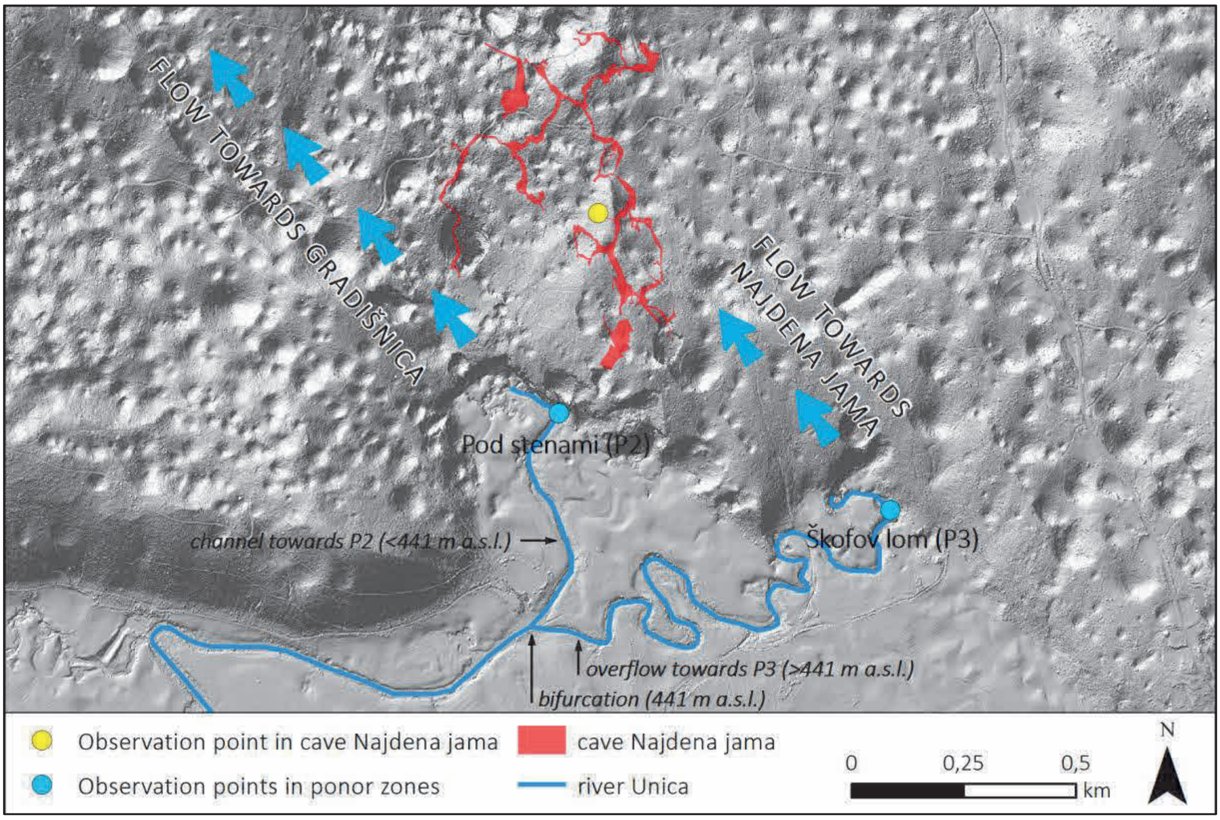


Fig. 2.08: Assumed groundwater flow directions between the northern ponors (Pod Stenami and Škofov Lom) and Najdena Jama and Gradišnica (DEM data from ARSO 2022; Cave data from Cave Register 2022).

SKEDNENA JAMA

Skednena Jama is 206 m long and 30 m deep cave, situated on the northern border of Planinsko polje (about 200 m straight line distance from the ponor zone Pod Stenami). Cave is a remnant of an old phreatic passage of a larger cave in a direction N–S. It is spacious with about 10 m of width and 5 m height (Mihevc 2016). It has three entrances, which are at different altitudes. The largest entrance is in the bottom of the collapse doline and smaller two are on the surface (496 m a.s.l.) of the terrain (Gams 1963) (Fig. 2.09). Cave passage is covered by clastic sediments: rocks, gravel and smaller particles the size of sand and silt. The main part of the cave passage, in the length of more than 100 m, is smooth and levelled to an even surface with inclination of 7–10 ° and horizontal in cross section (Mihevc 2016). The lowest part of the cave is at 450 m a.s.l., which is higher than the local groundwater level during floods. This means that only percolated water through fractures is present.

Recently, the cave has become more interesting climatologically. The mean annual temperature of the area is about 8 °C with the coldest month January (–1 °C) and the warmest July (+18 °C). During the winter there is a strong air draft through the cave, and the cave temperatures at the floor are for several weeks or even months below 0 °C. Air temperatures measured at the cave floor are similar to those on the surface, but in slightly isolated domes in the ceiling or on side passages temperature is evidently higher - above 0 °C (Mihevc 2016). The floor freezes and on the places with dripping water ice stalagmites form. During thawing of the surface, small and short lasting lakes can form there, whereas ground in the depth thaws several weeks later (Mihevc 2016).

Levelled cave floor show recent patterned ground cryoturbation features like sorted stone circles, sorted polygons, stripes and clay hummocks. These features develop due to repeated freezing and thawing of the cave sediment, which cause the shifting and movements of rocks mixed with fine sediment particles that contain more moisture (Kessler & Werner 2003; Hallet 2013). These features are present in all parts of the cave floor (Fig. 2.10), also on slopes, but are better developed in vicinity of the dripping points, where locally the ground contains more moisture (Urbančič & Mihevc 2019).

Cryoturbation develops due to cyclic changing of the volume of humid ground. This causes the upwards moving of the whole cave floor (Kessler & Werner 2003; Hallet 2013). After several seasons of observing, between 5 and 10 upward movements in the vicinity of the dripping water was noticed (Urbančič & Mihevc 2019). Vertical movements are also causing horizontal shifting of the particles down dip - because the particles, which are uplifted perpendicular to the inclined surface, are lowered vertically during the thawing. This is morphologically important, because it leveled the whole cave floor bottom to even dip.

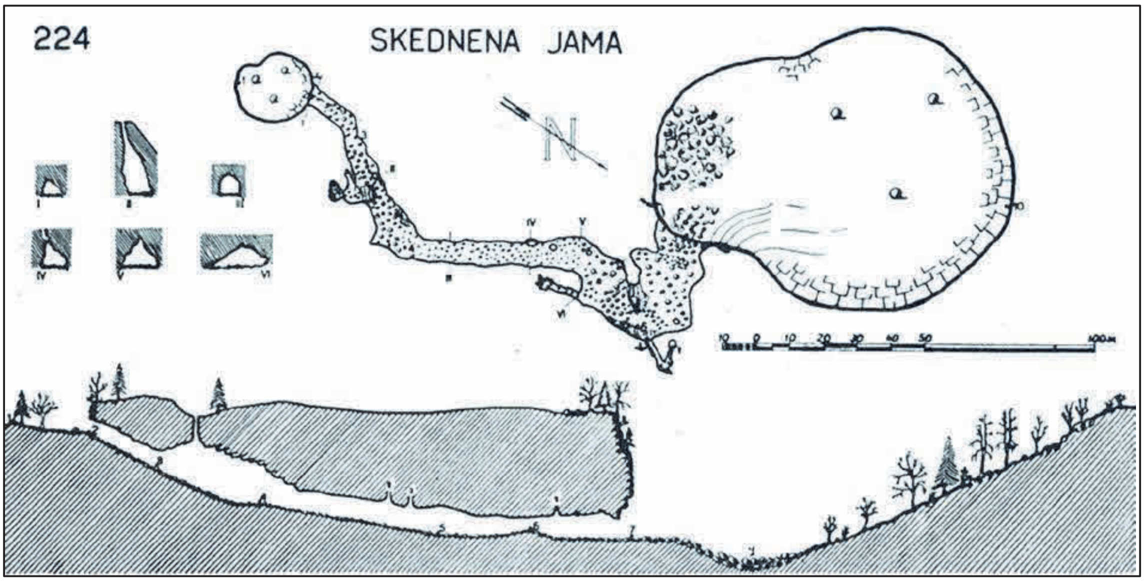


Fig. 2.09: Cross section through Skednena Jama (after Gams 1963). Through three entrances strong air currents occur, causing long lasting seasonal ice and periglacial processes.

Fig. 2.10: Sorted circles next to the spacious cave entrance at the bottom of the collapse doline (Photo: M. Blatnik).

REFERENCES:

- ARSO, 2018c: Lidar data fishnet.- [Online] Available from: http://gis.arso.gov.si/ [Accessed May 19th, 2022].
- Blatnik, M., Frantar, P., Kosec, D. & F. Gabrovšek, 2017: Measurements of the Outflow Along the Eastern Border of Planinsko Polje, Slovenija.- Acta Carsologica, 46, 1, 83–93.
- Blatnik, M., Mayaud, C. & F. Gabrovšek, 2019: Groundwater dynamics between Planinsko Polje and springs of the Ljubljanica River, Slovenia.- Acta Carsologica, 48, 2, 199–226.
- Blatnik, M., Mayaud, C. & F. Gabrovšek, 2020: Supplement to the paper "Groundwater dynamics between Planinsko Polje and springs of the Ljubljanica River, Slovenia" from Blatnik et al. (2019) published in Acta Carsologica 48/2.- Acta Carsologica, 49, 1, 143–147.
- Breg Valjavec, M., 2013: Nekdanja odlagališča odpadkov v vrtačah in gramoznicah.- Geografija Slovenije, 26, Založba ZRC, pp. 118, Ljubljana.
- Cave register, 2022. Cave Register of the Karst Research Institute ZRC SAZU and Speleological Association of Slovenia. Postojna, Ljubljana.
- Čar, J., 1982: Geološka zgradba požiralnega obrobja Planinskega polja.- Acta Carsologica, 10, 75–104.
- Frantar, P., (ed) 2008: Water balance of Slovenia 1971–2000.- Ministrstvo za okolje in prostor, Agencija Republike Slovenija za okolje, pp. 119, Ljubljana.
- Gabrovšek, F. & J. Turk, 2010: Observations of stage and temperature dynamics in the epiphreatic caves within the catchment area of the Ljubljanica river.- Geologia Croatica, 63, 2, 187–193.
- Gams, I., 1963: Logarček.- Acta Carsologica, 3, 5–82.
- Gams, I., 2004: Kras v Sloveniji v prostoru in času.- Inštitut za raziskovanje krasa ZRC SAZU, pp. 515, Ljubljana.
- Gospodarič, R. & P. Habič, (ed), 1976: Underground water tracing: Investigations in Slovenia 1972–1975.- Third International Symposium of Underground Water Tracing (3. SUWT), pp. 312, Ljubljana, Bled.
- Gospodarič, R., 1981: Morfološki in geološki položaj kraških votin v ponornem obrobju Planinskega polja.- Acta Carsologica, 10, 157–172.
- Habič, P., 1984: Vodna gladina v Notranjskem in Primorskem krasu Slovenije.- Acta Carsologica, 13, 37–78.
- Hallet, B., 2013: Stone circles: form and soil kinematics, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences.- 371, 2004.
- Kessler, M.A. & B.T. Werner, 2003: Self-Organization of Sorted Patterned Ground.- Science, 299, 5605, 380–383.
- Mayaud, C., Gabrovšek, F., Blatnik, M., Kogovšek, B., Petrič, M. & N. Ravbar, 2019: Understanding flooding in poljes: a modelling perspective. Journal of Hydrology.
- Mihevc, A., 2016: Afternoon field trip: Skednena jama cave and caves of the N edge of Planinsko polje.- 7th International Workshop on Ice Caves – Program guide and abstracts, Karst Research Institute ZRC SAZU, Postojna, 2016, 9–12.
- Petrič, M., Kogovšek, J., & N. Ravbar, 2018: Effects of the vadose zone on groundwater flow and solute transport characteristics in mountainous karst aquifers–the case of the Javorniki–Snežnik massif (SW Slovenia).- Acta Carsologica, 47, 1, 35–51.
- Placer, L., 2008: Principles of the tectonic subdivision of Slovenia = Osnove tektonske razčlenitve Slovenije.- Geologija, 51, 2, 205–217.
- Ravbar, N., Mayaud, C., Blatnik, M. & M. Petrič, 2021: Determination of inundation areas within karst poljes and intermittent lakes for the purposes of ephemeral flood mapping. Hydrogeology Journal, 29, 1, 213–228.
- Ravbar, N., Petrič, M., Kogovšek, B., Blatnik, M. & C. Mayaud, 2018: High waters study of a Classical Karst polje – An example of the Planinsko Polje, SW Slovenia.- In: Milanović, S. & Z. Stevanović (eds.): *Proceedings of the International Symposium KARST 2018 "Expect the Unexpected",*

6-9 June 2018, Trebinje. Belgrade: Centre for Karst Hydrogeology; Trebinje: Hydro-Energy Power Plant "Dabar", 417–424.

- Savnik, R., 1960: Hidrografsko zaledje Planinskega polja.- Geografski vestnik, 32, 212–224.
- Šušteršič, F., 2002: Where does Underground Ljubljanica Flow?- RMZ Materials and Geoenvironment, 49, 1, 61–84.
- Turk, J., 2010: Dinamika podzemne vode v kraškem zaledju izvirov Ljubljanice – Dynamics of underground water in the karst catchment area of the Ljubljanica springs.- Inštitut za raziskovanje krasa ZRC SAZU, pp. 136, Ljubljana.
- Urbančič, T. & A. Mihevc, 2019: Movements and polygonal ground formation monitoring with terrestrial laser scanning in the cave Skednena jama.- Proceedings of European Geosciences Union, General Assembly 2019, Vienna.
- Vrabec, M., 1994: Some thoughts on the pull-apart origin of karst poljes along the Idrija strike-slip fault zone in Slovenia.- Acta Carsologica. 23, 155–167.

Whole-day field trip (C):

POSTOJNSKA JAMA (POSTOJNA CAVE SYSTEM)

Wednesday, 15th June, 2022, 14:00–19:30

Zupan Hajna Nadja, Stanka Šebela, Franci Gabrovšek, Metka Petrič, Nataša Ravbar, Peter Kozel, Janez Mulec, Uroš Novak, Lara Valentić, Lovel Kukuljan, Bojan Otoničar

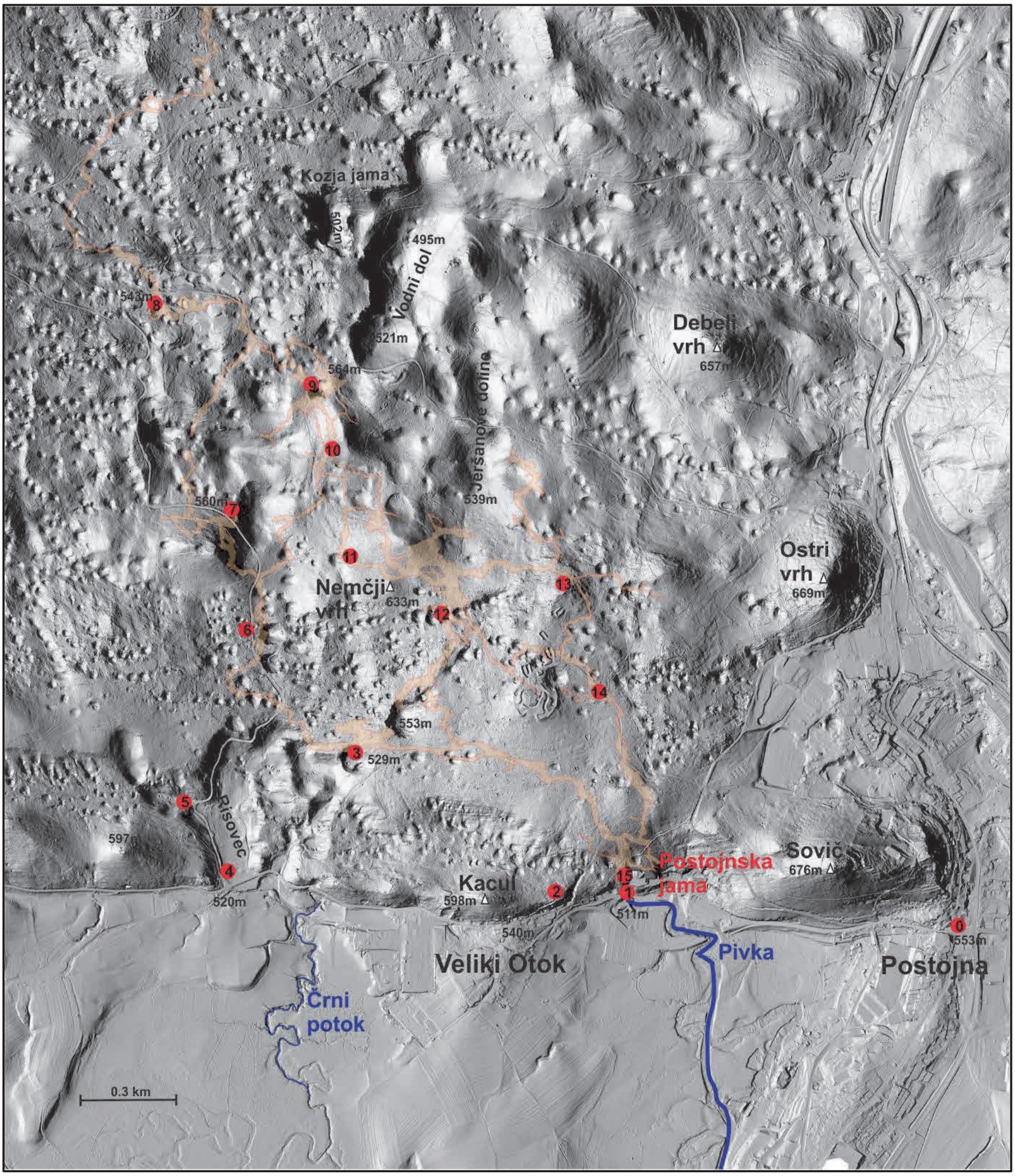


Fig. 3.01: Field trip stops; 0 – Karst Research Institute ZRC SAZU, 1 – ponor of Pivka, 2 – viewpoint, 3 – Otoška Jama (cave), 4 – blind valley Risovec, 5 - archaeological caves, 6 – Cretaceous paleokarst, 7 – Magdalena Jama (entrance), 8 – Pivka Jama (cave), 9 – Črna Jama (cave), 10 – artificial tunnel (cave), 11 – Lepe jame(cave), 12 – Koncertna Dvorana (cave), 13 – Brezimeni Rov (cave), 14 – Kristalni Rov (cave), 15 – tourist entrance.

INTRODUCTION

Postojnska Jama (Postojna Cave) is one of the most famous show caves in the world. It is located in the central part of the so-called Classical Karst in the SW part of Slovenia. The Classical Karst, as we understand it today, is the karst landscape between springs of the Ljubljanica River in the Ljubljana Basin (Slovenia) and the Trieste Bay (Italy), known for its remarkable speleological, hydrological and morphological phenomena, which have been explored and studied since the 17th century. The scientific term karst (from the local toponym "kras"), which refers to a rocky landscape with typical karst forms and underground water drainage, also comes from the wider area. In the 19th century, this area contributed to the emergence and development of karstology, speleology and speleobiology as scientific disciplines.

The cave is important because of its natural features and over 200 years of tourist development (since 1818), and especially because of the world's first ever scientific research in a cave. Famous natural scientists such as Valvasor (1683) and Hacquet (1778) described the cave in their works from the 17th and 18th centuries. Extensive research and discoveries continued in the early 19th century and were described by Hochenwart in 1832 and Schmidl in 1854. The first cave-dwelling animals in the world were discovered in Postojnska Jama: in 1797 the cave salamander (*Proteus anguinus*) was found in the cave for the first time. In 1831 a beetle (*Leptodirus hochenwarti*) was found there and in 1832 it was recognized and scientifically described as a true cave-dwelling animal by Ferdinand Schmidt.

SETTINGS

Postojnska Jama is a cave about 25 km long between the Pivka Basin and Planinsko polje (Planina Polje; Fig. 3.02).

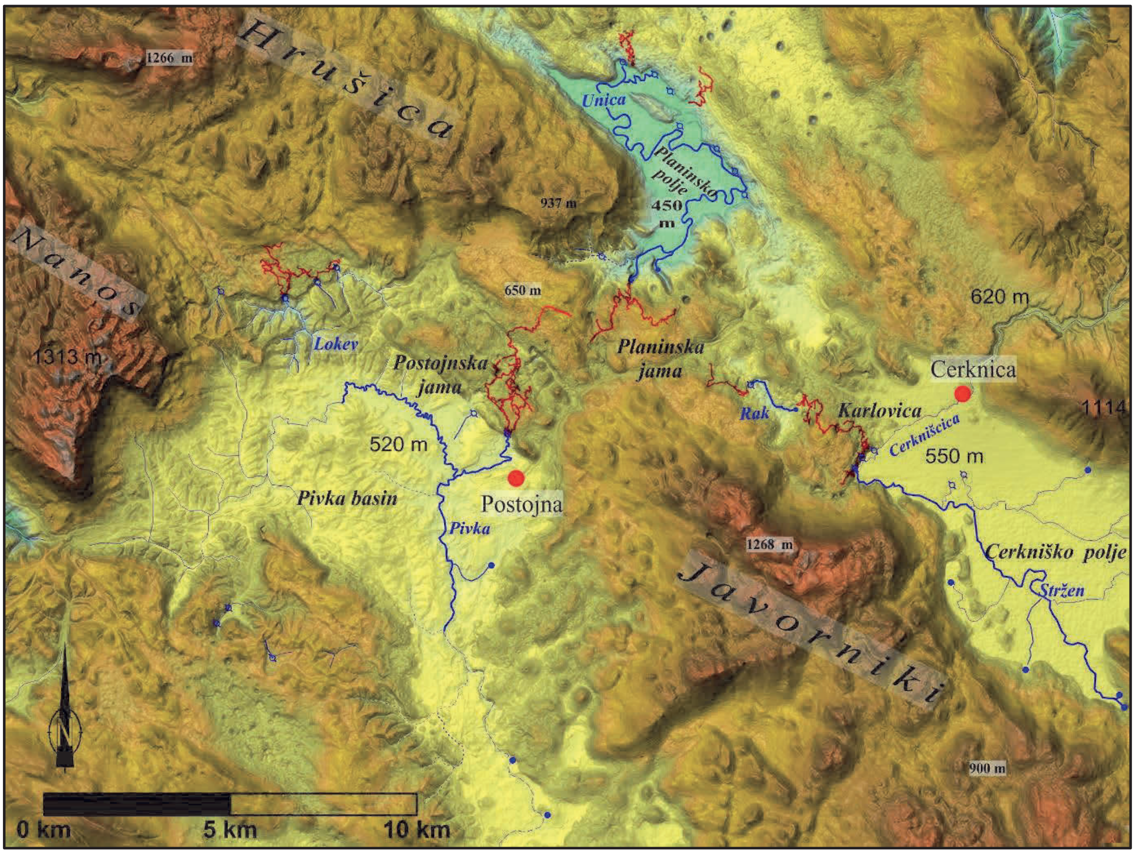


Fig.3.02: A geomorphological map of Postojnski kras (Postojna Karst) between the Pivka Basin and Planinsko polje (Planina Polje) with the location of major caves (A. Mihevc).

The Pivka River flows through impermeable Eocene flysch and sinks into the Postojnska Jama cave at the contact with limestones (Figs. 3.01, 3.02, 3.03). The Pivka flows underground to the Planinska Jama (Planina Cave), from which the Unica River then emerges.

The evolution of the Pivka basin (flysch rocks) is determined by the elevation of the ponors of the Pivka, which flow into this cave. The gentle fluvial surface of the Pivka basin itself contrasts sharply with the karst areas above the cave and with other higher karst plateaus, where there are no traces of fluvial valleys or other elements of early fluvial relief today (Fig. 3.02). Cave speleogenesis was controlled by allogenic rivers that penetrated the Postojna karst during the development of the cave system. The karst surface at an altitude of 600 to 650 m a.s.l. is dissected by numerous solution dolines and sixteen large collapse dolines formed above the cave passages, blocking some of the passages. Collapse dolines formed of the ceiling above large cave halls, where water flows are present to dissolve the fragmented rock. Therefore, collapse dolines on the surface also indicate where known and unknown cave passages are located below the surface. The floors of most collapse dolines above Postojna Cave are located at altitudes between 495 m and 540 m above sea level.

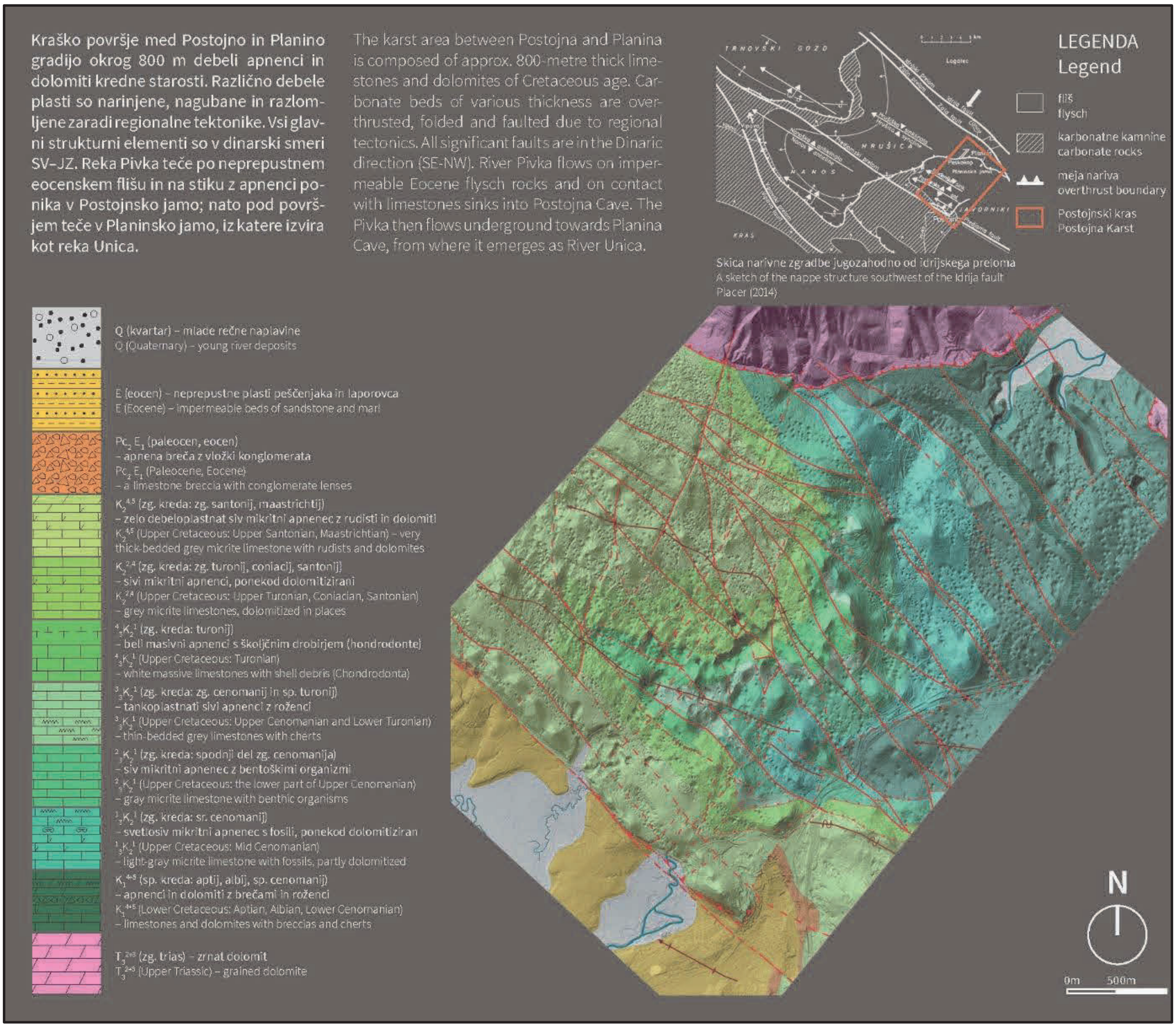


Fig. 3.03: The surface geology of the Postojna karst area between caves Postojnska Jama and Planinska Jama based on studies by Buser et al. 1967; Gospodarič 1976; Čar & Gospodarič 1984; Placer 1996; Rižnar 1997, Šebela 2010; the results of which were compiled in a new geological map for the purpose of exhibition at the Postojna Expo (Zupan Hajna 2015).

The karst between Postojna and Planina is formed in Cretaceous limestones and dolomites (Fig. 3.03). The entire cave is formed in a 800-metre-thick sequence of limestones confined by two distinct dextral strike-slip fault zones in the Dinaric direction (Predjama and Idrija faults). Carbonate beds of different thicknesses are overthrusted, folded and faulted due to regional tectonics (Placer 1996). Important structural elements of folding are the Postojna anticline and the Studeno syncline, which trend toward SE-NW. Significant faults are in Dinaric direction (SE-NW; dextral strike-slip fault) and in Cross-Dinaric direction (sinistral strike-slip fault); some of them are vertical.

The cave passages were mostly formed following inter-bedded slips (Šebela 1998) in the limestones of the Postojna anticline, which is oriented in the NW-SE (Gospodarič 1963, 1964, 1976). The cave is intersected by several fault zones in the Dinaric and cross-Dinaric direction (Figs. 3.03, 3.04). Some faults were important for the direction of the water flow and the formation of passages, while others were simply traversed by the water flow. Large breakdown halls in caves are formed in thick- bedded and tectonically collapsed limestones in the fluctuation zone of groundwater that dissolves the collapsed blocks.

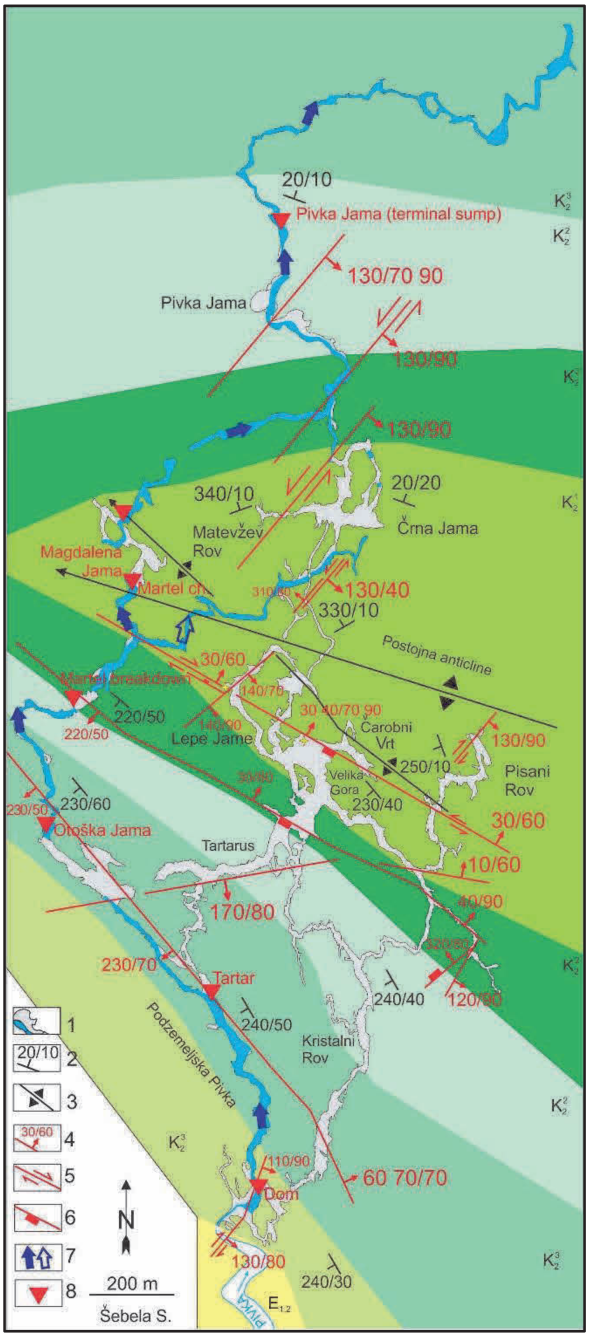


Fig. 3.04: Geology of Postojnska jam (Postojna Cave System). (1) Cave passage with underground River Pivka (filled blue), (2) strike and dip direction of bedding plane, (3) anticline, (4) strike and dip direction of fault, (5) dextral horizontal movement, (6) vertical movement, (7) Flow direction: full arrow-main flow, outlined arrow-overflow, (8) Monitoring stations. K21- K23 Cretaceous limestone, E1,2-eocene flysch, adopted from Šebela (2010); and position of river observation points (in this text; subchapter UNDERGROUND RIVER).

To understand dependence between formations of karst surface and underground features and structural geological features, generations and types of regional tectonic activity must be understood. In the area between Postojna, Planina and Cerknica, Čar and Gospodarič (1984) described generations of fault zones and the structural geometry of the Snežnik thrust sheet between the Idrija and Predjama faults. They established four generations of deformations from the Neogene and, supposedly, the Quaternary. The tectonic conditions of the terrain are divided into: 1) older movements, 2) thrust structures and folds, 3) fault deformations. At the end of the Eocene or in the Oligocene, the Alpine-Dinaric region was subjected to intense overthrusting. The beds were first folded and subsequently were broken. During the Miocene and Pliocene, the overthrusting was accompanied by folding (Placer 1981). The faults of the first generation trending NE-SW were active in all the tectonic events in the area, probably even up to the Holocene. The influence of tectonics is thought to be present also in collapse dolines around Vodni Dol and around the blind valley Risovec, as well as in the orientation of the water channels in Črna and Pivka Jama. All of these are active water channels that are perpendicular to the folded beds (Čar & Gospodarič 1984). The area is part of the Javorniki-Snežnik thrust unit, which has been thrusted over the Eocene flysch. The Hrušica thrust unit, which is upper Triassic dolomite, overthrusts the Javorniki-Snežnik thrust unit. Overthrusting took place after the deposition of the Eocene flysch. During the Miocene and Pliocene, the overthrusting was accompanied by folding. The principal folding deformation in Postojna Cave is the Postojna Anticline. Between Postojna and Planina Caves is the Studeno Syncline. Formation of the Postojna anticline is in the post- or co-thrusting period of the Upper Cretaceous limestones over Eocene flysch. The Postojna anticline axis is Dinaric oriented (NW-SE). The duplex in Postojna Cave is attributed to the period of overthrusting of the Upper Cretaceous limestones over Eocene flysch rocks. This was the same period that caused the vergence of the Postojna anticline axis towards SW by 7 - 14° (Šebela 1998). The Predjama Fault (Fig. 3.03) is one of the most significant regional faults in SW Slovenia. A steep NW-SE trending fault, runs along the NE part of the Pivka basin, passes Postojna and proceeds to the SE (Placer 1981). Predjama Fault is supposed to be still active (Atanackov *et al.* 2021; Šebela *et al.* 2021).

THE CAVE

The total length of known passages is (in May 2021) more than 24 km (Figs. 3.02, 3.05) and the calculated volume of all cave passages is 1.7 million cubic meters (Glažar *et al.* 2015). The passages have formed in two levels. The upper dry part of the cave is located between 520 and 530 m. The ponor is at an altitude of 511 m.a.s.l. There are several cave entrances located at an altitude of 529 m above the ponor of the Pivka (Fig. 3.06). Other entrances to the cave are Otoška Jama (Otok Cave), Magdalena Jama (Magdalena Cave), Pivka Jama (Pivka Cave) and Črna Jama (Black Cave). In the past, all of these entrances were known as separate caves and were later connected to the Postojna Cave system through research and exploration. The interconnected passages form a single cave, which is why the cave is also called Postojnska Jama. The calculated volume of all cave passages is 1.7 million cubic meters. The distance from the ponor of Pivka into Postojnska Jama to the siphon in Pivka Jama is about 3.5 km. The difference in altitude between the highest point at the entrance to Magdalena Jama and the lowest point at the siphon in Pivka Jama is 115 m. The known section of the Rov podzemne Pivke (Passage of the Subterranean Pivka) ends about 500 m before reaching the passages of the Planinska Jama (Fig. 3.02).

The cave has a network of hydrologically and morphologically very different passages in terms of their origin and enlargement. The active water passages are on average smaller than the passages in the dry sections. The dry passages up to an elevation of 520 m can be reached only by the highest water levels. Passages in the present dry section are large - up to 10 m high and wide. Their profiles are rounded here and show traces of paragenesis, such as levelled ceilings and side notches on the walls. The largest chamber, Velika gora (Big Mountain), has a volume of about 100,000 m3. The thickness of bedrock above the cave passages ranges from 30 to 120 m.

The currently active water passages are about 20 m lower than the dry sections and run along the western part of the cave (Fig. 3.05). The underground river Pivka flows behind the ponor towards north along the passages of the **Rov podzemne Pivke (Passage of the Subterranean Pivka; Fig. 3.05)**. In the northern direction, the riverbed slopes slightly - in the entire cave from 511 m at the ponor (Figs. 3.05, 3.06A) to 477 m at the syphon in Pivka Jama.

The first cave with its own entrance along the underground Pivka is **Otoška Jama (Otok Cave; Figs. 3.05, 3.06C)**. The entrance to the cave was discovered and excavated in 1889 in the Risovec blind valley. The cave is over 600 m long and offers an abundance of speleothems and access to the subterranean Pivka. The Pivka flows into the cave at an altitude of 505 m above sea level from Spodnji Tartarus. The total depth of the cave is 25 m. The active part of Otoška Jama continues with the underground river in the direction of Martelov podor (Martel's rockfall) and shortly after it splits into two branches; the first one flows into Magdalena Jama (Magdalena Cave) at low water level, and at high water level the other one flows into Perkov Rov (Perko Passage) in the direction of Črna Jama (Black Cave). In the Otoška Jama there is also a tributary of the Črni potok (Black Brook), which sinks into the **Lekinka (Lekinka Cave)** on the edge of the Postojna basin. The siphon between Lekinka and Otoška Jama has not yet been swum through, so the cave is not yet considered a part of the Postojnska

Jama.

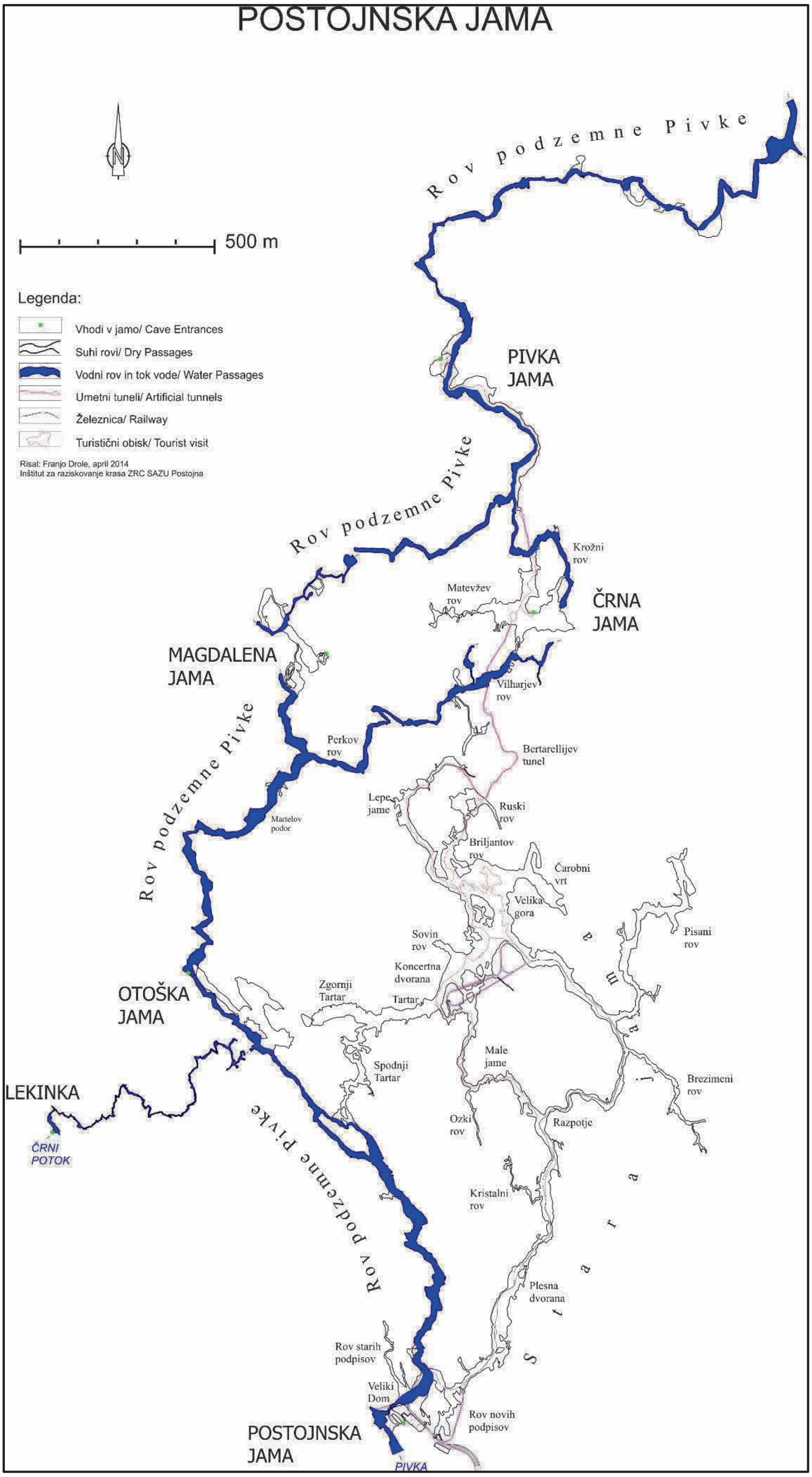


Fig. 3.05: The ground plan of Postojnska Jama (Postojna Cave) with its entrances (IZRK ZRC SAZU).

Fig. 3.06: Entrances to Postojnska Jama (photos Zupan Hajna); A - flooded ponor of the river Pivka in 2019, B - historical tourist entrance, C - to Otoška Jama, D - to Magdalena Jama, E - to Pivka Jama, F - to Črna Jama, G - cross-section of the entrance to Črna Jama (from Cvijić 1893).

Downstream along the passage of the underground Pivka is the next cave **Magdalena Jama (Magdalena Cave; Figs. 3.05, 3.06D)**, which can be reached by boat from Otoška Jama when the water level is low. French speleologist E.A. Martel and members of the Anthron Caving Society were the first to reach Magdalena Cave in 1893 by following the underground river Pivka. Magdalena Jama also has its own entrance from the surface, where the first shaft is about 20 m deep. The depth from the surface to the river is 89 m. The total length of passages of the cave is 1395 m. The lower passages end with siphons, upstream towards Martelov podor and downstream towards Pivka Jama (Pivka Cave).

The entrance to **Pivka Jama (Pivka Cave; Figs. 3.05, 3.06E)** leads through a collapse doline with vertical walls and a depth of 65 m. Its rim and bottom are located at 550 and 485 m a.s.l.. The underground river Pivka was reached from the surface by A. Schmidl in 1852. The total length of accessible cave passages is 794 m. The river flows into the Pivka Jama through siphons via two branches: from the Magdalena Jama and from the Črna Jama (Black Cave), where the river flows only when the water level is high. In this cave there are not many speleothems. From the entrance, the underground river flows through rapids for another 160 m towards the siphon, which is located at an altitude of 477 m. Behind the siphon, divers explored in 2015 a passage about 1.5 km long, which is interrupted by three siphons. From the last measured point at an elevation of 475 m, there are another approximately 0.5 km of unknown passages to the Pivka branch in Planinska Jama (Planina Cave). The inflow siphon in Planinska Jama is located at 468 m.a.s.l. and is over 50 m deep. The dry part of the cave, Paradise, is located at 495 m.a.s.l., but the collapse doline called Planinska koliševka is located in between.

The entrance to **Črna Jama (Black Cave; Figs. 3.05, 3.06F)** is on the bottom of a small collapse doline at 530 m above sea level. The doline was already known by Cvijić (1893; Fig. 3.06G), who mentions it as one of the example of a doline formation. The total length of the passages in the cave is 3,294 m, and the total depth is 39 m. Due to its location and easy accessibility, the Črna Jama has been known since time immemorial. The Črna Jama, which is in older German literature referred to as "Magdalenengrotte" and should not be confused with the Magdalena Cave, was visited by individual travelers as early as the 18th century, as evidenced by the old signatures on the cave walls. These visitors paid the locals a little money to guide them through the underground areas, and the locals carried torches or matchwood to show the visitors the way. Due to the water dripping down the walls, the inscriptions are quite damaged in some places. In winter, cold air flows into the cave through the large entrance, which leads to the decomposition of the speleothems and the cave walls. The bottom of Velika Dvorana (Great Chamber) in the entrance area is levelled at an elevation of 516 m; it is levelled with strewn material excavated during the construction of the artificial tunnel, which also covers the lower parts of the columns and stalagmites. The cave was named after the carbon coating that gives speleothems their characteristic black colour. The black particles (mainly carbon) were deposited on the exposed surfaces (not on the underside) 10,000 years ago. Older flowstone layers of speleothems are not coloured; younger speleothems - especially those that are currently growing - are completely white. In 1797, Josip Jeršinovič von Löewengreif discovered some specimens of Proteus (Proteus anguinus) in Črna Jama. This was the first time that a Proteus specimen was found in a cave, and it was a cave-dwelling animal (troglobiont). Previously, Proteus were known from karst springs in Slovenia, but that they can also live in the underground world was not known until then. A part of the underground Pivka flows through the lowest part of the Črna Jama when the water level is high. Črna Jama is connected to the tourist part of Postojnska Jama by a 500 m long artificial tunnel.

The **tunnels** between the tourist part of Pivka Jama, Črna Jama and Postojnska Jama were dug between World War I and II by Italians under the direction of L. V. Bertarelli, whose soldiers were digging about 1.5 km of artificial passages. The tunnels were dug for military reasons, as Postojna belonged to Italy at that time, and the border with the then Yugoslavia ran through Planina. Various fault zones are clearly visible in the artificial tunnels.

After the tunnel in Postojnska Jama, the lowest section of the tourist path is called **Ruski Rov (Russian Passage; Fig. 3.05)**. The passage was formed in thin-bedded chert lenses, which are the oldest layers in Postojna Cave (Cenomanian). The cherts consist of remains of quartz organisms. In **Lepe jame (Beautiful Caves; Fig. 3.05)** there is a large number of speleothems of various forms. An interesting section is the so-called Špagetna Dvorana (Spaghetti Hall), where tiny tubes grow from a network of small cracks in the ceiling.

Velika gora (Big Mountain or Calvary; Fig. 3.05) is the hill in the cave hall, formed from collapsed rocks, which visitors must climb. The hall has a volume of about 100,000 m^3; the highest point of the hall is 40 m above the level of the cave entrance and 60 m above the ponor of the Pivka. The thickness of the ceiling above the hall is about 30 m.

Koncertna Dvorana (Concert Hall; Fig. 3.05) is one of the largest halls in Postojnska Jama, with a volume of about 50,000 m^3. The hall was formed in thick- bedded limestone, which is crossed by a strong fault zone. The floor in the hall was artificially levelled. The path from Koncertna Dvorana to the west leads to **Tartarus (Lower and Upper Tartarus; Fig. 3.05)** and **Male jame (Small Caves; Fig. 3.05).** In Lower Tartarus the underground river can be reached. Male jame is a passage that connects Stara Jama (Old Cave) and the Concert Hall. The passage is rather small, but full of speleothems. Old sediments and scallops can be seen on the walls of the passage. The Male jame are not part of the regular visitor tours.

Stara Jama (Old Cave; Fig. 3.05) is the oldest known part of Postojnska Jama. The ground inside the Old Cave was artificially levelled for the construction of the cave railroad. The walls of the passages, sediments of different ages and speleothems reflect a variety of different processes and developments over time. There are a number of fallen stalagmites in the cave, mainly due to the movement of sediments. The Stara Jama is completely free of sediments and here the railroad line runs at 525 m a.s.l. From Stara Jama there are entrances to Pisani Rov, Brezimeni Rov and Kristalni Rov. Pisani and Brezimeni Rov are the easternmost and highest elevated passages of Postojnska Jama.

The entrance to **Pisani Rov (Coloured Passage; Fig. 3.05)**, that is 515 m long, is below the passage ceiling, as the passage was filled with sediments up to an altitude of 530 m. From the Pisani Rov the passage continues to the north and ends with breakdown related to the collapse dolina Velika Jeršanova dolina (Large Jeršan Dolina) at 535 m.a.s.l. The passage used to be filled with deposits, which were later partially eroded. In the passage grows a large number of different speleothems of various colors and forms. The evidence of floods above already existing speleothems is indicated by clay layers between dense calcite layers and in porous layers. A lot of speleothems are broken and fallen; Gospodarič (1962) explained them with subsiding of the sediments, Kempe (2004) by glacier movement through the cave, and Šebela (2008) by seismic activity. There are also a lot of broken points of stalactites which can indicate the relation of speleothem braking to floods (as mass flow).

Brezimeni Rov (Nameless Passage; Fig. 3.05) extends about 400 m to the southeast, rising and branching towards the end. It is characterized by a large collapse chamber halfway along the passage and a high chimney about 30 m further down the passage, which is probably connected to the surface. **Kristalni Rov (Crystal Passage; Fig. 3.05)** with the entrance at 528 m a.s.l., is a short passage about 100 m below the surface where is the monitored (since 1988) trickle located.

UNDERGROUND RIVER

The recent ponor of the sinking river Pivka lies at 511 m a.s.l. on the edge of the impermeable Eocene flysch rocks of the Pivka Basin, while several ancient ponors lie up to 529 m a.s.l. The active river flows towards the north, where the first sump is located in Pivka Jama at 477 m a.s.l. The river follows known and unknown passages and reappears in Planinska Jama at 460 m a.s.l. According to newly discovered passages in 2015, there are still about 500 m unexplored passages between Postojnska and Planinska Jama.

Pivka River is the main allogenic input into Postojnska Jama from the adjacent flysch basin (Q_{min} <0.01 m^3/s, Q_{max} > 60 m^3/s /s, Q_{av} = 5 m^3/s). The active flow can be followed without diving for most of the intitial 3.5 km, then the flow continues through a series of sumps connected by open surface river channels towards Planinska Jama (Planina cave), a large spring cave at the rim of Planinsko polje (Planina polje).

The flood water stagnates in narrow passages and breakdowns along the subterranean Pivka. The main obstacle is Martel's Rockfall (Fig. 3.07), in front of which the water can rise even up to 15 m, while the table between the collapse material and the entrance is almost horizontal. Behind Martel's

Rockfall, water fluctuations are not so pronounced. The average water discharge is 5.2 m^3/s. During floods, the water in the passages can rise up to 10 m. Signs of flows with different velocities are visible on the walls in scallops of different sizes. The inflow of River Pivka into Postojna Cave is during drought less than 100 l/s, whereas at times of heavy rain it may exceed 50 m^3/s.

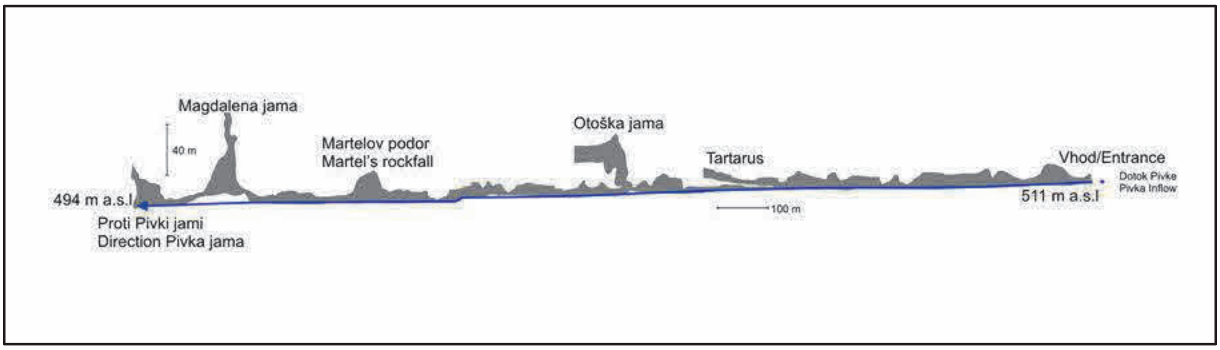


Fig. 3.07: A longitudinal section through the Passage of the Subterranean Pivka to the siphon in Magdalena Cave.

Between 2006 and 2008 were observed stage and temperature dynamics at seven points along its underground flow in Postojnska Jama (Covington et al. 2011; Kaufmann et al. 2016; Turk 2010). The goal was to relate flood dynamics to cave geometry and to study the heat exchange between allogenic river and the karst massif. The position of observation points is shown on Fig. 3.03. The sub-surface flow of the Pivka can be traced through the observation sites (white diamonds) from the Pivka Ponor to Postojnska Jama in the south (1) towards the terminal sump in Pivka Jama (beyond 7) in the north-east. Flow follows epiphreatic passages, which are large enough to accommodate even large floods. The main active system generally represents large channels with cross sections from 2-3 m by 10 m close to the Pivka Ponor up to 10 m by 10 m in the southern part of Pivka Jama. However, several constrictions along the flow path, the main being Martel's Breakdown, cause the back-flooding of the entire upper part of the Pivka channel, including flooding of the ponor area.

The period with a series of flood events in December 2008 is shown on Fig. 3.08. The right graph shows the absolute water level with almost flat water table upstream from Martel's Breakdown (orange to black) and rapid 20 m drop of water level between the breakdown and following station (Martel 's Chamber). This clearly shows that the Martel's Breakdown is the main flow constriction.

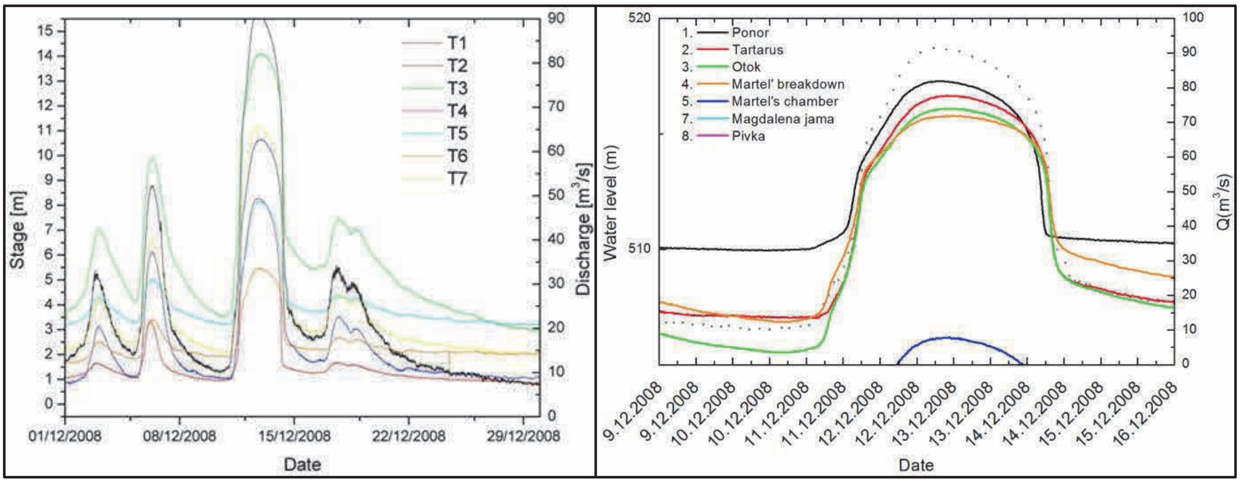


Fig. 3.08: Left: Discharge of Pivka river (black) and stage at all observation stations during highest flood pulses in December 2008. Right: Water level (m.a.s.l) and discharge (dotted line) during the highest flood.

We have then modelled the flood propagations through the system with Storm Water Management Model (SWMM). The model was optimized with inverse procedure based on the nearest neighborhood algorithm and root mean square between modelled and observed stages as a criterion. The geometry of the system was extracted the survey, while unknown passages were taken as optimization parameter. Fig. 3.09 shows a cross section of the system as used in SWMM. Conduits, which were taken as free parameters in optimization procedure are shown red. Fig. 3.10 shows satisfactory agreement between modelled and measured responses.

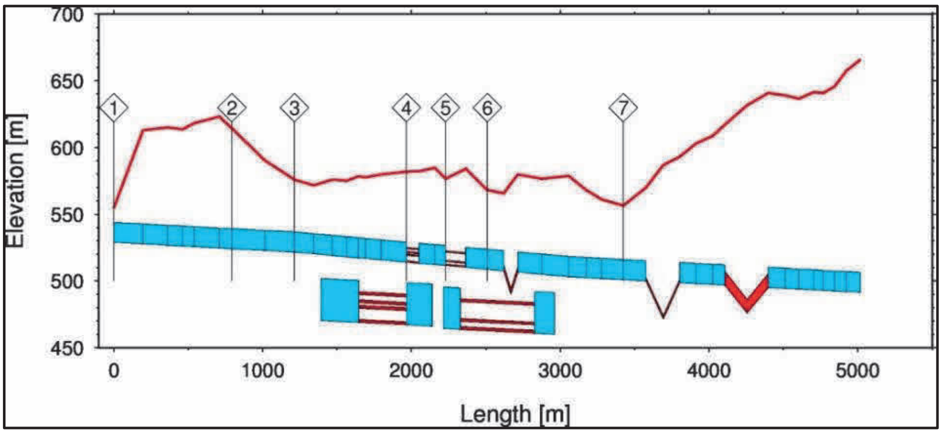


Fig. 3.09: A simplified SWMM geometry used for modelling flow in Pivka Channel. Surface topography is shown as thick red line, and modelled cave cross sections as blue (rectangular geometry, fixed cross-sections) and red (circular geometry, optimized conduits). The observation points are marked with diamonds and numbered. Both Martel's rockfall and Martel Chamber are additionally shown as enlargement in the inset.

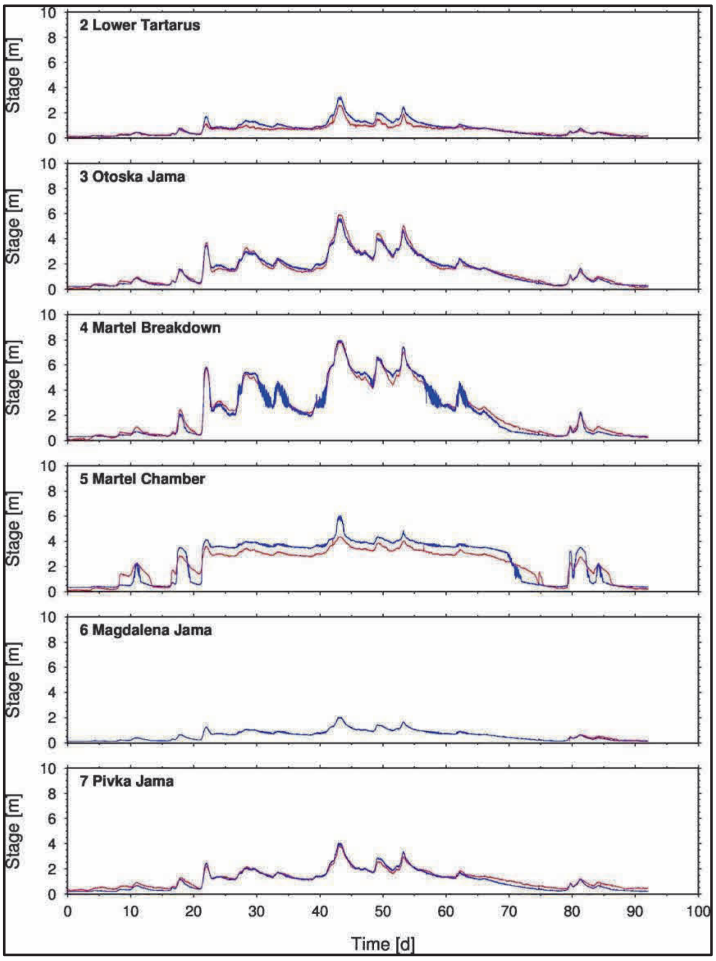


Fig. 3.10: Data and model for stage at seven locations in Postojnska Jama for the period Mar-May 2008. The time is given in days starting on 1. March 2008. Shown is observed stage (red lines) and modelled stage (blue lines) for all seven locations.

CAVE SEDIMENTS

In all passages, the sinking river deposited various sediments, including gravel, sand, clay, and loam. The deposits are derived from weathered flysch rocks of the Pivka Basin and are therefore more or less the same in terms of mineral composition, with quartz, plagioclase and clay minerals predominating (Zupan Hajna 1992). The remains of the deposits in the cave are up to several million years old, but in terms of their mineralogical composition they are identical to the present-day deposits of the Pivka. The remains of the allogenic sediments can be dated up to 2 million years old (Zupan Hajna et al. 2008a, 2008b, 2010, 2020); in terms of composition, they are identical to the present-day deposits of the Pivka. In the course of their history, the cave passages were repeatedly completely filled with sediments and then eroded again (this can be concluded from the remains of the floor, walls and ceiling, as well as between the layers of flowstone.

Table 1 shows the number of samples collected for the paleomagnetic study (Zupan Hajna et al. 2008a, 2008b, 2010, 2020), and Table 2 lists the main results of all the sites studied and the reinterpreted ages of the sedimentary sections and their segments from Postojnska Jama (Zupan Hajna et al. 2020). Sedimentary sections were divided into segments according to paleomagnetic parameters (polarity, I - inclination, D - declination, NRM - natural remanent magnetization, MS - magnetic susceptibility) and, where possible, lithology. Segments were correlated with chronometric dating of interbedded speleothems or overlying sediments, and with biostratigraphic data where available. Magnetostratigraphic dating was often uncertain due to generally small thickness of the sections and lack of correlated data. Studies and interpretations of the results are ongoing.

Table 1. Postojnska Jama, a number of section, paleomagnetic samples, and paleomagnetic segments (from Zupan Hajna et al. 2020)

Site No	Locality / section name	Coordinates	Morphology	No. of sections	No. of PM samples	No. of PM calculated segments	Sampled sediments
15	Postojnska Jama	N 45°46'58.00" E 14°12'13.58"	active cave, dry parts	11	687	27	allogenic, speleothem

Table 2. Postojnska Jama, sediments age interpretations from published results (F – flowstone; S – allogenic sediment) (from Zupan Hajna et al. 2020)

Site No	Locality / section name	Section	Type	Segments PMG			
				No.	Depth (m)	Age	Age alternative
15	Postojnska Jama	Spodnji Tartarus North	S, brown	1	7.455-6.525	(<0.13)->0.78<0.99	
			S, yellow	1	7.445-4.465	>0.13-<0.78?	>0.78->2.58
				2	4.415-3.05	>0.13-<0.78?	>2.58-<3.58
			S, red	1	4.835-3.895		>2.58-<3.58
				2	3.85-2.47		>2.58-<3.58
				3	2.35-0.03		>2.58-<3.58
		Spodnji Tartarus South	S red+yellow	1	9.41-9.11	>0.121-<0.78	>0.78->2.58
				2	9.06-6.26		
				3	6.21-5.55		
				4	5.49-0.02		
		White sands	S	1	Hand spec.	?(>>0.78)	>3.58
		Umetni tunnel 2003	S	1	0.04-0.34	~0.99-~2.15	>2.58-<3.58
			S	2	0.35-0.40		
		Umetni tunnel 2007	S	1	0.01-0.03		
			S	2	0.04-0.31		
			S	3	0.32-0.36		
			S	4	0.37-0.41		
		Umetni tunnel 2008	S	1	U60-U74		
			S	2	U80-U84		
		Kraški žep	S	1	0.54-0.04	?	
		Biospeleološka postaja	S	1	0.31-0.64	<0.04	
			S	2	0.955-1.04	<0.78	
		Male jame	S	1	0.95-0.74	<0.78	>0.78
			S	2	0.71-0.65		
			S	3	0.63-0.42		

			S	4	0.39-0.03		>2.58-<3.58
		Pisani Rov	F	2	1.46-1.37	>0.03-<0.78	
			S	1	1.92-1.19	<0.78	>0.78
		Stara Jama	S	1	1.35-0.01	<0.78	
		Vilharjev Rov	S	1	0.91-0.50	<0.78	
			S	2	0.47-0.03		

The passages in the now dry part of the cave were formed by the flow of water when the river was still flowing at this level. Later, the water flow shifted downward due to a lower gradient. Now, the dry passages up to the height of 520 m can be reached only by the highest waters. The passages in the now dry section are large - up to 10 m high and wide. Their profiles here are rounded and show traces of paragenesis (transformation by sediments), such as levelled ceilings and side notches on the walls.

Dry passages are largely full of speleothems, especially those that have not been filled with sediments for a long time. Speleothems vary in shape, color, and age (Fig. 3.11). The oldest known speleothem from Postojnska Jama's comes from Pisani Rov (Colourful Passage). Its core has been dated to about 530,000 years using ESR and U/Th methods (Ikeya et al. 1983; Zupan 1991). Outer rings of the same speleothem from the same passage have yielded ages of 23,000, 12,000, and 6,000 years (Zupan 1991). Dated speleothems from Velika gora (Great Mountain) reveal growth periods in warmer climate periods and the time of ceiling collapses in colder climate (Mihevc 2002). The age of speleothems on the collapse rocks at 527 m, dated by U/Th, were 152,000 47,000, 43,000, 37,000 years. In the entrance areas of Postojnska Jama and in the passages near the collapse dolines, a lot of periglacial cryogenic rubble was deposited during different glaciations. Data from the base parts of the stalagmites in the entrance parts of Postojnska Jama can constrain the youngest age of the last glacial deposition in Črna Jama cave to about 12 ±733 ka (Zupan Hajna et al. 2022). In the sedimentary section at the entrance to Rov novih podpisov, flowstone layers were dated to 30.2±0.6 ka, 103.2 ka BP, and 153.1 ka BP (Ferk et al. 2019).

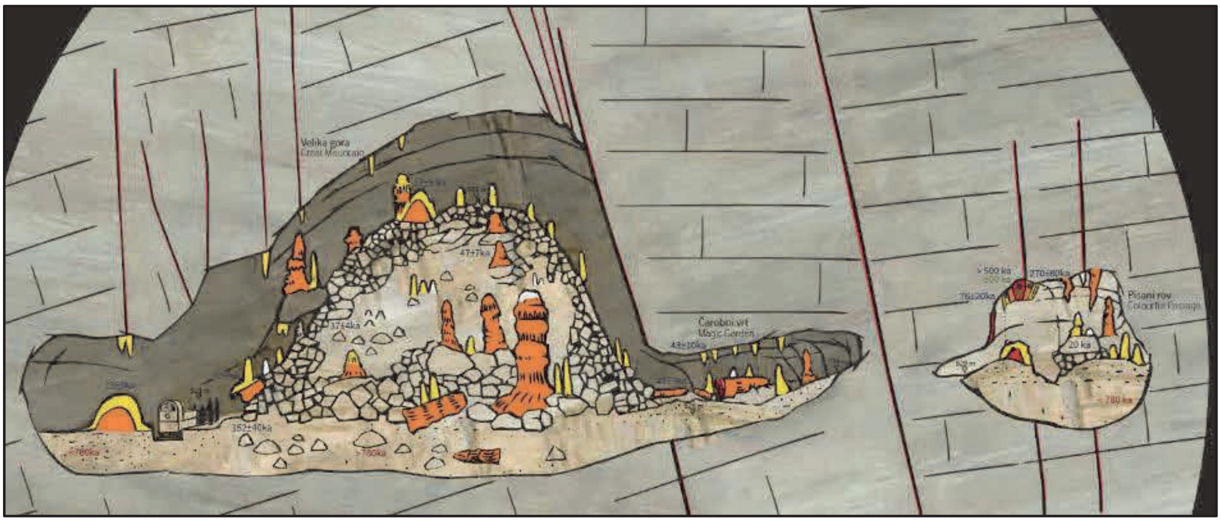


Fig. 3.11: Schematic cross-section of Velika gora, Čarobni vrt and Pisani Rov cave passages with dating results; speleothems: U/Th, ESR, C14; and fluvial sediments: paleomagnetic (from Zupan Hajna 2015).

MICROCLIMATIC CHARACTERISTICS

The climate of Postojnska Jama is (like in most caves) determined by the external weather conditions, the geometry of the cave and position of its entrances. The configuration of many entrances at different altitudes enables year-round ventilation of the cave. The ventilation shows two different seasonal regimes (Fig. 3.12), winter (typically upward) and summer (typically downward).

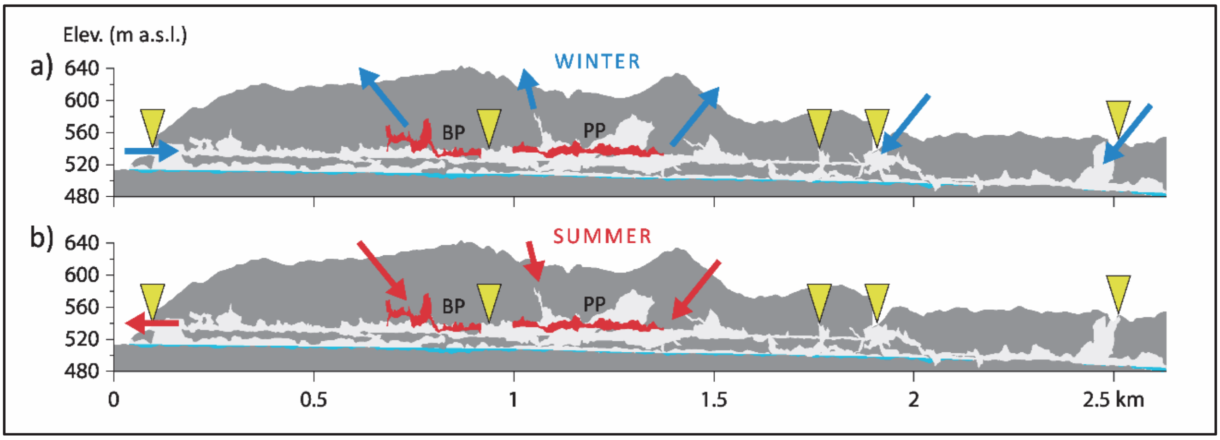


Fig. 3.12: Extended profile of Postojna Cave showing typical ventilation regimes – winter (a) and summer (b). Legend: Yellow triangles – cave entrances; blue arrows – updraft; red arrows – downdraft; BP – Brezimeni Passage; PP – Pisani Passage. The horizontal scale is reduced by 50%. In addition to the known entrances, many breathing holes, which are not explicitly shown, allow efficient ventilation throughout the year.

The average annual air temperature is 9.3°C, the coldest month is January with –0.1°C and the warmest is July with 19°C (average for the period 1981–2010). The average annual precipitation for the same climate period is 1500 mm, with generally heavier precipitation in autumn and in the colder months. The Postojna station recorded warming in the range of 0.35–0.45°C per decade. Postojna is also known for its windiness, particularly in colder month with frequent periods of cold katabatic wind Bora blowing from NNE. Bora has characteristic strong gusts, where speed frequently exceeds 20 m/s. All karst massifs exhibit characteristic temperature, which is a result of long term external climatic conditions and long-term heat exchange between rock infiltrating water and air. Such temperatures can be measure in isolated parts of caves in thermally equilibrated infiltrated water (autogenic groundwater flow and thermally equilibrated trickles). In Postojna region the equilibrium temperature is between 8.5°C and 9.0°C. In principle, this is the temperature one would expect to observe in caves in absence of ventilation, people and allogenic water. But it is not so.

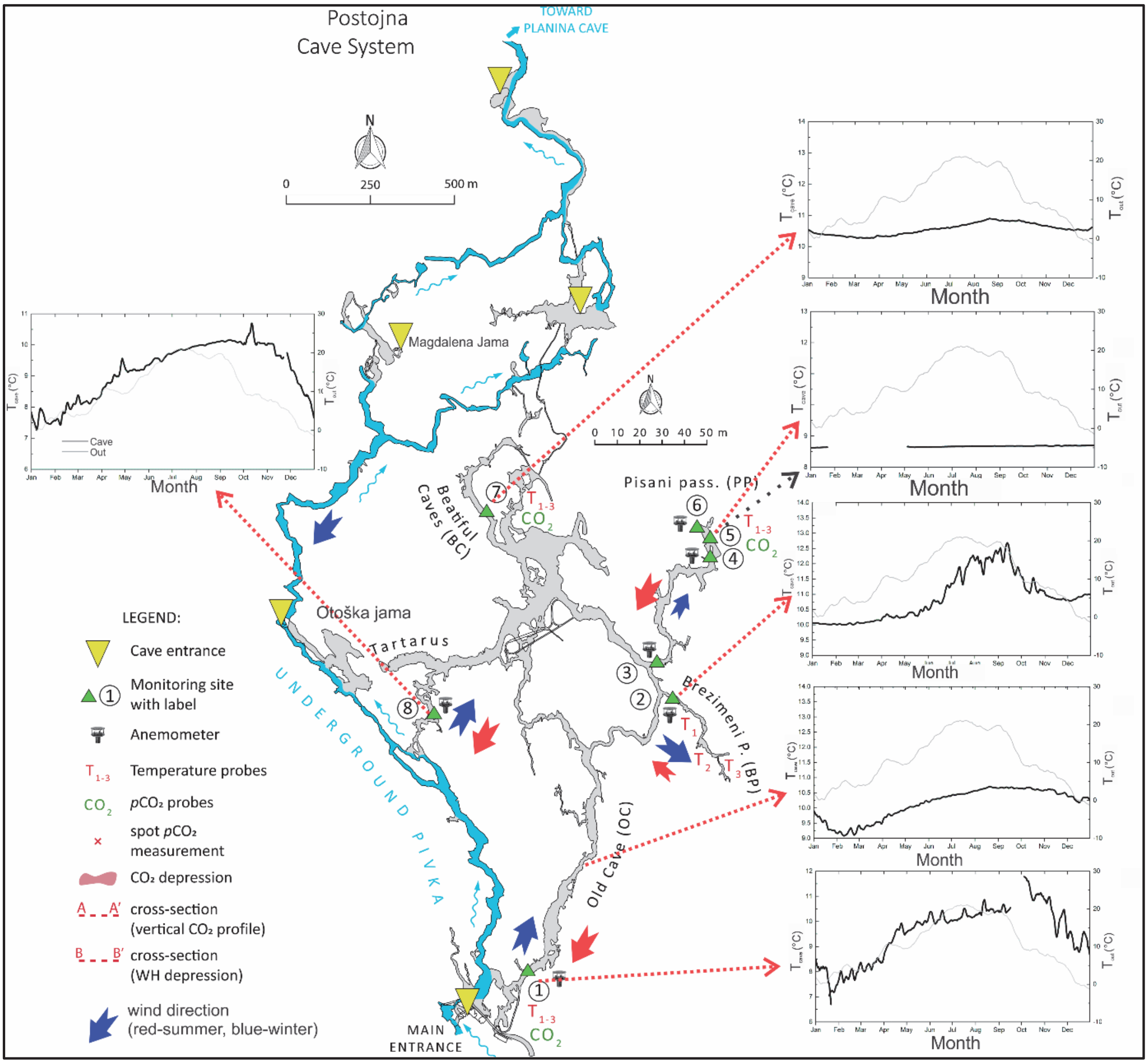


Fig. 3.13: Plan view of Postojnska Jama with entrances and locations of meteorological observations. Graphs on the right (and left) show yearly temperature variations at different locations (see red dotted lines). Arrows indicate winter (blue) and summer (red) airflow direction. Arrow size indicates relative winter/summer velocity. Map adopted from (Kukuljan et al. 2021).

The climate of Postojnska Jama is diverse. It is senseless to discuss about average values of any climatic parameter. The cave is over 24 km long, with two distinct levels, three entrances connected by open passages and two entrances connected to other parts of the system by an artificial tunnel closed by airtight doors. The prevailing airflow driving mechanism is chimney effect with *updraft* in the winter and *downdraf* in the summer. During *updraft,* the air enters the system through main entrances and exits through distributed (not explored) small channels and fractures to the surface above the cave. In the warm period, the direction is opposite.

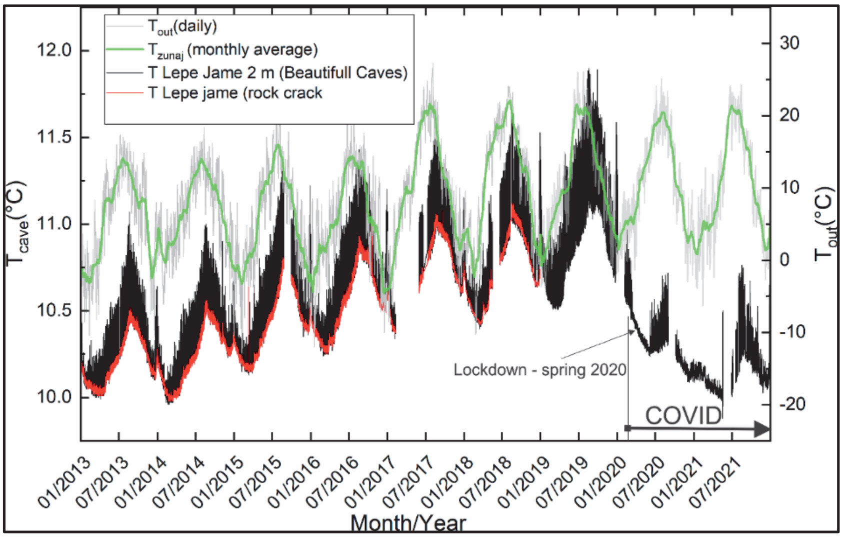


Fig. 3.14: Temperature variations in Lepe Jame (Beautifull Caves) between 2013 and 2021.

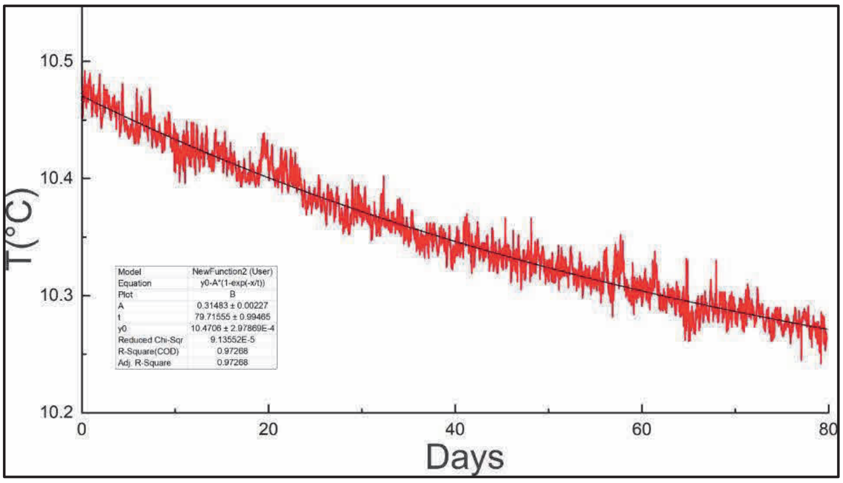


Fig. 3.15: Temperature relaxation at Lepe Jame location during spring 2020 lockdown.

We have established and maintained four stationary meteorological stations in the upper level of Postojnska Jama. They record temperature, airflow and CO_2. Although there are gaps in the data due to malfunctioning, while some stations have been established latter or abandoned, we have managed to gather a large data set, which is still being studied. Fig. 3.13 shows the measurement sites with parameters. These sites include dead- end no touristic passages (Pisani Passage, Brezimeni Passage), main touristic passages (Beautifull Caves), the main ventilation pathways (Tartarus, Old Cave), and near-entrance station (Old Cave). The graphs on the Fig. 3.13 show typical yearly temperature dynamics at different sites. Temperature variations are larger close to the entrance and along main ventilation sites. However, this need not to be, in a well ventilated Pisani Rov (Pisani Passage), the temperature is practically constant. The climate in Lepe Jame (Beautiful Cave) is strongly influenced by the presence of tourist groups. The passage is poorly ventilated and shows large diurnal and seasonal temperature and CO_2 variations, which are directly correlated with tourist visits. Fig. 3.14 shows the temperatures between 2013 and 2021. The temperature was increasing until the onset of Covid crisis. We anticipate, but cannot confirm, that the increase was related to increasing visit. During the Covid period, starting with March-June 2020 lockdown, the temperature drops exponentially towards 10.15°C. Fig. 3.15 shows the temperature dynamics during 80 days of lockdown in spring 2020.

Arrows in Fig. 3.13 indicate wind direction and relative intensity. In some passages (Tartarus) the winter and summer airflow velocities are comparable, while in some ventilation is dominant in winter (Brezimeni Rov) and in some in summer (Pisani Rov). See discussion latter. As we show latter in detailed site description, the airflow is also influenced by surface winds, particularly bora gusts: The wind flow over rough topography causes near surface pressure differences, which then cause subsurface airflow. The surface wind may enhance, diminish or even reverse the subsurface airflow. This is observed regularly in Postojnska Jama.

More details cave climate, including CO_2 dynamics and wind-driven ventilation for specific locations are given bellow. For an in-depth study, refer to original publications listed in References.

SPELEOBIOLOGY

Postojnska Jama is known after the first discoveries of subterranean animals (troglobionts) in the world. In 1797 *Proteus anguinus* (cave salamander, olm or human fish; Fig. 3.16A) was found for the first time in the cave Črna Jama. In 1831, one of the cave guides, Luka Čeč, found the first cave beetle *Leptodirus hochenwartii* (the Slenderneck beetle; F ig. 3.16B). With these first discoveries, the new biological explorations in the cave began and many new species were found and described in the cave: the cave spider (*Stalita taenaria*), the Postojna Cave pseudoscorpion (*Neobisium spelaeum*), the cave amphipod (*Niphargus stygius*), the giant cave trichoniscid (*Titanethes albus*), the cave snail (*Zospeum spelaeum*) and the cave centipede (*Lithobius stygius*). Consequently, Postojnska Jama is also known as a cradle of speleobiology as a science (Pretner 1968). Postojnska Jama is a hotspot of biodiversity, as 114 species of cave-dwelling animals (Zagmaister *et al.* 2014) have been discovered and described in the cave; for 84 of them the cave is the type locality (*locus typicus*).

Fig. 16: A - Proteus is an endemic species of the Dinaric Karst and was first found in 1791 in Črna Jama, which is part of Postojnska Jama; B - Leptodirus *is the first cave-dwelling beetle in the world, discovered in Postojnka Jama in 1831 and recognized and scientifically described as a true cave-dwelling animal a year later, in 1832, by Ferdinand Schmidt.*

PALEONTOLOGY AND ARCHEOLOGY

The first finds of fossil bones of a cave bear are connected with the discovery of the interior of Postojnska Jama in 1818 and later with finds from karst caves in the vicinity of Postojna (Osole 1975). The first finds of stone tools in the caves around Postojna are known from the Betalov Spodmol near the blind valley of Risovec (Anelli 1933).

Postojnska Jama (Postojna Cave), excavated test pits in dry parts at an elevation of about 520 m (Fig. 3.17A). Paleontological and archaeological excavations: 1) Freyer in 1819: Ballroom - paleontological finds; 2) Brodar S. in 1951: Slonova glava, Okovana polica, Gotska Dvorana, Rov za Plesno dvorano, Pisani Rov, Končna postaja jamske železnice, Za Veliko goro, Imenska Jama (Elephant's Head, Chained Shelf, Gothic Hall, Dance Hall Trench, Colorful Trench, Cave Railway End Station, For Great Mountain, Name Cave) - cultural remains, paleontological finds; 3) Brodar S. in 1964 (published in 1966): Rov za Biospeleološko postajo (Passage behind the Biospeleological Station) - paleontological findings and cultural horizon; 4) Brodar M. in 1969: Pri Ranžirni postaji (At the Range Station) - cultural horizon and paleontological findings; 5) Turk & Dirjec in 1986 (published in 1987): Behind the Hotel - cultural horizon and paleontological finds; and 6) Bavdek in 2002 (published 2003): entrance to the Biospeleološko postajo (Biospeleological Station), paleontological finds. Paleontological finds (Brodar 1951, Osole 1975, Rakovec 1975): Cave bear (*Ursus spelaeus*), cave lion (*Panthera leo spelaea*), cave hyena (*Crocuta crocuta spelaea*), hippopotamus (*Hippopotamus pentlandi* (?)), wolf (*Canis*), Bovidarum, various deer (*Cervus* sp.), horse (*Equus* sp.), etc. Human cultural remains: stone tools from the Mousterian and Aurignacian cultural stages (Middle and Late Paleolithic; 115,000 to 10,000 BC).

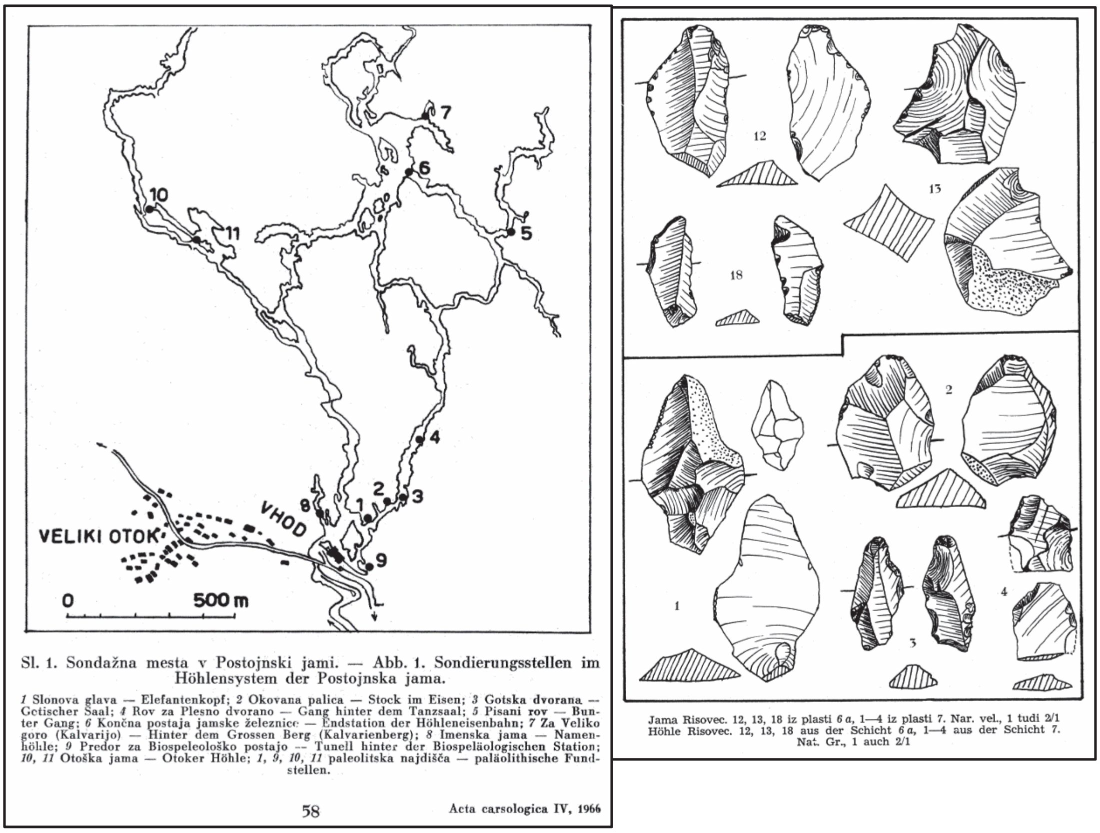


Fig. 3.17: A - Excavations by Srečko Brodar in Postojnska Jama (from Brodar 1966); B - Pre-Mousterian tool from the cave Risovec (from Brodar 1970).

Otoška Jama (Otok Cave), test pits in the dry parts of the cave at an altitude of about 530 m. Paleontological and archeological excavations were carried out by Brodar S. (1951), where he found paleontological findings and charcoal, as well as an artifact (part of a stone tool of the Mousterian culture stage). The paleontological finds (Brodar 1966, Rakovec 1975) were mainly bones of cave bears (*Ursus spelaeus*), snow voles (*Microtus nivalis*) and some others.

Risovec (Risovec Cave) is located at an altitude of about 530 m. Paleontological and archeological excavations were carried out by Brodar S. in 1967 and 1968 (published in 1970). They found cultural and paleontological findings. It is a site of primitive stone tools from the Pra-Mousterian (Fig. 3.17B). The paleontological remains (Brodar 1970, Rakovec 1975) were mainly broken bones and teeth (mainly hunting prey) of warm-blooded rhinoceros (*Dicerorhinus*), deer (*Cervus* sp.), elk (*Alces alces*) and beaver (*Castor fiber*).

CAVE TOURISM

Postojnska Jama is the largest show cave in Slovenia and in Europe, with a total of 37,000,000 registered visitors in August 2016. The entrance part, called **Veliki dom (Great Dome; Fig. 3.05)**, is a hall that was known to visitors to Postojnska Jama even before the inner parts were discovered. The river Pivka flows through the siphon from the outer ponor into the bottom of this chamber. When the water level rises, an underground lake about 10 meters deep is formed there. The inner parts of the cave were discovered only in 1818.

The worldwide fame of Postojnska Jama was achieved through almost 200 years of intensive tourist development: discovery of the inner parts in 1818, guided tours since 1819, railroad since 1872, permanent electric lighting since 1884 and something else very important: despite the constant use for tourist purposes, the cave remains a natural attraction in excellent condition with over 500,000 visitors per year. Sustainable management is a big challenge in show caves with such large visitor numbers.

CAVE MONITORING BY KARST RESEARCH INSTITUTE ZRC SAZU

Sustainable management is a major challenge in show caves. While the direct physical impacts of tourism infrastructure on the cave environment are relatively easy to assess, evaluating the indirect impacts of tourism is a difficult task. In this context, long-term monitoring and analysis of environmental parameters are critical. The chemical and physical parameters of the seepage and allogenic enrichment of the cave system have been monitored for decades.

Since 2007, monitoring has been conducted at several meteorological stations. Different meteorological patterns have been observed in different parts of the cave. Along the main advection pathways, the climate is strongly influenced by the external climate, while the climate in the more isolated chambers is quasi-stable. In some parts, the climate is influenced by the presence of tourist groups. This was also determined by several measurement campaigns. Measurements of radon concentration were carried out with regard to occupational safety and natural processes in the caves.

Quality of Pivka River

The Pivka which sinks and continues its underground flow through the caves of Postojska Jama represents an allogenic recharge of the Unica spring on Planinsko Polje. The Unica emerges through a network of large underground channels with discharges ranging from 0.2 to 89 m^3/s.
The catchment area of the Pivka in its southern part consists mainly of Cretaceous limestone. Due to the shallow karst in this area, the river has intermittent surface flow. The northern part of the catchment consists of Eocene flysch and has a surface water network. Human settlements and activities are concentrated in this area. Therefore, the Pivka is often polluted with nitrates and bacteria and as such enters the karst system (Mulec *et al.* 2019; Ćuk ĐuRović in review). Pollution may come from settlements and economic activities whose wastewater discharge is unregulated or inadequately regulated. Water quality is additionally affected by agriculture (poorly regulated manure and septic tanks). The spillage of large quantities of hazardous and toxic substances in the event of accidents is also a major hazard.

In order to maintain the quality of groundwater, protection and management of groundwater resources are generally provided for in national water and riparian use laws (Ravbar & Šebela 2015). Another important element of water source management is monitoring the qualitative and quantitative status of waters (Ravbar et al., 2017). However, the frequency of qualitative status monitoring is usually scheduled only a few times per year, and there are no specific requirements for water quality monitoring in karst areas. Because conditions in karst aquifers can change very rapidly, the results of sparse monitoring do not necessarily show representative values of water quality status. Due to the characteristics of groundwater flow, the quality of karst water changes significantly under different hydrologic conditions. Often their quality deteriorates very rapidly during periods of more intense precipitation, especially after rainfall following prolonged dry periods, when the most intense leaching and contaminant transfer takes place.

Water percolation study

Study of water percolation and solute transport in a karst vadose zone began in 1988. The passage Kristalni Rov in Postojnska Jama has been used as an experimental site for almost 35 years where the first systematic periodic measurements and analyses of selected drip points were done. The research included measurements of precipitation and discharge, temperature and electrical conductivity of drips in the cave, isotope analyses, analyses of contaminants, tracer tests and the use of electrical tomography. The main results are summarized in the monograph Characteristics of percolation through the karst vadose zone (Kogovšek 2010).

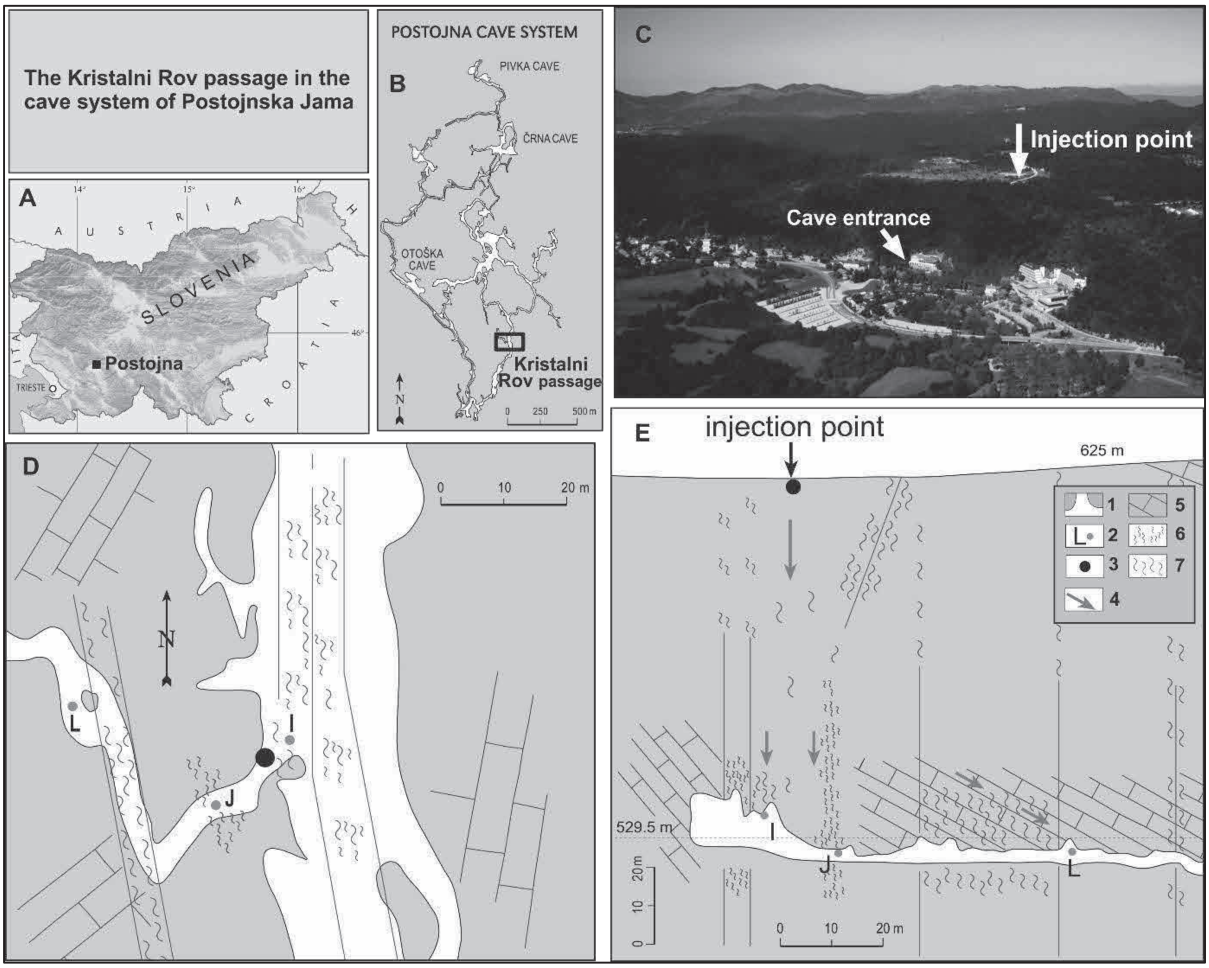


Fig. 3.18. Geological map (D) and cross-section (E) of the study area (1-ground plan or cross section of cave gallery, 2-observed drip, 3-injection point, 4-probable direction of percolation water, 5-Upper Cretaceous limestone, 6-fractured zone, 7-fissured zone). The Kristalni Rov cave gallery in the system of Postojnska Jama (B) is located near the town of Postojna in south-western Slovenia (A). The tracers were injected at the surface above the cave gallery (C).

Here, the findings on the processes affecting solute transport in the vadose zone of the karst are presented in more detail based on three long-term tracer tests. The Kristalni Rov is a short gallery in the initial part of the Postojnska Jama formed in the Upper Cretaceous limestone (Fig. 3.18B). Three drips of different hydrological characteristics were observed (Figs. 3.18D, E). The fastest percolation (drip I) occurs in fissured to moderately fractured zones, while the slower percolation flows along tectonically fractured zones (drip J) and bedding planes (drip L) (Kogovšek & Šebela 2004). The surface immediately above the cave passage is covered with grass and a layer of soil about 10 cm thick, and the surrounding area is overgrown with forest (Fig. 3.18C). Until 1991, there was a military facility there, from which the wastewater drained into a cesspool about four meters deep with bare rock at the bottom.

On June 7, 1993 (1st tracer test), first 0.5 m^3 of water was poured at the bottom of the cesspool, then a solution of 60 g of uranine was injected and flushed with 5.5 m^3 of water over a period of one hour. On November 17, 1996 (2nd tracer test), a solution of 15 g of uranine was injected at the same point and no artificial flushing was applied. On June 7, 2002 (3rd tracer test), a solution of 60 g of eosin was injected on the surface near the cesspool, directly on the approximately half a meter of deposited sediment with 10 cm thick layer of soil with grass. Simultaneously, a solution of 15 kg of sodium chloride as the second tracer was injected at the same point as in the two previous tracer tests. The two injected tracers were flushed only naturally by subsequent precipitation. The tracer breakthrough curves were monitored at three drips I, J, and L over several years (in the third test the last samples were taken 11 years after the injection).

The results are presented in more detail in Kogovšek & Petrič (2014). The tracer tests differ in 4 factors which have a significant influence on the characteristics of water flow and solute transport through the vadose zone of karst aquifers:

a) preceding hydrological conditions:
   - during longer dry periods with dry soil and poorly saturated vadose zone;
   - after intensive and abundant precipitation with wet soil and when the pores in vadose zone are mostly filled with water and hydraulically connected;
b) injection mode:
   - rain in natural conditions;
   - focused flush of a large amount of water (fluids in accidents);
c) infiltration conditions at the surface:
   - infiltration through a bare karst rock;
   - infiltration through an overlying layer;
d) permeability of different parts of the vadose zone:
   - different types of fissures and therefore different characteristics of transport dynamics with important influences of storage effects.

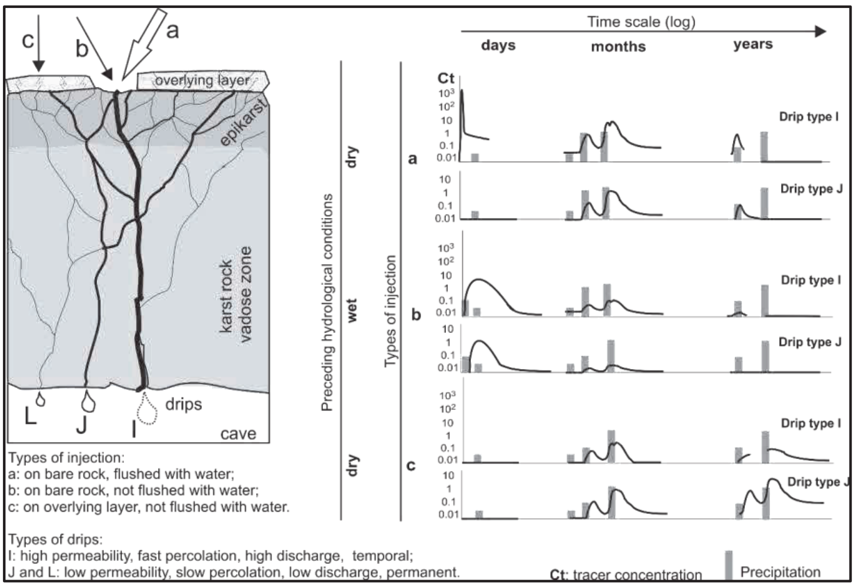


Fig. 3.19. Schematic presentation of the solute transport dynamics in a karst vadose zone.

In Fig. 3.19 these factors and their influences are presented schematically. For individual cases the shape of the breakthrough curves simulates the transit of tracer at various conditions on a time scale of days, months or years. By analogy the characteristics of the time and intensity of the first appearance of contaminants, as well as the duration of their storage within the vadose zone under various conditions can be foreseen. During dry periods with less productive and intense rainfall, water does not flow through the entire hierarchy of fissures but only along preferred pathways in the soil and karst rocks of the vadose zone. Therefore, most of the infiltrated precipitation and substances carried with the water are stored in the less permeable parts. Only after further abundant and intense precipitation events, the stored substances are gradually washed out. Such runoff triggered by precipitation events may occasionally occur over a period of several years. During wet periods, continuous flow through all types of hydraulically connected fissures is facilitated and immediate and relatively rapid homogeneous transport of solutes with significant dilution occurs. In addition, it has been demonstrated that overlying layers (soil and sediments) can delay water flow and solute transport through karst aquifers for many years or even decades.

The injection mode has a significant effect on the observed solute transport rates. Injection with artificial irrigation results in rapid infiltration, and transport velocities determined with such tracer tests cannot be used to evaluate migration of diffuse contamination. However, they can be used to evaluate the consequences of accidental spillage. Because some contaminants may appear in karst water sources in a very short time and in high concentrations, such rapid recharge should be considered when delineating source protection zones.

Extensometer measurements of tectonic activity

Postojna Cave lies between two active major regional Dinaric faults, Idrija Fault and Predjama Fault. The cave has a multitude of different speleothem forms, some amongst them are deformed or broken speleothems, consequently a proportion of them were possibly damaged by tectonic and seismic activity (Šebela 2008). In an effort to characterize and quantify active tectonic fault deformations within the Postojna cave, TM71 and TM72 extensometers were installed, instruments that measure micro-displacements (Šebela *et al.* 2021). The still lasting campaign of measuring active fault displacements within the cave started in 2004 with two TM71 extensometers (Fig. 3.20), in Velika Gora (PO1) and Lepe jame (PO2). In 2016 two newer additional TM72 extensometers were installed, in Koncertna Dvorana (PO3) and in a cave passage next to the cave railway tracks (PO4). The first two TM71 extensometers were replaced by TM72 extensometers in 2020. All of extensometers are situated in fault zones that have a Dinaric orientation, NW-SE strike. Each set of extensometers is located in different fault zone; the set of first installed extensometers (Velika Gora-Lepe jame) in one zone and the newer set, second installation (Koncertna Dvorana-cave railway tracks chamber) in another. The monitored faults exhibit small tectonic micro-displacements, up to 0.08 mm/year. Indicating that the wider zone of the southern fragments of Predjama Fault is most likely still active.

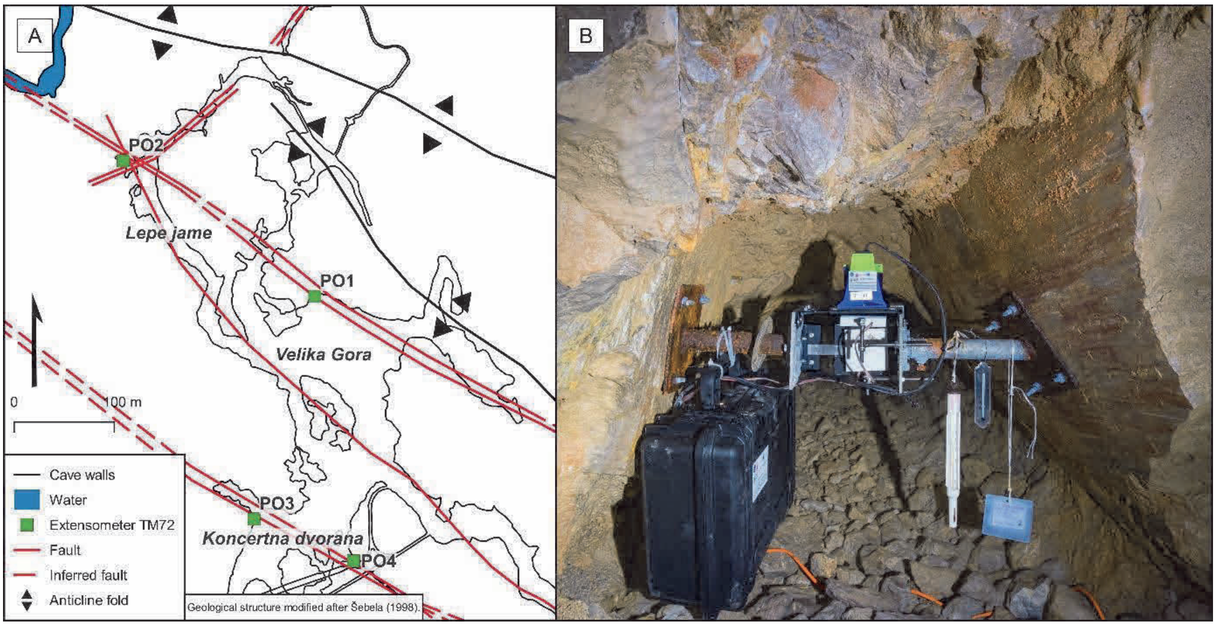


Fig. 3.20: Geological structure of a segment of the Postojna Cave with the locations of extensometer monitoring sites. B) Extensometer PO2 in Lepe jame.

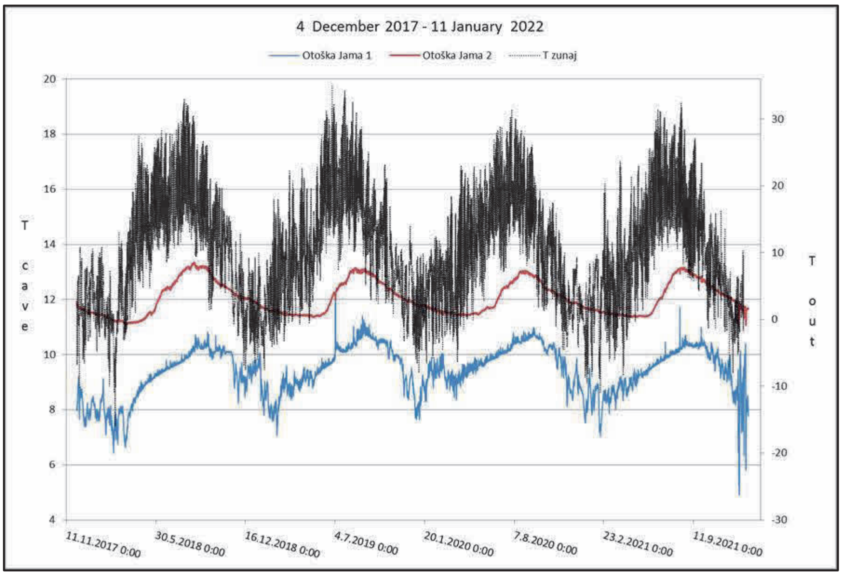
Microclimate monitoring(s)

Otoška Jama (Fig. 3.05). The cave is about 600 m long, mostly horizontal, with underground River Pivka at its SE edge. The cave has the name after Veliki Otok (Big Island) village in the vicinity. According to Crestani and Anelli (1939) the cave was discovered on August 18, 1884. Local people noticed that in winter in the area near the cave entrance snow melted more quickly as on other areas and so they suspected that warmer air as outside air is coming from unknown cave (Crestani and Anelli 1939). In 1889 F. Dolenec and J. Vilhar uncovered the entrance by digging (Kranjc and Malečkar 1988). Today the entrance situated at 531 m above the sea is closed by metal doors and just at the upper top there is open space for bats that use the cave for hibernation. The cave has limited number of visitors with only alternative visits and does not have electric illumination. Archaeological remains and animal bones in Otoška Jama belong to Palaeolithic period (Brodar 1951).

Air temperature monitoring started on 4 December 2017 (Fig. 3.21) at two monitoring sites. While the most visited parts of Postojna Cave have been subject to regular micro-climatic monitoring since 2008 and 2009, air temperature monitoring in non-heavily visited cave parts started not long ago (Šebela 2022). The first purpose to expand monitoring sites was to provide the new data-set from almost not-touristic parts and to make comparison between heavily visited and not heavily visited cave parts. The second purpose was to get familiar with micro-climatic conditions in not-touristic parts before they potentially become touristic (Šebela 2022).

Two monitoring locations show different air temperature range on the yearly basis (Fig. 3.21). Temperature at Otoška Jama 1 site is lower than at Otoška Jama 2. At Otoška Jama 1 site there are more pronounced air temperature daily oscillations as at Otoška Jama 2. Also the difference in mean annual air temperature between two locations shows that Otoška Jama 1 site had for 2.98°C lower value as Otoška Jama 2 site in 2018. Such difference was even higher in 2019 when it was 3.41°C (Šebela 2022). Low winter air temperature values at Otoška Jama 1 are due to the vicinity of monitoring site to cave entrance. Dense and heavy cold winter outside air reaches the Otoška Jama 1 site and causes the drop in cave air temperature (~2°C) during winter. The difference between the highest summer values and lowest winter values is even higher (4.4°C in 2018 and 5.14°C in 2019). The highest summer values at Otoška Jama 1 in 2018 demonstrated 10.82ºC and 12.21ºC in 2019 (Šebela 2022). Otoška Jama 2 site had minimum winter air temperature values of 11.1ºC in 2018 and 11.35°C in 2019. This shows that there is no strong impact of outside winter air to Otoška Jama 2 site. We must not forget that this site is situated near underground River Pivka passage. The position of Otoška Jama 2 site can have characteristics of warm air trap what is the cause to preserve high air temperature not only in summer but also in winter (Šebela 2022).

Regarding mean air temperature for the period 2018–2022 we become aware that Otoška Jama 2 is the warmest between all monitoring sites in the whole cave system if we compare it with mean outside air temperature. At Otoška Jama 2 air temperature is +1,95°C higher as outside. Otoška Jama receives very low visitor numbers and can be treated as almost not touristic cave. Here, we deal with natural micro-climate conditions and especially with the fact that a lot of heat is transmitted to the cave air from underground River Pivka and that the monitoring site probably represents warm air trap (Šebela 2022).



Fi. 3.21: Air temperature measurements at Otoška Jama and outside the cave in °C.

Pisani Rov (PP; Fig 3.05) and Brezimeni Rov (BP; Fig 3.05) are dead-end passages, connected to Stara Jama (Old Cave) less than 100 m apart. However, their microclimate is completely different. Starting from the temperature, its yearly variations in PP is less than 0.1°C, while the yearly variation in most of the BP exceeds 2°C. The summer CO_2 values in PP exceed 1%, while in most of the BP, the summer CO_2 is less than 0.1% or even close to external 400 ppm. Fig. 3.22 shows the position and profile of both passages and their airflow patterns.

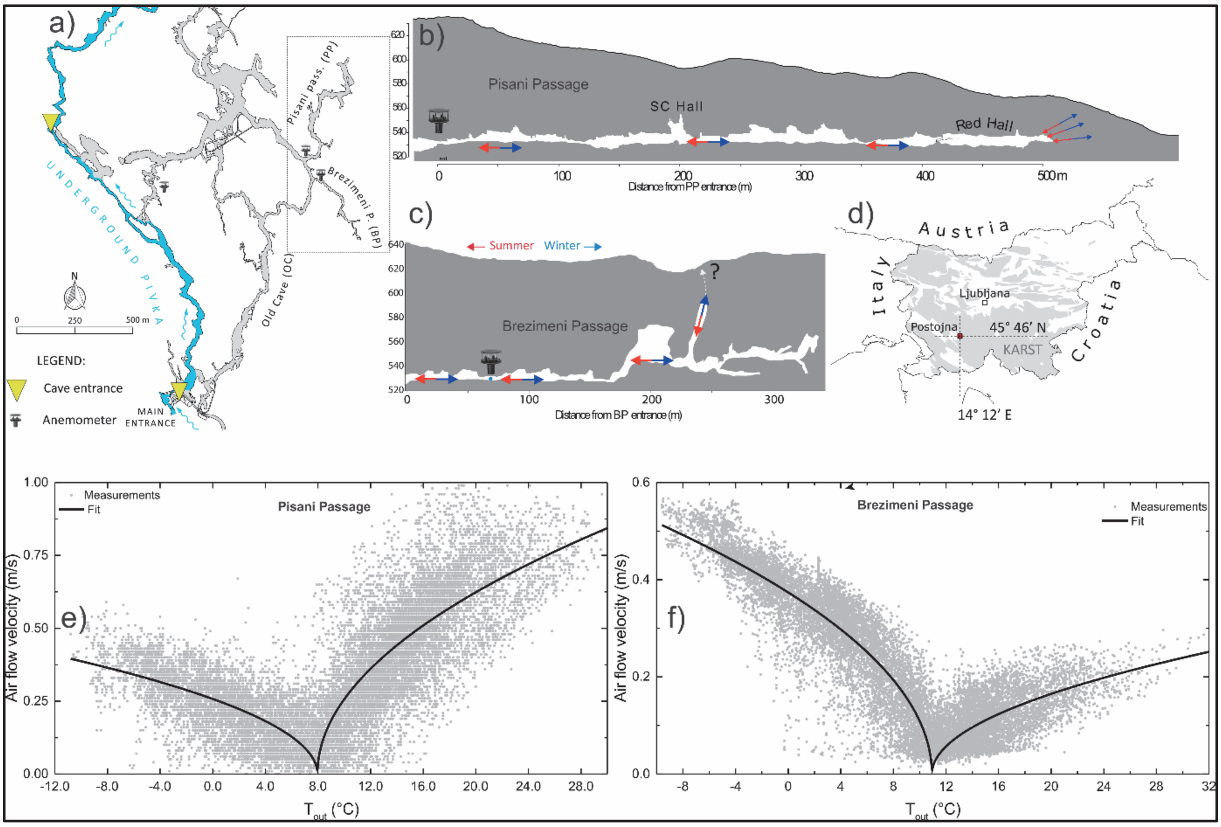


Fig. 3.22: a) Position of Pisani Rov (Pisani Passage, PP) and Brezimeni Rov (Brezimeni Passage, BP) in Postojnska Jama, b,c) Profile of BP and PP with position of anemometers and airflow directions in winter (blue) and summer (red) regime. e,f) Airflow speed as a function of external temperature in PP and BP for two year period. Black lines show square-root fits to point clouds presenting measurements.

While PP has stronger ventilation in summer, BP has stronger ventilation in winter. BP is also identified as the main air pathway connecting Stara Jama (Old Cave) to the surface. As shown in the profile, BP is connected to the surface via large yet unexplored chimney, which does not reach the surface, but provides excellent aeraulic connection. From Fig. 3.23 we see that inflow/outflow from/to the chimney controls the temperature (and also CO_2) concentration. Between the entrance from the Stara Jama and the chimney, the temperature variations are high (2.5°C); behind the chimney the temperatures vary for less than 0.5°C (Figs. 3.23).

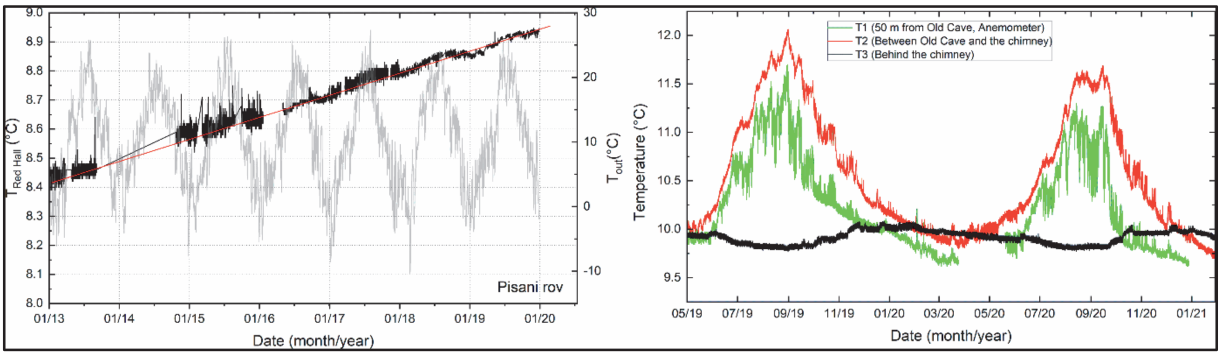


Fig. 3.23: Temperature records in Pisani Rov (PP) between 2013 and 2020. Right: Temperature at three locations in Brezimeni Rov (BP). Note the stable temperature behind the chimney, which is the main air inlet/outlet.

In Pisani Passage, there is no dominant connection to the surface. The flow into/from the terminal chamber is distributed from/to small channels and fractures, which provide aeraulic connection to the surface. The inflowing air is therefore thermally equilibrated to the massif. However, since the beginning of observations we rising temperature in PP as shown in Fig. 3.23, about 0.5°C in seven years. The cause has not yet been confirmed.

Interesting about the airflow patterns in BP and PP is that in BP winter regime is dominant, while in PP the dominant is summer regime. Follow the literature for further explanation of this phenomenon. The CO_2 in PP is the story on its own. In the final chamber (Red Hall), the CO_2 is low and well mixed during winter ventilation regime (updraft), when air comes into the passage and to the Red Hall from the main entrance along large passages (Fig. 3.24). In summer the air enters the Red Hall from the surface above through small conduits and fractures, highly saturated with CO_2 of the surrounding vadose zone. Furthermore, the CO_2 in the Red Hall has a distinct vertical profile that re-establishes within several hours after mixing (Fig. 3.25). These observations have been explained with a concept of multiple inlets with different flow rates and CO_2 content, and specific position of main outflow channel (Fig. 3.26).

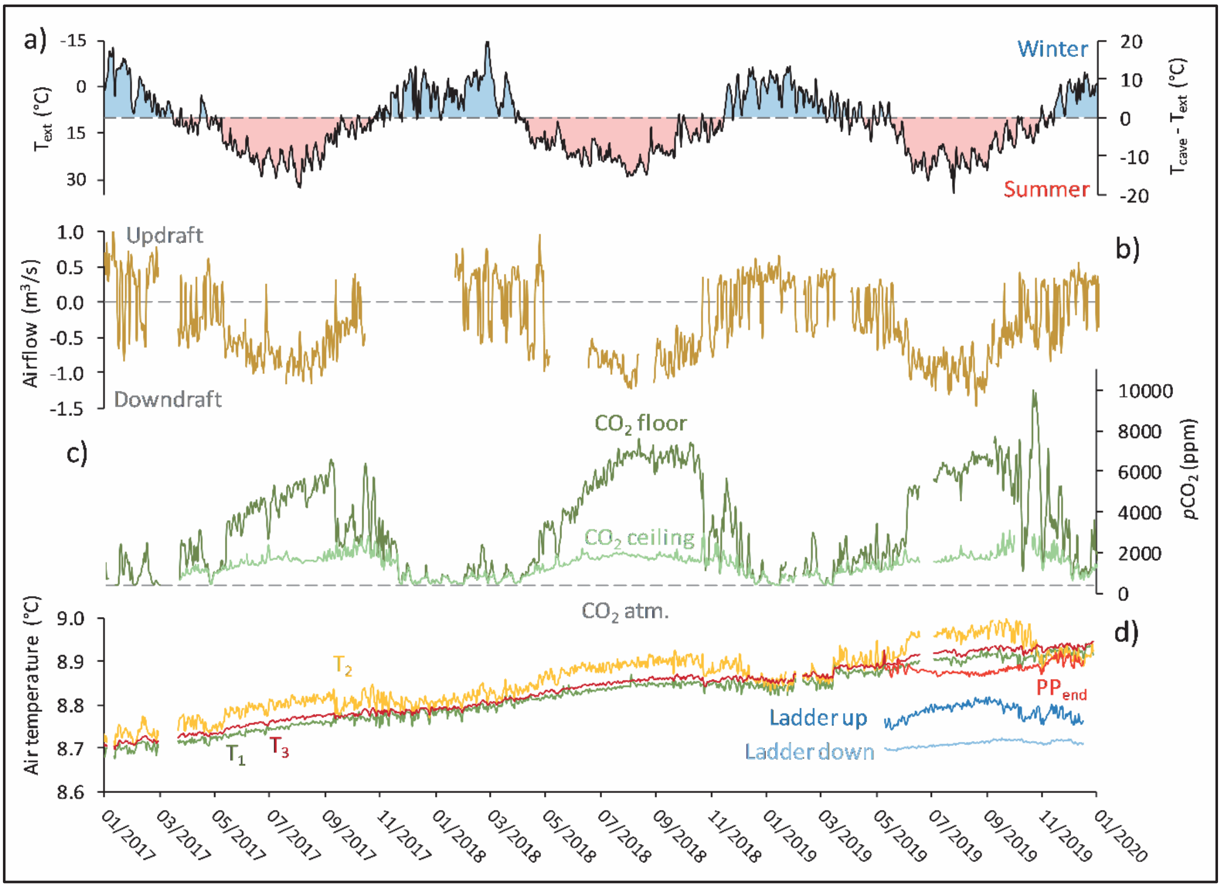


Fig. 3.24: Time series of the parameters of the Pisani Passage microclimate. (a) Difference between cave (T_3 in RH) and outside temperature (negative values typical in the summer season, positive values in winter); (b) airflow at PP_{ent} (negative = downdraft, positive = updraft); (c) pCO_2 in the RH at the floor and the ceiling stations (atmospheric pCO_2 = 410 ppm); (d) temperature dynamics in the RH at three different heights (T_1 is the highest, T_3 is the lowest).

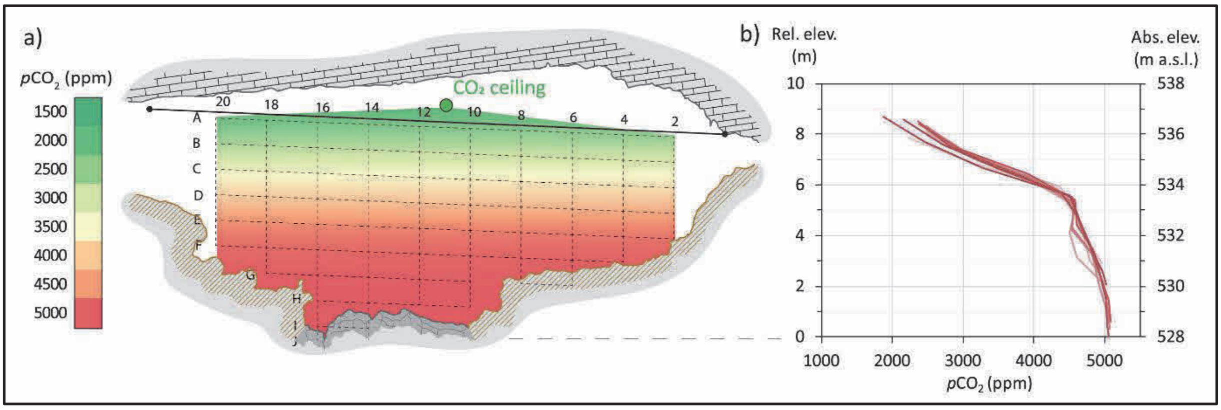


Fig. 3.25: Schematic representation of CO_2 stratification in the Red Hall as measured by profiling on 30 May 2018. Each grid intersection represents an average pCO_2 value for a certain horizontal (2–20; at 2 m intervals) and vertical position (levels A–J; at 1 m intervals). Note that the Tyrolean traverse used for instrument positioning is slightly tilted to the right. (b) All 10 vertical curves obtained from the profiling show a characteristic inflection point between 533 and 534 m above sea level.

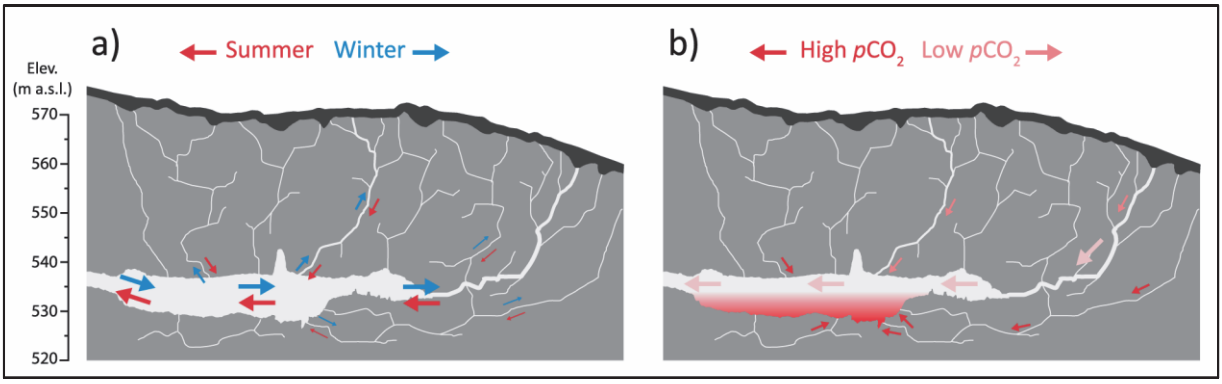


Fig. 3.26: Cross-section of the terminal part of Pisani Passage (Red Hall) with a schematic representation of many possible airflow pathways permeating the vadose zone and reaching the surface. a) Arrows show the direction and size (not to scale) of the airflow during the downdraft (red) and the updraft (blue). b) A simple conceptual view of the airflow into the RH during the downdraft and build-up of the CO_2 gradient. The size and transparency of the arrows indicate the flow rate and pCO_2 value of the incoming air, respectively. Large transparent red arrows = high flow rate, low pCO_2; small red arrows = low flow rate, high pCO_2.

Red Hall in Pisani Rov is also the site of highest observed radon concentration in Postojnska Jama. Highest measured values exceed 40 kBq/m^3 (Gregorič *et al.* 2013). Recently we have established measurements of gamma radiation, which is also highly correlated with CO_2 and related to airflow direction. During updraft the CO_2 and gamma rate dose drop, during downdraft they both increase (Fig. 3.27).

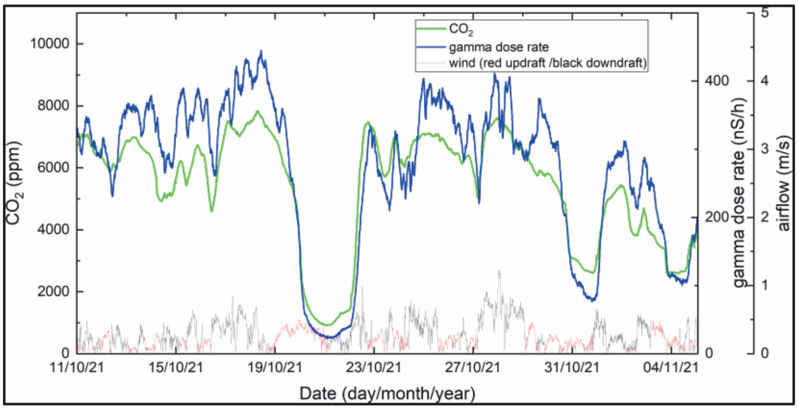


Fig. 3.27: CO_2, gamma dose rate and wind speed and direction in autumn 2021.

Correlation of airflow, CO_2 and temperatures in Postojnska Jama with external meteorological data showed that variations of cave atmospheric parameters often correlate with external winds. An in-depth study, which included CFD model of wind flow over topography above Postojnska Jama showed that wind cause near surface pressure variations and therefore pressure differences between the entrance. This differences may reach or even exceed difference caused by the chimney effect. In Pisani Passage, the winter updraft is often reversed by wind driven effect and the CO_2 in the Red Hall increases, as shown in Fig. 3.28.

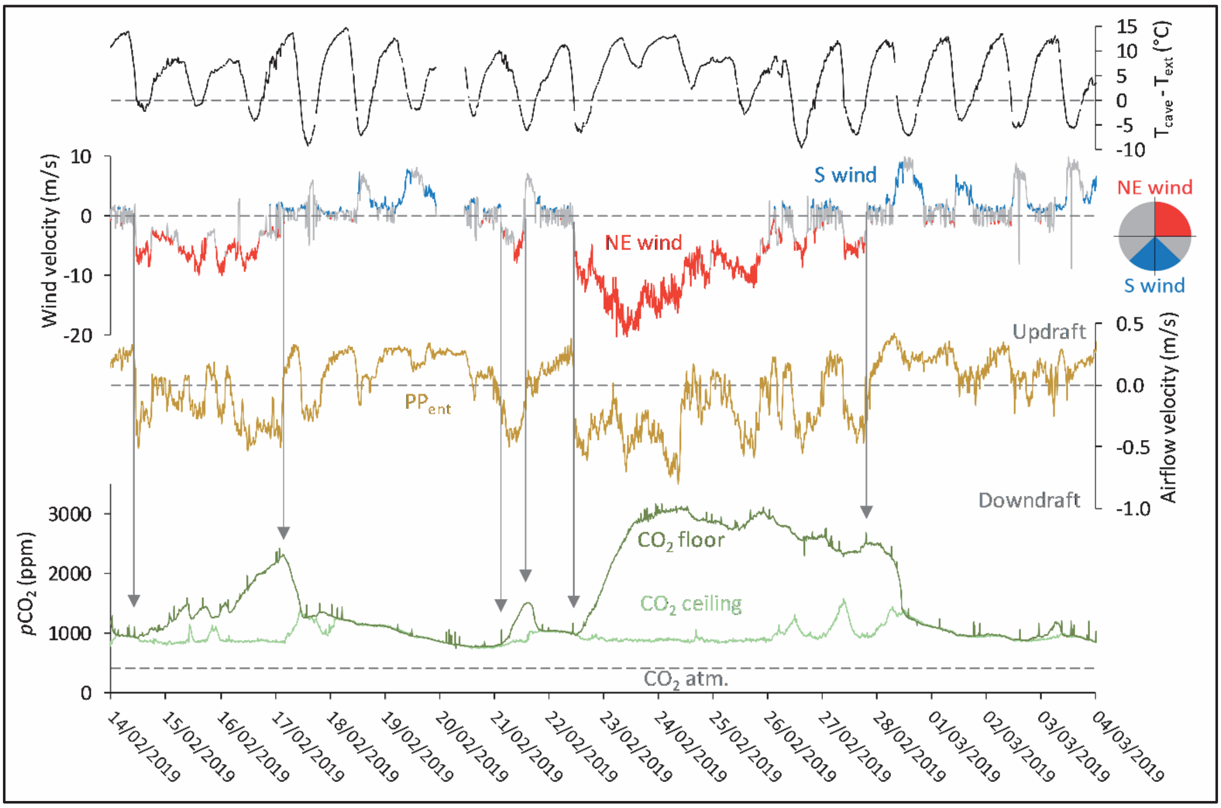


Fig. 3.28: CO_2 and airflow dynamics in Red Hall in relation to the outside wind. Vertical gray arrows mark the beginning of the characteristic pCO_2 change at floor and ceiling CO_2 stations. Although during some days T_{cave} >> T_{ext}, the NE wind will force the airflow towards the downdraft and indirectly cause CO_2 accumulation at the floor of the RH.

The complete studies in the CO_2 behavior and wind driven effect have been published (Kukuljan et al. 2021a, 2021b). Wind driven effect was also observed during wind-flow measurements in Magdalena Jama. There the airflow velocity during strong bora gusts exceeded 10 m/s.

Atmospheric methane

Methane is naturally formed by geological and biological processes. The Earth's atmospheric methane concentration has increased by about 150% since 1750, and it accounts for 20% of the total radiative forcing from all of the long-lived and globally mixed greenhouse gases, while CO_2 represents >50%.

In the side passage of **Lepe Jame** (Fig. 3.05) is since 9 September 2020 installed OPSIS LD500 analyzer, and represents first systematic methane measurements in the cave air in Slovenia (Šebela 2022). Within the project RI-SI-EPOS (https://izrk.zrc-sazu.si/sl/programi-in-projekti/ri-si-epos#v) the OPSIS LD500 analyzer, which is the central unit of laser diode system for methane measurements (https://www.opsis.se/en/Products/Products-CEM-Process/LD500-Laser-Diode-Gas-Analyser), was provided in 2020. Spectrometer works on the principle of DOAS (Differential Optical Absorption Spectroscopy). Beside methane (ppb), air T and air pressure together with CO_2

(ppm) are included into the monitoring. At the end of September 2021 spectrometer was calibrated showing that the accuracy of the instrument is 100 ppb.

Methane concentration in the period of 9 September 2020 to 9 March 2022 is up to 14,000 ppb (mean 4,300 ppb). The highest values have been obtained in April 2021 (Fig. 3.29), when the cave was closed for visitors due to covid-19 pandemic. Cave ventilation and seasonal cave climate variations show impact on methane concentrations. When methane is high, CO_2 is lower showing weak negative correlation (Šebela 2022). Regarding outside methane concentrations (~1850 ppb) methane in Lepe Jame is generally higher as outside the cave. It looks that also regarding other caves (Table 3) Lepe Jame site exhibits very high methane concentrations. Sources of atmospheric methane in the Postojnska jama are subject to future studies.

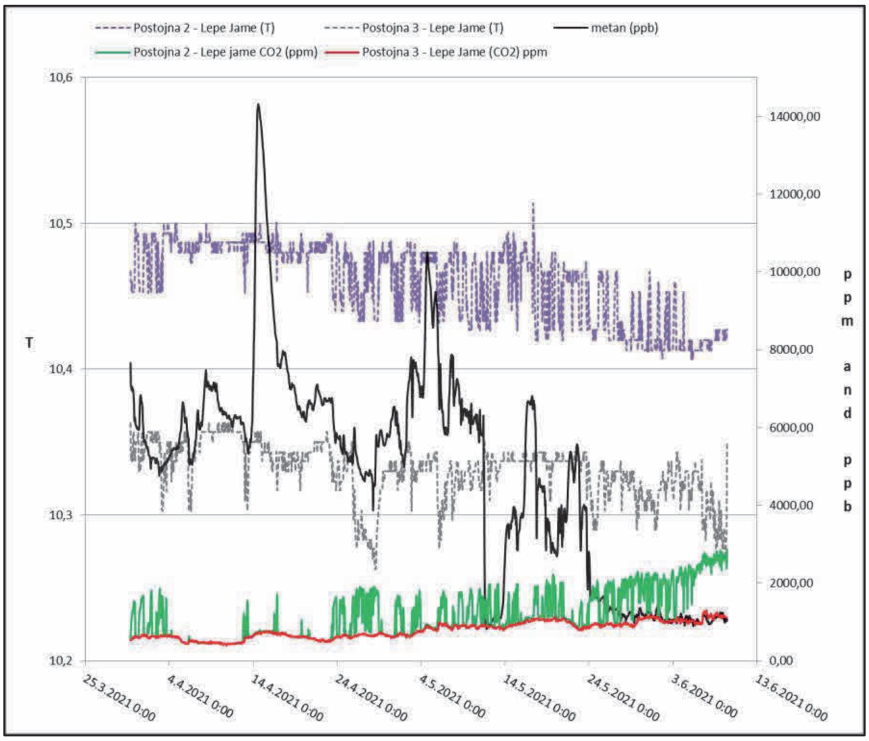


Fig. 3.29: Air temperature measurements (°C), CO_2 (ppm) and methane (ppb) concentrations at Lepe Jame in the period 30 March 2021 to 9 June 2021.

Table 3. Methane concentrations in caves

	CH_4 (ppb)	Reference
Vapour Cave (Spain)	1850	Fernandez-Cortes et al., 2018
Frasassi Cave (Italy)	1900-2200	Jones et al., 2012
Movile Cave (Romania)	10.000.000-20.000.000	Sarbu et al., 1996; Hutchens et al., 2004
Cueva de Villa Luz (Mexico)	1880-3670	Webster et al., 2017
Buckner Cave (USA)	100-1900	Webster et al., 2016, 2018
St. Michaels (Gibraltar)	1370	Mattey et al., 2013
Jenolan Caves (Australia)	max 1775	Waring et al., 2017

Subterranean fauna

Subterranean environments, especially deep subterranean habitats, are known for their unique combination of characteristics, i.e., perpetual darkness, reduced variability of particular abiotic factors, such as temperature, moisture and water chemistry, as well as by isolation from surface influences (Culver & Pipan 2019; Hüppop 2012). These habitats are also known for their specialized fauna, troglobionts, strictly bound to these habitats, that exhibit special morphological, physiological and behavioral adaptations (Sket 2008; Romero 2009; Culver & Pipan 2019). Many troglobiotic species are endemic with very narrow range of distribution. Many of them are known from a single cave, which makes them much vulnerable and crucial to protect.

Opening a cave to tourism inevitably implies the disturbance of the natural habitat, as it involves major physical alterations of the cave, such as the construction of walking surfaces, railways, widening of passages, and the installation of lighting. Changes introduced by the arrangement of caves for tourism are often said to have, at least potentially, a strong negative impact on subterranean biodiversity. Climatic conditions have a profound effect on specialized subterranean species, since these are mostly adapted to narrow ranges of temperature and humidity (Rizzo *et al.* 2015; Kozel *et al.* 2019; Pallarés *et al.* 2019). Therefore, even small changes in microclimate can negatively affect specialized subterranean fauna. In some cases, tourist use can lead to population declines of certain troglobiotic species (Pacheco *et al.* 2020). The electrification of tourist caves led to the problem with photoautotrophic organisms, called lampenflora. The lampflora represents an additional food source for both specialized (*i.e.,* troglobiotic) and non-specialized (*i.e.,* trogloxene and troglophile) species. This readily available food allows trogloxes and troglophiles to survive in deep cave zones, where they can compete with troglobiotic species for the same food source, or even predate on them. While the influence of tourism on resident terrestrial fauna could be expected, there is little evidence of the impact of tourism on subterranean fauna worldwide, despite the vulnerability and high biological value of this fauna.

Postojna Cave is recognized as one of the most prominent subterranean biodiversity hotspots (Culver & Sket 2000; Culver *et al.* 2021), inhabited by more than 100 specialized subterranean species. Regular monitoring of terrestrial subterranean fauna has been conducted in Postojna Cave since 2009. Since 2016, we have been using an adapted sampling methodology to monitor the occurrence, abundance and species composition in both the tourist (*i.e.*, sites along the tourist path) and non-tourist (*i.e.*, sites away from the tourist path, in the side passages not open to tourism) parts of the cave. In addition to fauna sampling, selected environmental factors (air temperature, relative humidity, substrate temperature) are measured continuously at each sampling site and in the laboratory (substrate moisture, substrate organic matter content, substrate pH). Such an approach allows a direct comparison between sites altered by tourism activities and undisturbed natural sites.
In addition to terrestrial fauna, fauna in dripping water is monitored as well. In the whole cave system, we found 23 species of copepods (including eight undescribed species) as the most abundant animal group presented in the epikarst. Six of these 23 species are endemic to Postojna Cave System. A total of five species were in a single genus *Bryocamptus*. Species composition is extremely heterogeneous; differences in drip rate, ceiling height, and nitrate concentrations are correlated with differences in species composition. There is also a strong distance effect, with drips closer than 100 m being more similar than those farther away. This probably reflects the semi-isolated nature of the small cavities that comprise the epikarst. The drips also exhibited considerable environmental heterogeneity. Drip rate itself ranged between 1.7 and 202 ml/min. Conductivity varied between 238 and 548 µS/cm, probably reflecting different residence times of the water in the subsurface. The results of our study suggest that a careful field study exploring the impact of variation in the physical and chemical characteristics of water on the likelihood of copepods being present may yield additional insights into the forces that control aquatic community structure and dynamics. These impacts could be implicit such as when variables act as surrogates for other factors (such as temperature) or explicit, with direct effects (such as is likely the case with Ca^{2+}).

Microbiology

Postojnska Jama is part of a large cave system with the sinking river, which has been visited by people for a long time and provides an almost ideal "natural microbiological laboratory" with various niches for studying various biogeochemical processes and human influence on the underground ecosystem.

Cave aerobiome. Microbiological monitoring has been focused on the occurrence and dynamics of airborne microorganisms. Air contains a complex mixture of gases, vapours, inorganic and organic particles, metabolites, organisms and their fragments. For aerosols, it serves as a means of transport from one place to another. Cave aerosols are formed by local air currents, animals, people, and splashing water. They can be considered natural tracers and, together with cave climate parameters, provide detailed insight into atmospheric conditions, climate changes, and human influence in caves. The microbial community in the air of Postojnska Jama is composed of different microbial groups, with the concentrations of bacteria and fungi ranging from 10 to 100 CFU/m^3. Their concentrations are significantly higher in places where the cave atmosphere interacts with the external climate, e.g. at cave entrances and in the area of river floods. In our study, airborne amoebae were the largest organisms examined. Several amebozoans from different genera were identified in the cave air of Postojnska Jama: *Acanthamoeba, Dictyostelium, Echinamoeba, Hartmanella, Lycogala, Physarum, Rhizamoeba, Trichia,* and *Vahlkampfia* (Mulec *et al.* 2012).

The presence of tourists significantly increases the concentration of carbon dioxide and organic and inorganic particles. Cultivation of air samples collected along the tourist pathway showed an increase in microbial load after tourists passed by. Microbial loads are usually highest at the peak of the tourist season in August. For example, biomass concentrations in Postojnska Jama in the Vivarij section exceeded 1,000 CFU/m3 in 2017. The most frequent microbial isolates belonged to the following genera: *Acinetobacter, Aerococcus, Arthrobacter, Bacillus, Cryptococcus, Micrococcus, Pseudomonas, Rahnella* and *Staphylococcus* (Tomazin *et al.* 2018).

Microorganisms and the water cycle. The Postojnski jamski sistem is a typical binary karst system fed by autogenic (diffuse infiltration) and allogenic recharge (sinking water from surrounding areas). The water cycle in the karst supplies the aquifers and supports the biogeochemical cycles and energy flow. The Pivka River flows into the Postojnska Jama (511 m a.s.l.) and is influenced by human activities from the surrounding area. This is reflected in locally elevated concentrations of sulphates, chlorides, and organic and microbial faecal indicators (Mulec *et al.* 2019). The Pivka River transports and deposits biota and accompanying organic and inorganic material along cave passages. During high waters, the originally deposited material is usually washed away. The Pivka River pRovides a dynamic environment for microorganisms that is largely dependent on external conditions. For example, the presence of anionic surfactants, even at low concentrations, indicates pollution upstream of the ponor (Mulec et al., 2019). In a previous study, chemical and bacterial parameters monitored in the Pivka River showed a clear and monotonous trend of decreasing concentrations from the ponor toward the interior of the cave during stable hydrologic conditions and a significant change during high water conditions. Regular surveys of chemical parameters and bacterial indicators, especially Escherichia coli and enterococci, is a critical step for monitoring the health of the underground ecosystem (Mulec et al., 2019).

An urgent problem related to the aquatic environment in karst is the occurrence of antimicrobial resistant bacteria. The WHO has listed antimicrobial resistant E. coli as one of the nine most dangerous microorganisms against which it is imperative to find new agents. A preliminary study of antimicrobial-resistant E. coli was conducted on some isolates from the Pivka River. Interestingly, one strain from the Pivka River at the ponor into the Postojnska Jama was resistant to all antimicrobials tested: ampicillin, chloramphenicol, ciprofloxacin, nalidixic acid, tetracycline, and trimethoprim. (Skok et al., 2020).

Dripwater infiltrates vertically through the rock matrix of the vadose zone into the phreatic zone. This infiltration originates from the soil cover, passes through the epikarst, and feeds the karst aquifer. Microbial biomass enters the cave via dripwater. In Postojnska Jama, many seeps are activated only during and shortly after precipitation. Flow cytometry, a culture-independent cell counting technique, has shown that microbial biomass entering Postojnska Jama via percolation water is not negligible (5,100-19,990 cells per ml), but is significantly lower compared to entry via the Pivka River (42,920-123,770 cells per ml) (Oarga-Mulec *et al.* 2017).

Lampenflora. Of particular concern is the monitoring of lampenflora and its relation to the cave lighting system and application of efficient and environmentally friendly procedure for its removal (Mulec 2019). Postojnska Jama has been regularly visited by tourists since 1819, and even today one can observe smoke-blackened and sooty surfaces from torches and oil lamps. Postojnska Jama was the third cave in the world to be equipped with permanent electric lighting as early as 1884. As a result of the lighting, green patches with phototrophic organisms began to develop around the lamps. This phenomenon was scientifically evaluated as early as 1941 by Morton (Morton 1941), making Postojnska Jama the cave with one of the oldest written records of the presence of lampenflora (Mulec 2014a). Lampenflora refers to the phenomenon of proliferation of mainly phototrophic organisms in the vicinity of artificial light sources in places where they would not occur under natural circumstances (Mulec 2019). Lampenflora develops around the lamps in the show caves and sometimes strongly adheres to the surfaces, causing their biodeterioration. Due to artificial lighting along the tourist part of Postojnska Jama, some parts are extensively colonized by lampenflora. Lampenflora consists mainly of three groups of microscopic phototrophs: prokaryotic cyanobacteria, eukaryotic Chlorophyta, and Chrysophyta (mainly diatoms). Analysis of the lampenflora from Postojnska Jama revealed 17 taxa of microscopic phototrophs: *Aphanocapsa muscicola*, *Gloeocapsa atrata*, *G. punctata*, *Lyngbya* sp., *L. bipunctata, L. fragilis*, *L. perelegans*, *Plectonema* cf. *puteale*, *Synechocystis* sp., *Chlorocloster* sp, *Cymbella ehrenbergii*, *Navicula gallica* var. *perpusilla*, *N. mutica*, *Chlorella* sp., *Pediastrum boryanum*, *Stichococcus bacillaris* and *Trentepohlia aurea* (Mulec *et al.* 2008). Lampenflora mats of microscopic phototrophs are sometimes overgrown by mosses and ferns. In a 2010 study, nine taxa of Bryophyta and Pteridophyta were found, with *Eucladium verticillatum*, *Rhynchostegium murale*, and *Bryum* sp. being the most abundant (Mulec & Kubešová 2010). The restriction of lampenflora represents one of the major challenges for cave management and sustainable use of caves. It is important to address lampenflora at several levels. In Postojnska Jama, they started to introduce LED lamps whose emission spectrum avoids the maximum absorption spectra of chlorophyll *a*, the main photosynthetic pigment responsible for photosynthesis. In addition, time-limited lighting and individual lighting sectors have been introduced, and the removal of lampenflora with a hydrogen peroxide-based solution (Mulec, 2014b) is performed regularly.

Cave alogenic sediments. They are not only important for interpreting sedimentation periods and reconstructing past geologic events, but they also pRovide a long-term refuge for microbes (>105 CFU per gram dry weight), a source of nutrients, and recolonization potential when released in a new habitat. In all alluvial sediment samples from Postojnska Jama, Proteobacteria dominated with more than 50% of sequenced OTUs, followed by Acidobacteria (11-19%) and Bacteroidetes (1-8%) (Mulec & Oarga-Mulec 2016a). Metabolic fingerprinting showed that temperature has a moderate effect on microbial utilization of selected substrates during aerobic cultivation, while it decreases significantly during anaerobiosis (Mulec & Oarga-Mulec 2016a).

The **surfaces of the cave walls** are subject to microbial colonization. The surfaces in Postojnska Jama showed similar or even higher levels of biological load than analogous surfaces exposed to the external atmosphere. Moreover, the results of our study showed that there is high variability in surface microbial biomass within individual cave systems and that they are colonized by physiologically distinct microbial communities in terms of their nutrient requirements, temperature requirements and r/K growth strategy (Mulec & Oarga-Mulec 2016b).

In show caves, tourists bring a considerable amount of organic and inorganic material and spread it on their shoes. A disinfection barrier was installed at the entrance to Postojnska Jama. The generally low abundance of microbial indicators on tourist footpaths in Postojnska Jama is due to regular cleaning of tourist footpaths and the disinfection barrier at the entrance to the tourist cave. Such an approach, e.g. disinfection of shoe soles, should also be considered by other cave managers (Skok *et al.* 2020).

Dust

The largest deposition of dust is along the underground railway; dust deposits are changing the color appearance of the passages and are serious threat to the cave touristic value and threaten rich cave biota. To understand the formation and transportation of the dust we have done the research of dust composition and measured seasonal air movements, temperatures and observe cave floor and walls humidity. Before changing of railway tracks eight heavy metals, aluminum (Al), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), strontium (Sr) and zinc (Zn) were determined in dust deposits (Muri *et al.* 2013). Metals are proving anthropogenic origin and are markers for vehicle, brake wear, railway tracks rust and railway wear.

Microplastics

Since 2018, the Karst Research Institute is doing the research of microplastics in karst environment. The first research in 2018 was conducted in several caves (Postojna cave, Pivka cave, Črna cave, Planina cave, Škocjan caves, Kačna cave, Jama 1 v Kanjaducah cave), together with short-time spring, sediment, surface water and rainfall sampling. Samples in Postojna cave were taken on different sampling sites next to the tourist paths and also in the non-tourst part of the cave. We took samples in Lepe jame (Fig. 3.30), Ruski Rov, Velika gora, Tartar, Razpotje, next to the railway tracks and also on one site in Pivka Jama and one site in Črna Jama (for all see Fig. 3.05).

The results of this research showed that 28% of all samples contained microplastic pollution, with majority of polluted samples being water samples. The highest concentrations were found next to the tourist paths inside caves, therefore cave tourism is an important source of microplastic pollution in karst underground. Sediment samples contained only a few microplastic particles, which indicates fast transport of microplastics pollution through karst aquifer. The results of this study are in process of publication in a scientific journal.

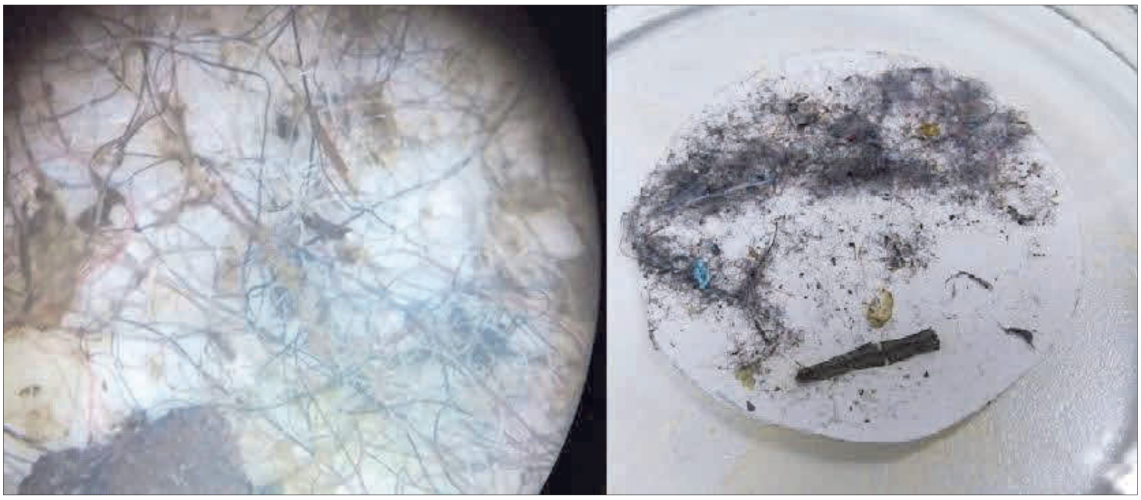


Fig. 3.30: Sample from rimstone pools in Postojna cave (sampling site Lepe Jame -Bela Dvorana). On the left side is sample under stereomicroscope, using 4x magnification, while on the right side it is a photo of the whole sample. Arrow and rectangle indicate a possible part of a plastic rope (photo Lara Valentić).

UPPER CRETACEOUS MISSING PALEOKARST

Turonian to Middle Coniacian Carbonate succession of South-West Limb of Postojna Anticline was studied (Uršič Arko et al., 2018) at Polhovica (Fig. 3.01, 3.06) point along the road to Pivka Jama. During most of the Upper Cretaceous, the northern sector of the Adriatic Carbonate Platform (ACP) was topographically highly differentiated. Temporally and spatially shallow subtidal and peritidal environments with subaerially exposed areas alternated with deepened lagoons. At the same time, land with karst features and bauxite existed NE from the studied area. Typical lithofacies with the foraminiferal assemblage *Murgella latta* occurring everywhere directly above the paleokastic surface indicate a relatively synchronous transgression in the middle Coniacian. On the contrary, SW from the studied area shallow marine sediments of the Sežana Formation were deposited, occasionally interrupted by sediments of deep lagoons (the Komen and Pliskovica Limestones).

A geological section about 180 meters thick, located above the passages of Postojnska jama cave in the area of Polhovica near Postojna, was studied along the road to Pivka jama cave. Thus, the studied sequences are likely to represent an intermediate zone between the inner, often slightly deepened areas of the northern sector of the ACP and its NE regions, which were subaerially exposed at the time under consideration. Most of the sedimentary sequences discussed were deposited in a very shallow subtidal environment of a closed to open lagoon and the intermediate zone during the highstand system tract established after the Cenomanian/Turonian transgression. The above-mentioned subaerially exposed and karstified part of the platform may have only "touched" the studied area in its greatest extent in the late Turonian or early Coniacian (common intertidal conditions). In the upper part of the geologic section, the foraminiferal-rich peloidal limestone was deposited during the middle Coniacian transgression.

REFERENCES:

- Anelli F., 1933: Ricerche paleontologiche nella Grotta Betal presso Postumia (Atti del I. congresso speleologico nazionale, Trieste, 230.
- Atanackov J., Jamšek Rupnik P, Jež J, Celarc B, Novak M, Milanič B, Markelj A, Bavec M, Kastelic V. 2021. Database of Active Faults in Slovenia: Compiling a New Active Fault Database at the Junction between the Alps, the Dinarides and the Pannonian Basin Tectonic Domains. Frontiers in Earth Science, 9, DOI=10.3389/feart.2021.604388
- Blatnik M, Culver D C., Gabrovšek F, Knez M, Kogovšek B, Kogovšek J, Liu Hong, Mayaud C, Mihevc A, Mulec J, Aljančič M, Otoničar B, Petrič M, Pipan T, Prelovšek M, Ravbar N, Shaw T R, Slabe T, Šebela S, Zupan Hajna N, 2020. Karstology in the classical karst. Cham: Springer, cop. XII, 222 pp. Advances in karst science. ISBN 978-3-030-26826-8. ISSN 2511-2066. DOI: 10.1007/978-3-030-26827-5.
- Brodar S., 1951: Otoška Jama, paleolitska postaja. Razprave SAZU 1, 203-242.
- Brodar, S., 1952: Prispevek k stratigrafiji kraških jam Pivške kotline, posebej Parske golobine. Geografski vestnik, 24, 43-–76, Ljubljana.
- Brodar, S., 1966: Pleistocenski sedimenti in paleolitska najdišča v Postojnski jami. Acta carsologica, 4, 57-–138.
- Brodar, M., 1969: Nove paleolitske najdbe v Postojnski jami. Arheološki vestnik, 20, 141-–144, Ljubljana.
- Brodar, S., 1970: Paleolitske najdbe v jami Risovec pri Postojni. Acta carsologica, 5, 273-–300.
- Buser, S., Grad, K. & Pleničar, M. 1967: Basic geological map of SFRJ, Sheet Postojna 1:100000. Zvezni geološki zavod, Beograd.
- Covington, M.D., Luhmann A.J., GabRovsek F., Saar M.O., Willis I., Wicks, C.M., 2011: Mechanisms of heat exchange between water and rock in karst conduits, Water Resources Research, 47.
- Crestani G., Anelli F., 1939: Ricerche di meteorologia ipogea delle grotte di Postumia. Istituto poligrafico dello stato Libreria, Roma (in Italian)
- Culver, D. C., Deharveng, L., Pipan, T., Bedos, A., 2021: An Overview of Subterranean Biodiversity Hotspots. Diversity, 13, 487.
- Culver, D. C., Pipan, T., 2019: The biology of caves and other subterranean habitats, second edition. Oxford University Press, New York, 336 pp.
- Culver, D. C., Sket, B., 2000: Hotspots of subterranean biodiversity in caves and wells. Journal of Cave and Karst Studies, 62/1, 11–17.
- Cvijić J.,1893: Das karstphänomen. Versuch einer morphologischen monographie. Geographische Abhandlungen, Bd. V, Heft 3., 113 p.
- Čar, J., 2018: Geostructural mapping of karstified limestones. Geologija, 61/2, 133-162. Doi: 10.5474/geologija.2018.010
- Čar, J., Gospodarič, R., 1984: About Geology of Karst among Postojna, Planina and Cerknica. Acta carsologica 12 (1983), 91-106, Ljubljana.
- Ćuk ĐuRović, M., Petrič, M., Jemcov, I., Mulec, J., Mazej Grudnik, Z., Mayaud, C., Blatnik, M.,

Kogovšek, B., Ravbar, N., in review. Multivariate Statistical Analysis of Hydrochemical and Microbiological Natural Tracers as a tool for Understanding Karst Hydrodynamics (the Unica Springs, SW Slovenia). Water Resources Research.

- Ferk, M., Lipar, M., Šmuc, A., Drysdale, R.N. & J. Zhao, 2019: Chronology of heterogeneous deposits inthe side entrance of Postojna Cave, Slovenia. Acta geographica Slovenica, 59/1, 103-116. http://dx.doi.org/10.3986/AGS.7059
- Fernandez-Cortes, A., Perez-Lopez, R., Cuezva, S., Calaforra, J.M., Cañaveras, J.C., Sanchez-Moral, S. 2018. Geochemical Fingerprinting of Rising Deep Endogenous Gases in an Active Hypogenic Karst System, Geofluids 4934520, 1-19, https://doi.org/10.1155/2018/4934520
- Gabrovšek F., 2012: Relevance and measurements of selected physical quantities representing cave environment: examples from Postojna cave and Škocjan cave (Slovenia). In: Šebela, S. (ed.): International Congress on "Scientific Research in Show Caves", 13th to 15th September 2012, Postojna, Guide book and abstracts, Inštitut za raziskovanje krasa ZRC SAZU, 24-25.
- Glažar S., Drole F., Hajna J., 2015: The preparation of a new plan of Postojnska Jama. Material for the Exhibition, Postojnska Jama EXPO.
- Gospodarič R., 1963: K poznavanju Postojnske jame – Pisani Rov. Naše jame, 4 (1962), 9-16.
- Gospodarič R., 1964: Sledovi tektonskih premikov iz ledene dobe v Postojnski jami. Naše jame, 5 (1963), 5-11.
- Gospodarič, R. 1965: Geology of the area between Postojna, Planina and Cerknica, 1-40 pp, Postojna, unpublished report (in Slovene).
- Gospodarič, R. 1976: The Quaternary Caves Development Between the Pivka Bassin and Polje of Planina. Acta carsologica 7, 8-135, Ljubljana.
- Gregorič A., Vaupotič J. & Šebela S., 2014: The role of cave ventilation in governing cave air temperature and radon levels (Postojna Cave, Slovenia). International journal of climatology, 34/5, 1488-1500.
- Gregorič, A., Vaupotič J., Gabrovšek F., 2013: 'Reasons for Large Fluctuation of Radon and CO2 Levels in a Dead-End Passage of a Karst Cave (Postojna Cave, Slovenia)'. Natural Hazards and Earth System Sciences 13 (2): 287–97. https://doi.org/10.5194/nhess-13-287-2013.
- Hüppop, K., 2012: Adaptation to low food. In: White, W. B., Culver, D. C. (Eds.), Encyclopedia of caves (Second edition). Academic Press, Amsterdam, 430–438.
- Hutchens, E., Radajewski, S., Dumont, M.G., McDonald, I.R., Murrell, J.C., 2004: Analysis of methanotrophic bacteria in Movile Cave by stable isotope probing, Environmental Microbiology 6, 2, 111-120, https://doi.org/10.1046/j.1462-2920.2003.00543.x
- Ikeya M., Miki T. & Gospodarič R., 1983: ESR Dating of Postojna Cave Stalactite. Acta Carsologica, 11 (1982), 117-130.
- Jones, D.S., Albrecht, H.L., Dawson, K.S., Schaperdoth, I., Freeman, K.H., Pi, Y., Pearson, A., Macalady, J.L., 2012: Community genomic analysis of an extremely acidophilic sulfur-oxidizing biofilm, The ISME Journal 6, 158-170, https://doi.org/10.1038/ismej.2011.75
- Kaufmann G, Gabrovšek F, Turk J., 2016: Modelling flow of subterranean Pivka river in Postojnska Jama, Slovenia. Acta Carsologica 45/1, 57-70. https://ojs.zrc-sazu.si/carsologica/article/view/3059.
- Kempe, S., 2004: "Natural speleothem damage in Postojnska Jama (Slovenia), caused by glacial cave ice?" Acta carsologica, 33/1, 265-289.
- Kogovšek, J., Petrič, M., 2014: Solute transport processes in a karst vadose zone characterized by long-term tracer tests (the cave system of Postojnska Jama, Slovenia). Journal of Hydrology, 519, 1205-1213. doi: 10.1016/j.jhydrol.2014.08.047
- Kogovšek, J., Šebela, S., 2004: Water tracing through the vadose zone above Postojnska Jama, Slovenia. Environmental Geology, 45, 992-1001. doi: 10.1007/s00254-003-0958-z
- Kozel, P., Pipan, T., Mammola, S., Culver, D. C., Novak, T., 2019: Distributional dynamics of a specialized subterranean community oppose the classical understanding of the preferred subterranean habitats. Invertebrate Biology, 00:e12254.
- Kranjc A., Malečkar F., 1988: Postojnska Jama, 170 let odkrivanja, raziskovanja in turističnega

razvoja. Vodnik 10. Tiskarna Tone Tomšič, Postojna.

- Kukuljan, L., Gabrovšek F., Covington M. D., 2021a. 'The Relative Importance of Wind-Driven and Chimney Effect Cave Ventilation: Observations in Postojna Cave (Slovenia)'. International Journal of Speleology 50 (3): 275–88. https://doi.org/10.5038/1827-806X.50.3.2392.
- Kukuljan, L., Gabrovšek F., Covington M. D., Johnston V. E., 2021b: 'CO2 Dynamics and Heterogeneity in a Cave Atmosphere: Role of Ventilation Patterns and Airflow Pathways'. Theoretical and Applied Climatology, July. https://doi.org/10.1007/s00704-021-03722-w.
- Mattey, D.P., Fischer, R., Atkinson, T.C., Latin, J.-P., Ainsworth, M., Lowry, D., Fairchild, L.J., 2013: Methane in underground air in Gibraltar karst, Earth and Planetary Science Letters 374, 71-80. doi: 10.1016/j.epsl.2013.05.011
- Mihevc A., 2002: Postojnska Jama cave system, U/Th datation of the collapse processes on Velika Gora. In: Gabrovšek F. (Ed.): Programme and guide booklet for the excursions: Evolution of Karst: from Prekarst to Cessation, September, 17th –21st, 2002. Postojna, 14-15.
- Mlakar, P., Grašič B., Zlata Božnar M., Popović D., Gabrovšek F., 2020: 'Information System for Scientific Study of the Micrometeorology of Karst Caves – Case of Postojnska Jama Cave, Slovenija'. Acta Carsologica 49 (2–3). https://doi.org/10.3986/ac.v49i2-3.7540.
- Morton, F., 1941: Piante verti presso le lampade dell'illuminazione elettrica nelle Grotte di Postumia. Le Grotte d'Italia, Serie 2A, 4: 23-28.
- Mulec, J., Kubešová, S., 2010: Diversity of Bryophytes in show caves in Slovenia and relation to light intensities. Acta Carsologica, 39, 587-596.
- Mulec, J., 2014: Human impact on underground cultural and natural heritage sites, biological parameters of monitoring and remediation actions for insensitive surfaces: Case of Slovenian show caves. Journal For Nature Conservation, 22, 132-141.
- Mulec, J., 2014a: Lampenflora as an accompaniment of mass cave tourism, problems and solutions for Postojnska Jama, Slovenia. The conservation of subterranean cultural heritage. CRC Press, Leiden, 253-256.
- Mulec, J., 2014b, Human impact on underground cultural and natural heritage sites, biological parameters of monitoring and remediation actions for insensitive surfaces: Case of Slovenian show caves. Journal For Nature Conservation, 22: 132-141.
- Mulec, J., 2019, Lampenflora, Definition of. In: White, W., Culver, D. and Pipan, T. (eds.), Encyclopedia of caves. Academic/Elsevier Press, Amsterdam, The Netherlands, 635-641.
- Mulec, J., 2019: Lampenflora, Definition of. In: White, W., Culver, D. and Pipan, T. (eds.), Encyclopedia of caves. Academic/Elsevier Press, Amsterdam, The Netherlands, 635-641.
- Mulec, J., Kosi, G. and Vrhovšek, D., 2008, Characterization of cave aerophytic algal communities and effects of irradiance levels on production of pigments. Journal of Cave and Karst Studies, 70: 3-12.
- Mulec, J., Oarga-Mulec, A., 2016b, ATP luminescence assay as a bioburden estimator of biomass accumulation in caves. International Journal of Speleology, 45: 207-208.
- Mulec, J., Oarga-Mulec, A., Year, Anaerobiosis in alluvial sediments in karst caves suppress microbial metabolic activities. 33rd SIL Congress, Torino, 264-265.
- Mulec, J., Petrič, M., Kozelj, A., Brun, C., Batagelj, E., Hladnik, A., Holko, L., 2019, A multiparameter analysis of environmental gradients related to hydrological conditions in a binary karst system (underground course of the Pivka River, Slovenia). Acta Carsologica, 48: 313-327.
- Mulec, J., Petrič, M., Koželj, A., Brun, C., Batagelj, E., Hladnik, A., Holko, L., 2019: A multiparameter analysis of environmental gradients related to hydrological conditions in a binary karst system (underground course of the Pivka River, Slovenia). Acta Carsologica, 48(3). https://doi.org/10.3986/ac.v48i3.7145
- Mulec, J., Vaupotič, J. and Walochnik, J., 2012, Prokaryotic and eukaryotic airborne microorganisms as tracers of microclimatic changes in the underground (Postojna Cave, Slovenia). Microbial Ecology, 64: 654-667.
- Mulec, J., Vaupotič, J. and Walochnik, J., 2012: Prokaryotic and eukaryotic airborne microorganisms as tracers of microclimatic changes in the underground (Postojna Cave, Slovenia). Microbial Ecology,

64: 654-667.
- Muri G., Jovičić A., Mihevc A., 2013: Source assessment of deposited particles in a Slovenian show cave (Postojnska Jama): Evidence of long-lasting anthropogenic impact. International Journal of Speleology (Edizione Italiana) 42/3, 225-233. DOI: 10.5038/1827-806X.42.3.6
- Oarga-Mulec, A., Holko, L., Kopitar, A., Mulec, J., Year, Study of water cycle in karst with chemical and microbiological parameters. 25th International Karstological School "Classical Karst": Milestones and challenges in karstology, Postojna, 43-44.
- Pacheco, G. S. M., de Oliveira, M. P. A., Cano, E., Souza-Silva, M., Ferreira, R. L., 2020: Tourism effects on the subterranean fauna in a Central American cave. Insect Conservation and Diversity. https://doi.org/10.1111/icad.12451.
- Pallarés, S., Colado, R., Pérez-Fernández, T., Wesener, T., Ribera, I., Sánchez-Fernández, D., 2019: Heat tolerance and acclimation capacity in subterranean arthropods living under common and stable thermal conditions. Ecology and Evolution, 9, 13731–13739.
- Placer, L., 1981, Geologic structure of southwestern Slovenia. Geologija 24/1, 27-60, Ljubljana.
- Placer L., 1996: O zgradbi Soviča nad Postojno. Geologija, 37/38 (1994/95), 551-560, Ljubljana.
- Pretner E., 1968: Živalstvo Postojnske jame. 150 let Postojnske jame, 1818-1968. Zavod Postojnske jame, Postojna, 59-71.
- Ravbar, N., & Pipan, T., 2022: Karst Groundwater Dependent Ecosystems—Typology, Vulnerability and Protection. In: Griebler C. (ED.) Encyclopedia of Inland Waters, Second Edition. https://doi.org/10.1016/B978-0-12-819166-8.00182-1
- Ravbar, N., Petrič, M., Rubinić, J., Diković, S., Koželj, A., Pipan, T., Kogovšek, J., 2017: Monitoring the quantitative status and quality of karst water sources. In: Zupan Hajna, N., Ravbar, N., Rubinič, J., Petrič, M. (Eds.) Life and water on karst, 143.
- Ravbar, N., Šebela, S., 2015: The effectiveness of protection policies and legislative framework with special regard to karst landscapes: Insights from Slovenia. Environmental Science & Policy, 51, 106-116. https://doi.org/10.1016/j.envsci.2015.02.013
- Rižnar I., 1997: Geology of Postojna area. MSc. Thesis, NTF, University of Ljubljana, 78 pp., Ljubljana.
- Rizzo, V., Sánchez-Fernández, D., Fresneda, J., Cieslak, A., Ribera, I., 2015: Lack of evolutionary adjustment to ambient temperature in highly specialized cave beetles. BMC Evolutionary Biology, 15, 10.
- Romero, A., 2009: Cave biology. New York, NY: Cambridge University Press.
- Sarbu, S.M., Kane, T.C., Kinkle, B.K., 1996: A chemoautotrophically based cave ecosystem, Science 272, 1953-1955.
- Šebela S., 2019: Postojna - Planina Cave System, Slovenia. In: White, WB (ed.), Culver DC (ed.), Pipan T (ed.). Encyclopedia of caves. 3rd ed. London [etc.]: Academic Press, an imprint of Elsevier, pp 812-821, ISBN 978-0-12-814124-3.
- Šebela S., Stemberk J., Briestenský M., 2021: Micro-displacement monitoring in caves at the Southern Alps-Dinarides-Southwestern Pannonian Basin junction. Bulletin of engineering geology and the environment. vol. 80, iss. 10, 7591-7611, DOI: 10.1007/s10064-021-02382-4.
- Šebela, S., 1998: Tectonic structure of Postojnska Jama cave system. ZRC Publishing, Ljubljana. https://doi.org/10.3986/961618265X
- Šebela, S., 2008: Broken speleothems as indicators of tectonic movements. Acta Carsologica 37, 51–62.
- Šebela, S., 2022: Koncentracije metana in ogljikovega dioksida v Lepih Jamah, Postojnska Jama, http://fgg-web.fgg.uni-lj.si/sugg/referati/2022/SZGG_2022_Sebela.pdf
- Šebela, S., 2022: Natural and anthropogenic impacts on cave climates: Postojna and Predjama show caves (Slovenia), (Earth and planetary sciences). 1st ed. [S. l.]: Elsevier, 2022. 274 pp. ISBN 978-0-12-822954-5. https://www.elsevier.com/books/natural-and-anthropogenic-impacts-on-cave-climates/sebela/978-0-12-822954-5, doi: 10.1016/B978-0-12-822954-5.00001-9.
- Šebela, S., M. Prelovšek, Turk J., 2013: 'Impact of Peak Period Visits on the Postojna Cave (Slovenia) Microclimate'. Theoretical and Applied Climatology 111 (1–2): 51–64.

https://doi.org/10.1007/s00704-012-0644-8.
- Šebela, S., Stemberk, J. & Briestenský, M., 2021: Micro-displacement monitoring in caves at the Southern Alps–Dinarides–Southwestern Pannonian Basin junction. Bull Eng. Geol. Environ. 80, 7591–7611. https://doi.org/10.1007/s10064-021-02382-4
- Šebela, S., Turk J., 2011: 'Local Characteristics of Postojna Cave Climate, Air Temperature, and Pressure Monitoring'. Theoretical and Applied Climatology 105 (3–4): 371–86. https://doi.org/10.1007/s00704-011-0397-9.
- Sket, B., 2008: Can we agree on an ecological classification of subterranean animals? Journal of Natural History, 42, 1549–1563. Kogovšek, J., 2010: Characteristics of percolation through the karst vadose zone. ZRC Publishing, Ljubljana.
- Skok, S., Kogovšek, B., Tomazin, R., Šturm, S., Ambrožič Avguštin, J., Mulec, J., 2020, Antimicrobial-resistant Escherichia coli from karst waters, surfaces and bat guano in Slovenian caves. Acta Carsologica, 49: 265-279.
- Tomazin, R., Simčič, S., Matos, T., Kopitar, A., Stopinšek, S., Mauko Pranjić, A., Zalar Serjun, V., Mulec, J., 2018, Vpliv turizma na kakovost zraka v Postojnski jami in Škocjanskih Jamah / Impact of tourism on air quality in Postojna Cave and Škocjan Caves. Sekcija za klinično mikrobiologijo in bolnišnične okužbe SZD, Ljubljana.
- Turk, J., 2010: Hydrogeological role of large conduits in karst drainage system: examples from the Ljubljanica River catchment area: dissertation.
- Uršič Arko, A., Otoničar, B., 2018: Turonijsko do srednje coniacijsko zaporedje karbonatnih kamnin jugozahodnega krila Postojnske antiklinale. In: Rožič, B. (Ed.) *Razprave in poročila = Treatises, reports.* 24. Posvetovanje slovenskih geologov = 24th Meeting of Slovenian Geologists, Ljubljana.
- Waring, C.L., Hankin, S.I., Griffith, D.W.T., Kertesz, M.A., Kobylski, V., Wilson, N.L., Coleman, N.V., Kettlewell, G., Zlot, R., Bosse, M., Bell, G., 2017: Seasonal total methane depletion in limestone caves, Scientific Reports, 7, 8314, doi:10.1038/s41598-017-07769-6
- Webster, K.D., Drobniak, A., Etiope, G., Mastalerz, M., Sauer, P.E., Schimmelmann, A., 2018: Subterranean karst environments as a global sink for atmospheric methane, Earth and Planetary Science Letters, 485, 9-18, doi: 10.1016/j.epsl.2017.12.025
- Webster, K.D., Mirza, Anmar, Deli, J.M., Sauer, P.E., Schimmelmann, A. (2016). Consumption of atmospheric methane in a limestone cave in Indiana, USA, Chemical Geology 443, 1-9, http://dx.doi.org/10.1016/j.chemgeo.2016.09.020
- Webster, K.D., Rosales Lagarde, L., Sauer, P.E., Schimmelmann, A., Lennon, J.T., Boston, P.J., 2017: Isotopic evidence for the migration of thermogenic methane into a sulfidic cave, Cueva de Villa Luz, Tabasco, Mexico, J. caves Karst Stud. 79, 1, 24-34, doi:10.4311/2016ES0125
- Zagmajster M., Prevorčnik S., Sket B., 2014: Seznam izključno podzemnih (troglobiotskih) vrst ali populacij živali v Postojnsko–planinskem jamskem sistemu. Poročilo, 5 str., Ljubljana.
- Zupan Hajna N, Bosák P, Pruner P, Mihevc A, Hercman H, Horáček I., 2020: Karst sediments in Slovenia: Plio-Quaternary multi-proxy records. Quat Int (2020) 546, 4-19. doi: 10.1016/j.quaint.2019.11.010
- Zupan Hajna N, Mihevc A, Pruner P, Bosák P., 2010: Palaeomagnetic research on karst sediments in Slovenia. Int J Speleol 39/2, 47-60. doi: 10.5038/1827-806X.39.2.1.
- Zupan Hajna N., 1992: Mineral composition of mechanical sediments from some parts on Slovenian karst. Acta carsologica, 21, 115-130.
- Zupan Hajna N., Mihevc A., Pruner P., Bosák P., 2008a: Palaeomagnetism and Magnetostratigraphy of Karst Sediments in Slovenia. Ljubljana: Založba ZRC. 266 p.
- Zupan Hajna N., Mihevc A., Pruner P., Bosák P., 2008b: Cave sediments from the Postojnska-Planinska cave system (Slovenia): evidence of multiphase evolution in epiphreatic zone. Acta carsologica, 37/1, 63-86.
- Zupan Hajna N., Ruan J., Genty D., Regnier E., Pierre M., Pons E., Gabrovšek F., 2022: Example of stalagmite growth during and at the end of the Last Glaciation, Slovenian Southern Alps and Dinarides. Abstracts, 9th International Workshop on Ice Caves (IWIC-IX), Lyptovsky Mikulaš.

- Zupan Hajna, N., 2015: The concept and settings of nature phenomena of an interpretative exhibition at Postojnska Jama. Exhibition, Postojnska Jama EXPO.
- Zupan N., 1991: Flowstone datations in Slovenia. Acta Carsologica, 20, 187-204.

https://izrk.zrc-sazu.si/sl/programi-in-projekti/ri-si-epos#v
https://www.opsis.se/en/Products/Products-CEM-Process/LD500-Laser-Diode-Gas-Analyser

Whole-day field trip (D):

GROUNDWATER FLOW IN THE LJUBLJANICA RECHARGE AREA

Friday, 17. June, 2022, 9:00–17:00

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

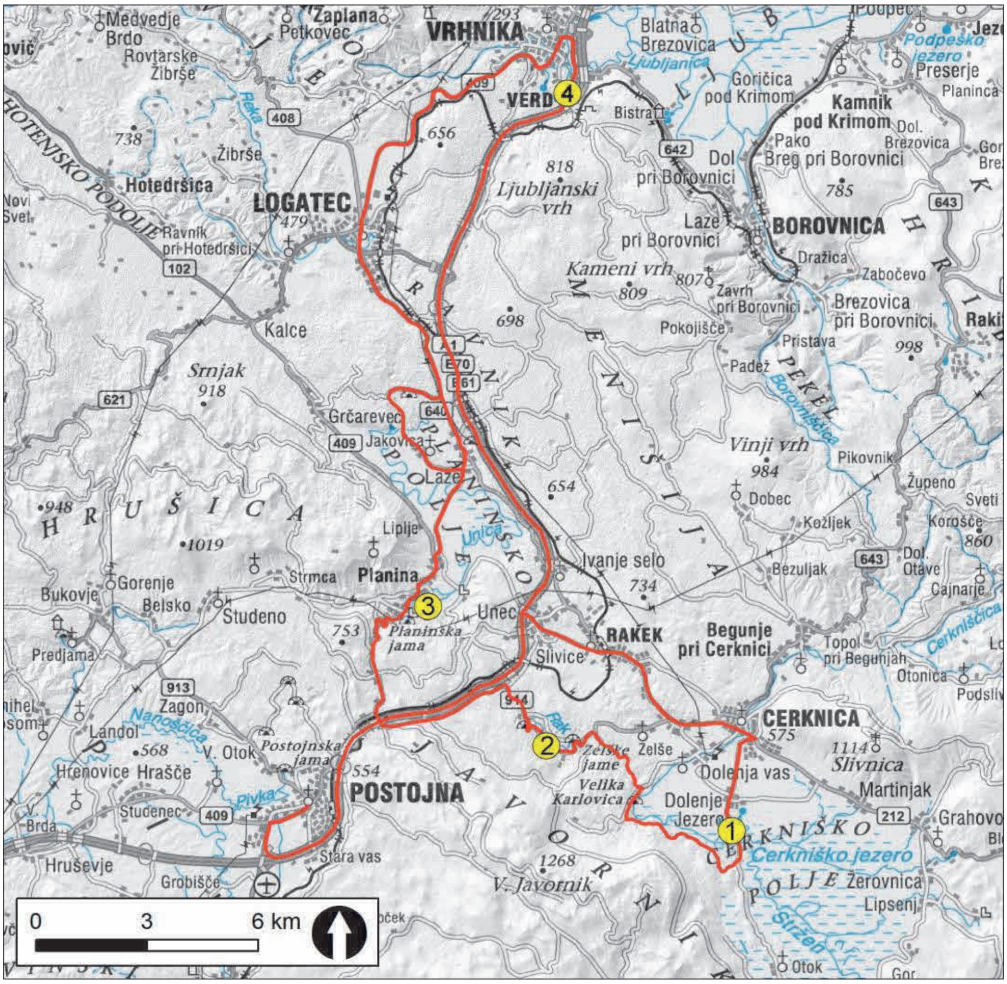
Stops:

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, 17. junij 2022;

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. 4.01). Although the area is about 26 km of straight-line distance close to the Adriatic Sea, intense tectonic activity has triggered drainage into the Sava-Danube river basin, which flows to the Black Sea. The 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).

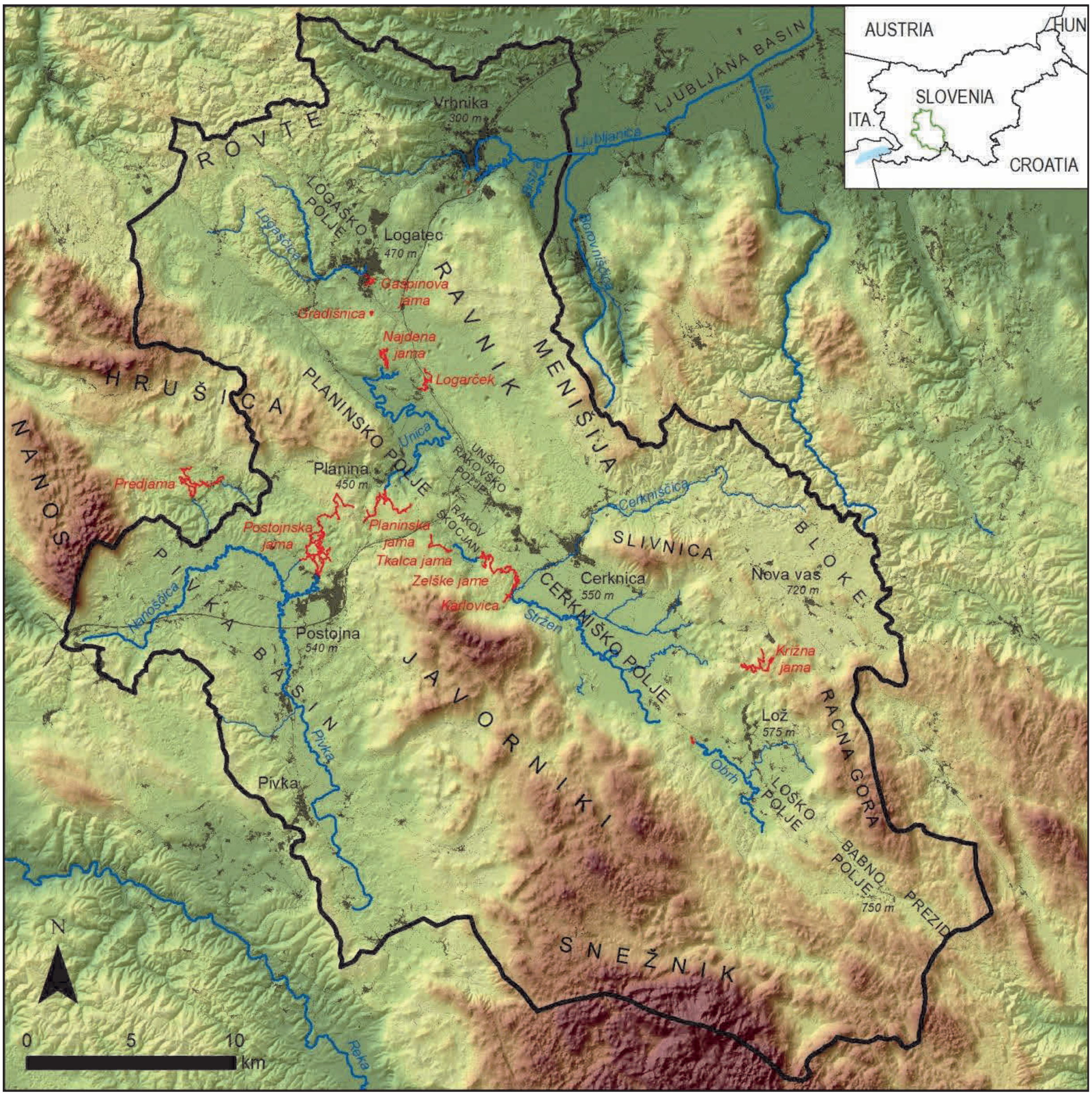


Fig. 4.01: Ljubljanica River recharge area with high karstic plateaus, karst poljes and surface rivers. The main caves are shown with red lines.

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

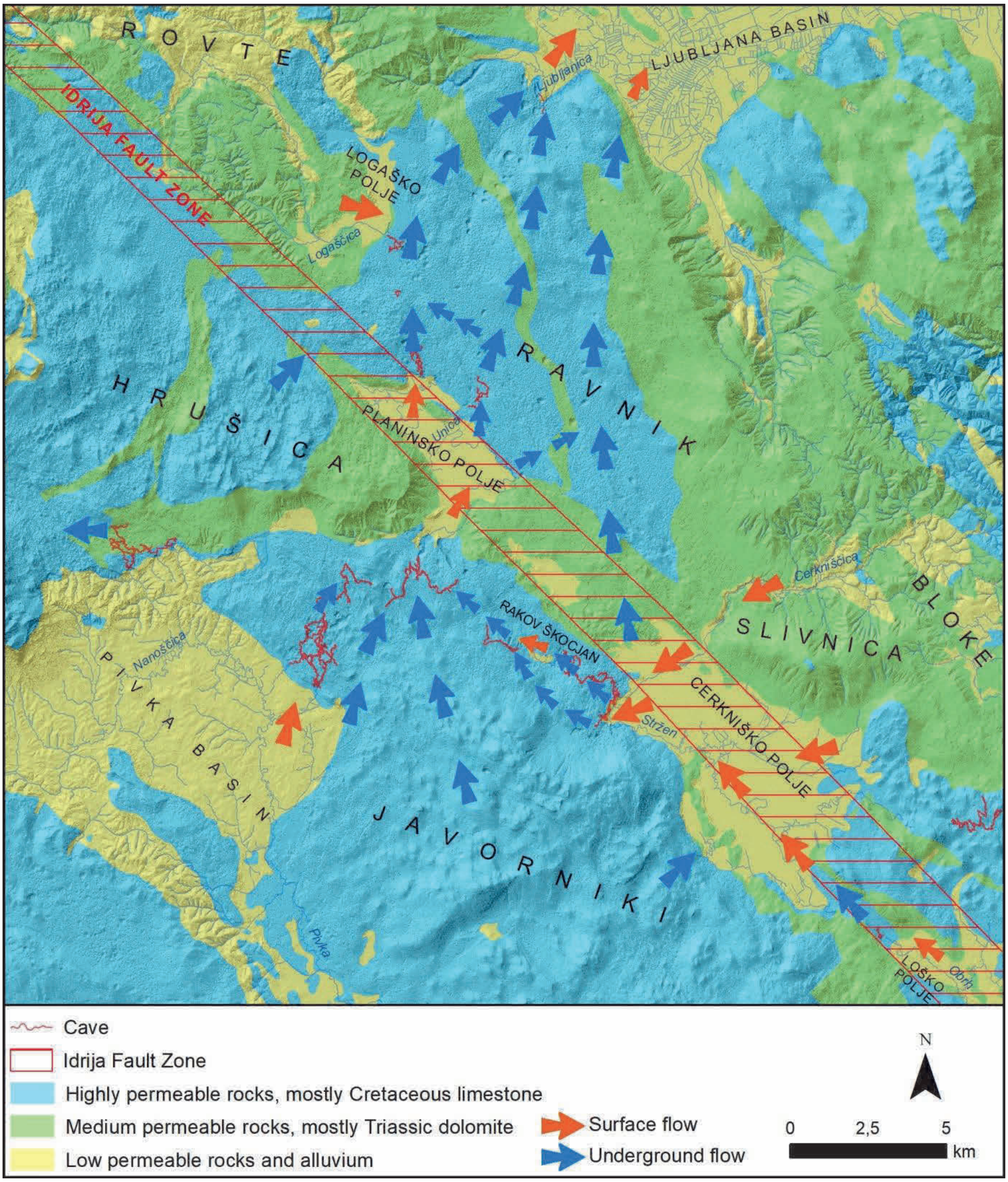


Fig.4.02: Geology and hydrology of the Ljubljanica recharge area (adapted from Krivic et al. 1976).

Several poljes have developed along the Idrija Fault Zone (Gams 1965, 1978; Šušteršič 1996). These large flat-bottomed depressions are regularly flooded and are often the only areas where water appears at the surface. The formation of poljes is preconditioned by tectonics, in this case by the structures within the Idrija strike slip fault (e.g. pull-apart zones), but the forming mechanism is the corrosional planation at the groundwater level.

In general, the water follows the SE-NW direction with surface flow on the poljes and groundwater flow in-between (Fig. 4.03). Additional water enters the flow system at numerous springs draining the areas of the Snežnik and Javorniki mountains in the south of the Idrija Fault Zone. Several sinking rivers draining dolomite or flysch areas also contribute to this system (Gams 2004). The altitude of the poljes drops from about 750 m to 450 m. 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. 4.03).

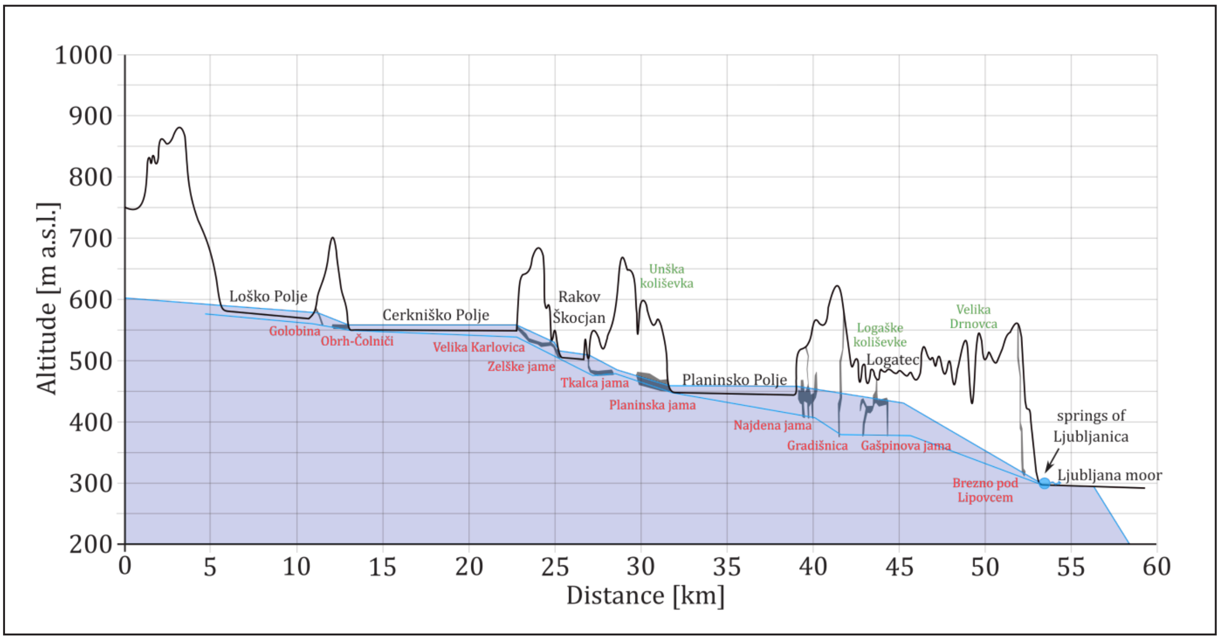


Fig. 4.03: Cross section of Ljubljanica River recharge area following an initially SE-NW trend along the Idrija Fault Zone between Loško and Planinsko Polje, and turning N from Planinsko Polje toward the Ljubljanica springs near Vrhnika. The major caves are indicated in red, large collapse dolines in 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. 4.04a). When full, the intermittent lake covers up to 26 km^2 out of 38 km^2 of the polje's total area. The bottom of the lake is at an altitude of 550 m. Its intermittency has attracted many scholars since the beginning of the New age including the polihistorian Valvasor, who published his famous study of the Cerkniško Jezero in 1689 (Shaw & Čuk 2015). The main part of the polje is underlained by Upper Triassic dolomite at its N, E and SE borders. The areas to the W and NW, on the other hand, are mainly underlain by Cretaceous limestone (Fig. 4.02).

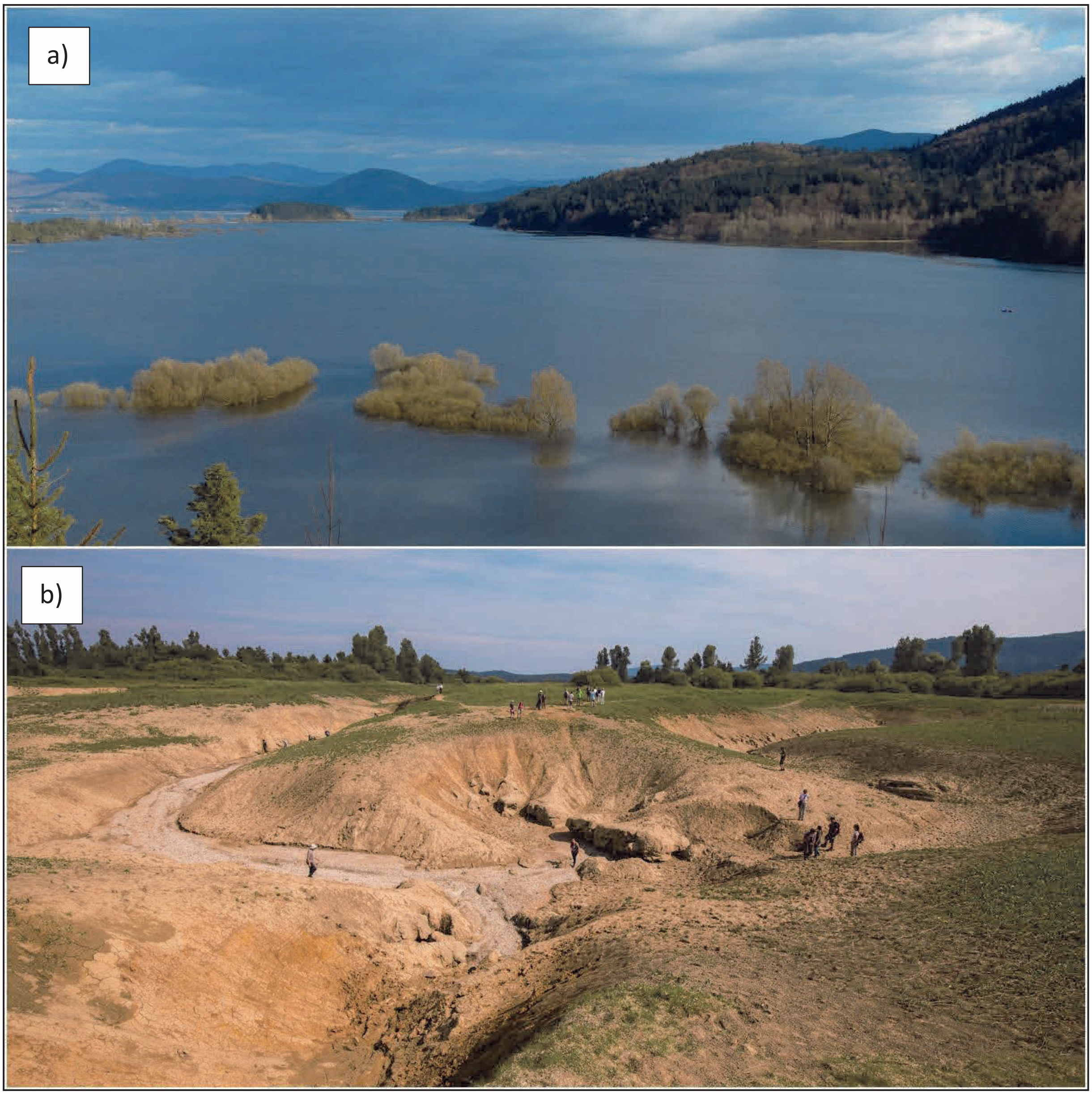


Fig. 4.04: (a) Flooded Cerkniško Jezero (Spring 2013) (Photo: C. Mayaud). (b) Ponors of Rešeta during low flow conditions (Summer 2017) (Photo: M. Blatnik).

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

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

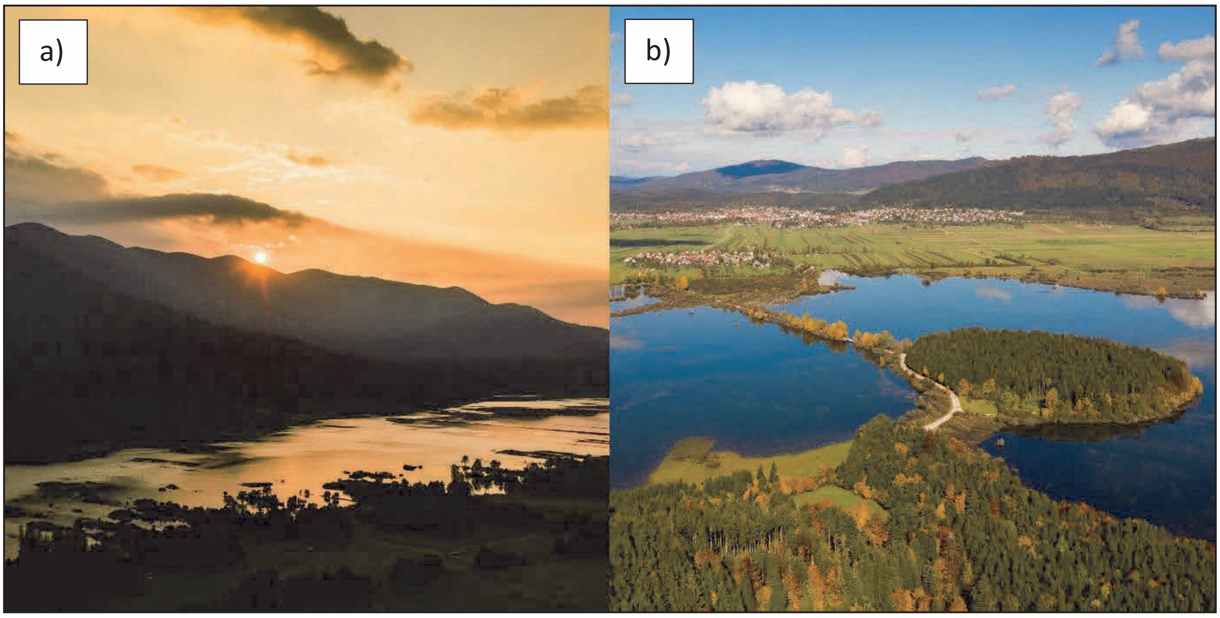


Fig. 4.05: Cerkniško Jezero. a) Lake and Javorniki Mountains at sunset. b) View toward the village of Dolenje jezero (Photos: M. Blatnik; RI-SI-EPOS).

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. 4.06). 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. 4.07a), where an impressive narrow arch, which was part of the former cave ceiling, crosses the collapse doline (Gams 2004).

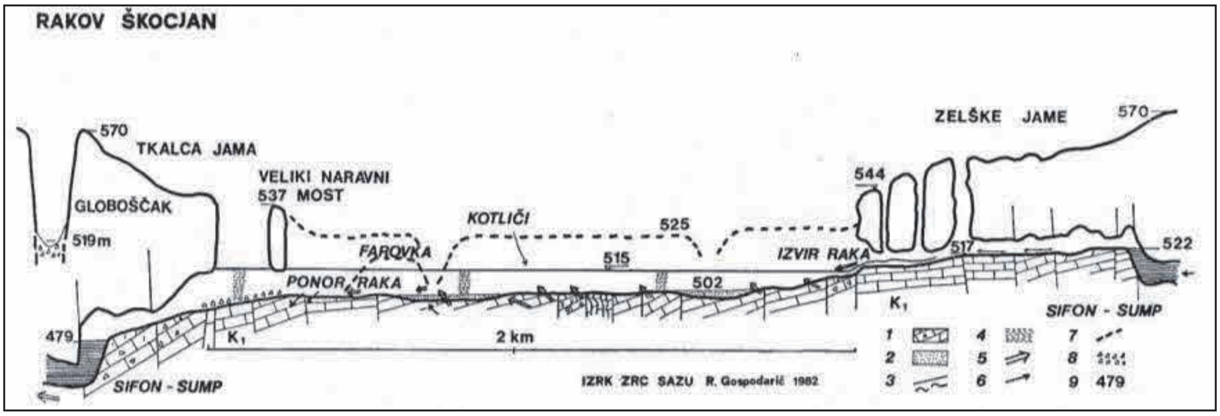


Fig. 4.06: Cross-section of the Rakov Škocjan karst valley between the Rak spring at Zelške Jame and the terminal ponor in Tkalca Jama. Legend: 1. rocky bottom; 2. alluvia; 3. fault zone; 4. flood level in 1982; 5. karst spring: 6. water flow directions; 7. terraces; 8. boulder rocks; 9. altitude.

Downstream, the valley widens and several springs (Fig. 4.07b) 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. 4.08). 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.

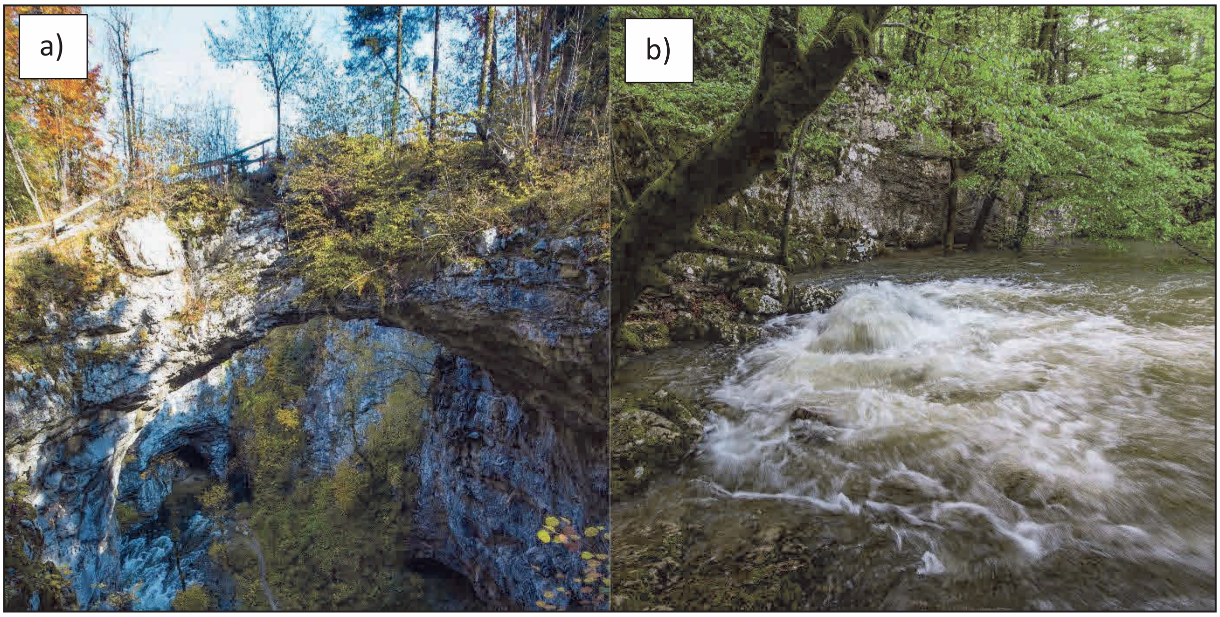


Fig. 4.07: Rakov Škocjan karst valley. a) The arch of Mali Naravni Most. b) Kotliči spring at the beginning of a hydrological event (Photos: M. Blatnik).

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 4.08a). 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.

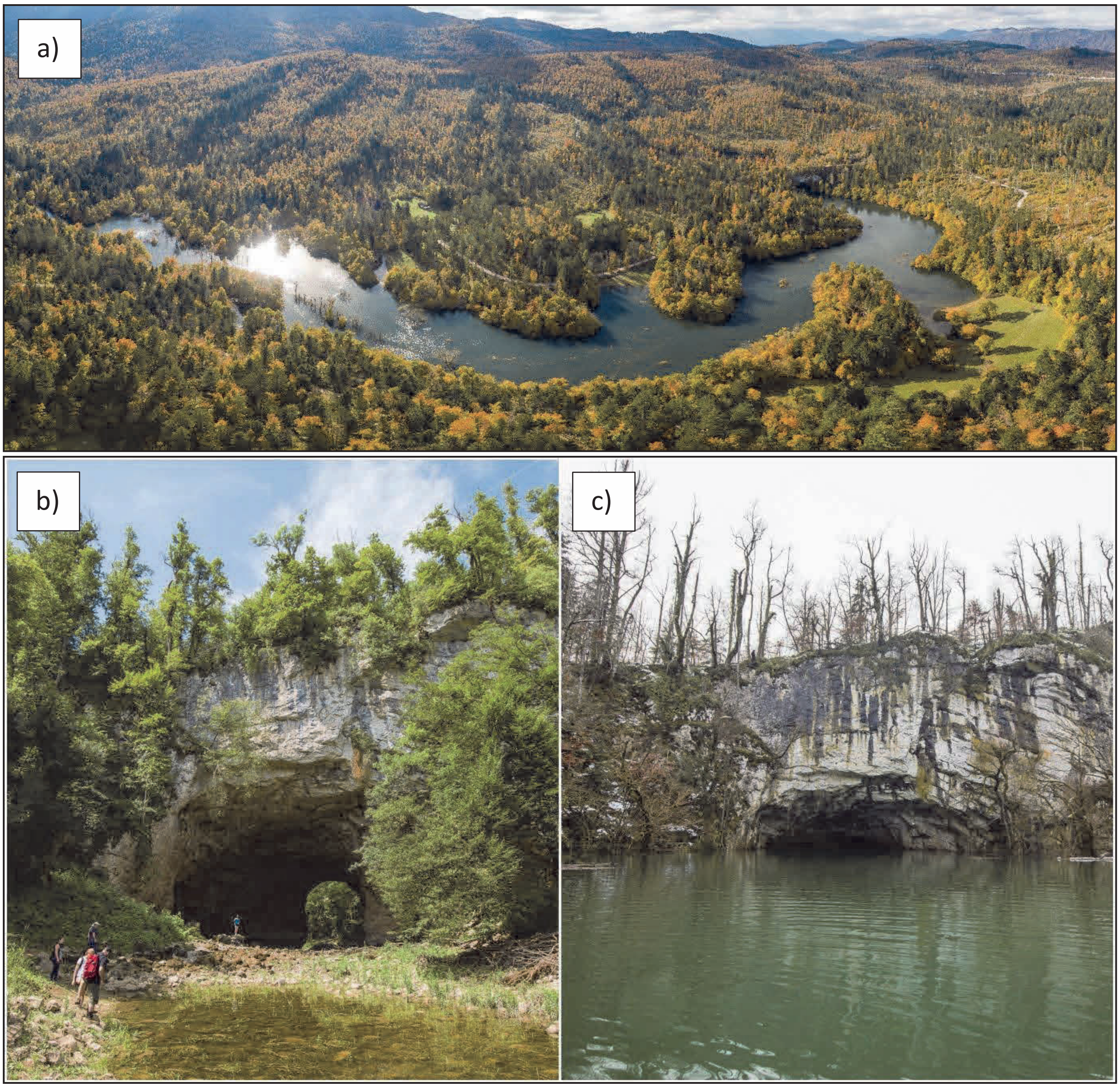


Fig. 4.08: a) Flooded Rakov Škocjan Karst Valley in October 2020, b) Veliki Naravni Most (Big Natural Bridge) during dry period in summer; and c) during high water event in winter (Photos: M. Blatnik; RI-SI-LifeWatch).

PLANINSKA JAMA – THE MYSTERIOUS LAKE

Planinska Jama (Planina Cave) is a large spring cave located on the southern edge of Planinsko Polje (Fig. 4.09a). 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. 4.09b; 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).

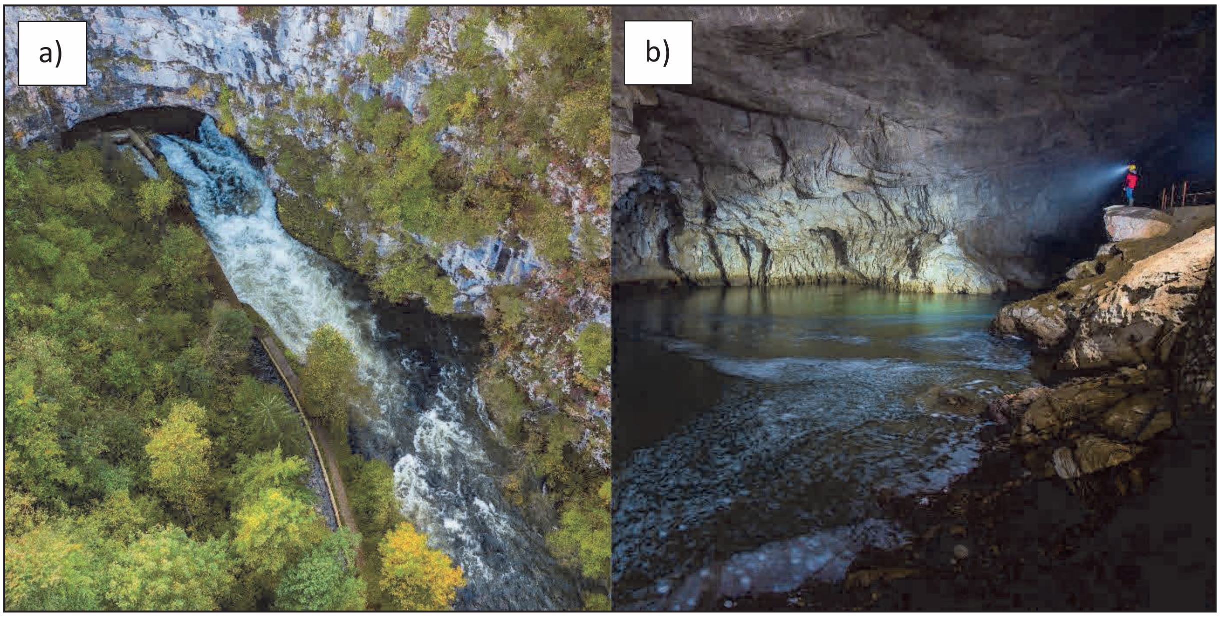


Fig. 4.09: Planinska Jama. a) Cave entrance. b) Confluence of the Pivka and Rak Branches (Photos: M. Blatnik; RI-SI-EPOS).

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).

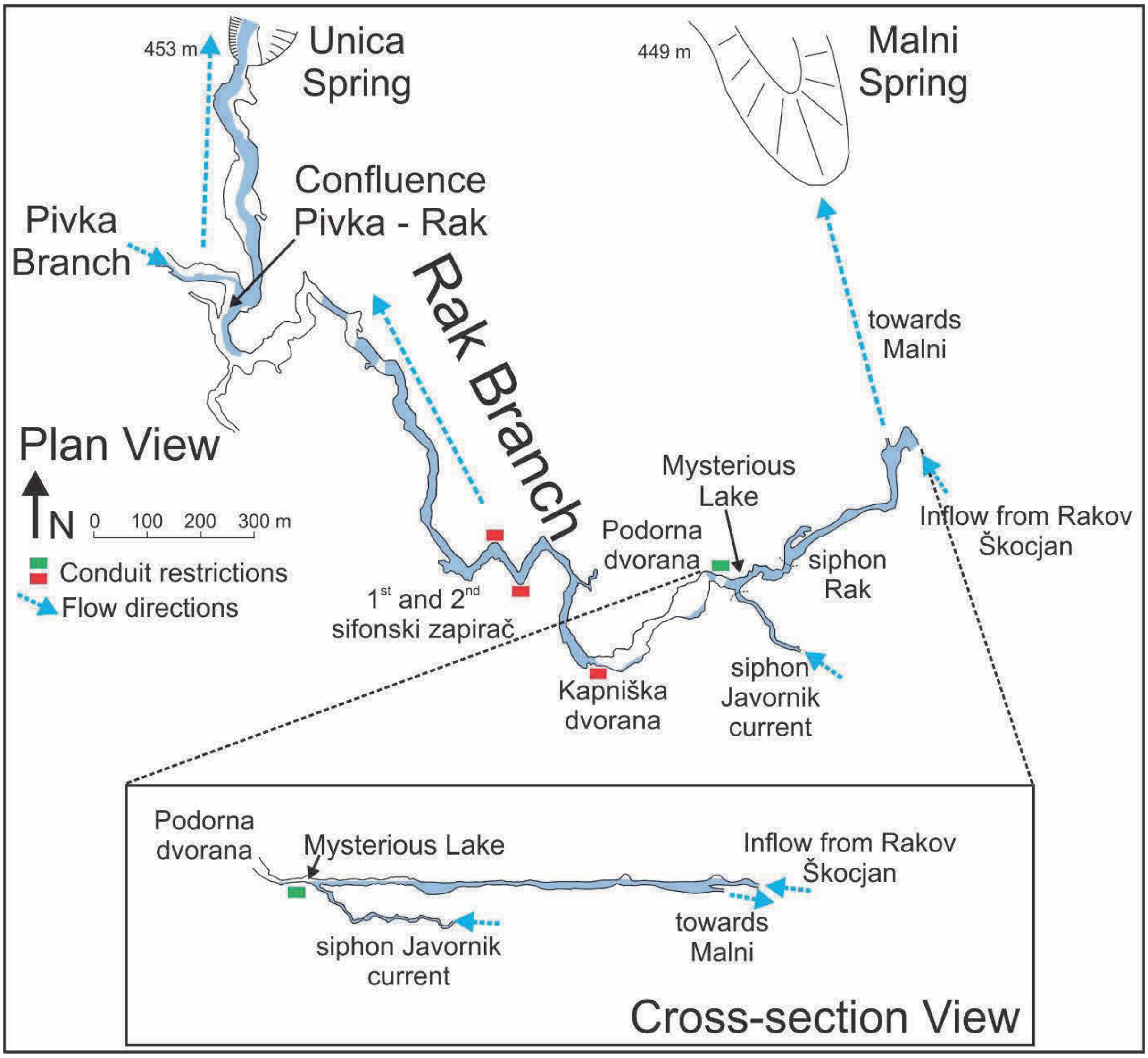


Fig. 4.10: Detailed view of the Rak Branch of Planinska Jama and cross-section of its terminal siphon in the Mysterious Lake (Gams 2004; Kaufmann et al. 2020).

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.

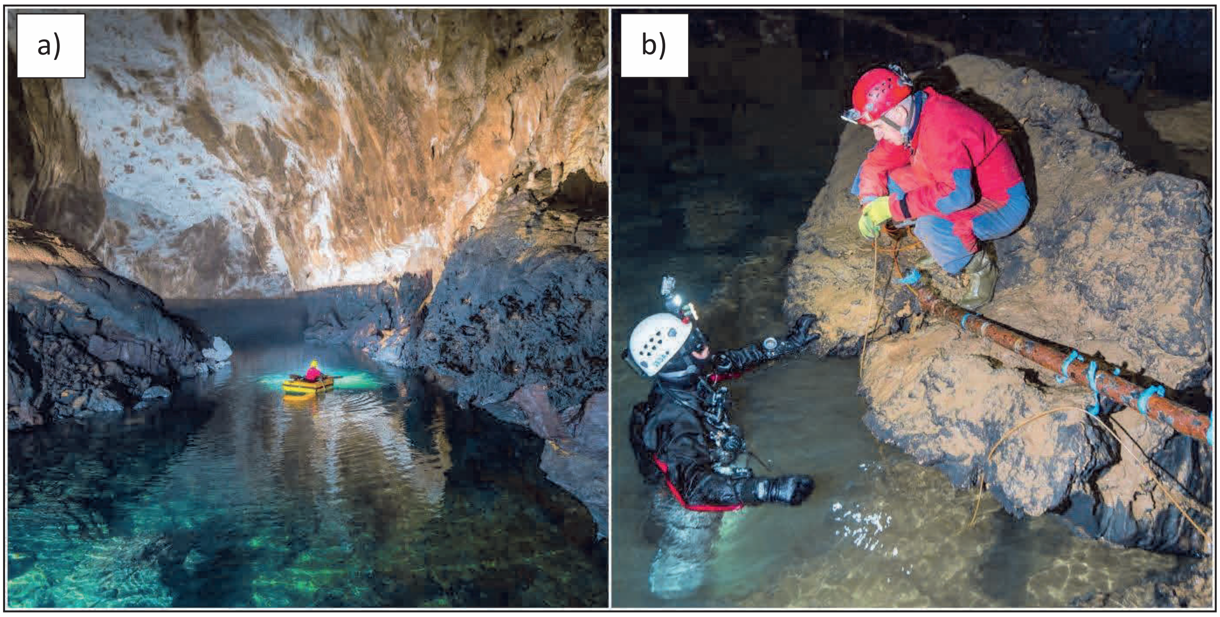


Fig. 4.11: Planinska Jama. a) example of typical large cave passage in the Rak Branch. b) recent diving exploration in the Mysterious Lake and Javornik Current (Photos: M. Blatnik).

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).

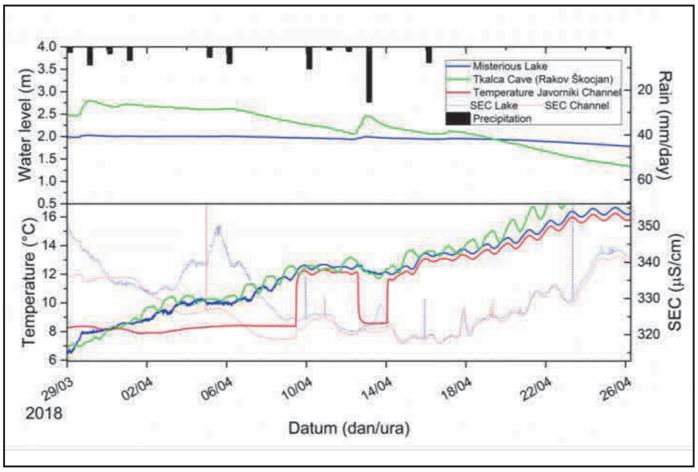


Fig. 4.12: Example of hydrological event showing a flow reversion in the siphon of the Javornik current.

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) (Fig. 4.13). Most important springs are aligned along the gradually retreating pocket valleys of Močilnik and Retovje. The springs at Močilnik ($Q_{av} \approx$ 6–7 m^3/s) feed Mala (=small) Ljubljanica and springs at Retovje ($Q_{av} \approx$ 16 m^3/s) feed Velika (= big) Ljubljanica, the main tributaries related to karst springs of the Ljubljanica River. Easterly, another tributary Ljubija ($Q_{av} \approx$ 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).

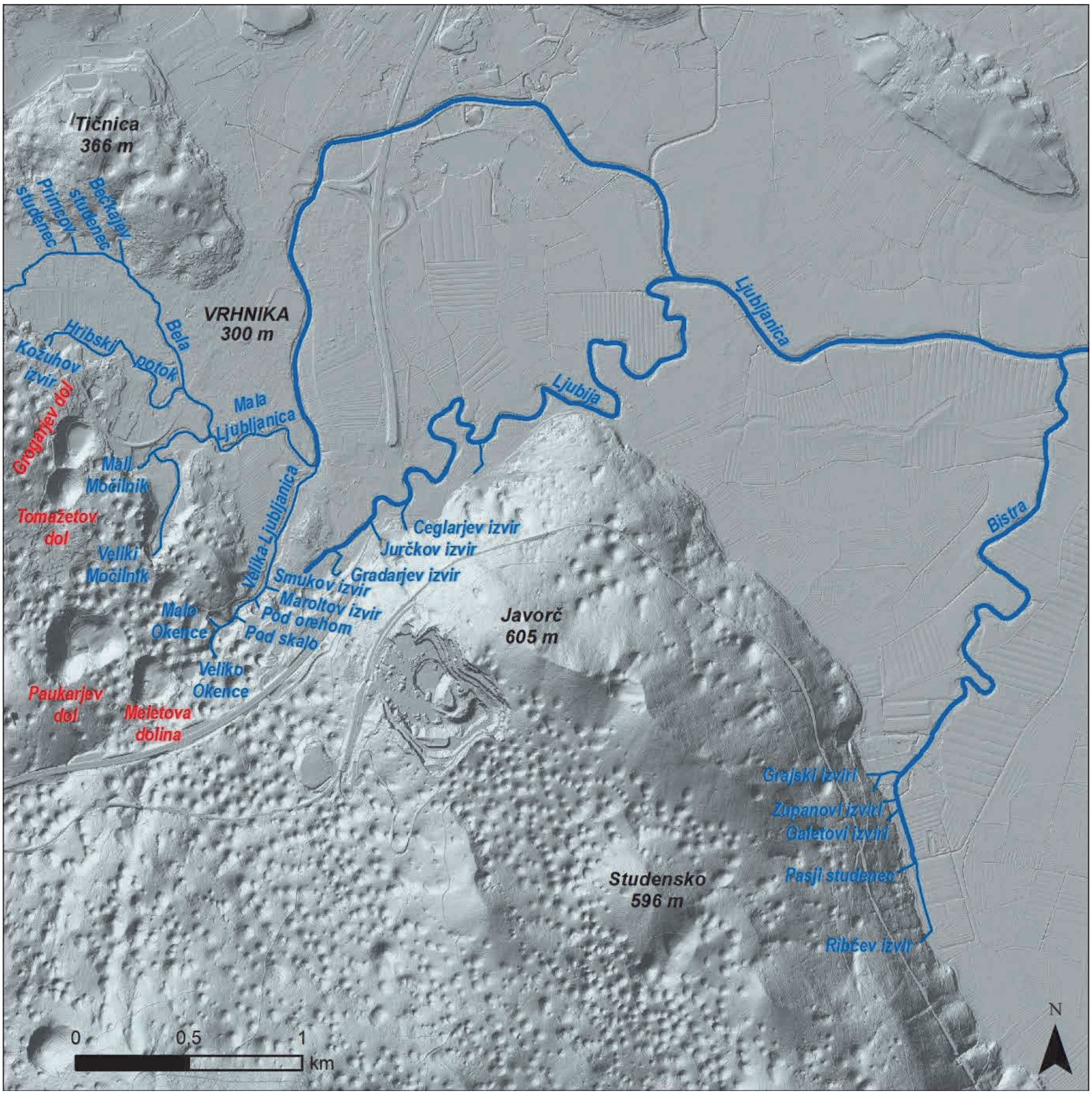


Fig. 4.13: Location of collapse dolines and Ljubljanica springs near Vrhnika.

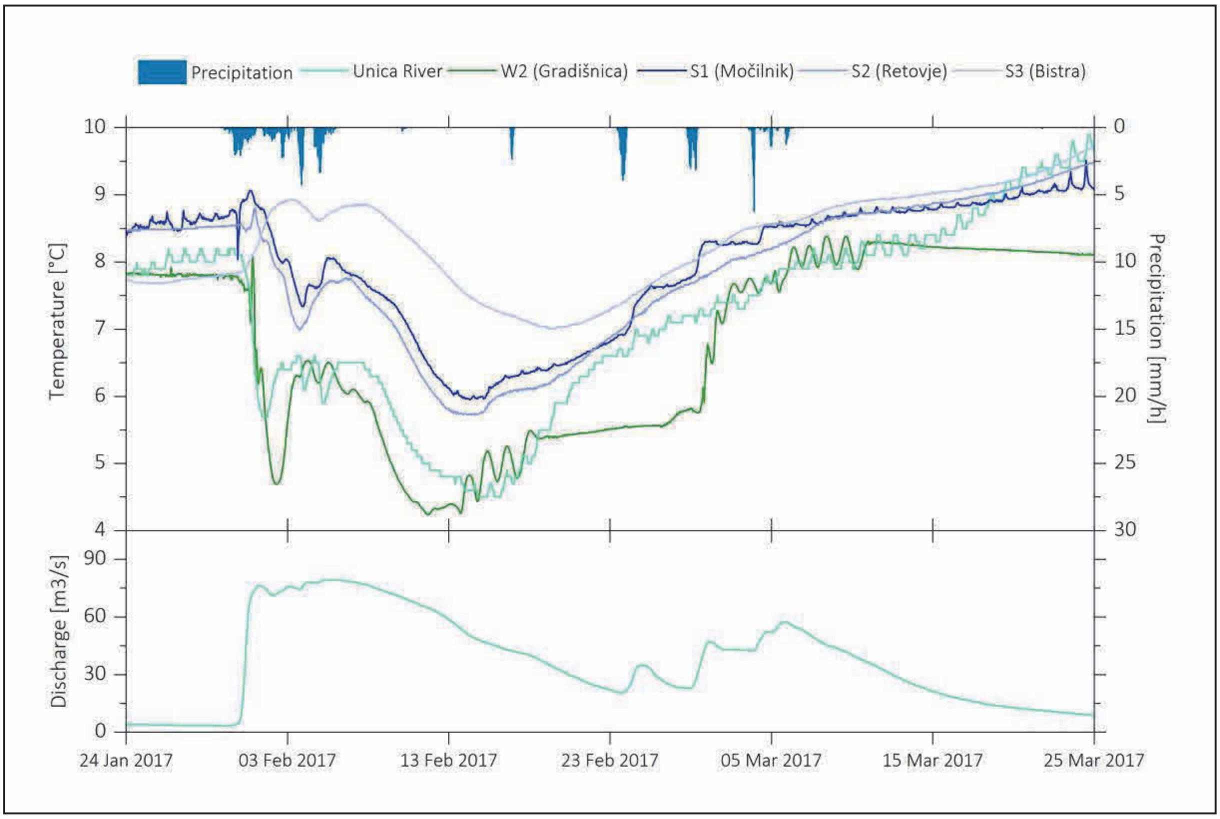


Fig. 4.14: Temperature hydrographs at springs of Ljubljanica compared to the cave Gradišnica and Unica River.

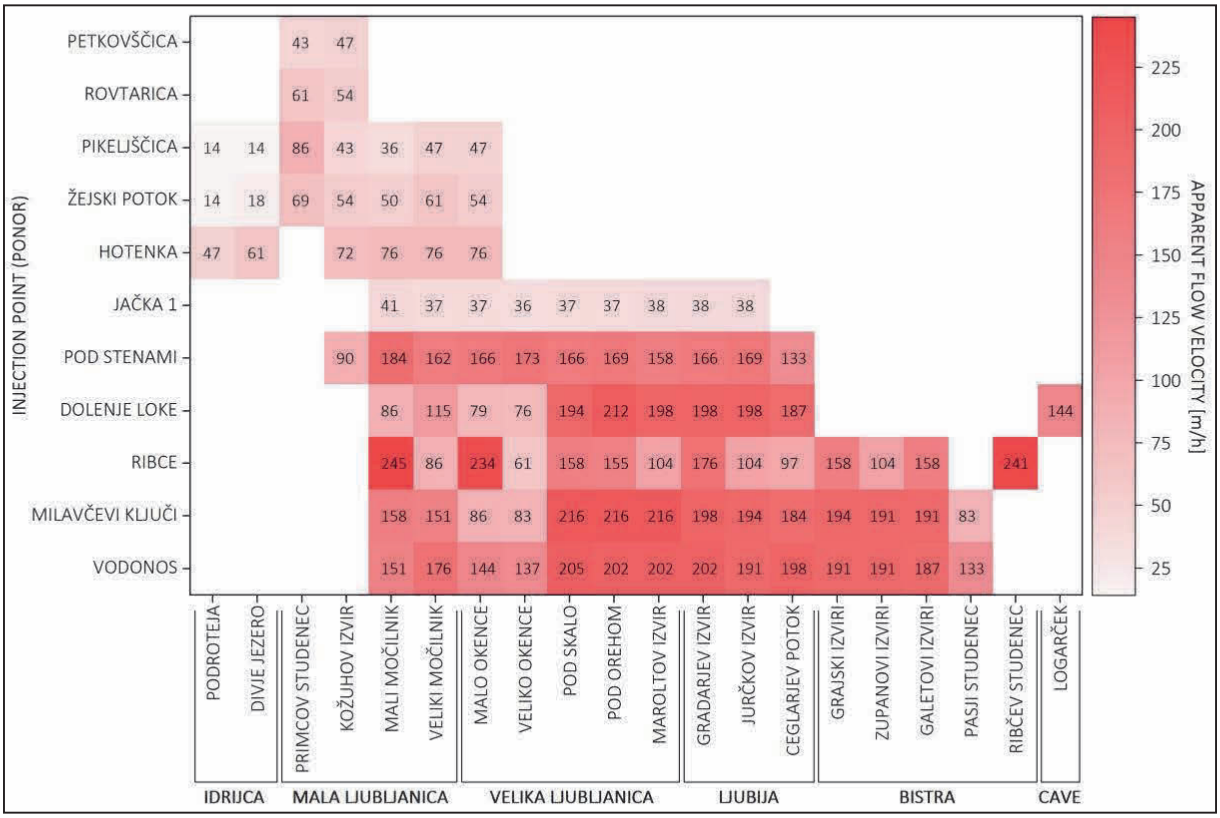


Fig. 4.15: Apparent flow velocities between the studied ponors and the springs obtained from the dye tracing campaign in 1975. On vertical axis injection points (ponors or surface streams) whereas on horizontal axis locations of sampling points (springs or caves) are listed.

REFERENCES:

- Blatnik, M., Mayaud, C. & F. Gabrovšek, 2019: Groundwater dynamics between Planinsko Polje and springs of the Ljubljanica River, Slovenia.- Under review in Acta Carsologica.
- Celarc, B., Jež, J., Novak, M. & L. Gale, 2013: Geološka karta Ljubljanskega barja 1:25,000.- Geološki zavod Slovenije, Ljubljana.
- Drole, F., 2015: Rakov Škocjan in Planinsko polje 2014.- Proteus, 76, 6, 275–281.
- Gabrovšek, F. & J. Turk, 2010: Observations of stage and temperature dynamics in the epiphreatic caves within the catchment area of the Ljubljanica river.- Geologia Croatica, 63, 2, 187–193.
- Gabrovšek, F. & U. Stepišnik, 2011: On the formation of collapse dolines: a modelling perspective.- Geomorphology, 134, 1-2, 23–31.
- Gabrovšek, F., Kogovšek, J., Kovačič, G., Petrič, M., Ravbar, N. & Turk, J., 2010: Recent results of tracer tests in the catchment of the Unica River (SN Slovenia).- Acta Carsologica, 39, 1, 27–38.
- Gabrovšek, F., Petrič, M., Ravbar, N., Blatnik, M., Mayaud, C., Prelovšek, M., Kogovšek, B., Mulec, J., Šebela, S. & G. Vižintin, 2019: Raziskave možnih rezervnih vodnih virov za oskrbo občin Postojna in Pivka.- Project report, pp. 84.
- Gams, I., 1965: On the Quarternary geomorphogenesis of the area among the karst poljes of Postojna, Planina and Cerknica (In Slovene, English Summary).- Geografski vestnik, 37, 61–101.
- Gams, I., 1978: The polje: the problem of definition: with special regard to the Dinaric karst.- Zeitschrift für Geomorphologie, 22, 170–181.
- Gams, I., 2004: Kras v Sloveniji v prostoru in času.- Inštitut za raziskovanje krasa ZRC SAZU, pp. 515, Ljubljana.
- Gospodarič, R., 1981: Morfološki in geološki položaj kraških votin v ponornem obrobju Planinskega polja.- Acta Carsologica, 10, 157–172.
- Gospodarič, R. & P. Habič, (ed), 1976: Underground water tracing: Investigations in Slovenia 1972–1975.- Third International Symposium of Underground Water Tracing (3. SUWT), pp. 312, Ljubljana, Bled.
- Habič, P., (ed) 1973: Speleološka karta – List Vrhnika 2-D.- Inštitut za raziskovanje krasa ZRC SAZU, pp. 156, Postojna.
- Habič, P., 1984: Vodna gladina v Notranjskem in Primorskem krasu Slovenije.- Acta Carsologica, 13, 37–78.
- Kaufmann, G., Gabrovšek, F. & J. Turk, 2016: Modelling flow of subterranean Pivka River in Postojnska Jama, Slovenia.- Acta Carsologica, 45, 1, 57−70.
- Kaufmann, G., Mayaud, C., Kogovšek, B. & F. Gabrovšek, 2020: Understanding the temporal variation of flow direction in a complex karst system (Planinska Jama, Slovenia).- Acta Carsologica, 49, 2/3, 213–228.
- Kogovšek, B., 2022: Characterization of a karst aquifer in the recharge area of Malenščica and Unica springs based on spatial and temporal variations of natural tracers.- PhD thesis. University of Nova Gorica, pp. 242.
- Kogovšek, J., 1999: Nova spoznanja o podzemnem pretakanju vode v severnem delu Javornikov (Visoki kras).- Acta Carsologica, 28, 1, 161–200.
- Kovačič, G., 2010: An attempt towards an assessment of the Cerknica Polje water balance.- Acta Carsologica 39, 1, 39–50.
- Kovačič, G., 2011: Kraški izvir Malenščica in njegovo zaledje : hidrološka študija s poudarkom na analizi časovnih vrst.- Univerza na Primorskem, Znanstveno-raziskovalno središče, Univerzitetna založba Annales, pp. 408, Koper.
- Kovačič, G. & N. Ravbar, 2010: Extreme hydrological events in karst areas of Slovenia, the case of the Unica River basin.- Geodinamica Acta, 23, 1–3, 89–100.
- Krivic, P., Verbovšek, R. & F. Drobne, 1976: Hidrogeološka karta 1: 50 000.- In: Gospodarič, R. & P. Habič (eds.): Underground water tracing: Investigations in Slovenia 1972–1975. Inštitut za raziskovanje krasa ZRC SAZU, Postojna.

- Mihevc, A., Prelovšek, M., & N, Zupan Hajna, 2010: Introduction to Dinaric Karst.- Inštitut za raziskovanje krasa ZRC SAZU, pp. 71., Postojna.
- Petrič, M., Kogovšek, J., & N. Ravbar, 2018: Effects of the vadose zone on groundwater flow and solute transport characteristics in mountainous karst aquifers–the case of the Javorniki–Snežnik massif (SW Slovenia)-. Acta Carsologica, 47, 1, 35–51.
- Placer, L., 2008: Principles of the tectonic subdivision of Slovenia = Osnove tektonske razčlenitve Slovenije.- Geologija, 51, 2, 205–217.
- Placer, L., Vrabec, M. & B. Celarc, 2010: The bases for understanding of the NW Dinarides and Istria Peninsula tectonics.- Geologija, 53, 1, 55–86.
- Ravbar, N., Barberá, J.A., Petrič, M., Kogovšek, J. & A. Bartolomé, 2012: The study of hydrodynamic behaviour of a complex karst system under low-flow conditions using natural and artificial tracers (the catchment of the Unica River, SW Slovenia).- Environ Earth Sciences, 65, 2259–2272.
- Ravbar, N., Mayaud, C., Blatnik, M. & M. Petrič, 2021: Determination of inundation areas within karst poljes and intermittent lakes for the purposes of ephemeral flood mapping. Hydrogeology Journal, 29, 1, 213–228.
- Savnik, R., 1960: Hidrografsko zaledje Planinskega polja.- Geografski vestnik, 32, 212–224.
- Shaw, T. & A. Čuk, 2015: Slovene karst and caves in the past.- Inštitut za raziskovanje krasa ZRC SAZU, pp. 464, Postojna.
- Šušteršič, F., 1996: Poljes and caves of Notranjska.- Acta Carsologica, 25, 251–290.
- Šušteršič, F., 1999: Speleogenesis of the Ljubljanica River Drainage Basin, Slovenia.- In: Klimchouk, A.B., Ford, D.C., Palmer, A.N. & W. Dreybrodt (Eds.): Speleogenesis: Evolution of Karst Aquifers. NSS, Huntsville, Alabama, 397–406.
- Šušteršič, F., 2002: Where does Underground Ljubljanica Flow?- RMZ Materials and Geoenvironment, 49, 1, 61–84.
- Šušteršič, F., 2006: Relationships between deflector faults collapse dolines and collector channel formation.- International Journal of Speleology, 35, 11–12.
- Vrabec, M., 1994: Some thoughts on the pull-apart origin of karst poljes along the Idrija strike-slip fault zone in Slovenia.- Acta Carsologica. 23, 155–167.

ABSTRACTS
IZVLEČKI

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

Listening to the Davorjevo abyss

Poslušanje Davorjevega brezna

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This study focuses on the analysis of spectral trends of the atmospheric pressure in the Davorjevo abyss, observed in natural and altered regime. Given external but internally detectable variations, the Davorjevo abyss can be described according to baric and microbaric behaviour. By applying the "FFT" algorithm to the internal pressure data and ignoring the variations related to the main components of the atmospheric tides and diurnal signal, two particularly large oscillations were detected, with a period of 2h40min and 3h25min, respectively. Assuming that these could be associated with the seventh and ninth harmonics of the diurnal signal, the two oscillations could be attributed to a particular external atmospheric resonance. Furthermore, by applying the FFT algorithm to the monthly pressure data, a monthly variation of the background noise was detected, which apparently results from the phases of the Arctic Oscillation and is represented by the AO index: during the positive phase of the polar vortex, the spectral peaks associated with the detected frequencies are clearly visible, while during the negative phase they are indistinguishable from the background noise. We tried to estimate the volume of the cave by artificially perturbing its internal atmosphere with a fan placed at the entrance that we switched on and off. However, after the forced air extraction, it has not been possible to maintain the atmospheric decompression of the abyss, probably because of unknown entrances. We also recorded the pressure variations caused by the shock wave generated by the eruption of the Polynesian volcano Hunga Tonga. It has not been possible to isolate a frequency referrable to a Helmholtz resonance by analysing internal pressure data after the artificial transient and the shock wave. However, the repeated application of artificial pressure transient could allow a future identification of peculiar resonant spectrum which characterized the abyss.

Key words: *pressure, harmonic, spectrum, transient*

Ključne besede: *tlak, harmoniki, spekter, prehodno*

Monitoring anthropogenic influences from spring to the ponor of the Pivka River, Slovenia

Monitoring antropogenih vplivov od izvira do ponora Pivke, Slovenija

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The Nanoščica River and the Stržen River are the main tributaries of the Pivka River before it sinks into the Postojnska jama. Along its 23 km long course, the Pivka collects water discharged from agricultural activities, settlements and two large wastewater treatment plants (WWTP), Postojna WWTP and Pivka WWTP. The influence of treated water from the WWTPs was monitored before and after discharge into the river body. Chemical and microbiological quality of the water was followed from June 2021 to March 2022. The discharge of the Postojna WWTP into the Stržen River had a great influence on the water quality. The sampling site after the discharge of the Postojna WWTP had the highest values for total microbial biomass measured as total ATP (5428 RLU), Escherichia coli (980 CFU/ml) and total heterotrophic bacteria (14050 CFU/ml). The highest nitrate value in the Stržen

River during this period was measured at the sampling point upstream of the Postojna WWTP (19.8 mg/l). Sulphates and chlorides were also high at the sampling site downstream of the WWTP, but the highest values were measured downstream of this site in the Pivka River (sulphates – 36.2 mg/l, chlorides – 196.6 mg/l). The quality of the Pivka River was also affected by point discharge from the nearby village, as indicated by the highest values for ammonium (5.9 mg/l) and enterococci (1520 CFU/ml). Regular monitoring should continue during different hydrological conditions, with the addition of more sampling sites to provide a more detailed spatial overview of the water quality of the Pivka River. A more detailed survey aimed at identifying point source pollution will provide the basis for protective measures for the river ecosystem and improvements in river management and sustainable land use.

Key words: *monitoring, water quality, wastewater treatment plant, pollution*
Ključne besede: *monitoring, kakovost vode, čistilna naprava za odpadne vode, onesnaženje*

3D mapping of connectivity between solution dolines and near-surface caves: case study Polina peč Cave

3D kartiranje povezanosti med vrtačami in jamami plitvo pod površjem: primer jame Polina peč

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Geoscience has been devoting increased attention to understanding the complex pathways and flows of material, energy, and the multidimensional coupling between various geological systems. Our main interest is to study the direct flows between enclosed karst depressions (solution dolines) and near-surface caves (up to 50 m below surface) that are prone to human influence. The doline-cave coupling zone represents the upper part of a karst aquifer for which specific connectivity characteristics between dolines and near-surface caves can be identified. Polina peč Cave (NW Dinaric Karst) was selected as a case study cave. We used geoinformatic methods (three-dimensional (3D) laser scanning) and available data (Registry of maps, Lidar DEM 1x1m, optical remote sensing data), geomorphometric analyse, speleological mapping and surveying. With precise georeferencing (using the GNSS system), we placed the 3D point cloud of cave in a geographical coordinate system, compared it with the surface above (using existing national aero-laser scanning data – Lidar DEM 1x1m), and determined dolines that are most directly connected to cave. Potential connections were detected and are the basis for further research by using additional hydrological (tracking) and geophysical methods (electrical resistivity tomography/ERT).

Key words: *connectivity, dolines, caves, 3D laser scanning, electrical resistivity tomography*
Ključne besede: *povezanost, vrtače, jame, 3D lasersko skeniranje, električna upornostna tomografija*

Hydrocarbon pollution in the karst system: first monitoring and bioremediation approach

Onesnaženje kraškega sistema z ogljikovodiki: prvi monitoring in pristop z bioremedijacijo

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The cave named "Caverna presso la 17 VG" (1423/4362VG) is located on the Trieste karst plateau (Italy) very close to the "Abisso di Trebiciano" (Jama Labodnica) (3/17VG). The cave is made up of a compartment almost all encumbered by a "lake" of hydrocarbons and polluting solvents resulting from decades of spills by oil companies in the past years. The caving club has started a chemical and microbiological monitoring project of the lake. The samplings were carried out in different areas of the lake plus a sampling of soil on the external shores. Dataloggers were positioned for continuous monitoring of temperature and humidity and the 3D survey was performed by laser scanner as well as fauna studies. The analyzes confirmed the high degree of pollution by heavy hydrocarbons. For organic compounds the analysis of the liquid sample (surface film in contact with air) reported extremely high concentrations of volatile solvents. Excluding the possibility of recent sources of pollution, the presence of these solvents in this system becomes extremely interesting. For the microbiological part, massive DNA sequencing of the various species found in the liquid / muddy / solid matrix was performed. It was possible to highlight the presence of 50 main taxa of which 23 described as capable of metabolizing hydrocarbons and therefore involved in the degradation of oil, an explanation of the presence of volatile solvents in the surface film. It is planned to proceed with the project which involves as experimental pilot field in the lake by increasing the number of bacteria already present capable of degrading the oil by introducing them from the outside or by selectively increasing the number of bacterial families already present in the cave with the consequent monitoring of bacterial species at the same time as the chemical behavior of the pollutants as bioremedion.

Key words: *cave, hydrocarbon pollution, microbiological bioremediation*
Ključne besede: *jama, onesnaženje z ogljikovodiki, mikrobiološka bioremedijacija*

How aerology and biocorrosion processes influence the morphologies of the galleries and the conservation of the archaeological remains in Mas d'Azil cave

Kako aeroologija in biokorozija vplivajo na morfologijo galerij in na ohranjanje arheoloških ostankov v jami Mas d'Azil

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In the last decade, the importance of condensation corrosion phenomena in the evolution of cave gallery morphologies is increasingly taken into account in cave studies. This is particularly the case in archaeological contexts, either for questions related to the taphonomy of cave art or for the understanding and the conservation of the paleo-environmental contexts that the caves could have recorded. These aspects become even more important with current or past presences of chiropteran colonies that will amplify, sometimes in an exponential way, the effects of the condensation corrosion on the morphologies of the cave. The bat colonies modify the local climatology of gallery by increasing the CO2 rate in the atmosphere and trigger the variations of the temperature due to their important presence, concentered in certain parts of the cavity, or by the productions of leachates and acid aerosols but also bacterial developments resulting from the guano and its decomposition Mas-d'Azil cave which engulfs the Arize river, is located in the SW of France, in the northern part of the Pyrenean mountains. The cave is more particularly known for many archaeological records from the Paleolithic period, studied from the end of the 19th century to present. The current strong presence of chiropteran colonies raises questions about the evolution of morphologies in some parts of the cave and the presence/absence of cave art in certain parts of the cave. An inventory of parietal morphologies is being carried out as part of the archaeological studies and is being continued with the high-definition description and study of remarkable points. In parallel, the monitoring of areological flows is undertaken to improve the understanding of the climatology of the different parts of the cave. For this, the continuous monitoring of temperatures provides essential observations of the phenomena implied and allows analyses and modeling of flows to establish thermodynamic profiles of the different parts of the cave. After the analyses of the data recording during a year, different modes of the cave aerology can be distinguished according the geometry of the cave network and the distance from the river. It is also possible to highlight phases of evolution of the cave with regard to processes such as condensation corrosion and its amplification by biocorrosion, which have been or are being carried out in the different parts of the galleries.

Key words: *cave climate, pyrenean karst, condensation-corrosion, biocorrosion, archaeology*
Ključne besede: *jamska klima, pirenejski kras, kondenzacijska korozija, biokorozija, arheologija*

Interactions among cave airflow, CO_2 dynamics, and speleogenesis

Interakcije med pretokom jamskega zraka, dinamiko CO_2 in speleogenezo

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In over a decade of field work, we have quantified calcite dissolution rates in a variety of cave streams and karst springs. This work demonstrated that CO_2 dynamics are a primary control on both the spatial and temporal variability in dissolution rates. Since ventilation patterns are a strong driver of subsurface CO_2 concentrations in karst, we also found that the strength, or direction, of ventilation can determine the rates and patterns of active cave dissolution. Here, we develop a new speleogenetic model that incorporates these processes. The model simulates the evolution of cave passage cross-sectional shape along a 1D stream profile. Tracking of the passage shape enables calculation of cave ventilation and coupled CO_2 transport within the air and water. Observations of the longitudinal changes in CO_2 concentrations and dissolution rates within Lekinka Cave, Slovenia, elucidated potential feedback mechanisms between stream morphology, CO_2 dynamics, and patterns of erosion. We use this model to explore the impact of such feedback mechanisms on longer timescales and show that they can produce chemically driven knickpoints within the stream profile. We also use the model to explore relationships between cave evolution and ventilation, finding that onset in cave ventilation can produce systematic changes in channel morphology.

Key words: *carbon dioxide, dissolution, speleogenesis, modeling, cave morphology*
Ključne besede: *ogljikov dioksid, raztapljanje, speleogeneza, modeliranje, jamska morfologija*

What determines airflow patterns in caves?

Kaj določa značilnosti zračnih tokov v jamah?

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Chimney effect is the most common driving mechanism of airflow in caves. The airflow is driven by the density difference between the external and the cave air. If the cave air column is on average denser then the outside atmosphere, the airflow goes from higher to the lower entrance (downdraft) and vice versa, if the outside atmosphere is denser, the result is updraft. But the *cave air* comes from the outside, and it takes some distance (*penetration length*) until it thermally equilibrates with the cave walls. The penetration length depends primarily on the on the hydraulic diameter of passage and less on the airflow velocity. To explore this phenomena and consequence of non-zero penetration length I present a numerical model which simulates airflow and heat exchange between the cave air and the surrounding rock mass. In a hypothetic case of constant temperature difference between the outside atmosphere and the karst massif, the airflow velocity drops exponentially with square root of time; if the air is colder than rock, the rock walls are cooled by the air and the penetration length increases, which reduces the density difference between the external and internal air columns. In case of more realistic diurnal and seasonal variation of external temperature, the result is hysteretic behaviour of airflow vs. temperature difference curves. If tube has smaller diameter in the proximity of one of the entrances, the penetration length will be smaller when the airflow enters at that entrance; for example, if the region at the higher entrance is smaller, the downdraft in warm period will be dominant and vice versa, the updraft will be stronger if passage at the lower entrance has smaller diameter. In a passage with non-uniform outline it is the density in the section with vertical changes that matters. As an example, in an L-shaped tube, the air will be closer to thermal equilibrium with rock in the vertical part during updraft, which makes the airflow in winter stronger. Non-zero penetration length also causes airflow in V-shaped systems; in fact, the system is unstable with strong airflow in cold periods even if the entrances are at the same altitude, and at rest in the warm period. The model can also be used to study how the presence of ice in the passages changes the airflow pattern. Ice may cause cold traps, unidirectional flow and other unusual phenomena.

Key words: *airflow in caves, chimney effect, heat exchange, penetration length*
Ključne besede: *zračni tok v jamah, učinek dimnika, izmenjava toplote, relaksacijska dolžina*

Get the elephant out of the room: Building a complete spatial database of karst distribution in Slovenia

Vrela kaša je ohlajena: Izgradnja baze podatkov o razširjenosti krasa v Sloveniji

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Slovenia is a country of the Classical Karst, a country with a rich history of karst research and a vibrant community of researchers and professional services that either deal directly with karst (e.g. speleology, karst geomorphology, speleobiology) or deal with phenomena or activities that take place in karst (agriculture, forestry). Therefore, there is a great need for a spatial database on the distribution of karst in Slovenia. Various studies on the distribution of carbonate rocks and karst in

Slovenia have been published in the Slovenian karstological, geographical and geological literature (Gams 1974, 1983, 2003; Habič 1982, 1993; Gabrovec 1994; Verbič 1998; Komac 2005; Rejec Brancelj & Zupan 2007, Verbovšek 2008; OneGeology-Europe 2010; Komac & Urbanc 2012, Gostinčar 2016, 2017). However, most studies were either published as small-scale maps or only consider areas where carbonate rocks occur - leaving out karst areas such as poljes, areas of covered karst, etc. The complete database of karst in Slovenia was created using surface geology data (Geological Map of Slovenia, scale 1: 100,000), taking into account the spatial distribution of dolines (Mihevc & Mihevc 2021), the location of cave entrances and the spatial location or lack of a surface hydrological network. In addition, the entire surface of the land was visually inspected on a Lidar-based shaded relief basemap. In total, over 12 thousand polygons were examined over an area of about 20 thousand square kilometres. Our analysis shows that karst occurs on 49.8% of the area of Slovenia: 26% limestone, 13% dolomite, 3% clastic carbonate rocks, 3% carbonate gravel, 2% of covered karst (mostly on alluvium), 2% on flysch and 1% on unconsolidated till. The spatial database is set up in a GIS environment and allows further use, expansion and revision by the interested public.

Key words: *Slovenia, karst, spatial distribution, spatial database GIS*
Ključne besede: *Slovenija, kras, prostorska razporeditev, GIS prostorska baza podatkov*

The diversity of crustaceans in subterranean karst waters in the world

Diverziteta rakov v podzemnih kraških vodah po svetu

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Incredibly numerous natural subterranean voids in the world potentially provide refuges and habitats for a remarkably high taxonomic diversity of aquatic cave animals. After more than two and a half centuries of considerable efforts in describing new cave species, the data on crustacean diversity of some Earth's regions with the potential aquatic subterranean environment is still missing. During the last decades, so much scientific research and biological surveys have significantly increased knowledge of the world crustacean stygofauna. After Stygofauna Mundi (Botosaneanu 1986), more than 300 new amphipod and isopod species have been described in aquatic cave habitats worldwide. The contributed research summarises the present state of knowledge on taxonomic diversity and species richness in the subterranean realm of the karst caves in the world. The present research covers a broad ecological and taxonomic range of crustaceans that inhabits the world's aquatic (freshwater, brackish, and marine) cave environment, with some examples of three types of biodiversity measures (α, β,γ) for some crustacean groups. More than 2000 named species and subspecies of obligate cave crustaceans from 26 orders confirmed the world's uniquely diverse and precious subterranean treasure. Amphipods dominate the obligate (stygobiotic) cave crustaceans with 39 families, more than 150 genera, and more than 750 species. The majority of the obligate cave inhabitants occurred in the karstic caves of North America and Europe. The total number of recorded and described obligate subterranean species among crustaceans is not a good reflection of species richness among biogeographical regions of the world but rather illustrates differences in taxonomic productivity and sampling effort between different regions.

Key words: crustacea*, stygobionts, cave habitats, karst subterranean waters, species richness*
Ključne besede: *raki, stiglobionti, jamski habitati, kraške podzemne vode, vrstna pestrost*

Practice guidelines for managing forest lands above karst caves in British Columbia (Canada): concepts and implementation challenges

Praktične smernice za upravljanje gozdnih zemljišč nad kraškimi jamami v Britanski Kolumbiji (Kanada): izzivi koncepta in izvedbe

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In British Columbia (BC), Canada's westernmost province, caves are defined as natural cavities large enough to admit a human and connecting to interior passages with zones of complete darkness. The mapped karst caves in BC meeting these criteria can reach 18 km in length and 674 m in depth. Caves throughout the province have many natural and cultural values and can be vulnerable to a wide range of anthropogenic pressures and climate change. Industrial forestry in BC is a widespread land-use activity, with the potential to alter cave environments. In 2004, the BC Government introduced a results-based regulatory framework for forestry and made legal orders to protect all karst caves from the damaging effects of forestry activities in six administrative districts. Under the results-based "freedom to manage" regime in BC, the forestry sector is expected to protect and manage caves with limited government oversight. Provincial practice guidelines published in 2003 recommend restricting certain surface activities: a) around cave entrances, b) over top of caves with thin ceilings, and c) on the surface area above caves projected at a 45° angle from the underlying cave passages. The approach to establishing reserves and management zones above caves varies based on passage depth and relative cave significance. We review the basic concepts and techniques that are the foundation of managing caves in BC, give examples of implementation challenges, and suggest ways to improve practice outcomes. Our research findings reflect that although the practice guidelines for karst caves are clear, important aspects and considerations are often overlooked or excluded from forest planning and decision-making. Finally, we compare BC's approach to establishing reserves and management zones over caves to those used in the analogous public forest lands in neighbouring Southeast Alaska (USA).

Key words: *karst, caves, forestry, Canada, British Columbia*

Ključne besede: *kras, jame, gozdarstvo, Kanada, Britanska Kolumbija*

Analysis of black deposits from Austroalpine caves

Analize črnih depozitov iz jam Avstroalpina

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In the Eastern Alps, black sediments in caves were described in 1913 and were first studied by Schauberger (1957). He interpreted the thin black layers, which cover clays and limestones in Hirlatzhöhle (Dachstein), as soot and reported a similar occurrence in the nearby Dachstein-Mammuthöhle. Schauberger assumed that the black layers derive from wildfires. Black crusts on cave walls were described from caves with active stream and were identified as microbial iron and manganese minerals. To date, no comprehensive study has been carried out for the black coatings on cave sediments in the Eastern Alps. The aim of this study is to characterise 42 samples taken from 12 karst-caves in Austria. Four types of black deposits can be distinguished: submillimetre thin, soot-like layers on top of clays and limestones; millimetre to few centimetre-thick crusts on walls of caves

with active stream, as well as palaeo-phreatic; submillimetre-thick crusts on boulders and flowstones; layers and lenses within clastic cave sediments or coatings of pebbles. Mineral composition was determined using X-ray diffraction (XRD), and total carbon (TOC) contents were analysed using a multiphase carbon and moisture detector. To constrain the presence of microorganisms, lipid biomarker analysis was performed. The lipids were analysed with a gas chromatograph coupled to a mass spectrometer. The soot-like layers show a TOC content of up to 18%. XRD allowed determination of minerals only from the clay layers below the black coatings. Detected biomarker did not include polyaromatic hydrocarbons like coronene, which are often used as evidence for wildfires, but included (bacterial) fatty acids and other bacterial compounds like hopanoids. Total Carbon content for most black crusts is approximately 1% or less with two exceptions reaching up to 9%. Some crusts consist of iron oxyhydroxides like goethite as well as manganese oxides (todorokite). Surprisingly, also hydroxyapatite was found in four samples, even though a significant contribution of bat excrement or mammal bones can be ruled out because of the remoteness of the locations. Most studied caves are several kilometres away from the entrance and several 100 m below the surface. Chemical analysis using ICP-OES of the bulk samples as well as extraction of oxides in oxalate and dithionite are ongoing and will hopefully give further insights into the diverse origins of black sediments in caves.

Key words: *black sediments, soot, iron-manganese oxides, black hydroxyapatite, microorganism*
Ključne besede: *črni sedimenti, saje, železovo-manganovi oksidi, črn hidroksi-apatit, mikroorganizmi*

Understanding regional hydrogeology, topography and vegetation assemblages as the key to interpretation of speleothem paleoclimate proxy records from mountainous regions; Trentino, Italian Alps

Razumevanje regionalne hidrogeologije, topografije in vegetacijskih združb kot ključ do interpretacije paleoklimatskih proksi-zapisov v kapnikih iz gorskih področij; Trentino, Italijanske Alpe

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Karst regions with well-developed soil and vegetation are favorable to speleothem development through the acidity provided by the soil CO_2 that leads to host-rock dissolution and, ultimately, carbonate precipitation in the cave upon degassing. By contrast, cool climates with little to no vegetation cannot supply infiltration waters with high-enough calcite saturation to form speleothems. High-altitude karst regions are, therefore, not conducive for speleothem development, yet, we find speleothems in caves at high-elevations. These speleothems are, however, often ancient and no longer actively forming; often testament to a period in the past where conditions for speleothem development were better than today. Here, we present speleothem proxy records from Cesare Battisti Cave (1880 m a.s.l.) and Bigonda Cave (370 m a.s.l.) in the Italian Alps. U-series dating shows the speleothems grew between 132 ka and 106 ka, during the Last Interglacial (LIG) period. Stable isotopes (δ13C and δ18O) and trace elements were used to reconstruct the state of the soil, the moisture source and rainfall amount. Moreover, a novel method allowed us to calculate the absolute temperature during the LIG period. However, for an improved understanding of the past

climate conditions, knowledge of the regional karst hydrology, geology and glacial history is required. This permits, for example, reconstruction of the source of trace ions, which can indicate infiltration pathways and the extent of past glaciers. Despite giving only short, interrupted records, speleothems in mountainous regions can provide a rich source of information for the reconstruction of past climates required to test climate models and, thus, aid the prediction of future climate. This is particularly important in mountainous regions where water supplies are diminishing and resource planning is urgently required.

Key words: *speleothems, palaeoclimate, last interglacial, stable isotopes, Italy*
Ključne besede: *kapniki, paleoklima, zadnja medledena doba, stabilni izotopi, Italija*

Hypogenic karst in Peninsular Malaysia – implications for active tectonics

Hipogeni kras na Malezijskem polotoku – posledice aktivne tektonike

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As part of the Sundaland block, the Malaysian Peninsula is considered tectonically stable. In search of features indicating tectonic activity, we studied karst features and associated hydrogeological regime of the Peninsula. Extensive features of hypogenic karst (scallops, lateral and ceiling niches, cupolas, ledges, pendants, windows, discharge slots, dykes, rift conduits, corrosion tables, notches) were identified. The host rock is Paleozoic to Triassic compact limestone. Cave fill is mostly Late Pliocene-Early Pleistocene Old Alluvium, locally containing tin placer deposits of economic value. Adjacent high-temperature, sulphurous thermal springs release water of 27 to 98°C. Chemical composition is mostly of the Na-Ca-(K) group. One-third of the springs have the odour of hydrogen-sulphide. Springs and karstified limestone are extending up to hundreds of metres above sea level. Thermal springs are arranged along a narrow NW-SE zone, mostly within limestone in the north and granite in the south. There is mountainous terrain to the east and an alluvial plain to the west. 24°C ground temperature plus 35°C/km average geothermal gradient adds up to 2-3 km minimum depth of the hydrothermal reservoir. The relatively low water yield of the springs indicates that open faults and/or karstic conduits guide thermal water to the surface. We suggest that fossil (Early Quaternary) hypogenic karst is the surface evidence for ongoing hypogenic processes in depth. The instrumental seismicity of the Peninsula is minimal; there is no historical record of earthquakes. However, the linear arrangement of high-temperature springs in 750 km length along the west coast of the Peninsula suggests that open, therefore, active faults exist.

Key words: *hypogenic karst, thermal water, Malaysia, tropics, active tectonics*
Ključne besede: *hipogeni kras, termalna voda, Malezija, tropi, aktivna tektonika*

Planning of the new railway line from the top of the Classical Karst plateau to the Port in Koper has ended, construction has begun

Načrtovanje nove železniške proge od začetka Kraške planote do Koprskega pristanišča je zaključeno, začela se je gradnja

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We, researchers from the Karst Research Institute, closely collaborated with the project designers for over a decade as they planned the new railway line between Divača and Črni Kal; we have summed up our scientific findings at the closure of two multi-annual projects. During our research work, we arrived at several fundamental conclusions that will make the jobs of construction workers much easier. When siting the route, we discovered that it crossed one of the larger known water caves at a contact between the carbonates and flysch, and that in its vicinity the groundwater table was occasionally higher than the railway line. That is why we moved this section of the route away from the area with known cave passages and envisaged the design of a non-draining tunnel with potential bypass water tunnels. By conducting several tracer tests of groundwater, we greatly contributed to our knowledge of the water flow in this part of the Classical Karst and the cross-border aquifer between Slovenia and Italy, and demonstrated the importance of protecting the karst aquifer. By studying the karst terrain and taking into account all the karstological data known so far, we predicted the number of caves and the largest diameters of cave passages for individual sections of the route of the railway line. Based on these findings, the decision was made to build the tunnels using the NATM method instead of the TBM method. Now that construction has commenced, NATM has proved to be the right choice.

Key words: *railway line planning, Classical Karst, Slovenia*
Ključne besede: *načrtovanje železniške proge, Kras, Slovenija*

Assessment of the water balance of the karst aquifer in the catchment area of the Malenščica spring

Vodna bilanca kraškega vodonosnika v prispevnem območju izvira Malenščice

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Karst aquifers can be quite complex in terms of their structure and water flow. In order to properly characterise them and better understand their functioning, it is necessary to continuously monitor them at various points, such as springs, ponors, water-active caves and surface streams. The Malenščica karst spring is one of the most important water sources in Slovenia, supplying water to more than 22,000 people. The binary karst aquifer covers an area of almost 800 km2 and is fed by both an allogenic and an autogenic component, which may vary depending on hydrological conditions. The allogenic inflow makes the water resource highly susceptible to contamination at medium to high flows. On the other hand, an estimate of the volume of autogenic water available at low flow is crucial for water supply. To better understand these relations, the water balance and its dependence on hydrological conditions were assessed. A monitoring network of autonomous data

loggers was set up in autumn 2016, measuring water pressure and temperature at 30-minute intervals at various points in the aquifer. In the context of the water balance calculations, data from two streams at ponor zones as the input to the system, one nearby spring, which is recharged from almost the same catchment, and two points in a water-active cave within the aquifer were used. Based on occasional manual discharge measurements at these points the rating curves were produced and discharge time series for the period from October 2016 to November 2021 were obtained. Discharges of the Malenščica spring were measured by the Slovenian Environment Agency. The quantification of the discharge components enabled the assessment of the water balance and its dependence on hydrogeological conditions. Additionally, the influence of different recharge type and relationships between recharge and discharge were evaluated and possible trends identified. The results improve the current understanding of the studied aquifer and show the importance of considering temporal variations of the catchment area in hydrogeological studies. The results can further be used for risk assessment of the karst aquifer and for strategies to protect drinking water sources.

Key words: *karst aquifer, autonomous measurement, discharge measurements, water balance, hydrologic variability*

Ključne besede: *kraški vodonosnik, zvezne meritve, meritve pretokov, vodna bilanca, hidrološka raznolikost*

Phreatic overgrowths on speleothems (POS) as indicators of relative sea-level change along the eastern Adriatic coast

Epifreatični sigovi prerastki (POS) kot pokazatelj relativnih sprememb morske gladine vzdolž vzhodne Jadranske obale

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Phreatic overgrowth on speleothem (POS) is a secondary depositional structure (carbonate phreatic encrustation) which precipitates at the water table around pre-existing vadose speleothems if favourable geochemical conditions are acquired. Since the POS precipitate at the very top of the water column, i.e. at the water-air interface, their occurrence is limited to a very narrow band of the tide-induced groundwater level fluctuation. POS can be precisely dated with U-Th as well as with radiocarbon method. The combination of their narrow occurrence, datability, and preservation makes POS an excellent sea-level indicator. So far, it has been used in sea-level research in only several locations in the world while most of the investigated sites are located in Mallorca. Recently, within the project SEALeveL (HRZZ-IP-2019-04-9445) funded by Croatian Science Foundation, phreatic overgrowths on speleothems (POS) have been discovered in Croatian coastal caves. Since the POS investigation is the first of that kind in the Adriatic, information on their morphology, conditions and time of deposition, will contribute to a better understanding of the POS as sea-level indicator and will allow comparison with results from other parts of the Mediterranean basin. Here, we present the preliminary results of U-Th dating, XRD and XRF analyses of POS samples from Šipun Cave (Cavtat, southern Dalmatia) and Medvjeđa špilja Cave (Lošinj island, Kvarner region). POS from Lošinj Island provides evidence on few hundred years of relative sea-level stability 1 m below the modern mean sea-level at 3000 years BP.

Key words: *cave, phreatic overgrowth on speleothem (POS), sea-level, Croatia, eastern Adriatic*
Ključne besede: *jama, epifreatični sigovi prerastki (POS), morska gladina, Hrvaška, vzhodni Jadran*

Changes in CO_2 and ^{222}Rn concentrations in cave environment – Modrič Cave (Croatia) case study

Spremembe koncentracij CO_2 in ^{222}Rn v jamskem okolju – primer iz jame Modrič (Hrvaška)

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Caves are located within the Earth's Critical Zone (ECZ), which is marked by intensive interactions between atmosphere, biosphere and hydrosphere. Temporal changes in these interactions can be recorded in cave sediments (i.e. speleothems) which led to caves and cave sediments being extensively used in various palaeoenvrionmental and palaeoclimatical studies. Within those researches, the need for long-term environment monitoring emerged as a necessity. Furthermore, monitoring programmes have also provided valuable data for show caves' sustainable management. We present the results of ongoing continuous measurement of CO_2 and ^{222}Rn concentrations in the Modrič Cave (Croatia), a relatively small show cave located at the foothills of the Velebit Mt. near Adriatic coast at 32 m a.s.l. It is a simple cave with two mainly horizontal passages with total length of 829 m. Previous monitoring campaigns in the Modrič Cave with monthly and seasonal resolution showed strong seasonal changes in CO_2 concentrations with two distinctive seasons: summer/autumn with the highest, and winter/spring with the lowest values. The ^{222}Rn concentration in the cave air follows spatial and temporal patterns similar to the CO_2 concentrations. Monitoring data also showed significant differences in cave air CO_2 and ^{222}Rn concentrations between the two main passages. The diverse features of the two passages can explain these differences as the wider left passage is well ventilated in comparison to the more constrained right passage. The continuous logging of cave air CO_2 and 222Rn launched in 2021 provided high-resolution data, which revealed sudden variations in both CO_2 and ^{222}Rn concentrations that had not been detected in the previous campaign as they occur on smaller time scales. Apparently, these peaks concur with intensive rain events indicating more dynamic cave atmosphere system than previously thought, which will affect future (palaeo)environmental studies in this cave.

Key words: caves, monitoring, CO_2, radon, Croatia
Ključne besede: *jame, monitoring, CO_2, radon, Hrvaška*

Dissolution-precipitation experiments in Postojna cave (Slovenia) using limestone tablets and SEM techniques

Opazovanje raztapljanja-odlaganja kalcita v Postojnski jami (Slovenija) z uporabo apnenčastih ploščic in vrstičnega elektronskega mikroskopa

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Carbonate tablets have been widely used in karst systems to evaluate natural dissolution, measuring the mass difference before and after exposure to the field environment. However, this method often

require long time periods of exposure to gain meaningful results, and the procedure of cleaning, drying and weighing of rock tablets may be challenging. For the study of dissolution and precipitation processes in shorter periods of time we have developed a method that examines polished limestone tablets under a Scanning Electron Microscope (SEM) before and after exposure to natural and experimental conditions. This approach was designed to understand the formation of very peculiar cylindrical dissolution features ("corrosion cups") in Pisani Rov, a chamber in Postojna cave with very high air CO_2 concentrations. Resin-encased polished limestone tablets were observed under SEM in exactly the same points before and after being placed in the cave for periods up to 28 weeks, showing significant differences in the rock surface after just six weeks. The insoluble resin was used as a reference surface for quantitative estimations, comparing it with the surface of the rock after exposure via a 3D SEM stereoscopic reconstruction. To assess the possible role of microbes in the dissolution and precipitation processes, limestone tablets were polished and sterilised and some of them inoculated with microorganisms collected from the corrosion cups. After incubation in the lab at different conditions, inoculated tablets and sterile controls were observed under SEM, showing both dissolution and precipitation of carbonate associated with the microorganisms and their EPS. These methods have demonstrated their use in identification and quantification of carbonate dissolution and precipitation at micro-scale in a short time-frame. In addition, this SEM-based techniques can be combined with other methods for calculating dissolution rates and the tablet construction can be easily modified to suit different research aims. Acknowledgements: this work was financially supported by the Slovenian Research Agency (ARRS) through the projects J1-9185 and L6-9397.

Key words: *rock tablets, carbonate dissolution, SEM, microbial-mineral interactions, cultivation experiments*

Ključne besede: *apnenčaste ploščice, raztapljanje karbonatov, vrstični elektronski mikroskop, mikrobiološko-mineralna interakcija, gojitveni poizkus*

Changes in the hydrogen sulfide content of Hévíz thermal lake - an interplay between chemistry and flow

Spremembe koncentracije hidrogensulfida v termalnem jezeru Heviz – igra med kemijo in tokom

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Lake Hévíz is the largest thermal lake in Europe, fed by a spring cave at a depth of almost 40 meters. The cave contains a cluster of separate springs, each discharging water of different temperature and composition. The mixture of these waters enters the lake through the narrow cave mouth, creating a circular flow bringing the hot thermal water to the surface while pulling the cooler surface water towards the bottom of the crater-shaped lake bed. The water of the lake has a curative effect on various rheumatic diseases. The healing power of thermal water is partly attributed to its dissolved hydrogen sulfide content. By the end of the 1980s decades of mining activity caused a significant decrease in the karst water levels around Hévíz lake. The discharge of the springs nearly halved, and the water temperature dropped. The cessation of mining activity in the 1990s led to an increase in karst water levels. Despite of the restoration of the original discharge and temperature, the decrease of the hydrogen sulfide content was detected in the lake recently. During the years 2021 and 2022 several sampling campaigns were performed by cave divers in the spring cave and the lake. Determination of the different sulfur species in the collected samples allowed us to establish the equilibrium between the reduced and oxidized forms of sulfur. Regular observation of the current pattern in the lake and the installation of flow monitoring devices showed that oxygen rich waters

are drawn from the surface directly to the mouth of the cave, where the oxidation of the sulfur happens within a very short distance. The decreased sulfide content in the lake is not the consequence of the changing chemistry of the springs, but the altered flow in the lake itself - caused probably by the recent reconstruction of the shores.

Key words: *karst water, Lake Hévíz, hydrogensulfide, thermal cave*
Ključne besede: *kraška voda, jezero Heviz, hidrogensulfid, termalna jama*

Geochemical tracing of coin counterfeiting during Middle Ages in Koněprusy caves

Geokemično sledenje ponarejanja kovancev v srednjem veku v Konepruških jamah

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A medieval legend recounted in the countryside of central Bohemia mentions a dwarf sitting in a cave giving a present of silver coins to a poor herdsboy. About half of millennium later, the Koněprusy cave complex was discovered in the Bohemian karst by chance. In the upper part of cave complex, the “Mint”, money forgers’ secret workshop, was operated. Archeological research of the Mint revealed coppaer semi-finished coins and equipment used for money forging in 1958. The mintage was dated to the period 1465-1470. One of the archeological research objectives was to clarify whether the silvering process of the copper coin bases, was the technique based on evaporating the metallic mercury from silver amalgam from the surfaces of copper circles. This hypothesis was tested by geochemical prospection in the Mint focused on detection of contamination with mercury (Hg). Cave sediments, including sinters, calcites and cave clays, were sampled in various parts of the Koněprusy cave complex. The Mint and surrounding area were contaminated with Hg, with the highest concentration of 1940 µg Hg/kg. Background levels from uncontaminated cave areas averaged at 10 µg Hg/kg. The distribution of Hg contamination in the cave was heterogenous, suggesting a smoke-driven movement of evaporated Hg0 along chimney fissures. Mercury contamination was predominantly associated with clay materials, whereas cave sinters were uncontaminated. In-situ analyses documented ongoing Hg release from the contaminated spots. The highest air Hg0 concentration was 8.0 ng/m3, while the mean background concentration was 1.9 ng/m3. Thus considerable amounts of Hg must have been manipulated in the cave area, further supporting the hypothesis of silvering in fire within the Mint. Hence, the geochemical research of the Mint confirmed the part of legend telling about the counterfeiting the coins in the caves.

Key words: *mercury, Czech Karst, amalgam, silvering in fire, geochemical archive*
Ključne besede: *živo srebro, Češki kras, amalgam, posrebrenje v ognju, geokemični arhiv*

New insights on the water balance of Planinsko Polje (Slovenia)

Nova spoznanja o vodni bilanci Planinskega polja (Slovenija)

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Planinsko Polje is located about 30 km SW from Ljubljana (Slovenia) and belongs to the north-westernmost part of the Dinaric Karst. This polje is considered as a typical overflow polje due to its hydrogeological characteristics. The inflow is provided by a set of several springs located in the S and W, while the two main outflow zones are found on the polje E and N margins. Finally, an important estavelles group is located on the polje northwestern border, contributing to both inflow and outflow. The flow of the two main springs is recorded at the gauging station Unica – Hasberg, in the polje southern parts. This station is not the most appropriate, as important uncertainties occur in its rating curve as soon as the polje becomes flooded. In addition, as the contribution of all other inflows is not taken into account due to technical difficulties to measure them, the total amount of flow entering in the polje during the flood is underestimated. This work aims refreshing the water balance of Planinsko Polje in light of modern monitoring techniques. To do so, a network of several water level stations is installed on the polje surface and in the nearby water-active caves. Combining a Lidar dataset with recorded water levels and inflow of the main two springs made possible to evaluate the polje flooding dynamics and to characterize its water balance more precisely. The method estimated the polje total inflow and outflow, while the main ungauged signals were identified and separated. These values are used in a numerical model to reproduce the flood dynamics. Modelling results validate the water balance, and justify the significance of installing a network of several hydrological stations to monitor the floods. The method can be applied to other poljes flooding in a similar way.

Key words: *Planinsko Polje, Slovenia, flood, water balance, modelling, inflow reconstruction*
Ključne besede: *Planinsko polje, Slovenija, poplava, vodna bilanca, modeliranje, rekonstrukcija pritoka*

Cave sediment analysis of Molnár János Cave – Hungary

Analize jamskih sedimentov v jami Molnár János – Madžarska

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Sediment deposition in a cave represents historical processes that can be studied to better understand the climatic and landscape evolution of the area, including past local and regional environments. In caves, sediments are preserved based on their environmental conditions, making them a good source of historical data. The Molnár János Cave (MJC), located in Budapest, Hungary, is considered a hypogenic cave, isolated from large-scale interference from the surface. Since the cave is supposed to be formed by mixing corrosion, and we can observe only extreme low flows in the submerged cave passages, we expect that the sediments are composed of the dissolution residues from the rocks in the vicinity. However, our preliminary investigations found that at some sample

sites the sediment is not chemically similar to the rock dissolution residues. We noted that some sites display a layered sediment structure indicating a periodically changing flow in the past. The presence of a very fast flow can also be postulated from the large average size of the sediment particles in some layers. The presence of these flows in the past extends our knowledge about the formation of the cave and opens the possibility that the sediment samples carry historical information from the surface conditions at the time of deposition. Our study focuses on the composition of the sediments, as a historical record of the evolutionary processes that formed one of the largest active hydrothermal caves in the world and the environmental changes above the cave.

Key words: *sediment, cave landscape evolution, cave flow, physical and chemical analysis*
Ključne besede: *sediment, razvoj jamske pokrajine, jamski tok, fizikalne in kemijske analize*

Evaporite minerals suggesting marine submergence of a stalagmite from Kvarner region (Croatia)

Evaporitni minerali kot namig za potop stalagmita v Kvarnerskem morju (Hrvaška)

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We present the preliminary results of mineralogical analyses of submerged speleothem collected within the project SEALeveL (HRZZ-IP-2019-04-9445) funded by Croatian Science Foundation. The ML-12 stalagmite was collected 12 m below the water table in a submerged coastal cave on Lošinj Island. Several orange layers are visible on the longitudinal cross section of the stalagmite. A thin section was prepared for investigation by petrographic and scanning electron microscope (SEM) equipped with an energy dispersive spectroscopy (EDS) system. Prior to SEM analysis, the freshly-cut surface was also analysed by X-ray fluorescence (XRF) analysis. Oil was used for thin section preparation to avoid dissolution of highly soluble minerals. Optical inspection shows reduction in crystal size and relatively high porosity within the orange-coloured layers indicating a change in the depositional environment. XRF analysis shows the presence of chlorine, sulphur and silicon bearing minerals in these orange layers but not in the clean calcitic parts. SEM inspection shows the presence of several minerals in the pores within these orange layers. Chemical composition obtained by EDS analysis suggests that these minerals are quartz, halite, gypsum, muscovite, hematite, and an unidentified phosphate. Especially halite, but also gypsum are highly soluble minerals that are abundant in solute form in the sea. This indicates that the sea might have played a key role in the speleothem formation environment and deposition of the minerals found in the orange layers. The occurrence of the latter might have been controlled by sea-level oscillations. Further analysis is necessary to confirm such hypothesis.

Key words: *speleothem, sea-level change, Quaternary, Adriatic Sea*
Ključne besede: *kapnik, spremembe morske gladine, kvartar, Jadransko morje*

Karst groundwater biodiversity and habitats. Building in-situ virtual laboratories to assess the ecology of Proteus anguinus and its subterranean habitat throughout data platforms

Biodiverziteta kraške podzemne vode in njeni habitati. Vzpostavitev virtualnih laboratorijev »in-situ« za oceno ekologije *Proteus anguinus* in njenega podzemnega habitata, s pomočjo podatkovne platforme

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Karst areas are among the world's landscapes most affected by environmental pollution. Most of the pollution in karst areas is due to unsustainable anthropogenic activities (intensive agriculture and industry, unregulated urbanization), which are reflected in the decline of subterranean biodiversity and loss of drinking water resources. Slovenia is particularly vulnerable in this regard, as it is a prime hotspot of subterranean biodiversity, while its groundwater provides 99% of its drinking water needs. Slovenia thus faces urgent biodiversity conservation challenges, and among the critically affected organisms is the olm (Proteus anguinus) - a global symbol of endangered subterranean biodiversity. Given the vulnerable and difficult-to-access environment, karst scientists need new, non-invasive technologies to monitor and assess the current conservation status of subterranean species and their habitats. One of the most appropriate approaches for meeting this need is based on virtual laboratories (vLabs), currently most suitable platforms for integrating and linking AI and media technologies, life sciences, and research data. A Slovenian and Belgian multidisciplinary research team plans to set up two virtual laboratories dedicated to assessing the subterranean biodiversity and their karst habitat: ProteusWatch vLab and Karst Groundwater Habitats vLab. The two envisioned vLabs, the first of their kind within a karst environment, will complement each other with data on behaviour of proteus (monitored via IR video cameras and imaging sonar) and correlated to the sensed changes in its groundwater habitat (e.g., pollution levels, meteo events - flooding). The research aims to monitor groundwater biodiversity and its habitat having a direct benefit to advancing the state-of-the-art in this research domain (24/7 monitoring, advanced video tracking, standardized FAIR data and machine learning to analyze data, and to minimize the human presence in the cave) as well as an indirect impact on our conservation efforts to preserve proteus in the wild.

Key words: *virtual laboratory,* Proteus anguinus*, karst, cave biodiversity, FAIR data, research infrastructure*

Ključne besede: *virtualni laboratorij,* Proteus anguinus*, kras, jamska biodiverziteta, podatki FAIR, raziskovalna infrastruktura*

The hydroclimate variability in the coastal levant from speleothem records: a synthetic review on the LIG & PIG and new perspectives

Spremenljivost hidroklime v obalnem levantu iz kapniških zapisov: sintetični pregled LIG in PIG ter nove perspektive

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The Levant region, known for its long history of human settlement, face nowadays drier climate in the context of global warming. Water & food availability have been, & still are, major factors influencing the complex social & political situation. In this region with strong North-South & East-West topography, temperature & precipitation gradients, subtle changes in regional climate patterns may induce changes over short spatial & temporal scales. In the last 30 years, several studies in the coastal Levant using marine & terrestrial palaeoclimate records, revealed a complex climatic pattern, more particularly distinct N-S differences in precipitation variability. In a region where a drier climate is expected, a robust reconstruction of past precipitation patterns even on local scales, is important to understand future water stress. Hence, the Levant is an ideal region to study the impact of climate as one of the potential factors influencing societal change. Speleothems, which form by cave dripwaters (rainwater - water lost by evapotranspiration) are karst archives that recorded G-IG changes, past decadal to millennial variations as well as episodes of sapropel development, linked to increased freshwater influx from the Nile River. In the latter case, the $\delta^{18}O_{spel}$ show good agreement with $\delta^{18}O_{marine}$ records from the East-Mediterranean, a source region for rainwater. Besides source variations, lower $\delta^{18}O_{spel}$ values are also suggested to be linked to higher amounts of rainfall. Changes in the $\delta^{13}C_{spel}$, depend on several factors, including C3/C4 vegetation changes & the contribution of soil CO_2. The latter is controlled by the vegetation activity & soil development, & consequently by the contribution of soil CO_2 relative to that derived from the host rock. In southern Levant, soil activity & subsequent soil CO_2 contribution is more directly linked to precipitation amounts than to temperature. This talk, synthetizes palaeoclimate data for the Holocene & Last interglacial intervals recorded in speleothems from northern Levant: Pentadactylos from Cyprus; Jeita, Kanaan caves & lately Qadisha cave located at higher altitude from Lebanon. These sets of records are compared to other datasets in the coastal Levant.

Key words: *speleothems, Levant, stable isotopes, gradient, paleoclimate*
Ključne besede: *kapniki, levant, stabilni izotopi, gradient, paleoklima*

Effects of air temperature on extensometer micro-displacement measurements in caves

Vpliv zračne temperature na ekstenziometrske meritve mikro-premikov v jamah

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Active tectonics monitoring in Slovenian caves, via quantification of micro-displacements with TM extensometers began in 2004. At present there are 9 monitoring sites in natural and artificial cave environments throughout Slovenia, of overall 12 instruments. The scope of this study is to evaluate the effects of air temperature fluctuations on the micro-displacement measurements in two caves, Postojna cave and Sveti Trije Kralji cave. Both monitoring sites are located within the moderately active Dinaric Fault system in western Slovenia. Each site is situated in the proximity of an active regional fault, Postojna cave to the Predjama fault and Sveti Trije Kralji cave to the Ravne fault. Micro-displacement monitoring in Postojna cave began in 2004, the Sveti Trije Kralji cave began in 2012. Sveti Trije Kralji cave was discovered during construction of a tunnel in a system of military fortifications along the Yugoslav-Italian border during the Interwar period. The artificial tunnel with three entrances transects the natural cave which has no other recorded entrances. As the extensometer monitoring site is positioned at the transection of the artificial tunnel and the natural cave, the instrument is exposed to the seasonal climatic fluctuations. That are larger than the climatic stable extensometer monitoring sites in Postojna cave. Thermal expansion of the instrument due to the seasonal climatic fluctuations in Sveti Tri Kralji cave is clearly evident from the micro-displacement records, whereas they are not present in any micro-displacement record in Postojna cave. Cave climates are considered to be stable and thus provide a reliable environment for micro-displacement monitoring. Study is performed within the programme Karst Research (P6-0119), doctoral thesis of U. Novak (2020-2024), all financially supported by the Slovenian Research Agency and project operation "Development of research infrastructure for the international competitiveness of the Slovenian RRI space – RI-SI-EPOS" and Horizon 2020 project EPOS SP.

Key words: *micro-displacement, TM extensometer, cave air temperature, karst active tectonics, Slovenia*
Ključne besede: *mikro-premiki, TM ekstenziometer, jamska temperatura zraka, aktivna tektonika, Slovenija*

Comparison of optical methods to generate 3-D models in order to quantify processes in a frost weathering cave

Primerjava optičnih metod za izdelavo 3D modelov za količinsko opredelitev procesov v jami z zmrzalnim preperevanjem

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The use of optical methods such as Terrestrial Laser Scanning to acquire 3D models is common practice in geoscience research for detailed geometric analyses of structures or observing deformation processes. Morphological changes can be detected and monitored using various optical techniques, depending on the object's scale and complexity as well as the lighting conditions. The scientific question determines the required resolution and thus the choice of method. In addition, the financial resources influence the decision, especially when it comes to repeated monitoring. Frost weathering on rock walls results in the separation of fragments from sub-millimeter to meter size. During a field study in a frost weathering cave in eastern Austria, fragments ranging from sub-millimeter to decimeter size have been observed. In order to capture the effectiveness of frost weathering as a speleogenetic process, a quantification of the fragment's accumulated volume or the volume increase of the cave is crucial. To find out whether the change in surface morphology and the volume change of a frost weathering cave can be detected with optical methods, three methods for creating a 3D models were compared: A Terrestrial Laser Scan, a Handheld Laser Scan and Structure from Motion were used simultaneously during several visits some months apart. The objective was to find out the resolution limits of the different methods for this specific application in order to be able to detect, ideally even small spatial changes in short time intervals.

Key words: *optical methods, 3D model, point cloud processing, frost weathering*
Ključne besede: *optične metode, 3D model, obdelava oblaka točk, zmrzalno preperevanje*

Speleohydrology and climate change

Speleohidrologija in klimatske spremembe

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The topic of climate change is one of the fronts of scientific research in the 21st century. A special focus of speleological research is the discovery of records of climate change in caves. However, the question arises as to the impact of climate change on the conditions of speleological research and on the hydrological dynamics in karst. Extreme weather conditions around the world have become more frequent. That is why we need to define new standards of speleological research. New recommendations to the speleological community should include methods for monitoring, collecting and analyzing climate data for risk assessment purposes. Analyzes of hydrological extremes and other climate-related processes in karst and caves are of interest to the wider community. We will highlight examples from the Dinaric Karst in Croatia (deep pits, hydrologically active caves, caves with ice).

Key words: *speleohydrology, climate change, extreme weather, Dinaric Karst*
Ključne besede: *speleohidrologija, klimatske spremembe, ekstremne vremenske razmere, dinarski kras*

Ice in caves: questions and no answers

Led v jamah: vprašanja brez odgovorov

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Ice deposits in caves have been first recorded more than 700 years ago and extensively and intensively studied since the early 20th century. A wide body of knowledge on ice caves has accumulated in the past two decades; however, many more questions than answers have also surfaced. Importantly, these are linked to the "fundamentals" of ice cave research, thus making studies addressing them both necessary and thrilling (for those doing them, at least). Thus, the main issues we encountered would be: how old could ice accumulations in cave be? Which are the climatic conditions most favorable for their inception? How does climate variability control ice mass balance in caves? Is cave morphology or climate the most important factor in the dynamics of ice? What does actually the age of a particular ice layer tell us? Is it the age of ice or that of a melting event? Are

paleoclimate proxies archived in ice reliable? We present here these research questions, a few potential answers and several avenues to be followed upon to stimulate future research.

Key words: *ice caves, morphology, climate, questions*
Ključne besede: *ledene jame, morfologija, klima, vprašanja*

Karst and caves along excavated part of the T1 railway tunnel in the SW Classical Karst

Kras in jame vzdolž izkopanih delov T1 železniškega predora na JZ delu Krasa

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Construction of more than 6-kilometers-long railway double-tube tunnels T1 and T2 between Divača and Koper (2TDK) almost entirely through limestones is an excellent opportunity to get insight into the vadose and epiphreatic zone of the SW Classical Karst. Primary goal of the Karst Research Institute is to explore, survey and document all accessible caves discovered during construction. In addition, caves are 3D scanned either manually using Disto X2 or automatically using professional 3D scanner, positioned into the national geodetic coordinate system and compared with tunnel route to propose cave protection, geo- and hydrotechnical measures. Speleogenetic evaluation mainly involves definition of general speleogenesis (vadose/phreatic), hydrological and meteorological conditions. Where cave protection measures are impossible due to tunnel route, scientifically or educationally important speleothems are taken out from caves. Additional karstification data are provided by geotechnical supervision, borehole and surface GPR. Until now, 600 m of main and the same length of service tube are excavated so far with 11 newly discovered caves. This results in surveyed cave density of ten per kilometer of excavated tube. The number of smaller registered but not surveyed caves is at least one time higher. Six caves are classified as vadose by origin and five as phreatic. As expected, phreatic passages are usually altered in vadose conditions that make definition of initial origin of cave passages uncertain. Two phreatic passages (in the caves 2TDK-009 and 2TDK-014) had extra ordinary diameter of about 7 m; however, they were accessible for only several tens of meters due to collapsing from a vadose part of the cave. In nearly all caves, direct connection with the surface (troglophiles, charcoal) has been noticed to the depth of at least 70 m although natural entrances are not known so far. In one cave (2TDK-009), connection with bowl-shaped doline through collapse material was evident. Only two cave passages (2TDK-009, 2TDK-016) have been developed along bedding planes while initiation of the others is related to (sub)vertical faults and fractures.

Key words: *caves, limestone, speleogenesis, tunnel, railway*
Ključne besede: *jame, apnenec, speleogeneza, predor, železnica*

Biotechnological potentialities of spore-forming bacteria isolated from deep cave ecosystems in North Africa

Biotehnološki potencial sporulirajočih bakterij izoliranih iz globokih jamskih ekosistemov v severni Afriki

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With the discovery of numerous caves on planet Mars and the exploration of different types of caves on Earth, the interest and use of cave microorganisms has increased significantly during the last years. Hence, the purpose of this study is to present the first novel data on the presence of culturable, spore-forming bacteria in 10 different caves in Algeria, at depths down to 450 m. Two hundred fifty spore-forming isolates were obtained and their probiotic potential was tested with different methods (pathogenicity, growth at 37°C, survival in gastric juice and simulated intestinal fluid, antibiotic sensitivity, presence of digestive enzymes such as ⍰-galactosidase and gliadinase). 13 of these tested strains (affiliated either to Bacillus or Paenibacillus, according to 16S rRNA analyses by FISH and gene sequencing) showed a rich spectrum of enzymatic and probiotic potential. These strains and their enzymes may therefore serve as useful candidates for future research in food processing and in reducing the effect of digestive disorders. These findings also suggest that novel strains with biotechnological potential can be discovered in pristine, subsurface ecosystems.

Key words: *subsurface, cave geobiology, probiotics, spore-forming bacteria, Bacillus, Paenibacillus*
Ključne besede: *podzemno, jamska geobiologija, probiotiki, sporogene bakterije,* Bacillus, Paenibacillus

On microlocation of the Koper bay submarine sulphur springs: a small correction makes a crucial difference again

O mikrolokaciji podmorskega žveplenega izvira v Koperskem zalivu: ko manjši popravek ponovno privede do ključne razlike

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In the Slovenian part of the Gulf of Trst/Trieste, submarine springs occur as funnel-shaped depressions in the Holocene sand-silt marine sediment that forms the flat seafloor. These springs have elevated temperatures (up to 29.6°C) and high sulphur content. Based on their location, they are divided into three clusters: Izola cluster (3 springs), Bele skale cluster (2 springs) and Ronek cluster (6 springs). Already earlier these springs were connected to the geological structure of the area, which is characterised by an Izola anticline. Practically the entire Slovenian coast is marked by a thick sequence of Eocene flysch deposits. In the core of the Izola anticline, the underlying Eocene limestone outcrops. We propose that sulphur groundwater originates from a deep source, springs from the limestone (karst springs), and occurs at the stratigraphic boundary between limestone and flysch in the nearshore area, where the sedimentary cover of Quaternary deposits is thin enough to be washed out. According to existing data, the axis of the anticline NW-SE directed and the Izola

cluster lies approximately on the seaward extension of the axis. Therefore, this interpretation fits perfectly for the Izola cluster, while the other two clusters are completely off-axis extensions and require reinterpretation. The observation of flysch beds on the cliff between Izola and Strunjan led to the hypothesis of another anticline near Cape Ronek, which would be parallel to the Izola anticline. In order to confirm this, we conducted a detailed sedimentological study of the flysch deposits and geological mapping. The investigations revealed that: A) limestone outcrops occur only in the town of Izola, B) two prominent calciturbidite megabeds occur in the flysch, allowing for very detailed geological mapping, and C) there is no additional anticline in the vicinity of Cape Ronek, but dip of beds is uniform from Izola towards Cape Ronek (this discouraged our hypothesis). However, our research revealed that the axis of the Izola anticline is oriented in the WNW-ESE direction and this moderate change in the inclination of the anticline axis perfectly explains the microlocations of all springs. The Ronek and Bele skale clusters are located on the southern side and the Izola cluster on the northern side of the limestone core of the Izola anticline.

Key words: *sulphur, submarine, karstic spring, geological structure, Gulf of Trst/Trieste*
Ključne besede: *žveplo, podmorski, kraški izvir, geološka tekstura, Tržaški zaliv*

The response of aquatic fauna to environmental conditions variability in Ghețarul de la Vartop cave (Apuseni Natural Park, Romania)

Odziv vodne favne na spremembe okoljskih pogojev v jami Ghețarul de la Vartop (Naravni park Apuseni , Romunija)

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Ice caves with permanent and temporary ice formations exists in mid-to-high latitude regions of the Northern Hemisphere, on elevations between 0 and >3000 m above sea level. In these caves besides other common restrictive factors of the subterranean realm the negative temperatures are likely to contribute significantly in shaping the structural pattern of both terrestrial and aquatic communities. In such caves, several rare and endemic species or glacial relicts strictly tied to cold microclimates habitat conditions have evolved. Aquatic dwellers inhabiting ice caves are likely to show resistance and have special physiological adaptation to cope with constantly low temperature. Ghețarul de la Vârtop cave is a short (340 m long) temporary ice cave located in the Apuseni Natural Park (northwest Romania). Here we aim to provide preliminary data on the environmental conditions and aquatic invertebrate communities present in percolation water and associated gours from this cave. The sampling design imply monitoring on a monthly basis over a period of 1.5 years of air temperature (hourly measurements using data loggers), water physico-chemistry and aquatic fauna communities' structures in order to depict the relationships among environmental condition fluctuations and the aquatic fauna. Aquatic fauna is represented by nematodes, oligochaetes and several crustacean species the majority stygobites, of which at least three are potentially new to science, i.e., Syncarida, Ostracoda, Cyclopoida, Harpacticoida and Amphipoda. The presence of Acanthocyclops reductus considered a Tertiary relict (warm water conditions) raise discussions on one side about its ability to have large range of tolerance to temperature and on the colonisation history at the regional level on the other. Investigations of cave aquatic fauna in caves with permanent and temporary ice offer hints to understand the ecology of the fauna, and also to further assess the mechanisms involved in adaptations of species to cope with constantly low-water temperatures.

Key words: *karst, stygofauna, speleobiology, percolating water, invertebrates, ice caves*
Ključne besede: *kras, stigofavna, speleobiologija, prenikla voda, nevretenčarji, ledene jame*

Enhancing Scholarship in Karst Hydrogeology through Cultural Exchange

Nadgradnja štipendijam v kraški hidrogeologiji s kulturnimi izmenjavami

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Groundwater provides more than 25% of fresh water used in the United States, while in Serbia groundwater supplies approximately 80% of public water use (Dieter et al. 2018; Polomcic et al. 2011). Concerns surrounding groundwater availability and contamination have motivated scientific studies across the globe to better characterize groundwater resources. The reliance on karst aquifers is a common issue shared by many countries, yet novel technologies that can better inform investigation of these critical resources are not always effectively communicated internationally. In 2019, Crawford Hydrology Lab (CHL), Cave Research Foundation, and Dr. Nenad Marić, University of Belgrade, identified an opportunity to address this issue through an international scholar program funded by the Trust for Mutual Understanding. Chief outcomes of this exchange include improved communication and respect creating a cultural frame of reference from which US and Serbian scientists can consider new approaches to managing karst aquifers. Interactions during this visit resulted in Dr. Marić receiving a Fulbright Scholar position to expand his expertise in hydrocarbon natural attenuation processes to the cave systems of Kentucky. The impact of these efforts has been far-reaching not only in terms of advancing understanding between scientists but also the research it supported. New discoveries include the hydrologic connection of Great Onyx Cave to Mammoth Cave proper, assisting in exploration efforts for the physical connection which would add more than six kilometers to the world's longest known cave. The endangered Kentucky cave shrimp was observed in a new drainage basin, which is of critical importance to expanding our knowledge of endangered species in the region and associated prioritization of water quality efforts. This exchange created a platform for support of additional research allowing for continued collaboration between CHL and eastern European scientists as we continue to better understand each other and the world around us.

Key words: *karst, hydrogeology, dye tracing, cave survey, Mammoth Cave National Park USA*
Ključne besede: *kras, hidrogeologija, sledilni poizkusi, pregled/nadzor jame, Narodni park Mammoth Cave USA*

Graphical modelling of karst aquifers and monitoring of karst springs to aid in the management of forested karst catchments, Vancouver Island, British Columbia, Canada

Grafično modeliranje kraških vodonosnikov in monitoring kraških izvirov kot pomoč pri upravljanju gozdnatih kraških zajetij, otok Vancouver, Britanska Kolumbija, Kanada

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Various approaches are being taken to model karst aquifers and monitor their associated karst springs at two sites on Vancouver Island - one close to Port Alberni and the other on nearby Quadra Island. Both sites have karst springs that are used as domestic water resources and have catchments that occur in areas of current forestry and other land use activities. The first approach has been to delineate the karst catchments by dye tracing and then monitor spring water quality and quantity parameters to characterize the nature of the karst aquifers over time. The second approach has been to apply the web-based karst aquifer mapping software, Visual KARSYS, to outline the 3D aquifer geometry, and to better understand groundwater flow and the associated geological structures and lithologies. Preliminary analysis of continuous spring-water flow, conductivity, temperature, and other parameters has indicated that the karst aquifers at both sites are dominated by input from streams that originate from allogenic (non-karst) catchments and have occasional water quality issues (e.g., turbidity events). Initial trials of graphical 3D modeling of the karst aquifers using Visual KARSYS software has highlighted the need for more and careful collection of selected field structural and lithological data to assist in the delineation of the subsurface geology. The results of this research and modeling are intended to better understand the nature of the karst aquifers at these two sites and the connections to their respective forested karst catchments. The findings will also be important for forest companies, where the cumulative effects of multiple harvested areas (or cutblocks) and forest roads on karst aquifers is poorly understood. Communicating ideas regarding subsurface flow in karst aquifers is a challenge and the 3-D modelling will greatly assist in explaining these concepts to both land users and forest managers.

Key words: *modelling, monitoring, karst aquifer, spring, forestry*
Ključne besede: *modeliranje, monitoring, kraški vodonosnik, izvir, gozdarstvo*

Holocene environmental records from Croatian speleothems

Holocenski okoljski zapisi iz hrvaških kapnikov

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Several speleothem studies from Croatian karst caves proved to be valuable archives of local to regional palaeoenvironmental changes on various time scales. Variations of oxygen and carbon stable isotope ratios (δ18O and δ13C) from eight stalagmites recovered from six caves demonstrated diverse responses to hydroclimate changes throughout the Holocene. The main reason for this diversity stems from their geographical distribution and specific locations: Nova Grgosova Cave (239 m a.s.l.) is in the continental part of Croatia, mid-Adriatic region is represented by the coastal Modrič Cave (32 m a.s.l.), mountainous Manita peć Cave (570 m a.s.l.) and Strašna peć Cave (74 m a.s.l.) on the island of Dugi otok, while the records from the southernmost part of Croatia are kept in Mala špilja (60 m a.s.l.) and Velika špilja (90 m a.s.l.) caves on Mljet Island. According to the long term

continuous or periodical monitoring of cave environmental settings and in accordance with other regional records, spelean carbonate δ13C is interpreted as a proxy for spring/summer environmental conditions. It is proposed that this proxy mainly reflects bioproductivity (i.e. microbial activity and vegetation density) which is at its highest in spring and summer. δ18O is interpreted as a proxy for autumn/winter conditions held to be linked to the rainfall amount variability. Starting from possible record of Younger Dryas, signals of some major hydroclimate events are more (e.g. 4.2 ka) or less (e.g. 8.2 ka) pronounced when compared to some other European records. Within Holocene Climate Optimum, around 7.4 ka, continental region experienced sudden drought, which is not clearly expressed in speleothem records from South Croatian coastal region. Additionally, human intervention into the natural landscape left anthropogenic signal, sometimes hiding or modifying the latest short-term (centennial) climatic variability throughout the last millennium.

Key words: *speleothems, stable isotopes, hydroclimate, Holocene, Croatia*
Ključne besede: *kapniki, stabilni izotopi, hidroklima, holocen, Hrvaška*

Cave in the Mežica mine

Jama v rudniku Mežica

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The Mežica lead-zinc mine is located in the northern Slovenian region of Carinthia (Koroška) in the Karavanke mountains. Mining took place in the Peca Massif, which consists of reef and lagoonal carbonate rocks belonging to the Middle Triassic (Ladinian) Watterstein Formation. The ore deposit formed in these carbonate rocks represents a Mississippi Valley Type (MVT) deposit. The main ore minerals are galena and sphalerite. During mining, one of the tunnels was dug into a 223 m long and 103 m deep natural cave investigated in 2021. It is important to note that the cave was almost completely flooded until World War II, when the artificial tunnel was dug to lower the local groundwater level due to mining activities. The uppermost parts of the cave are filled with material that collapsed along the fault zone. Downward follows a more spacious chamber with clastic material covering the floor. This chamber ends with collapsed boulders several meters in size, forming a vertical step 10 meters high, below which a steeply dipping debris fan has formed. The topmost deposit of the fan is fresh and was probably brought in by mining as tailings. The vertical step also marks the beginning of the huge collapse chamber with an area of 40 x 35 meters and a height of 28 meters. At the bottom, the chamber floor is levelled and consists of collapsed material and isolated boulders up to several meters in size. The chamber floor, including the collapsed material except for the tailings, is covered with up to half a meter thick sticky, yellowish-brown clay (containing varying amounts of calcite, dolomite, illite, chlorite and quartz, depending on the location), on which desiccation cracks 5 to 10 cm wide have formed. After a short ascent, the cave turns into a horizontal, rounded channel with a diameter of 1 to 3 meters, which at the end turns into a steeply inclined to vertical channel. Again, the floor is covered with clay and there is also collapsed material at the entrance and at the end. At the very bottom of the cave, there is a small opening between collapsed blocks that is half a meter in size and filled with water, probably representing the groundwater level. In the walls of the end channels, rock features characteristic of slow-flowing,

ascending water can be seen (e.g., cupolas, wall pockets, side niches, feeders, etc.). In some places, the walls of the lower channels are covered with calcite crystals of various shapes and habits, up to 1 cm in size, which predate all of the above sediments. Preliminary analyses found two phase secondary fluid inclusions in one type of the crystals. Most of the cave walls are weathered and covered by a dark brown to black coating which gives a dark appearance to the cave. This dark coating, which postdates calcite crystals and predates the sediments, is composed of ferromanganese oxides and also contains lead, zinc, copper, and various other trace elements. Since the cave is located about 500 m below the surface of the Peca Massif, it has no hydrological influence of vadose water percolating from the surface, moreover, no speleothems have been observed so far. The remoteness from the surface at 500 m depth, no natural entrance, the above mentioned features of the cave walls, two phase secondary fluid inclusions in calcite crystals indicate a hypogene speleogenesis of the presented cave. We assume that most of the cave was never naturally exposed to the vadose zone. To date, we do not know when and under what hydrogeochemical conditions the brownish crust and weathered wall rock formed, but most likely the cave sediments representing the final phase of cave development were deposited from "normal" groundwater in the phreatic and/or epiphreatic zone. We plan to continue the research in the near future.

Key words: hypogene cave, hypogene speleogenesis, hydrothermal crystals, Mežica mine, Slovenia
Ključne besede: *hipogena jama, hipogena speleogeneza, hidrotermalni kristali, rudnik Mežica, Slovenia*

Implementation of RI-SI-EPOS project - SLO KARST NFO

Izvedba RI-SI-EPOS projekta – SLO KARST NFO

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The RI-SI-EPOS project (Research Infrastructure-Slovenia-European Plate Observing System) provided new scientific equipment in solid Earth science for partner organizations: ZRC SAZU, GeoZS, IJS and UL FGG. The new research infrastructure of ZRC SAZU is primarily used at SLO KARST NFO site, which covers 1,000 m2 of territory between Postojna and Jelšane. ZRC SAZU is observer of EPOS NFO (Near Fault Observatory) international community. The area south of Postojna is one of the most seismically active areas in SW Slovenia. It is composed mostly of karstified Mesozoic carbonate rocks and partly of non-karstified Eocene flysch. The landscape has numerous karst features including caves, poljes, dolines, uvalas, karst springs, ponors, and karst periodical lakes, with typical karst underground water drainage. The Postojna flysch basin represents the hydrological divide between the Adriatic and Black Sea watersheds, which depends on regional active tectonics. The site development commenced with the installation of seven temporary seismic stations in the area, which were, together with other geoscientific equipment (gravimeter, 3D laser terrestrial scanner, GNSS antenna, TM72 extensometers, spectrometer for methane, drone) provided in 2020. With the new dense seismic network, it is possible to accurately determine locations and other seismic parameters that contribute to the understanding of the kinematics and dynamics of active faults in this area. In addition, in Postojna Cave methane measurements have been added to already existing cave microclimatic monitoring (organized since 2009) and the new TM72 extensometers have replaced older instruments as part of micro-displacement monitoring that has been ongoing since 2004. With new research infrastructure we are collecting a big amount of data based on FAIR principles (make data Findable, Accessible, Interoperable and Reusable) with the aim to be included in national and international database centres (https://www.youtube.com/watch?v=NM1so88QNgc).

Key words: *SLO KARST NFO, Postojna Cave, NW Dinarides, RI-SI-EPOS, Slovenia*
Ključne besede: *SLO KARST NFO, Postojnska jama, SZ Dinaridi, RI-SI-EPOS, Slovenija*

Uncovering the subsoil karst surface morphology

Odkrivanje morfologije podtalnega kraškega površja

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The bare karst surface in the North Adriatic region (Krk Island, Croatia) is specific for a large density and huge variety of negative karst surface morphologic features that are partially or completely filled with sediments so that the rough terrain appears entirely flat. The true roughness of the karst rocky surface and the potential existence of morphological features of considerable sizes was investigated by the ground-penetrating radar (GPR), a non-invasive geophysical method capable of distinguishing between materials with different permittivity as expected in the existing depressions in carbonate bedrock filled with clayey sediments. GPR profiles showed that the present vegetation and coverage with the weathered carbonate rock fragments is generally a relatively good indicator of the actual sediment accumulation thickness. The GPR profiling revealed a considerable thickness of some sediment accumulations with a rather small planar size. In such formations, the radargrams evidenced sub-vertical rocky walls which indicates that they might actually represent entirely sediment-filled shafts. On the contrary, larger sediment accumulations are, based on the GPR indications, mostly relatively shallow and reach the sediment thickness of approximately 2 m. We identified nearly 0.4 m² of sediment accumulations over an area of approximately 3 km², suggesting that 13% of the analysed karst surface is occupied by various surface features filled with sediments. Complete sediment filling of karst surface features indicates generally low vertical sediment conductivity of the karst in the study area. Partially sediment-filled dolines, on the contrary, suggest locally effective downward sediment transport into the karstified subsurface.

Key words: *karst geomorphology, subsoil karst, GPR, Dinaric karst*
Ključne besede: *kraška geomorfologija, podtalni kras, GPR, Dinarski kras*

Preliminary results on the sedimentation and speleogenesis of the cave Šimčev spodmol (Slavinski ravnik corrosional plain, SW Slovenia)

Preliminarni rezultati sedimentacije in speleogeneze jame Šimčev spodmol (Slavinski ravnik, JZ Slovenija)

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Šimčev spodmol is a small cave in the corrosional plain of Slavinski ravnik and a bypass channel to the Unroofed cave Loza. By itself it is a cave of minor importance, but in the context of the speleogenesis of studied contact karst area it plays a very important role. Our aim was to decipher its sedimentological record in order to understand the morphogenesis of the study area. We sampled a profile of allogenic sediments with flowstone and stalagmite in a side passage, and a flowstone dome at the entrance of the cave and the unroofed cave. Allogenic sediments were studied for mineralogical and paleomagnetic properties and paleontology, while the autochthonous deposits were sampled for paleomagnetic properties and U-series dating. We found that the majority of the allogenic sediment consists of quartz and illite (together 65–88%) and to a lesser extent to chlorites and plagioclase (together 10–35%), with the amount of the latter slowly decreasing in depth. Mineral composition of allogenic sediments is consistent with transport from the Postojna Basin flysch and shows strong weathering. Preliminary paleomagnetic results reveal both normal and reverse polarities. Subsequent rock magnetic analysis will help to clarify the primary carrier of magnetization. The paleomagnetic investigation shows eastward counter clockwise rotation more intensive than in the cave Markov spodmol (Zupan Hajna et al., 2020), located at the northern border of the Slavinski ravnik. In summary, the preliminary results from the cave Šimčev spodmol give us two distinct simultaneous phases of sedimentation: allogenic sedimentation within the epiphreatic zone which was confirmed by fauna remains, and sedimentation of the flowstone crust and speleothems in the vadose zone of cave development. This shows as, that the entrance to Šimčev spodmol was closed, while the 25 m lower inner part was still frequently flooded. This study with comparison with previous research (Zupan Hajna et al. 2008, 2020) has indicated, that the sedimentation of Šimčev spodmol is older than the allogenic sedimentation in Markov spodmol, whereas the formation of the Unroofed cave Loza is the oldest, which provides new insights into the speleogenesis of the Slavinski ravnik corrosional plain.

Key words: *allogenic sediment, speleothem, paleomagnetism, epiphreatic cave, contact karst*
Ključne besede: *alogeni sedimenti, kapnik, paleomagnetizem, epifreatična jama, kontaktni kras*

Insight into hydrothermal speleogenesis from combined use of conventional and clumped carbonate stable isotope analysis of cave walls and secondary calcite deposits

Vpogled v hidrotermalno speleogenezo na osnovi analize standardnih izotopov in izotopskih skupkov v vzorcih jamskih sten in sekundarno izločenega kalcita

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We demonstrate that by combined use of conventional and clumped stable isotope analysis of carbonates we can better constrain the character of the isotopic alteration of cave walls by thermal waters, as well as unambiguously identify different alteration events. On the example of Provalata Cave (N. Macedonia), we identify two different isotope alteration trends, reflecting two distinct hydrothermal events. The older, hotter one, caused lowering of the δ18O values, likely related to isotope diffusion, while the δ13C values remained unchanged. The younger one was related to the cave formation by low-temperature CO_2-rich thermal waters, with dissolution-reprecipitation as the alteration mechanism, causing decrease in δ18O values, and an increase in δ13C values. While most of the examples of cave wall isotope alteration reported in the literature show lowering of δ18O values and either unchanged or lowered δ13C values, our findings show a rare example of isotope alteration with lowered δ18O values and significantly increased δ13C values, the latter due to the dominantly metamorphic origin of the CO_2. We expect that such case is not a unique one and it is likely to be found at sites with high metamorphic CO_2 flux. Based on the stable isotope composition of the secondary calcite deposits we also show a non-linear thermal evolution of the hydrothermal cave system, suggesting that simple cooling, as usually assumed for such systems, is likely simplifying the evolution, especially for karst systems related to volcanic areas.

Key words: *hydrothermal caves, stable isotopes, clumped isotopes, isotope alteration, speleogenesis*
Ključne besede: *hidrotermalne jame, stabilni izotopi, izotopski skupki, spremembe izotopov, speleogeneza*

Cave Jama v Dovčku: through speleogenesis towards climate recontructions

Jama v Dovčku: preko speleogeneze do rekonstrukcije klime

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The Jama v Dovčku cave on the eastern edge of the Dinaric Karst region in Slovenia provides suitable conditions for the study of Holocene paleoclimatic events by dating stalagmites. However, in order to determine the context of stalagmite growth, a thorough speleogenetic reconstruction of the cave was undertaken. The cave entrance opens on the Gorjanci Hills about 300 m above the Krško Basin at the contact of Triassic dolostones and limestones. The cave, 316 m long and 54 m deep, consists of 5 different collapsed chambers connected by smaller passages. The passages dip towards SE according to the local strata, and the chambers are covered with boulders resulting from the disintegration of the original passages. Two smaller shafts, up to 20 m deep, extend beyond the bottom of the chambers. The boulders are mostly covered with stalagmites, which have cemented the boulders and represent the core of the last phase of cave formation. Some have already been fractured by tectonic activity as observed in earthquakes in the area. Field techniques included detailed identification of the cave and conducting terrestrial 3D laser scans of the cave. Rock samples were also collected from the subsurface and surface to provide information on the geologic background of the cave development. The samples were analyzed in detail using XRF to determine the composition of the samples. Dating of two sampled stalagmites was performed using the standardized 14C dating technique. The first dating of the stalagmites showed the relative stability of stalagmite growth in the Holocene from the last 11.2 ka to 1.3 ka.

Key words: *speleogenesis, 3D laser scan, stalagmite datation, XRF, Gorjanci Hills, Slovenia*
Ključne besede: *speleogeneza, 3D lasersko skeniranje, datacije stalagmitov, XRF, Gorjanci, Slovenija*

Drawing [with / as / by] Karst

Risanje [z / kot / od] kras

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Drawing is the initial act of architecture. This project explores the spatial ecologies of the karst forest ecosystems on Vancouver Island, testing architectural drawing conventions that learn from karsts, and become fluid in their depiction of edge, scale, and time. Line drawing has become an anthropogenic tool for architects to understand and record the world, yet these lines rarely occur in natural phenomena. In order to represent spaces that are beyond the human, this exploration seeks to reframe architectural drawing in relation to the geologic and ecologic forces of the earth, matter which is usually considered outside the concern of the field of architecture. Verbs associated with karst processes were explored as methods of writing. Eroding, etching, carving, aggregating, soaking, and erasing were all tested as ways to embed a more fluid understanding of time into drawing, creating active drawings that respond to the vast spatial and temporal scales of karst landscapes.

Key words: *drawing, karst, representation, coastal temperate rainforest, British Columbia, Canada*
Ključne besede: *risanje, kras, zastopanje, obalne temperature deževnega gozda, Britanska Kolumbija, Kanada*

Račiška pečina, cave sedimentary sequence studies (SW Slovenia)

Račiška pečina, študije jamske sedimentne sekvence (JZ Slovenija)

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The Račiška pečina cave sediment sequence represents chronostratigraphy and climate records from the late Pliocene to the Holocene. It is one of the best preserved cave records of paleoenvironmental changes of the last 3.4 Ma. The sedimentary sequence studied was mainly characterized by the deposition of flowstone layers in huge speleothem domes with long hiatuses that began to grow as the cave was detached from its hydrological function. Occasionally, the deposition of flowstone layers was interrupted by sedimentation of clay to silt material derived from the surface above the cave. The interlayered clastic clays contained a Pleistocene fauna (e.g. Ursus ex gr. Spelaeus, and Apodemus cf. atavus, Borsodia sp., Pliomys sp., and Clethrionomys cf. glareolus), in which specimens of the subterranean gastropod Zospeum sp. were also found. A detailed chronology of the Račiška pečina section based on magnetostratigraphy and isotope-oxygen stratigraphy was prepared and correlated with paleontological, U-series, and radiocarbon results. The section contains important and representative Pleistocene fauna, Pliocene to Pleistocene transition and Matuyama/Brunhes boundary, and climate change records. Exploration of the section has shown that speleothem domes contain a lot of different data that cannot be collected in a single borehole or stalagmite.

Key words: *karst, cave sediments, dating, magnetostratigraphy, Pleistocene fauna, climate change*
Ključne besede: *kras, jamski sedimenti, datiranje, magnetostratigrafija, pleistocenska favna, klimatske spremembe*

Cyanobacteria in underexplored karst and other extreme environments

Cianobakterije v neraziskanem krasu in drugih ekstremnih okoljih

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Cyanobacteria are pioneers and dominant organisms in many extreme habitats. Although they are phototrophic organisms, they are also found in low-light habitats, which are generally less studied than surface waters. For some species, their abundance and occurrence are influenced by human activities. The objective of this study was to investigate the occurrence of cyanobacteria in poorly studied extreme aerial and aqueous environments. Three types of samples were selected from different geographical areas: water, biofilm, and aerial microbial mat. Water samples were collected from springs, rivers, the sea, ice, cave dripwater, and wells. Biofilm samples were collected from springs and a karst cave. Microbial mats were collected from karst caves and facades. Molecular DNA analyses were performed to detect cyanobacteria: qPCR for the cyanobacterial 16S rRNA gene, which also detects plant chloroplast DNA, and PCR for the phycocyanin gene (intergenic spacer cpcBA), which is unique to cyanobacteria. The vast majority of the samples proved positive for the presence of phototrophs (16S rRNA), with the exception of some samples from deep wells and springs. The unequivocal presence of cyanobacteria (cpcBA) was detected in water samples from saline (Croatia), acidic (Serbia), karst (Italy) and non-karst (Georgia) springs, cave ice (Slovenia), a surface river (Italy) and the sea (Italy), karst (Slovenia) and non-karst (Georgia) dripwater, and deep wells (Georgia). Cyanobacteria were also detected in biofilm communities from sulphur springs (Slovenia), a cave (Slovenia), and a hyperalkaline spring (Serbia), and in most, but not all, light-exposed microbial mats from cave entrances, around lamps, and on facades (Slovenia). Overall, molecular methods allowed detection of cyanobacteria even in environments where their presence was not expected due to environmental factors. Our further analyses will reveal more details about their taxonomy and potential toxicity.

Key words: *microbial mat, biofilm, water, cave, PCR, qPCR*
Ključne besede: *mikrobiološka prevleka, biofilm, voda, jama, PCR, qPCR*


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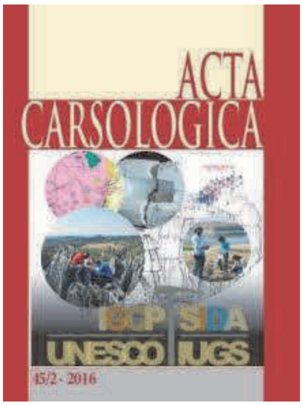

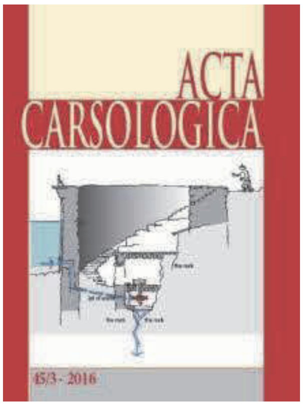

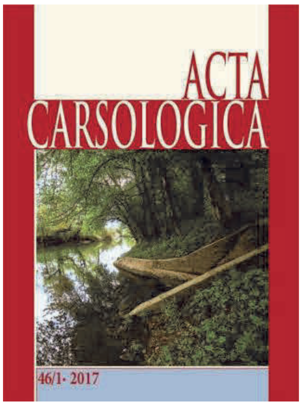

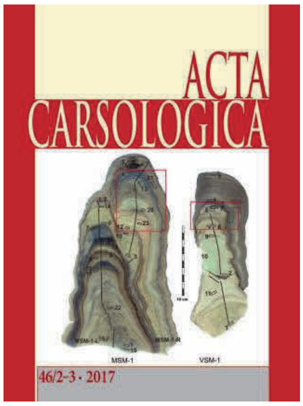

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*Papers will be considered for publications in one of the forthcoming regular issues. Therefore, no submission deadlines are given.

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The Karstology doctoral study programme is a world-wide unique programme which provides a comprehensive study of karst science, combining the study of the karst landscape, karst caves, karst hydrogeology, biology and ecology of karst in one course of study. It was designed for students who wish to gain deeper insight of this broadly integrated system of karst sciences. The fundamental objective of the programme is to produce two types of karstologists. The first is the karstologist-researcher who can conduct independent research on karst and karst phenomena from multiple aspects.The second type is the karstologist- manager who can apply the full knowledge of karst conveyed by narrowly specialized experts for different applications (economy, education, protection).

The programme was developed with researchers of the Karst Research Institute at Research Centre of the Slovene Academy of Sciences and Arts (ZRC SAZU) and is carried out by professors and researchers from Karst Research Institute and invited foreign professors, and is coordinated and managed by the University of Nova Gorica. Lectures and research take place in the premises of the Karst Research Institute in Postojna where students are provided all necessary professional and scientific support for their own research work. Successful functioning of doctoral study programme Karstology resulted in naming it in 2014 as the UNESCO Chair on Karst Education**.**

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UNESCO Chair on Karst Education
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